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INTERVENTIONAL RADIOLOGY

ORIGINAL ARTICLE

Computed tomography-guided percutaneous thermal ablation of pulmonary metastases: safety, local tumor control, and factors associated with treatment failure—a single-centre experience

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PURPOSE

This study aimed to evaluate local tumor control, procedural safety, factors associated with treatment failure, and overall survival after computed tomography (CT)-guided percutaneous thermal ablation of pulmonary metastases.

METHODS

This retrospective single-center study included 21 consecutive patients (10 men, 11 women; median age 58 years) who underwent CT-guided thermal ablation of pulmonary metastases by cryoablation (n = 14), microwave ablation (n = 5), or radiofrequency ablation (n = 2). Local tumor control at 6, 12, and 24 months was estimated by Kaplan–Meier analysis, and factors associated with failure were assessed by univariate analysis. Median follow-up was 50.8 months.

RESULTS

Technical success was 100%. Kaplan–Meier local control was 89.9% at 6 months and 84.7% at both 12 and 24 months. Five patients (23.8%) developed local failure. On univariate analysis, larger tumor size ($P = 0.042$), ablation-zone diameter ($P = 0.008$), and ablation margin ($P = 0.009$) were associated with local failure; these associations are exploratory and hypothesis-generating. Pneumothorax, the only complication, occurred in 57.1% of patients, with no procedure-related mortality. The number of probes was not correlated with complications ($P = -0.033$, $P = 0.886$), and pneumothorax was not associated with nodule location (laterality $P = 1.000$, lobe category $P = 0.396$, pleural proximity $P = 0.659$). Five-year overall survival was 82.5% (95% confidence interval, 46.1–95.3%). Distant disease progression occurred in 66.7%, and repeat ablation of the treated lesion was required in 1 patient (4.8%).

CONCLUSION

CT-guided thermal ablation of pulmonary metastases achieved favorable local control with an acceptable safety profile. Larger tumor size was associated with local failure on univariate analysis. These associations are exploratory and, given the small number of events, require validation in larger multicenter cohorts.

CLINICAL SIGNIFICANCE

In real-world practice, CT-guided thermal ablation offers a safe, lung-preserving option for selected patients with pulmonary metastases, achieving durable local control and favorable long-term survival. Tumor size may help refine patient selection and procedural planning.

KEYWORDS

Tomography, X-ray computed, lung neoplasms, neoplasm metastasis, catheter ablation, cryosurgery

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The lung is one of the most frequent sites of hematogenous metastatic spread from solid tumors, most commonly from colorectal, thyroid, renal, breast, and soft-tissue sarcoma primaries.[1,2] Surgical metastasectomy has historically been the standard local treatment for selected patients,[3] yet many are unsuitable because of limited cardiopulmonary reserve, comorbidity, multifocal disease, or preference,[4] and minimally invasive alternatives can offer comparable local control in selected cases.[5]

Over the past two decades, image-guided percutaneous thermal ablation—radiofrequency ablation (RFA), microwave ablation (MWA), and cryoablation (CA)—has emerged as a parenchyma-sparing, repeatable alternative for primary and metastatic lung tumors.[2,6-8] Systematic reviews and multicenter series report local control of approximately 80%–90% for nodules ≤ 3 cm,[9,10] with durable control and favorable survival in well-selected oligometastatic colorectal disease.[11,12] International societies, including the Cardiovascular and Interventional Radiological Society of Europe (CIRSE) and the Society of Interventional Radiology (SIR), endorse ablation for appropriately selected patients with primary or secondary lung tumors,[7,8] and newer guidance platforms continue to improve feasibility and safety.[13]

Main points

- In 21 patients with pulmonary metastases, computed tomography-guided percutaneous thermal ablation achieved 100% technical success and durable local tumor control (Kaplan–Meier estimates of 89.9% at 6 months and 84.7% at 12 and 24 months), supporting its use as an effective lung-preserving local therapy in carefully selected patients.
- Long-term outcomes were favorable, with a 5-year overall survival of 82.5% (95% confidence interval: 46.1%–95.3%) over a median follow-up of 50.8 months.
- Larger tumor size was associated with local treatment failure on univariate analysis. Ablation-zone diameter and ablation margin were also associated with failure but were paradoxically larger in the failure group—most plausibly because larger tumors prompted more extensive ablation while the proportional margin remained insufficient—underscoring the importance of achieving an adequate margin relative to tumor size and meticulous procedural planning.
- Pneumothorax was the only complication, with no major complications or procedure-related deaths, and complication rates were unrelated to the number of probes or lesion location, confirming a favorable safety profile.

Despite growing experience, most evidence remains retrospective and heterogeneous,[14,15] and reports from Middle Eastern institutions with standardized outcome and safety reporting are scarce. As clinical adoption widens, institutional outcomes are needed to determine whether internationally reported benchmarks for local control and safety are reproducible across diverse populations and practice settings. We therefore report a single-center retrospective experience of computed tomography (CT)-guided percutaneous thermal ablation for pulmonary metastases. The primary objective is to assess local tumor control at 6, 12, and 24 months; secondary objectives are procedural safety, identification of factors associated with local failure (tumor size, number of nodules, ablation modality, number of probes, and lesion location), overall survival, patterns of disease progression, and the need for repeat ablation.

Methods

Study design and setting

This retrospective single-center cohort study was conducted at King Fahad Medical City between January 2019 and December 2025. The Institutional Review Board of King Fahad Medical City approved the study (institutional review board log number: 26-171/ date: June 22, 2026) and waived the requirement for informed consent owing to the retrospective design and use of anonymized data. Reporting follows the Strengthening the Reporting of Observational Studies in Epidemiology statement for observational studies.

Eligibility criteria

Consecutive adults (aged ≥ 18 years) with a histologically or clinically confirmed extra-pulmonary primary malignancy and pulmonary metastases treated by CT-guided percutaneous thermal ablation were eligible. Inclusion required no more than five metastatic nodules per patient, each ≤ 3 cm in maximum diameter on pre-ablation imaging, and ≥ 6 months of post-procedural imaging follow-up. Patients with a primary lung malignancy, uncontrolled extra-thoracic disease, suitability for surgical metastasectomy on multidisciplinary review, or contraindications to percutaneous intervention (including uncorrectable coagulopathy) were excluded. Eligible cases were identified from institutional radiology and oncology databases; all procedures were performed as routine clinical care following multidisciplinary discussion. These represent the study inclusion and exclusion criteria applied when assembling the cohort; because all patients were treated as routine clinical care, they closely mirror the institutional criteria used to select patients for ablation at multidisciplinary review, and no additional research-specific selection was applied beyond the availability of ≥ 6 months of follow-up imaging. The final cohort comprised the entire eligible population of 21 patients (Figure 1).

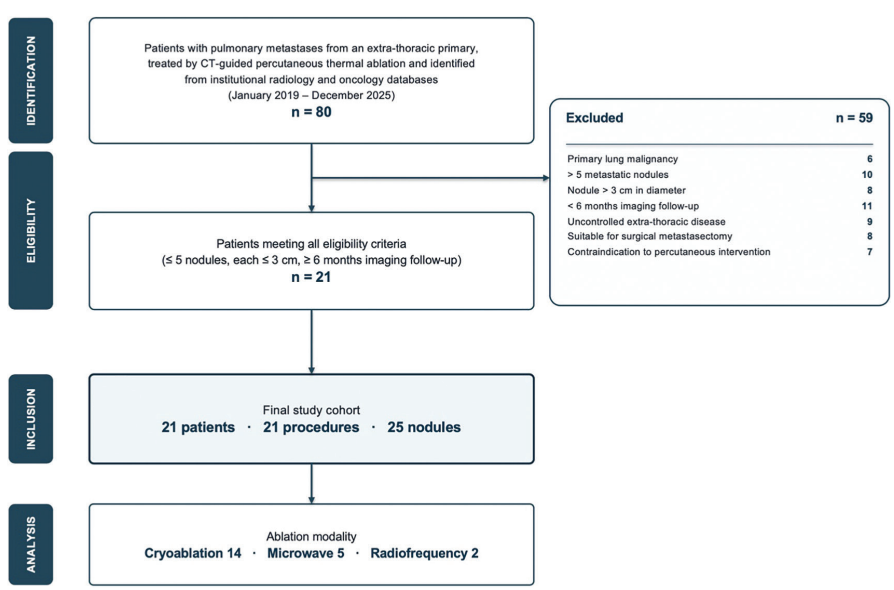

Figure 1. Flowchart of patient selection. Consecutive patients with pulmonary metastases from an extra-thoracic primary treated by computed tomography (CT)-guided percutaneous thermal ablation between January 2019 and December 2025 were identified from institutional radiology and oncology databases; of 80 patients identified, 59 were excluded for not meeting the eligibility criteria, yielding the final study cohort of 21 patients (21 procedures, 25 nodules). Each excluded patient was assigned to a single primary reason.

Ablation technique

All procedures were performed under CT guidance by experienced interventional radiologists using RFA, MWA, or CA. The ablation modality was selected at multidisciplinary review according to explicit lesion- and patient-related considerations. CA was preferred for lesions abutting or close to the pleura or chest wall (better tolerated, with real-time ice-ball visualization permitting precise margin monitoring), for lesions adjacent to critical structures where a well-demarcated ablation zone was desirable, and when multiple or larger nodules required careful margin control. MWA was preferred for larger or perivascular lesions, where its higher intratumoral temperatures and relative resistance to the heat-sink effect, together with shorter ablation times, were advantageous. RFA was reserved for small (typically ≤ 2 cm), well-circumscribed nodules situated away from large vessels and the pleural surface. Where more than one modality was suitable, the final choice also reflected device availability and operator experience. Probes were positioned to achieve complete lesion coverage with an adequate ablative margin, in accordance with standard protocols and manufacturer recommendations. The number of probes and the ablation parameters were individualized to each lesion's size, morphology, and proximity to critical structures.

Modality-specific protocols were applied as follows: RFA was performed using the Cool-tip™ RF Ablation System (Medtronic) with the manufacturer's recommended stepwise power-escalation lung protocol, aiming for complete tumor coverage with an adequate safety margin; MWA was performed using the Emprint™ Ablation System with Thermosphere™ Technology (Medtronic, Minneaplis, Minnesota, USA) following the manufacturer's lung ablation protocol, with power and ablation time selected based on lesion size; CA was performed using the CryoCare system (Varian) with a modified triple freeze–thaw protocol comprising a 3-minute freeze, a 3-minute passive thaw, a 7-minute freeze, a 3-minute passive thaw, and a final 10-minute freeze; the number of cryoprobes was tailored to achieve complete ice-ball coverage extending at least 5–10 mm beyond the tumor margins whenever anatomically feasible.

Data collection and follow-up

Clinical, procedural, and imaging data were extracted from electronic records and the picture archiving and communication system. Variables included demographics, Eastern Cooperative Oncology Group (ECOG) performance status, primary histology, prior systemic therapy, number and size of nodules, lobar location, distance from the pleura, ablation modality, number of probes, technical success, and immediate complications. Post-ablation follow-up most commonly uses contrast-enhanced CT, with non-contrast CT or positron emission tomography (PET)-CT when clinically indicated. All follow-up studies were re-evaluated for local control at the ablation site, recurrence at the ablation margin, and new pulmonary or extra-pulmonary disease, based on interval changes in lesion size, ablation-zone morphology, and enhancement. All follow-up studies were assessed for local control by a single radiologist with > 15 years of experience in thoracic imaging, who assigned the final local-control vs. local-failure classification. Because all assessments were made by a single reader, inter-observer agreement (Cohen κ) was not calculated; consistent with the retrospective design, the reader was not blinded to the ablation modality and had access to prior imaging and the original procedural reports at the time of assessment. Ablation-zone diameter was measured as the maximum diameter of the ablation zone on the earliest post-ablation contrast-enhanced CT on which the ablation zone was measurable, in the axial plane, at a non-standardized follow-up time point; the ablation margin was derived as (ablation-zone diameter–maximum tumor diameter)/2 under a concentric-sphere convention. Technical success (complete tumor coverage with an adequate ablative margin) was judged at the time of ablation on the immediate post-procedural imaging, whereas the ablation-zone diameter used for the margin calculation was taken from later follow-up CT, on which the ablation zone involutes; consequently, the small number of non-positive calculated margins reflect involution of the ablation zone at follow-up rather than incomplete coverage at treatment and are fully consistent with the 100% immediate technical-success rate. Multiplanar or three-dimensional volumetric assessment of the minimal ablative margin with image registration was not performed.

Outcome definitions

Local tumor control was defined as the absence of new or nodular enhancement at the ablation margin and no increase in treated-lesion size beyond expected post-ablation involution on serial imaging; findings suspicious for residual or recurrent tumor within or adjacent to the ablation zone were classified as local failure. Secondary outcomes were procedure-related safety (incidence and type of immediate complications), overall disease progression (new pulmonary or extra-pulmonary metastases), and the need for repeat ablation.

Statistical analysis

Analyses were performed using the SPSS software package. Descriptive statistics summarized patient and procedural characteristics. Complications were graded using the Common Terminology Criteria for Adverse Events Version 5.0 grading scale. Local tumor control and overall survival were estimated by the Kaplan–Meier method, with stratified comparisons by log-rank testing. Univariate associations with local failure were assessed using the Mann–Whitney U test for continuous variables and Fisher's exact test for categorical variables. Correlations between probe number and complications were examined with Spearman and point-biserial coefficients. A two-sided P value of < 0.05 was considered significant. Multivariable analysis was not performed because of the small sample size. Because 10 univariate comparisons (5 continuous and 5 categorical) were performed in a cohort with only five local-failure events, no adjustment for multiple testing was applied; under repeated testing at α: 0.05, approximately 1 comparison in 20 would be expected to reach nominal significance by chance alone. All P values are therefore reported as exploratory and hypothesis-generating rather than confirmatory. Because ablation modality was selected according to lesion characteristics and the modality subgroups are small and unequal, inter-modality outcome comparisons are presented descriptively and were not formally tested.

Results

Baseline characteristics

Twenty-one consecutive patients [11 women, 10 men; median age 58 years; interquartile range (IQR): 48–63] underwent 21 procedures for 25 pulmonary metastatic nodules. Baseline characteristics are summarized in Table 1. The most common primary was colorectal carcinoma (n = 12; 57.1%), followed by head and neck carcinoma (n = 3; 14.3%) and sarcoma (n = 2; 9.5%). All patients had received prior systemic therapy, and most had an ECOG performance status of 0 (n = 15; 71.4%). The median maximum nodule diameter was 10 mm (IQR: 8–13; range 3–23); 12 nodules (57.1%) measured

≤ 10 mm. Seventeen patients (81.0%) had a single nodule treated, and 4 (19.0%) had two nodules treated in one session. Ten procedures (47.6%) involved left-sided lesions and 11 (52.4%) involved right-sided lesions; the median distance from the pleura was 8 mm (IQR: 0–19), with 6 nodules (28.6%) abutting the pleura. Twenty patients (95.2%) were never-smokers and 17 nodules (81.0%) were of solid consistency; because both were near-uniformly distributed, they are reported as baseline descriptors only and were not entered into the association analysis.

Technical success and follow-up

Technical success (completion of the planned ablation with adequate target coverage) was achieved in all 21 procedures (100%). The median post-ablation zone diameter was 17 mm (IQR: 12–23), giving a median ablation margin of 3.5 mm (IQR: 1–6). Median follow-up from ablation to the most recent imaging was 50.8 months (IQR: 33.0–75.0; range: 10.4–95.1). No contrast enhancement within the ablation zone was seen in 20 of 21 evaluable cases (95.2%).

Local tumor control

At the most recent follow-up, the ablation zone showed expected post-ablation changes in 16 of 21 patients (76.2%), indicating sustained local control, and 5 patients (23.8%) had findings suspicious for residual or recurrent tumor (local failure). Post-ablation morphology was fibrotic or scar tissue in 7 cases (33.3%), persistent solid in 7 (33.3%), cavitary in 6 (28.6%), and ground-glass in 1 (4.8%). Among patients with imaging available at each time point, crude local control was 11 of 15 (73.3%) at 6 months, 14 of 17 (82.4%) at 12 months, and 10 of 12 (83.3%) at ≥ 24 months (Table 2). Kaplan–Meier estimates were 89.9% [95% confidence interval (CI), 65.3%–97.4%] at 6 months and 84.7% (95% CI: 59.5%–94.8%) at 12 and 24 months (Figure 2). The curve plateaued after 12 months, indicating that most failures occurred within the 1st year. The number of patients evaluable at 12 months (n = 17) exceeds that at 6 months (n = 15) because follow-up imaging was not obtained at fixed intervals: 3 patients underwent 12-month imaging without a study in the 6-month window (and 1 had a 6-month but not a 12-month study). Each landmark therefore reflects the patients actually imaged in that window rather than a strictly attritional cohort.

Table 1. Baseline patient demographics, tumor characteristics, and procedural details (n = 21)

Characteristic	Value
Patient demographics	
Age, median (IQR), years	58 (48–63)
Female sex, n (%)	11 (52.4)
Male sex, n (%)	10 (47.6)
ECOG performance status 0, n (%)	15 (71.4)
ECOG performance status 1, n (%)	2 (9.5)
ECOG performance status 2, n (%)	2 (9.5)
ECOG performance status 3, n (%)	1 (4.8)
Never-smoker, n (%)	20 (95.2)
Primary malignancy	
Colorectal carcinoma, n (%)	12 (57.1)
Head and neck carcinoma, n (%)	3 (14.3)
Sarcoma, n (%)	2 (9.5)
Other, n (%)	4 (19.0)
Tumor characteristics	
Maximum nodule diameter, median (IQR), mm	10 (8–13)
Size ≤ 10 mm, n (%)	12 (57.1)
Size > 10 mm, n (%)	9 (42.9)
Single nodule treated, n (%)	17 (81.0)
Two nodules treated, n (%)	4 (19.0)
Distance from pleura, median (IQR), mm	8 (0–19)
Abutting pleura, n (%)	6 (28.6)
Solid consistency, n (%)	17 (81.0)
Nodule location	
Left lower lobe, n (%)	7 (33.3)
Right lower lobe, n (%)	5 (23.8)
Right upper lobe, n (%)	4 (19.0)
Left upper lobe, n (%)	3 (14.3)
Right middle lobe, n (%)	2 (9.5)
Procedural details	
Cryoablation, n (%)	14 (66.7)
Microwave ablation, n (%)	5 (23.8)
Radiofrequency ablation, n (%)	2 (9.5)
Number of probes, median (IQR)	2 (1–3)
Ablation-zone diameter, median (IQR), mm	17 (12–23)
Ablation margin, median (IQR), mm	3.5 (1–6)

Data are n (%) or median (interquartile range). Ablation margin: (ablation-zone diameter − maximum tumor diameter)/2, representing the minimal rim of ablated tissue beyond the tumor edge under the concentric-sphere convention. Lobar location is reported per patient (index nodule). ECOG, Eastern Cooperative Oncology Group; IQR, interquartile range.

Procedural safety

Pneumothorax was the only procedural complication, occurring in 12 of 21 patients (57.1%); 7 (33.3%) were managed conservatively with observation, and 5 (23.8%) required chest-tube insertion (Table 3). No major complications (hemorrhage, infection, bronchopleural fistula, or procedure-related mortality) were recorded. Complication rates were broadly similar across modalities (Figure 3a). Eleven patients (52.4%) were discharged within 1 day, 2 (9.5%) at 2 days, and 8 (38.1%) required > 2 days.

Factors associated with local treatment failure

Univariate associations with local failure are shown in Table 4 and Figure 4. Among continuous variables, tumor size was larger in the failure group [median 13 mm (IQR: 13–17) vs. 9 mm (IQR: 8–11); U = 15; $P = 0.042$], as were the ablation-zone diameter [25 mm (IQR: 22–41) vs. 15 mm (IQR: 9–17); U: 8; $P = 0.008$] and the ablation margin [7 mm (IQR): 6–10.5] vs. 1.5 mm (IQR: 0.5–4.5); U = 8; $P = 0.009$]. The larger margins in the failure group likely reflect larger initial tumors that require more extensive ablation, rather than a causal effect of wider margins.

Among categorical variables, laterality showed the strongest univariate association: all 5 failures occurred in right-sided lesions, whereas none of the 10 left-sided lesions failed (Fisher $P = 0.035$; log-rank $\chi^2 = 8.29$, $P = 0.004$; Figure 5b). With only five events and no capacity for multivariable adjustment, this association is most plausibly confounded and is regarded as exploratory (see Discussion). Tumor size > 10 mm showed a numerically higher failure rate [44.4% vs. 8.3%; odds ratio (OR): 8.80; $P = 0.119$], and the size-stratified log-rank test approached significance (χ^2: 3.01; $P = 0.083$; Figure 5a). Lesions abutting the pleura trended towards higher failure (50.0% vs. 13.3%; OR: 6.50; $P = 0.115$). The number of treated nodules (OR: 1.08; $P = 1.000$), ablation modality (CA vs. other; OR: 2.40; $P = 0.624$), and number of probes (U: 42; $P = 0.862$) were not significantly associated with local failure. Local failure occurred in 0 of 5 MWAs, 4 of 14 CAs, and 1 of 2 RFAs. Because modality was selected according to lesion characteristics and the subgroups are very small, these raw fractions are presented only descriptively and were not formally compared (Figure 6).

Probe number, complications, and nodule location

There was no significant correlation between the number of probes and procedural complications, either overall (Spearman ρ: –0.033; $P = 0.886$; point-biserial r: –0.015; $P = 0.949$) or within the CA subgroup (Table 5; ρ: –0.118, $P = 0.689$), indicating that increasing probe number did not elevate complication risk in this cohort (Figure 3b). Likewise, pneumothorax was not associated with nodule location by laterality (60.0% left vs. 54.5% right; OR: 0.80; $P = 1.000$), lobe category (lower 66.7% vs. upper/middle 44.4%; OR: 0.40; $P = 0.396$), or pleural proximity (abutting 66.7% vs. non-abutting 53.3%; OR: 1.75; $P = 0.659$); the median distance from the pleura was 8 mm in both groups (U: 47; $P = 0.640$) (Table 6).

Table 2. Local tumor control at serial follow-up

Timepoint	Evaluated, n	Local control, n (%)	Local failure, n (%)	KM estimate, % (95% CI)
6 months	15	11 (73.3)	4 (26.7)	89.9 (65.3–97.4)
12 months	17	14 (82.4)	3 (17.6)	84.7 (59.5–94.8)
24 months	12	10 (83.3)	2 (16.7)	84.7 (59.5–94.8)
Overall	21	16 (76.2)	5 (23.8)	—

Crude rates are calculated among patients with imaging available at each time point; KM estimates account for censoring and give the cumulative probability of local control. KM, Kaplan–Meier; CI, confidence interval.

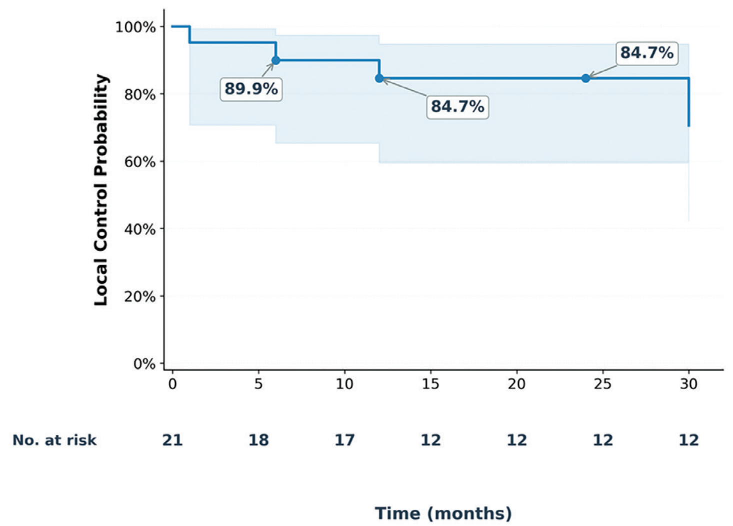

Figure 2. Kaplan–Meier curve of local tumor control after computed tomography-guided percutaneous thermal ablation of pulmonary metastases. The shaded area is the 95% confidence interval; annotations indicate cumulative local control at 6, 12, and 24 months.

Table 3. Procedural safety and complication profile (n = 21).

Outcome	n (%)	Severity
Technical success	21 (100)	—
Any complication	12 (57.1)	—
Pneumothorax (total)	12 (57.1)	—
Observation only	7 (33.3)	CTCAE Grade 1
Chest tube required	5 (23.8)	CTCAE Grade 2
Other complications	0 (0)	—
30-day mortality	0 (0)	—
Hospital stay ≤ 1 day	11 (52.4)	—
Hospital stay 2 days	2 (9.5)	—
Hospital stay > 2 days	8 (38.1)	—

CTCAE, Common Terminology Criteria for Adverse Events, version 5.0. Pneumothorax was the only complication observed; the any-complication rate, therefore, equals the pneumothorax rate.

Overall survival and disease progression

Five of 21 patients (23.8%) had died at data collection. Kaplan–Meier overall survival was 100% at 48 months, then fell to 82.5% (95% CI: 46.1%–95.3%) at 60 months (Figure 7); median survival was not reached. Despite favorable local control, overall imaging showed distant disease progression in 14 of 21 patients (66.7%), and 7 (33.3%) had a complete radiological response. Repeat ablation of the index lesion for local recurrence was performed in 1 patient (4.8%). Among the 5 patients (23.8%) with local failure, this single patient underwent repeat ablation of the treated site, whereas the remaining 4 did not undergo further local therapy and were managed with systemic treatment or imaging surveillance in accordance with multidisciplinary decisions, most often in the context of concurrent distant progression. Separate-

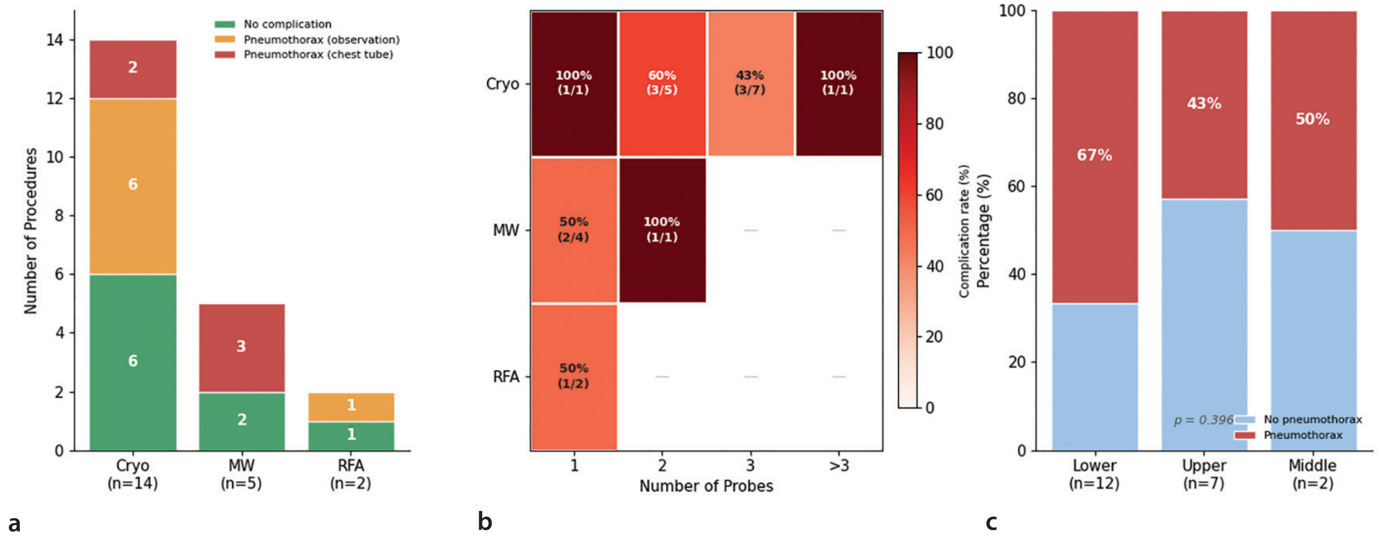

Figure 3. Procedural safety analysis. **(a)** Complication distribution by ablation modality, stratified by severity. **(b)** Complication rates by number of probes and modality. **(c)** Pneumothorax rates by lobe category. Cryo, cryoablation; MW, microwave ablation; RFA, radiofrequency ablation.

ly, 3 patients (14.3%) underwent ablation of a new pulmonary nodule representing distant intrapulmonary progression rather than index-site failure. Of the 16 patients (76.2%) with sustained local control at the treated site, these 3 had a new-site ablation, and the remaining 13 required no further intervention.

Representative cases

Representative imaging from two CA cases is shown. In a 35-year-old man with a right lower lobe metastasis from colorectal carcinoma treated with three cryoprobes, the procedure was complicated by pneumothorax requiring chest-tube insertion; follow-up CT and fluorodeoxyglucose (FDG) PET/CT at 3 months demonstrated interval enlargement and persistent metabolic activity within the treated lesion, consistent with local progression, and the lesion was re-treated with a second CA session (Figure 8). In a 67-year-old woman with a right upper lobe metastasis from sigmoid carcinoma treated with three cryoprobes and no immediate complication, follow-up CT at 3 months showed expected post-ablation change without residual enhancement, FDG PET/CT showed complete metabolic response, and CT at 12 months demonstrated a stable post-ablation scar without evidence of local recurrence (Figure 9).

Table 4. Univariate analysis of factors associated with local treatment failure.

Variable	Local control (n = 16)	Local failure (n = 5)	Statistic	*P* value
Continuous variables[†]				
Tumor size, mm	9 (8–11)	13 (13–17)	U: 15	0.042*
Distance from pleura, mm	10 (5–20)	0 (0–5)	U: 56	0.210
Number of probes	2 (1–3)	2 (1–3)	U: 42	0.862
Ablation zone, mm	15 (9–17)	25 (22–41)	U: 8	0.008*
Ablation margin, mm	1.5 (0.5–4.5)	7 (6–10.5)	U: 8	0.009*
Categorical variables[‡]				
Size > 10 mm	5/16 (31.3%)	4/5 (80.0%)	OR: 8.80	0.119
Right-sided location	6/16 (37.5%)	5/5 (100%)	OR: ∞	0.035*
Multiple nodules	3/16 (18.8%)	1/5 (20.0%)	OR: 1.08	1.000
Cryoablation	10/16 (62.5%)	4/5 (80.0%)	OR: 2.40	0.624
Abutting pleura	3/16 (18.8%)	3/5 (60.0%)	OR: 6.50	0.115

*Statistically significant ($P < 0.05$). [†]Continuous variables: median (IQR), Mann–Whitney U test. [‡]Categorical variables: n/N (%), Fisher exact test. IQR, interquartile range; OR, odds ratio; U, Mann–Whitney U statistic.

Table 5. Correlation between the number of probes and complications, by ablation modality

Modality	n	Spearman ρ	P	Point-biserial r	*P*
Cryoablation	14	−0.118	0.689	−0.113	0.700
All modalities	21	−0.033	0.886	−0.015	0.949

The microwave (n = 5) and radiofrequency (n = 2) subgroups were too small for meaningful correlation and are omitted. Spearman's rank and point-biserial correlations assessed the association between the number of probes (ordinal) and complication occurrence (binary).

Discussion

In this single-center cohort of 21 consecutive patients, CT-guided percutaneous thermal ablation of pulmonary metastases achieved Kaplan–Meier local control of 89.9% at 6 months and 84.7% at 12 and 24 months, a 100% technical success rate, 5-year overall survival of 82.5%, and an acceptable safety profile with pneumothorax as the only complication. Tumor size, right-sided laterality, ablation-zone diameter, and ablation margin were associated with local failure on univariate analysis; given the small number of events and the multiple comparisons performed without correction, these are exploratory associations rather than independent predictors, with implications for procedural planning and patient selection.

These local control rates are consistent with the broader literature, in which Matsui et al.[2] reported approximately 80%–90% control across most studies. In the Evaluating Cryoablation of Metastatic Lung/Pleura Tumors in Patients—Safety and Efficacy (ECLIPSE) trial of CA, de Baère et al.[16] reported control of 96.6% at 6 months and 94.2% at 12 months, and their largest RFA series (566 patients, 1,037 metastases) reported 89.0% at 4 years;[9] a meta-analysis of 1,804 patients estimated 91% at 1 year.[10] Our 84.7% at 12 months falls within this range, given the heterogeneity of primaries and inclusion of all three modalities. The plateau after 12 months, with no subsequent failures, mirrors findings from Zhong et al.[11] and Hasegawa et al.[12] and suggests that patients with local control at 1 year are likely to maintain durable control, which may inform surveillance scheduling. The predominance of colorectal carcinoma (57.1%) aligns with the literature;[2] the somewhat lower crude control in our series (76.2%) likely reflects larger tumors (up to 23 mm) and a heterogeneous primary mix including head and neck carcinoma and sarcoma.

Factors associated with local failure

Larger tumor size as a factor associated with failure (median 13 vs. 9 mm; $P = 0.042$) is among the most consistent findings in the ablation literature.[6,9,17] The biological basis is well established: larger tumors require more energy and are less likely to achieve adequate margins, particularly near large vessels where the heat-sink effect reduces efficacy.[7] This supports the CIRSE and SIR recommendations that the best candidates have tumors ≤ 3 cm, preferably ≤ 2 cm.[7,8] The significant associations of ablation-zone diameter ($P = 0.008$) and ablation margin ($P = 0.009$) with failure are paradoxical in direction—larger zones and margins occurred in the failure group—most plausibly because larger tumors prompted more aggressive ablation, whereas the proportional margin remained insufficient. This is consistent with evidence that a margin of < 2–5 mm predicts progression and that a minimum margin of 5–10 mm optimizes control,[18-20] underscoring the value of intra-procedural three-dimensional margin assessment.[21] This paradox also highlights a measurement limitation: absolute margins in millimetres do not account for tumor size, so a proportional margin (margin relative to tumor diameter) is more informative in a heterogeneous cohort. Moreover, the diameter-based, concentric-sphere calculation used here cannot capture the true minimal ablative margin, which may be insufficient at a single point even when the mean margin appears adequate; multiplanar or volumetric margin assessment with image registration would address this.

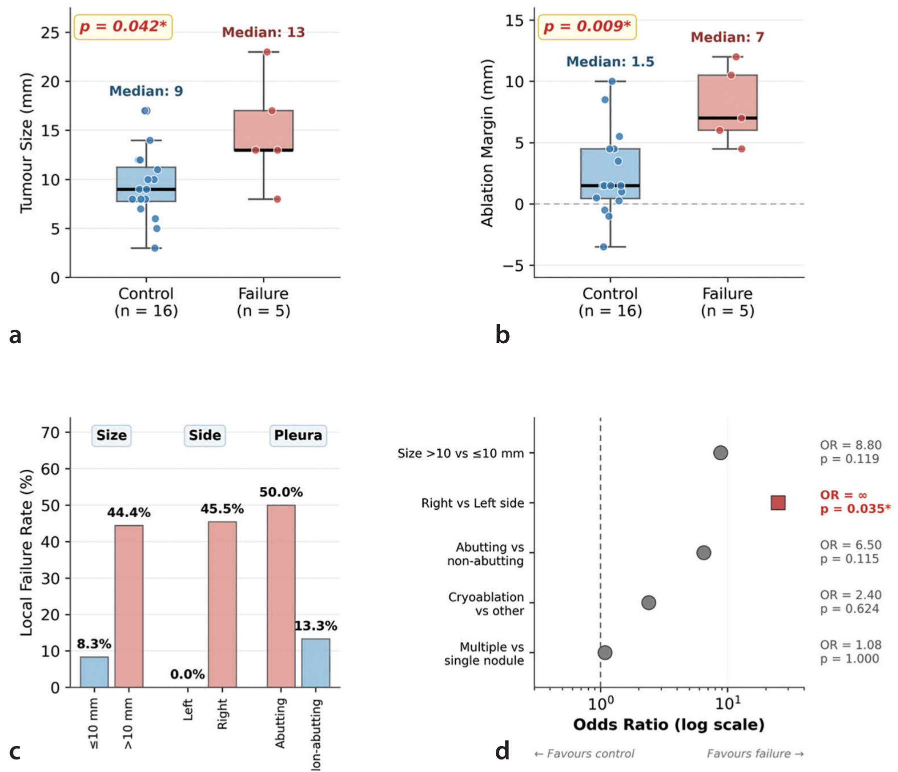

Figure 4. Factors associated with local treatment failure. **(a)** Tumor size by group ($P = 0.042$). **(b)** Ablation margin by group ($P = 0.009$). Non-positive values in a few control cases reflect ablation zones measured on involuted follow-up imaging and do not indicate incomplete coverage; technical success was assessed on the immediate post-ablation imaging (see Methods and Limitations). **(c)** Local-failure rates by category. **(d)** Forest plot of odds ratios for categorical variables. OR, odds ratio.

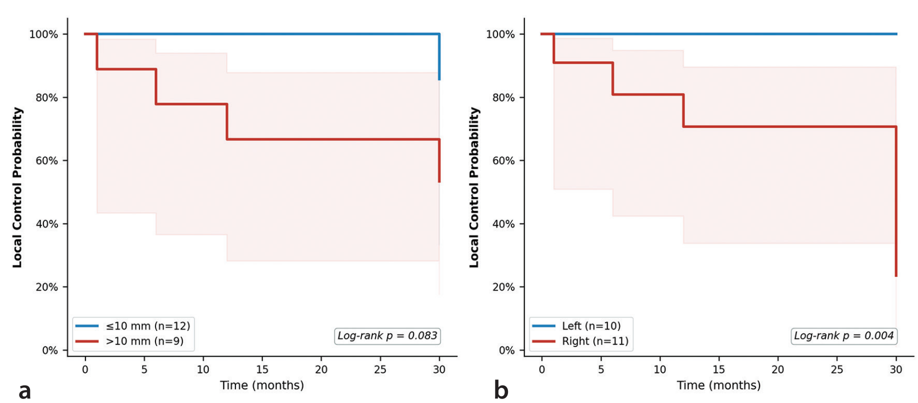

Figure 5. Kaplan–Meier local control stratified by **(a)** tumor size (log-rank $P = 0.083$) and **(b)** laterality (log-rank $P = 0.004$).

Table 6. Association between pneumothorax and nodule location.

Location factor	Pneumothorax, n (%)	No pneumothorax, n (%)	OR	P
Laterality				
Left (n = 10)	6 (60.0)	4 (40.0)	0.80	1.000
Right (n = 11)	6 (54.5)	5 (45.5)		
Lobe category				
Lower (n = 12)	8 (66.7)	4 (33.3)	0.40†	0.396
Upper/middle (n = 9)	4 (44.4)	5 (55.6)		
Pleural proximity				
Abutting (n = 6)	4 (66.7)	2 (33.3)	1.75	0.659
Non-abutting (n = 15)	8 (53.3)	7 (46.7)		

OR, odds ratio (Fisher's exact test). †OR for lower vs. upper/middle lobe. No association was significant at the 0.05 level.

An unexpected finding was the apparent association between right-sided location and local failure: all five failures were right-sided, whereas no left-sided lesion failed (Fisher $P = 0.035$; log-rank $P = 0.004$). To our knowledge, laterality has not previously been reported as a factor associated with local control after lung ablation. Emerging evidence from other thoracic treatments suggests laterality can influence outcomes—McWilliam et al.[22] linked laterality to survival after radiotherapy, and Yang et al.[23] found laterality-related survival differences after ablation in a Surveillance, Epidemiology, and End Results Program analysis. Plausible mechanisms include the larger right-lung volume and pulmonary blood flow (enhancing the heat-sink effect) and the more complex three-lobe segmental anatomy. Importantly, however, this association is not supported by any established biological rationale in the current ablation literature and rests on only five failure events. With such a small sample and no capacity for multivariable adjustment, laterality is most likely acting as a surrogate for coexisting, unmeasured, or imbalanced risk factors—such as differences in tumor size, lobar distribution, or pleural proximity between the two sides—rather than representing a genuine independent effect. The mechanisms proposed above are therefore speculative. This finding should be interpreted with considerable caution as hypothesis-generating only, and would require prospective, adequately powered, multivariable-adjusted multicenter studies before any inference could be drawn.

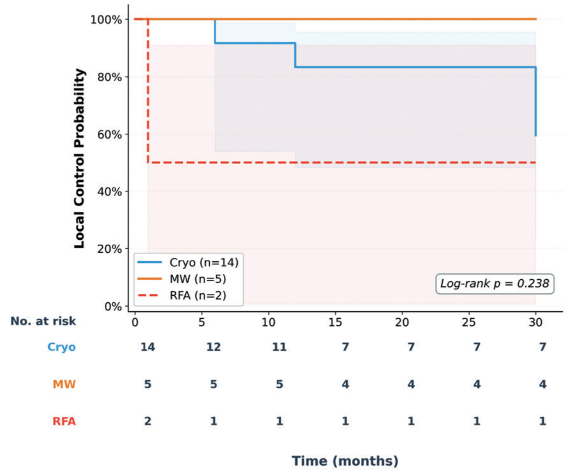

Figure 6. Kaplan–Meier local control stratified by ablation modality (descriptive; not formally compared). Cryo, cryoablation; MW, microwave ablation; RFA, radiofrequency ablation.

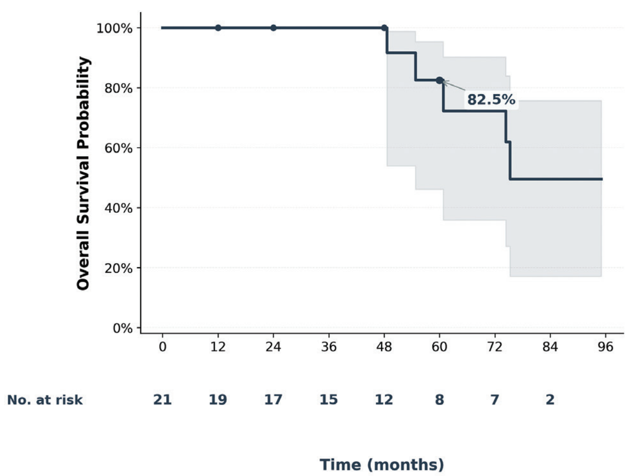

Figure 7. Kaplan–Meier curve of overall survival; the 5-year estimate was 82.5% (95% confidence interval: 46.1%–95.3%).

Safety

Pneumothorax was the only complication (57.1%), with chest-tube drainage in 23.8% of cases. Reported pneumothorax rates range widely—Welch et al.[24] reported 38.4% nationally and Hiraki et al.[25] 52% after RFA, with 9.8% requiring drainage; the ECLIPSE CA chest-tube rate was 18.8%.[16] Our slightly higher rate likely reflects the predominant use of CA (66.7%), which often involves multiple pleural punctures, and the inclusion of subpleural lesions (28.6% abutting the pleura). No major complications or procedure-related deaths occurred, consistent with reported mortality of < 1%.[26] Probe number was not correlated with complications (ρ: -0.033; $P = 0.886$), in contrast to Kim et al.;[27] power was limited by the narrow probe range (median 2) and small sample, and our data align with Zhu et al.[28] in suggesting that tumor-related factors outweigh probe count. No association was found between pneumothorax and location, which differs from that reported by Nour-Eldin et al.,[29] again likely reflecting the sample size and the high baseline pneumothorax rate.

Survival, progression, and modality

The 5-year overall survival of 82.5% compares favorably with pooled estimates of approximately 50%–55%,[9,10,30] likely reflecting favorable single-center selection (oligometastatic disease, small median tumor size, 71.4% ECOG 0) and long median follow-up (50.8 months). Distant progression in 66.7% underscores the systemic nature of metastatic disease and the role of ablation within a multimodal strategy: as de Baère et al.[16] noted, disease control relates more to new distant metastases than to local progression.[9] The low same-lesion re-treatment rate (4.8%) compares favorably with prior reports[14] and reflects the high technical success and adequate margins achieved. Because the ablation modality was selected according to lesion characteristics, the treated tumors differed systematically in baseline risk; inter-modality outcomes are therefore reported descriptively and were not formally compared, and the raw failure fractions (0/5 MWA, 4/14 CA, 1/2 RFA) should not be read as a head-to-head efficacy comparison. This descriptive picture is broadly consistent with comparative studies,[15,31] although some series report advantages for MWA in selected settings.[32] CA—our predominant modality—offers real-time ice-ball visualization and less procedural pain, which may contribute to the high technical success observed.[7]

This study contributes the following: it offers real-world, single-center data complementing larger multicenter series; it reports an exploratory, hypothesis-generating association of right-sided laterality with local failure that most likely reflects confounding; it reinforces the importance of ablation-zone and margin assessment;[18,19] it provides detailed probe–complication and location–pneumothorax analyses often missing from the literature; and it adds long-term outcomes (median follow-up 50.8 months; 5-year survival 82.5%). These findings support thermal ablation for oligometastatic lung disease in patients unsuitable for resection, in line with SIR, CIRSE, and National Comprehensive Cancer Network guidance.[7,8,33] A comparison with key published series is summarized in Table 7.

This study has several limitations. The retrospective, single-center design introduces selection bias and limits generalizability; the small sample size (n = 21) restricts power and precludes multivariable analysis;

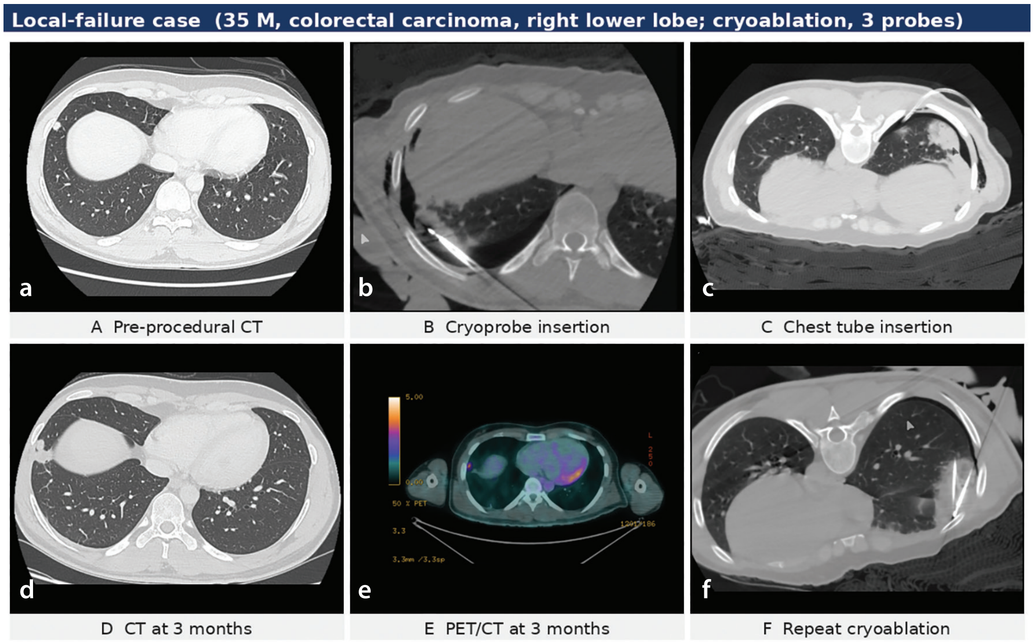

Figure 8. Computed tomography-guided cryoablation (CA) of a right lower lobe metastasis (colorectal carcinoma) with local progression at 3 months, treated by repeat CA; the immediate pneumothorax in **(c)** was managed with a chest tube. **(a)** Pre-procedural axial computed tomography (CT) lung window demonstrating a right lower lobe pulmonary metastasis. **(b)** Intraprocedural CT showing placement of cryoprobes within the target lesion. **(c)** Immediate post-procedural CT demonstrating a pneumothorax, managed with chest tube insertion. **(d)** Follow-up contrast-enhanced CT at 3 months demonstrated interval enlargement of the treated lesion, concerning for local tumour progression. **(e)** FDG PET/CT performed at 3 months showed persistent increased metabolic activity within the treated lesion, confirming residual viable tumour. **(f)** Repeat CT-guided cryoablation performed for local tumour recurrence. FDG, fluorodeoxyglucose; PET, positron emission tomography.

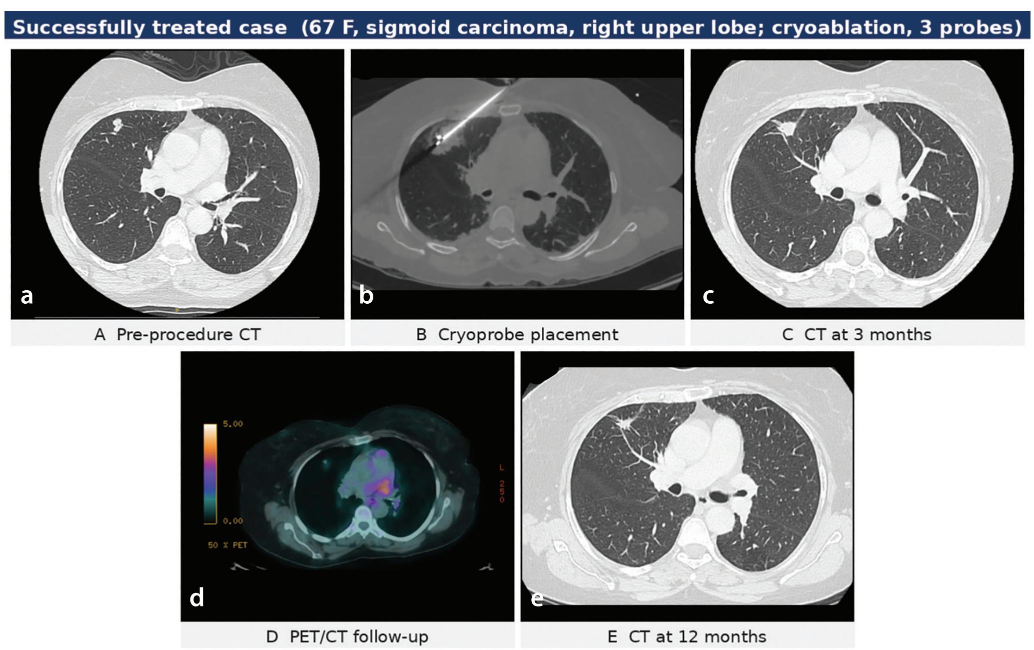

Figure 9. Successful computed tomography (CT)-guided cryoablation of a right upper lobe metastasis (sigmoid carcinoma) with complete metabolic response and durable local control to 12 months. **(a)** Pre-procedural axial CT demonstrating a right upper lobe pulmonary metastasis. **(b)** Intraprocedural CT demonstrating accurate placement of cryoprobes within the lesion prior to cryoablation. **(c)** Follow-up contrast-enhanced CT at 3 months demonstrated the expected post-ablation changes, with no residual enhancement. **(d)** FDG PET/CT at 6-month intervals demonstrating complete absence of metabolic activity within the treated lesion, consistent with complete response. **(e)** CT chest obtained 12 months after cryoablation, demonstrating a stable post-ablation scar without evidence of local recurrence. FDG, fluorodeoxyglucose; PET, positron emission tomography.

Table 7. Comparison of the present study with key published series on thermal ablation of pulmonary metastases

Study	n	Modality	Local control	OS (5-yr)	Pneumothorax
Present study	21	CA/MWA/RFA	84.7% at 12 mo	82.5%	57.1%
de Baère et al.[16] (ECLIPSE)	40	CA	94.2% at 12 mo	46.7%[36]	18.8% (CT)
de Baère et al.[9]	566	RFA	89.0% at 4 yr	51.5%	NR
Nguyenhuy et al.[10] (meta)	1804	Mixed	91% at 1 yr	50.7%	NR
Hasegawa et al.[12]	70	RFA	91% at 3 yr	69%†	NR
Kurilova et al.[34]	50	MWA	90%	NR	NR
Callstrom et al.[35] (SOLSTICE)	128	CA	77.2% at 2 yr	NR	NR
Fonck et al.[30]	209	RFA/MWA/CA	94.2%	54.7%	NR

†Estimated from the Hasegawa et al.[12] prospective trial. CA, cryoablation; MWA, microwave ablation; RFA, radiofrequency ablation; CT, chest tube; NR, not reported; OS, overall survival.

therefore, the univariate associations are hypothesis-generating. No correction for multiple comparisons was applied across the 10 univariate tests; with only five events, approximately 1 comparison in 20 would be expected to reach nominal significance by chance (α: 0.05); therefore, any single significant association—including the laterality finding—may represent a Type I error. The ablation margin was derived from a single maximum-diameter measurement under a concentric-sphere assumption rather than from multiplanar or three-dimensional volumetric assessment with image registration; because ablation zones are frequently irregular and non-concentric, this cannot reliably capture the true minimal ablative margin, and the counterintuitive margin findings may partly reflect this. In particular, the ablation-zone diameter was recorded from non-standardized follow-up imaging; because ablation zones involute over time, zones measured at later time points can fall below the original tumor diameter, which produced the small number of non-positive calculated margins observed in the control group. Future studies should incorporate multiplanar or three-dimensional volumetric assessment of the minimal ablative margin with image registration and should measure the ablation zone at a standardized, immediate post-ablation time point. Several principal findings (high technical success, tumor-size dependence, and durable local control) confirm rather than extend larger published series, so the incremental contribution lies chiefly in the long-term, real-world single-center data. Local tumor control was assessed by a single reader; therefore, inter-observer reproducibility of the local-control/failure classification could not be quantified. Heterogeneity of primaries, modalities, and nodule number introduces confounding that cannot be fully controlled; the uneven modality distribution (CA: n = 14; MWA: n = 5; RFA: n = 2) limits inter-modality comparison. The absence of a comparator (surgery or stereotactic radiotherapy) precludes a direct comparison of efficacy, although Tselikas et al.[5] reported comparable outcomes for RFA and surgery. The exploratory laterality association rests on only five events, is unsupported by any established mechanism, and most likely reflects unadjusted confounding rather than a true effect; it requires prospective validation. Finally, follow-up imaging was not fully standardized, introducing variability in the assessment of local control. In addition, imaging was not available for every patient at each landmark time point (crude local control was assessable in 15, 17, and 12 patients at 6, 12, and 24 months, respectively), and this incomplete and variable follow-up may bias the crude time-point estimates; Kaplan–Meier analysis mitigates but does not eliminate this limitation. The accrual of only 21 patients over a 7-year period reflects a low procedural volume that, further divided across three ablation modalities, limits the depth of single-center experience for any individual technique and constrains inter-modality comparison. The apparent association between right-sided location and local failure is unsupported by any established biological mechanism, rests on only five events, and—in the absence of multivariable adjustment—most likely reflects confounding by other risk factors rather than a true laterality effect; it is presented purely as a hypothesis to be tested. Given the small sample and heterogeneous cohort, the univariate associations reported here are exploratory and should not be interpreted as establishing independent predictors of failure. Despite these limitations, the study provides real-world, long-term single-center data and generates hypotheses for further investigation.

CT-guided percutaneous thermal ablation of pulmonary metastases is a safe and effective option, providing durable local control in most patients with an acceptable complication profile. Local control of 84.7% at 12 and 24 months and 5-year overall survival of 82.5% (95% CI: 46.1%–95.3%) compare favorably with published data. Larger tumor size was associated with local failure on univariate analysis, and the exploratory association with right-sided laterality—based on few events and most likely reflecting unadjusted confounding—should be regarded as hypothesis-generating and requires validation; adequate ablation margins remain essential. These results support the use of thermal ablation as part of the multidisciplinary management of oligometastatic pulmonary disease and emphasize the need for careful patient selection and procedural planning. Because these single-center observations derive from a low-volume cohort accrued over 7 years, they require confirmation in adequately powered, prospective multicenter registries capable of multivariable adjustment before any of the observed associations can inform practice.

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Footnotes

Conflict of interest disclosure

The authors declared no conflicts of interest.

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