ORIGINAL ARTICLE

Safety and Efficacy Outcomes From a Single-Center Study of Image-Guided Percutaneous Microwave Ablation for Primary and Metastatic Lung Malignancy

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ABSTRACT

Introduction: Image-guided percutaneous microwave ablation (MWA) is becoming a more common treatment option for patients with primary and metastatic lung malignancies. Nevertheless, there is limited literature on the safety and efficacy of MWA compared with standard-of-care therapy, including surgical resection and radiation. This study will report the long-term outcomes after MWA for pulmonary malignancies and investigate the factors related to efficacy, including lesion size, location, and ablation power.

Methods: Retrospective single-center study analyzing 93 patients who underwent percutaneous MWA for primary or metastatic lung malignancies. Outcomes included immediate technical success, local tumor recurrence, overall survival, disease-specific survival, and complications.

Results: At a single institution, 190 lesions (81 primary and 109 metastatic) were treated in 93 patients. Immediate technical success was achieved in all cases. Freedom from local recurrence was 87.6%, 75.3%, and 69.2% and overall survival was 87.7%, 76.2%, and 74.3% at 1 year, 2 years, and 3 years, respectively. Disease-specific survival was 92.6%, 81.8%, and 81.8%. The most common complication was pneumothorax, which occurred in 54.7% (104 of 190) of procedures, with 35.2% (67 of 190) requiring a chest tube. No life-threatening complications occurred.

Conclusions: Percutaneous MWA seems safe and effective for treatment of primary and metastatic lung malignancies and should be considered for patients with limited metastatic burden and lesions less than 3 cm in size.

Keywords: Percutaneous thermal ablation; Microwave ablation; Lung cancer; Metastatic cancer

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Introduction

Lung cancer and lung metastases are significant causes of morbidity and mortality.[1,2] Traditional standard of care, wide surgical resection, although effective, carries significant risk and is not possible in all patients. Therefore, standard-of-care treatment for lung cancer has shifted in the past two decades, now favoring more targeted approaches, including limited resections such as wedge or segmental resection.[3–5] Within that paradigm, percutaneous thermal ablation (PTA) and stereotactic body radiation therapy (SBRT) have become increasingly common modalities for treatment of pulmonary malignancies.

PTA was found to have similar outcomes in overall survival and disease-specific survival to both SBRT and surgical excision.[6,7] Although PTA generally falls short of both modalities in reported local recurrence outcomes, it continues to offer distinct advantages. PTA leaves pulmonary function virtually unchanged, even in patients with a single lung[8]; this allows patients with tenuous pulmonary function to safely undergo definitive local management, active patients to continue their chosen lifestyle, and allows multiple retreatments in refractory cases. PTA also leaves the lung and mediastinum unirradiated and with minimal scarring, facilitating surgical resection or radiation therapy if subsequently required. In addition, the postoperative course is shorter and better tolerated compared with surgical excision.[9]

Multiple methods of percutaneous ablation are currently in use, including radiofrequency ablation (RFA), cryoablation, and microwave ablation (MWA). Each of these modalities comes with relative advantages and disadvantages. RFA is the oldest and most extensively researched modality and relies on heat generated by alternating current directed into the tissue through a multipronged probe.[10] RFA causes heat sink effect when applied near medium-to-large–sized vessels and has poor thermal penetration through charred tissue and aerated lung, limiting the effective ablation zone size.[10,11]

Cryoablation uses extreme cold to freeze the cells and multiple freeze-thaw cycles to cause cell death through membrane lysis and vascular obstruction. This process preserves extracellular collagen architecture making it safer around the bronchi, while also causing less pain and skin necrosis when used near the chest wall.[10] Cryoablation has long procedure times owing to the multiple necessary freeze-thaw cycles. Rates of pneumothorax are also higher than other thermal ablation modalities, likely due to its use primarily on the peripheral masses and frequent use of multiple probes.[11]

MWA is relatively new and has less published data relative to RFA. MWA generates heat by oscillating water molecules with electromagnetic waves in the microwave energy range.[12] It has shorter procedure times, causes less heat sink effect, and is not affected by thermal resistance in the charred tissue or aerated lung, in contradistinction to RFA.[10,11] The potential of more reliable, homogeneous, and larger ablation zones is promising, though this advantage has yet to yield significant clinical differences in published data, and MWA remains similar to RFA in terms of outcomes and complication profile.[13–17]

Here, we present a long-term retrospective analysis of safety and efficacy of patients with primary or metastatic lung lesions treated with percutaneous MWA at a single center.

Materials and Methods

Study Design

All patients who underwent percutaneous MWA for lung malignancy between December 2011 and December 2017 were reviewed for inclusion into this study. Approval was obtained from the institutional review board at the Cedars-Sinai Medical Center before data collection, and all patients gave written consent to use their deidentified medical information for research purposes.

Before the treatment, all patients were evaluated by a multidisciplinary team consisting of pulmonology, oncology, thoracic surgery, and interventional radiology. An in-person evaluation with the performing interventional radiologist was also performed with detailed history, physical examination, relevant laboratory studies, and computed tomography (CT) imaging of the chest. Patients were referred for MWA owing to medical comorbidities preventing surgery, tumor burden, or patient preference to avoid surgery.

Exclusion criteria for MWA included inability to tolerate general anesthesia and lung lesions greater than 4 cm in maximum axial diameter. Although most patients had limited or no metastatic disease beyond the ablation target area, several patients with extensive metastases were accepted on a palliative basis.

Ablation Procedure

All ablations were performed under general anesthesia, by a single interventional radiologist, using the NEUWAVE Microwave Ablation System with one or two NeuWave PR 15ga or 17ga probes (NeuWave Medical, Inc., Madison, WI). Preprocedural computed tomography scan was obtained for lesion localization and assessment of lesion size. Lesion size was evaluated on the basis of maximum axial diameter.

Ablation was initially performed for 5 minutes under continuous temperature and intermittent CT monitoring.

Further ablation was performed in 2 to 5-minute increments until the criteria for technical success was met or ablation time exceeded 15 minutes.

A limited postprocedural CT was obtained to assess for pneumothorax. Chest tube was placed for any symptomatic pneumothorax and all pneumothoraxes greater than 20% of hemithoracic volume. Postablation, the patients were observed in postanesthesia care unit for 4 hours. Radiographs were obtained at 1 and 3 hours to rule out pneumothorax. At 4 hours postprocedure, patients without complications were discharged home.

Patients with chest tubes or uncontrolled pain were admitted for observation. The chest tubes were placed to suction until the pneumothorax resolved radiographically. At that time, if there was no evidence of air leak, the chest tube was removed and patient was discharged home. All patients with persistent air leak 48 hours after admission were discharged with a Heimlich valve and short-interval follow-up.

Outcomes

Technical success, defined as complete coverage of the target lesion by new ground-glass opacity with a minimal margin of at least 5 mm, was determined by intraoperative CT. Maximum temperature, power, and duration were collected from the NeuWave Call Home ablation device records. Total ablation energy is reported in kJ and was determined by multiplying ablation time by average procedure power and number of probes used.

Local recurrence, defined as new or enlarging soft tissue (ground glass for some adenocarcinomas) at the ablation site, was determined by noncontrast chest CT at 1 month, 3 months, and 6 months in the first year after MWA, after which follow-up CT was obtained every 6 months. In patients with positive positron emission tomography (PET)-CT result before ablation, the first follow-up PET-CT was performed at 6 months and again every 6 months for a minimum of 2 years. For PET-CT, recurrence was defined as any lesion increasing in size or PET activity at the ablation site, with standard uptake value greater than 2.5 at 6 months or more postablation. All CTs and PET-CTs were evaluated by an expert body radiologist with at least 10 years in clinical practice, in addition to the interventional radiologist. Consensus between readers was achieved in all follow-up imaging (Representative examples of follow-up imaging are provided in figures 3 and figures 4).

Mortality and cause of death were determined through review of the medical center-integrated electronic medical record or through follow-up with the referring physician. Complications were evaluated through review of nurse and physician documentation in the electronic medical record.

Statistics

Evaluation was performed on all patients (190 lesions in 93 patients) with an additional subanalysis on patients with primary lung adenocarcinoma (77 lesions in 56 patients). Numerical variables were summarized by mean and SD or median and interquartile range (IQR) and range. Categorical variables were summarized by frequency and percentage.

Recurrence and survival times were estimated by the Kaplan-Meier method and were compared across groups by the log-rank test. For ordinal groups (e.g., tumor size), recurrence and survival also were compared using the trend test. Freedom from local recurrence was evaluated at the lesion level, whereas overall survival and disease-specific survival were evaluated at the patient level. For patients with multiple procedures, survival was calculated from the time of the first procedure.

Local recurrence was evaluated with respect to lesion and procedure characteristics. Lesions were grouped into size categories of less than 1 cm, 1 to less than 2 cm, 2 to less than 3 cm, and greater than or equal to 3 cm in maximum axial diameter; location categories of peripheral, middle, or central on the basis of axial distance from the hilum; quartiles on the basis of average ablation power; and evaluated by log-rank and trend tests.

A two-sided 0.05 significance level was used throughout. Statistical analysis was performed with SAS version 9.4 (SAS Institute, Cary, NC) and Microsoft Excel version 2108 (Microsoft Corporation, Redmond, WA).

Results

Study Patients

Retrospective analysis was performed on 93 patients (median age 70 y, IQR: 64–78, range: 33–90) who underwent CT-guided percutaneous MWA of 190 lung lesions (median size 12 mm, IQR: 9–18, range: 4–39)

Table 1. Patient Demographics

Patient Demographics	
Sex	41/93 M (44%)
	52/93 F (56%)
Average age at time of procedure	69 y (range: 33–90)
Average lung nodules per patient	2.0 nodules (range: 1–35)
Average maximum axial diameter	13.3 mm (range: 4–39)
Average approximate axial cross-sectional area	177 mm^2 (range: 16–1521)

F, female; M, male.

(Table 1). A total of 77 nodules were primary lung adenocarcinoma, four were primary lung squamous cell carcinoma, and 109 were metastases (including 51 tumors of epithelial origin, 56 sarcomas, and two melanomas). Additional subanalysis was performed on the primary lung adenocarcinoma subgroup of 56 patients with 77 lesions ablated. Histologic diagnosis with biopsy at time of procedure was performed for 16 lesions (16 of 190, 8.4%). Diagnosis in most cases was made on the basis of overwhelming clinical evidence, imaging data, and prior pathologic data for morphologically similar masses. Median follow-up time was 895 days (range: 118–2470 d).

In cases of local recurrence, multidisciplinary discussion between oncology, radiation oncology, pulmonology, thoracic surgery, and interventional radiology determined follow-up treatment. Patient comorbidities, tumor size and location, overall prognosis, and patient preference were all considered in determining appropriate follow-up treatment.

Three patients were excluded from analysis owing to immediate loss of follow-up. Patients within the analysis have marked heterogeneity in terms of oncologic and treatment history. Metastatic primaries include breast and gastrointestinal adenocarcinoma, melanoma, sarcomas of various etiologies, and several others (Table 2). Some patients underwent MWA as first-line treatment, whereas others were treated palliatively after first line treatment with one or more other modalities (Supplementary Appendix a). Multiple patients underwent more than one ablation procedure, either to address multiple lesions or to treat recurrent lesions. A total of seven patients (eight nodules) were retreated with MWA for local recurrence, with subsequent local recurrence occurring at five of the eight re-ablated nodules.

Table 2. Lesion Etiology

Lesion Etiology	Number (Nodules)	Frequency (of 190), %
Adenocarcinoma (breast)	2	1.1
Adenocarcinoma (colon)	5	2.6
Adenocarcinoma (esophagus)	5	2.6
Adenocarcinoma (lung)	77	40.5
Adenocarcinoma (rectum)	9	4.7
Carcinoid (lung)	1	0.5
Fibrolamellar carcinoma	2	1.1
HCC	2	1.1
Head and neck adenocystic carcinoma	13	6.8
Hemangioepithelioma	1	0.5
Invasive ductal carcinoma	4	2.1
Leiomyosarcoma (abdomen)	4	2.1
Leiomyosarcoma (left supra-acetabular)	1	0.5
Leiomyosarcoma (renal)	8	4.2
Leiomyosarcoma (thigh)	3	1.6
Leiomyosarcoma (uterine)	35	18.4
Metastatic melanoma	2	1.1
Renal cell carcinoma	4	2.1
SCC (lung)	4	2.1
Sarcoma (L calf)	1	0.5
Sarcoma (buttocks)	2	1.1
Sarcoma (left breast and chest wall)	2	1.1
Thymic carcinoma	2	1.1
Urothelial carcinoma	1	0.5

HCC, hepatocellular carcinoma; L, left; SCC, squamous cell carcinoma.

Ablation Procedure

Ablation was performed at varying power levels throughout this study. Initial ablations were performed at 60 W. After several pneumothoraxes, this was lowered out of an abundance of caution to 20 W and later incrementally increased to 65 W (Supplementary Appendices b and c). There was no significant relationship between pneumothorax rate and power.

Ablation time was generally limited to 15 minutes. Two cases were extended beyond 15 minutes of total ablation time owing to lower-than-expected temperatures. The median ablation time was 10 minutes (IQR: 7–14, range: 2–19), and mean ablation power was 42.9 W (SD = 13.8 W).

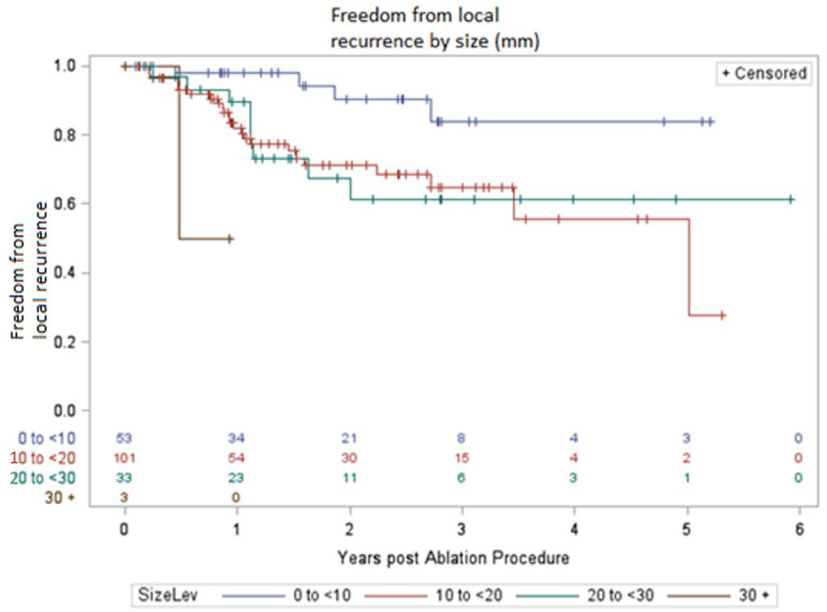
One probe was used for most of the lesions (132 of 190, 69.5%). Two probes were used for large lesions to increase the ablation zone, often required for lesions larger than 2 cm. Two probes were also used for smaller lesions if a single probe could not penetrate the lesion. In those cases, two probes were placed on either side of the lesion in a bracket configuration.

Efficacy

Immediate technical success was achieved in all cases. Freedom from local recurrence was 87.6%, 75.3%, and 69.2% at 1 year, 2 years, and 3 years, respectively, for all patients (Supplementary Appendix d). Freedom of local recurrence in the primary lung adenocarcinoma subgroup was similar at 86.4%, 70.4%, and 67.7%, respectively (Supplementary Appendix e).

Rate of local recurrence was statistically related to lesion size, with lesions less than 1 cm less likely to recur than lesions in the larger categories (log-rank $p = 0.006$, trend $p = 0.008$) (Fig. 1). There was also a statistically significant relationship between local recurrence and lesion location (Fig. 2). Measured from the hilum, lesions with a central or peripheral location were significantly more likely to recur compared with those in a middle location ($p = 0.009$ and $p = 0.026$, respectively).

Ablation power (W) was not significantly related to rate of recurrence (log-rank $p = 0.42$, trend $p = 0.92$) (Supplementary Appendix f). Increased rates of recurrence in the first quartile are suggested but not



Freedom from local recurrence by size			
	1 year	2 years	3 years
0 to <10 mm (n=53)	98.0%	90.2%	83.8%
10 to <20 mm (n = 101)	82.1%	71.2%	64.9%
20 to <30 mm (n = 33)	89.5%	61.4%	61.4%
30+ mm (n = 3)	50.0%	NF*	NF*

Figure 1. Freedom from local recurrence by size.

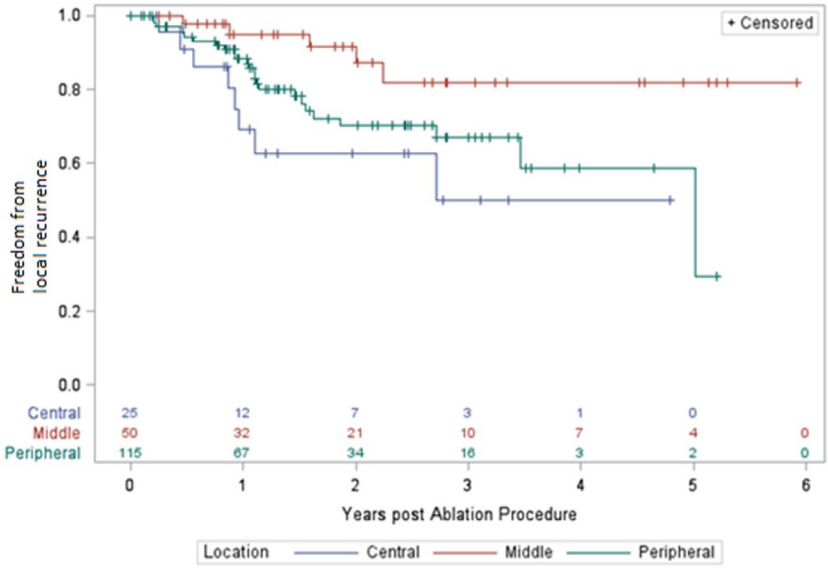
significant at *p* equals to 0.109. There was no statistically significant relationship between recurrence rate and ablation energy (kJ) or ablation time (s) (Figs. 3 and 4).

Survival

Overall survival was 87.5%, 76.2%, and 74.2% at 1 year, 2 years, and 3 years, respectively, for all patients (Supplementary Appendix g). Disease-specific survival was 92.6%, 81.8%, and 81.8% at 1 year, 2 years, and 3 years, respectively (Supplementary Appendix h). For the primary lung adenocarcinoma subgroup, overall survival was 83.6%, 74.9%, and 74.9% and disease-specific survival was 92.1%, 82.2%, and 82.2% at 1 year, 2 years, and 3 years, respectively (Supplementary Appendices i and j).

Complications

No cases of procedure-related mortality were observed. There were no cases of significant morbidity, including but not limited to new long-term oxygen requirement, air leak requiring surgery, postprocedural hypoxia requiring intubation, or hemorrhage requiring blood transfusion (see Supplementary Appendix k for complications).



Freedom from local recurrence by location			
	1 year	2 years	3 years
Central (n = 25)	69.0%	62.8%	50.2%
Middle (n = 50)	94.9%	91.5%	82.0%
Peripheral (n = 115)	88.4%	70.1%	66.9%

Figure 2. Freedom from local recurrence by location.

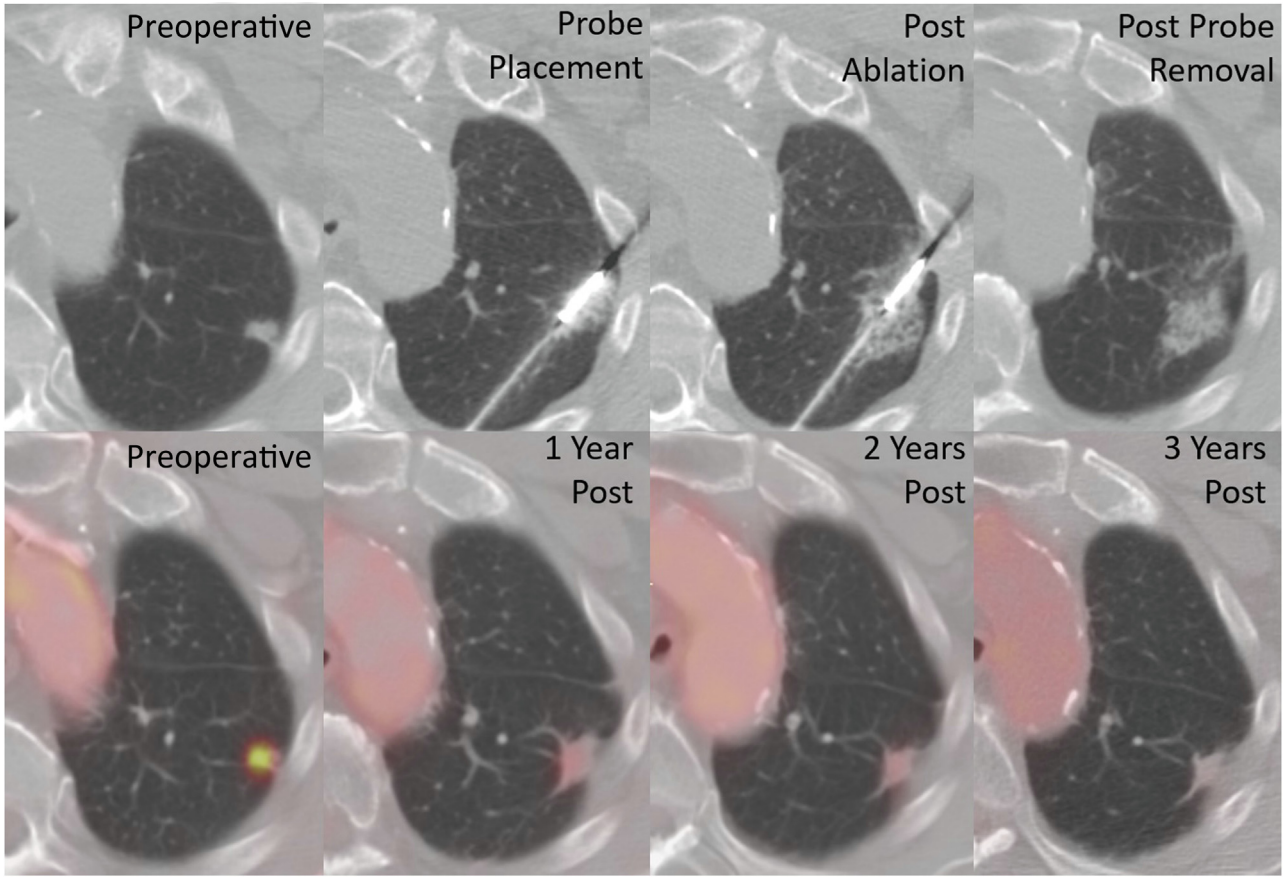


Figure 3. Preoperative and intraoperative CT and preoperative and postoperative PET/CT images revealing progressive decrease in size and hypermetabolism of left lower lobe metastasis from contralateral lung adenocarcinoma. CT, computed tomography; PET, positron emission tomography.

Two cases of phrenic nerve paralysis occurred in this series. In one patient, this was permanent but asymptomatic and discovered on subsequent chest radiographs. The second patient experienced temporary phrenic nerve paralysis, which resolved by 1-year post-procedure (proven by fluoroscopy). During that time, the patient experienced mild dyspnea but did not require supplemental oxygen.

Pneumothorax was the most common complication, occurring in 104 of 190 cases (54.7%). Chest tubes were placed in 67 cases (35.2%), 46 of which were removed in less than 24 hours (24.2%). Two patients received Heimlich valves for persistent air leak 48 hours after admission. There was no statistically significant difference in pneumothorax or other complication rates at varying power levels.

Discussion

Our rate of recurrence compares favorably with those previously published for RFA and MWA, ranging from 33% to 57% and 56% to 61% freedom from local recurrence at 3 years, respectively.[6,18–21] Overall survival also compared favorably, with 1-, 2-, and 3-year overall survival ranging from 77.6% to 95%, 58.47% to 83%, and 36% to 76% for RFA, and 65% to 89%, 44.9% to 63%, and 24.6% to 45.5% for MWA, respectively.[6,7,14,16,18,19,20,21–23] The favorable results relative to other PTA studies are likely partially attributable to patient demographics and exclusion of patients with lesions larger than 4 cm. Although early PTA study cohorts were comprised largely of medically inoperable patients, we had a number of relatively healthy patients undergoing PTA as first-line treatment owing to patient preference to avoid surgery.[6,22,23]

Our freedom from local recurrence was worse than typically reported after SBRT, which has been estimated as 97%, 92%, and 88% at 1 year, 2 years, and 3 years, respectively, for patients with stage I NSCLC.[6] Freedom from local recurrence was also worse compared with surgical wedge resection, which has reported 5-year disease-free survival of 91.6% to 97% for treatment of T1A NSCLC.[3,24]

Overall survival was generally better than SBRT, which has been reported as 85%, 68%, and 56% at 1

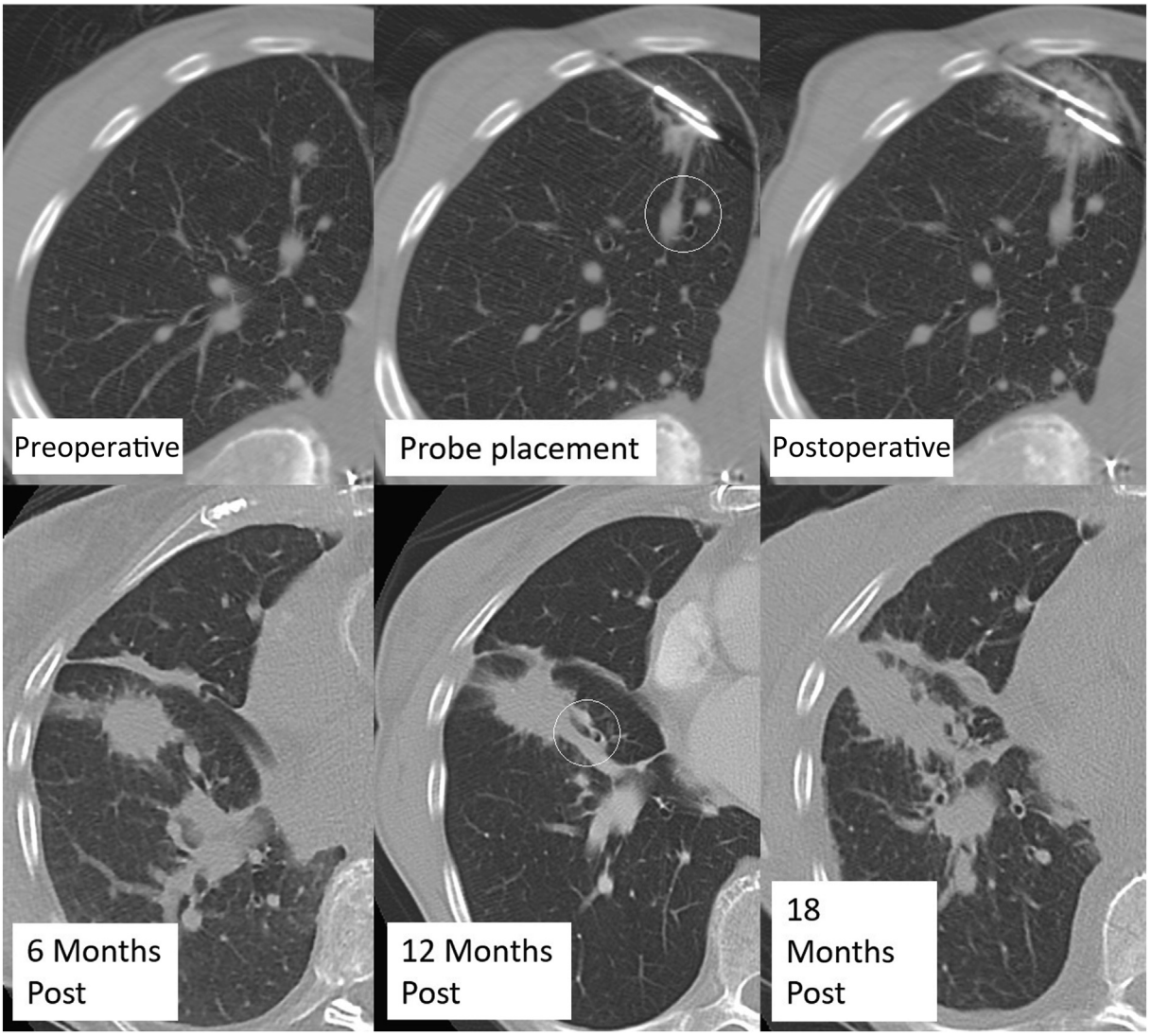


Figure 4. Preoperative, intraoperative, and postoperative CT images revealing progressive increase in size of right lower lobe adenocarcinoma after ablation, consistent with recurrence. Patient was rotated at time of ablation; note the relative location of the fissure and the adjacent vessels and airway (white circles). CT, computed tomography.

year, 2 years, and 3 years, respectively, for stage I NSCLC.[6] Our survival outcomes were similar to wedge resection, which is reported as 88.6% and 79.3% at 1 year and 2 years, respectively, and 71% at 5 years for stages IA to IB lung cancer.[3,7]

The high rate of pneumothorax in our cases (104 of 190, 54.7%) is likely multifactorial, with observational and procedural causes. All ablations in this study were performed under general anesthesia and positive pressure ventilation. Although this approach provides greater respiratory control and patient comfort, it likely increases risk of pneumothorax. Patients were also under close observation, with at least two postprocedural radiographs required before discharge. Furthermore, more than one-third of pneumothoraxes were subclinical, requiring no supplemental oxygen and resolving without chest tube. Of 67 chest tubes placed, 46 (68.6%) were removed in less than 24 hours, and no air leak requiring surgery occurred.

Several strategies were considered to decrease rates of pneumothorax in the future. Use of moderate sedation rather than general anesthesia with intubation has been hypothesized to decrease pneumothorax rates owing to the lack of positive pressure ventilation. Positioning the patient in the lateral decubitus position with the target lung down decreases respiratory motion and may also reduce rates of pneumothorax. Both approaches have their trade-offs, however; general anesthesia allows for greater control over breathing and more precise probe placement than moderate sedation, and lateral decubitus positioning limits the potential approach trajectories.

PTA for treatment of pulmonary malignancy offers many attractive benefits than surgery. It is far less invasive, requires shorter hospital stays, and incurs lower procedural costs.[5,9,25] Complications in PTA are typically less severe and easier to manage, and there are few reported long-term complications.[13,26] Although its rates of local control are often reported to be inferior to surgical treatment, overall survival is similar, despite the more severe medical comorbidities on average in patients undergoing PTA relative to those undergoing surgery.[7,9,14,15]

Because of the minimally invasive and precise nature of PTA, a wide range of patients can be treated with either curative or palliative intent or retreated in the case of tumor recurrence. Many of those patients would have no safe surgical alternative. Anecdotally, one patient at this institution exhibits normal pulmonary function tests despite receiving more than 35 separate MWA treatments in several years for pulmonary metastases from uterine leiomyosarcoma. This sort of palliative management would not be possible with SBRT or surgery.

PTA faces several limitations, specifically in treatment of large lesions. Lesion size greater than 3 cm has been consistently reported to increase rates of recurrence, and although we had few lesions larger than 3 cm, we saw similar effects in our study.[11,15,19,21,20,26,27]

We also found significantly increased rates of recurrence at central and peripheral lesions. Recurrence in central lesions is likely related to "zones of resistance" as described by Al-Hakim et al.,[28] which revealed smaller ablation zones with equal microwave energy deposited. These "zones of resistance" were generally near and inferior to the hilum and likely caused by heat sink effect from mediastinal vasculature. Recurrence in peripheral lesions was more surprising, but it is likely attributable to the difficulty in delivering adequate thermal energy to the peripheral lesions while avoiding damage to the pleura.

Synergy between systemic chemotherapy or immunotherapy and PTA is an exciting avenue of research to potentially improve the efficacy of PTA. The synergistic effect between chemotherapy and PTA has been attributed to increased local concentrations of pharmaceutical agents caused by focal hyperthermia during the ablation procedure.[10,11] A more targeted mechanism involving cryotherapy and immunotherapy has been proposed, in which the large quantity of intact antigen released during cryoablation potentiates the immune system to malignant cells.[10] Irreversible electroporation, a new technology which causes cell death through short electrical pulses, may further improve our ability to effectively treat neoplastic lung lesions with minimal damage to healthy tissue.[10,27]

This is the first study of its kind to investigate recurrence rates related to power in MWA. Although we found no significant relationship between power applied at time of ablation and rate of recurrence, there was a suggestion of increased rates of recurrence at the lowest quartile power level ($p = 0.109$). There was no significant increase in pneumothorax or other complications at power levels up to 65 W.

In conclusion, MWA seems to be a safe and effective treatment for malignant pulmonary lesions. Although local recurrence rates are worse than surgical resection or SBRT, overall survival is similar, the technique less invasive, and complications less severe. In general, patients who are not amenable to surgery with stage 1 primary pulmonary malignancy or pulmonary oligometastases, with lesions less than 3 cm in size, should be considered for PTA. Educating providers on its indications, strengths, and weaknesses will be imperative as PTA becomes a more common treatment option. Further research into synergy between systemic therapy and PTA and new techniques such as irreversible electroporation reveal exciting potential to further improve the percutaneous treatment of cancer.

Multiple limitations are present within this study. This was a single-center retrospective study with limited sample size, and, as such, patient demographics may not generalize to other patient populations. There was marked heterogeneity in patient demographics, lesion primary, stage, number of lesions ablated, and prior and concurrent treatment, which may diminish or exaggerate some outcomes we observed. Histologic confirmation was performed for a minority of treated tumors in this series, and lack of definitive tissue diagnosis could potentially have a small effect on survival and efficacy outcomes.

Our rationale for including patients with such a wide range of pathologies and comorbidities is our belief that thermal tumor destruction does not discriminate on the basis of a histologic basis and that the effectiveness of thermal ablation is not dependent on tumor composition, but is rather related to tumor size and adequate energy delivery. The variability in our patient population reveals the safety of this procedure across a wide spectrum of medical conditions and contexts.

Future prospective or large matched retrospective studies would be helpful in clarifying clinically significant differences between different MWA, surgery, and radiation therapy. No prospective comparative studies have been performed, and comparison of prior retrospective studies is complicated by demographic, procedural, and outcome heterogeneity. Further studies will be helpful in clarifying the role of MWA relative to SBRT

and limited surgery, and ongoing research coupling immunotherapy with PTA offers potential for exciting new treatment paradigms in the future.

CRediT Authorship Contribution Statement

Stephen M. Chan: Conceptualization, Investigation, Formal analysis, Writing—original draft, Writing—review and editing, Visualization.

Peter J. Julien: Conceptualization, Methodology, Resources, Data Curation, Writing—review and editing, Supervision, Projection administration, Funding acquisition.

Peter Kaganjo: Investigation.

Robert J. McKenna, Jr: Supervision, Writing—review and editing.

Charles Forscher: Supervision, Writing—review and editing.

Ronald Natale: Supervision, Writing—review and editing.

Robert N. Wolfe: Supervision, Writing—review and editing.

Kristi Butenschoen: Data curation.

Rene J. Siegel: Resources, Project administration, Funding acquisition.

James Mirocha: Formal analysis.

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Supplementary Data

Note: To access the supplementary material accompanying this article, visit the online version of the *JTO Clinical and Research Reports* at www.jtocrr.org and at 10.1016/j.jtocrr.2022.100454.

References

1. Islami F, Ward EM, Sung H, et al. Annual report to the nation on the status of cancer, Part 1: National Cancer Statistics. *J Natl Cancer Inst*. 2021;113:1648–1669.
2. Duma N, Santana-Davila R, Molina JR. Non-small cell lung cancer: epidemiology, screening, diagnosis, and treatment. *Mayo Clin Proc*. 2019;94:1623–1640.
3. Ijsseldijk MA, Shoni M, Siegert C, et al. Oncological outcomes of lobar resection, segmentectomy, and wedge resection for T1a non-small-cell lung carcinoma: a systematic review and meta-analysis. *Semin Thorac Cardiovasc Surg*. 2020;32:582–590.
4. Sihoe ADL. Video-assisted thoracoscopic surgery as the gold standard for lung cancer surgery. *Respirology*. 2020;25(suppl 2):49–60.
5. Hoy H, Lynch T, Beck M. Surgical treatment of lung cancer. *Crit Care Nurs Clin North Am*. 2019;31:303–313.
6. Bi N, Shedden K, Zheng X, Kong FS. Comparison of the effectiveness of radiofrequency ablation with stereotactic body radiation therapy in inoperable Stage I non-small cell lung cancer: a systemic review and pooled analysis. *Int J Radiat Oncol Biol Phys*. 2016;95:1378–1390.
7. Kwan SW, Mortell KE, Talenfeld AD, Brunner MC. Thermal ablation matches sublobar resection outcomes in older patients with early-stage non-small cell lung cancer. *J Vasc Interv Rad*. 2014;25:1–9.e1.
8. Hess A, Palussière J, Goyers JF, Guth A, Aupérin A, de Baère T. Pulmonary radiofrequency ablation in patients with a single lung: feasibility, efficacy, and tolerance. *Radiology*. 2011;258:635–642.
9. Welch BT, Brinjikji W, Schmit GD, et al. A national analysis of the complications, cost, and mortality of percutaneous lung ablation. *J Vasc Interv Radiol*. 2015;26:787–791.
10. Chu KF, Dupuy DE. Thermal ablation of tumours: biological mechanisms and advances in therapy. *Nat Rev Cancer*. 2014;14:199–208.
11. Palussière J, Catena V, Buy X. Percutaneous thermal ablation of lung tumors - Radiofrequency, microwave and cryotherapy: where are we going? *Diagn Interv Imaging*. 2017;98:619–625.
12. Vogl TJ, Nour-Eldin NA, Albrecht MH, et al. Thermal ablation of lung tumors: focus on microwave ablation [Thermoablation von Lungentumoren: Mikrowellenablation im Fokus]. *Rofo*. 2017;189:828–843.
13. Tsakok MT, Jones D, MacNeill A, Gleeson FV. Is microwave ablation more effective than radiofrequency ablation in achieving local control for primary pulmonary malignancy? *Interact Cardiovasc Thorac Surg*. 2019;ivz044.
14. Sun YD, Zhang H, Liu JZ, et al. Efficacy of radiofrequency ablation and microwave ablation in the treatment of thoracic cancer: a systematic review and meta-analysis. *Thorac Cancer*. 2019;10:543–550.
15. Nelson DB, Tam AL, Mitchell KG, et al. Local recurrence after microwave ablation of lung malignancies: A systematic review. *Ann Thorac Surg*. 2019;107:1876–1883.
16. Chi J, Ding M, Shi Y, et al. Comparison study of computed tomography-guided radiofrequency and microwave ablation for pulmonary tumors: a retrospective, case-controlled observational study. *Thorac Cancer*. 2018;9:1241–1248.
17. Macchi M, Belfiore MP, Floridi C, et al. Radiofrequency versus microwave ablation for treatment of the lung tumours: LUMIRA (lung microwave radiofrequency) randomized trial. *Med Oncol*. 2017;34:96.
18. Omae K, Hiraki T, Gobara H, et al. Long-term survival after radiofrequency ablation of lung oligometastases from five types of primary lesions: a retrospective evaluation. *J Vasc Interv Radiol*. 2016;27:1362–1370.
19. Simon CJ, Dupuy DE, DiPetrillo TA, et al. Pulmonary radiofrequency ablation: long-term safety and efficacy in 153 patients. *Radiology*. 2007;243:268–275.
20. Wolf FJ, Grand DJ, Machan JT, Dipetrillo TA, Mayo-Smith WW, Dupuy DE. Microwave ablation of lung

malignancies: effectiveness, CT findings, and safety in 50 patients. *Radiology*. 2008;247:871–879.
21. Healey TT, March BT, Baird G, Dupuy DE. Microwave ablation for lung neoplasms: a retrospective analysis of long-term results. *J Vasc Interv Radiol*. 2017;28: 206–211.
22. Yang X, Ye X, Zheng A, et al. Percutaneous microwave ablation of stage I medically inoperable non-small cell lung cancer: clinical evaluation of 47 cases. *J Surg Oncol*. 2014;110:758–763.
23. Lu Q, Cao W, Huang L, et al. CT-guided percutaneous microwave ablation of pulmonary malignancies: results in 69 cases. *World J Surg Oncol*. 2012;10:80.
24. Moon Y, Park JK, Lee KY, Kim ES. Prognosis after wedge resection in patients with 8th edition TNM stage IA1 and IA2 non-small cell lung cancer. *J Thorac Dis*. 2019;11:2361–2372.
25. Tandberg DJ, Tong BC, Ackerson BG, Kelsey CR. Surgery versus stereotactic body radiation therapy for stage I non-small cell lung cancer: a comprehensive review. *Cancer*. 2018;124:667–678.
26. Zheng A, Wang X, Yang X, et al. Major complications after lung microwave ablation: a single-center experience on 204 sessions. *Ann Thorac Surg*. 2014;98: 243–248.
27. Jahangeer S, Forde P, Soden D, Hinchion J. Review of current thermal ablation treatment for lung cancer and the potential of electrochemotherapy as a means for treatment of lung tumours. *Cancer Treat Rev*. 2013;39:862–871.
28. Al-Hakim RA, Abtin FG, Genshaft SJ, Kutay E, Suh RD. Defining new metrics in microwave ablation of pulmonary tumors: ablation work and ablation resistance score. *J Vasc Interv Radiol*. 2016;27:1380–1386.