Lung Cancer 217 (2026) 109467

Contents lists available at ScienceDirect

Lung Cancer

journal homepage: www.elsevier.com/locate/lungcan

Sublobar resection, stereotactic body radiotherapy, and thermal ablation for early-stage non-small cell lung cancer: a systematic review and meta-analysis

Shahar Adar [a], Alexandra Ádám [a], Tamara Balogh [a], Mátyás Rédei [a,b], Karen Krisztina Fazekas [a], Mátyás Paczkó [a], Nina Galdzytska [a], Marie Anne Engh [a], András Bibok [a,c], Gábor Zoltán Duray [a,d,g], Péter Hegyi [a,e,f], Dénes Balázs Horváthy [a,c,*]

[a] Centre for Translational Medicine, Semmelweis University, 1085 Budapest, Hungary
[b] Department of Radiology, Medical Imaging Centre, Semmelweis University, 1082 Budapest, Hungary
[c] Department of Interventional Radiology, Heart and Vascular Centre, Semmelweis University, 1122 Budapest, Hungary
[d] Department of Cardiology, Central Hospital of Northern Pest - Military Hospital, 1134 Budapest, Hungary
[e] Institute for Translational Medicine, Medical School, University of Pécs 7624 Pécs, Hungary
[f] Institute of Pancreatic Diseases, Semmelweis University, 1083 Budapest, Hungary
[g] Heart and Vascular Center, Semmelweis University, 1122 Budapest, Hungary

ARTICLE INFO

Keywords:
Early-stage non-small cell lung cancer
Sublobar resection
Stereotactic body radiation therapy
Image-guided thermal ablation

ABSTRACT

Introduction: For patients with early-stage non-small cell lung cancer (NSCLC) who are unable to tolerate lobectomy, alternative locoregional treatments, including sublobar resection (SLR), stereotactic body radiation therapy (SBRT), or image-guided thermal ablation (IGTA) are available, yet their relative risks and benefits remain uncertain. This systematic review and *meta*-analysis aims to synthesize existing evidence and compare the survival outcomes of these modalities in early-stage NSCLC.

Methods: A systematic search was conducted through MEDLINE (PubMed), Embase, and CENTRAL on April 20, 2026. Comparative analyses were restricted to propensity score-matched (PSM) studies reporting hazard ratios (HRs) for overall survival (OS) and cancer-specific survival (CSS) in pathologically confirmed early-stage NSCLC. Single-arm pooled survival analyses were performed using reconstructed individual patient data to estimate time-to-event outcomes. Risk of bias was assessed using ROBINS-I for comparative analysis and the JBI checklist for single-arm analyses.

Results: Seven PSM studies comparing SBRT and SLR were included in the comparative analysis. SLR was associated with improved OS compared with SBRT (HR 1.51; 95% CI: 1.18–1.93), while CSS did not differ significantly (HR 1.08; 95% CI: 0.48–2.45). Sixteen studies were included in the single-arm analyses. Pooled 3-year OS estimates were 80% (95% CI: 75–86%) for SLR, 64% (95% CI: 56–73%) for SBRT, and 64% (95% CI: 48–86%) for IGTA. Corresponding pooled 3-year CSS estimates were 88% (95% CI: 84–92%), 84% (95% CI: 82–87%), and 76% (95% CI: 50–100%), respectively.

Conclusions: SLR was associated with improved OS, although CSS did not differ significantly between the modalities. SBRT and IGTA represent acceptable alternatives in patients unsuitable for surgery. Treatment selection should be individualized through multidisciplinary assessment.

1. Introduction

Lung cancer remains the leading cause of cancer-related mortality worldwide, with an estimated 1.8 million deaths in 2022 [1]. Among its subtypes, non-small cell lung cancer (NSCLC) accounts for approximately 85% of all cases [2] (see Table 1).

For patients with early-stage NSCLC, surgery remains the standard of care, with lobectomy and systematic mediastinal lymph node evaluation as the preferred approach [3,4]. However, a substantial proportion of patients are not able to tolerate lobectomy due to limited

* Corresponding author at: Határőr út 18, 1122 Budapest, Hungary.
E-mail address: horvathy.denes@semmelweis.hu (D.B. Horváthy).

https://doi.org/10.1016/j.lungcan.2026.109467
Received 3 March 2026; Received in revised form 17 May 2026; Accepted 21 May 2026
Available online 22 May 2026

Table 1
Baseline characteristics of studies included in the single-arm analysis.

Author (year)	Data Source (Years)	Study Design	Patient Risk Status	Tumor size	Intervention	Number of Patients (Female %)	FEV_1 (L), Reported	FEV_1 (% Predicted)
Matsuo (2014) [41]	Kyoto University Hospital, Japan (2003–2009)	R	High surgical risk	<5 cm	SBRT (48 Gy × 4; 60 Gy × 8; 60 Gy × 4; 56 Gy × 4)	115 (27.8%)	Median 1.4 L	NA
Matsuo (2014) [41]	Kyoto University Hospital, Japan (2003–2009)	R	High surgical risk	<5 cm	SLR (wedge/ segmentectomy)	65 (33.8%)	Median 1.77 L	NA
Tamura (2019) [32]	Kanazawa University & Fukui Prefectural Hospital, Japan (2006–2013)	R	High surgical risk	<5 cm / <2cm	SBRT (48 Gy × 4 or 60 Gy × 5)	106 (17.0%)	Mean 1.56 L	61.0%
Tamura (2019) [32]	Kanazawa University & Fukui Prefectural Hospital, Japan (2006–2013)	R	High surgical risk	<5 cm / <2cm	SLR (wedge/ segmentectomy)	141 (29.8%)	Mean 1.88 L	67.5%
Yuan (2021) [37]	Zhejiang Cancer Hospital, China (2012–2015)	R	High surgical risk	<5 cm	SLR (wedge/ segmentectomy)	79 (48.1%)	Median 1.8 L	NA
Yuan (2021) [37]	Zhejiang Cancer Hospital, China (2012–2015)	R	High surgical risk	<5 cm	SBRT (50 Gy × 5)	86 (30.2%)	Median 1.48 L	NA
Snider (2024) [30]	Veteran Affairs Cancer Registry, USA (2000–2020)	R	Standard/low surgical risk	<3 cm	SBRT	103 (2.9%)	NA	89%
Snider (2024) [30]	Veteran Affairs Cancer Registry, USA (2000–2020)	R	Standard/low surgical risk	<3 cm	SLR (wedge/ segmentectomy)	103 (2.9%)	NA	87%
Yun (2023) [45]	Korea Central Cancer Registry (2014–2016)	R	Mixed surgical risk	<5 cm	SBRT (60 Gy (48–64) × 4(3–4))	43 (30.2%)	NA	69.6%
Yun (2023) [45]	Korea Central Cancer Registry (2014–2016)	R	Mixed surgical risk	<5 cm	SLR (wedge/ segmentectomy)	339 (46.3%)	NA	88%
Paul (2016) [44]	SEER Database, USA (2007–2012)	R	Mixed surgical risk	<2 cm	SLR (wedge/ segmentectomy)	415 (61.2%)	NA	NA
Paul (2016) [44]	SEER Database, USA (2007–2012)	R	Mixed surgical risk	<2 cm	SBRT	275 (64.4%)	NA	NA
Yerokun (2017) [33]	NCDB, USA (2008–2011)	R	Mixed surgical risk	<2 cm	SLR (wedge)	4517 (60.9%)	NA	NA
Yerokun (2017) [33]	NCDB, USA (2008–2011)	R	Mixed surgical risk	<2 cm	SBRT	1778 (59.0%)	NA	NA
Alexander (2013) [38]	Rhode Island Hospital, USA (2000–2009)	R	High surgical risk	<3 cm	IGTA (RFA)	56 (57.4%)	NA	52.03%
Alexander (2013) [38]	Rhode Island Hospital, USA (2000–2009)	R	High surgical risk	<3 cm	SLR (wedge/ segmentectomy)	28 (57.14%)	NA	54.36%
Ambrogi (2015) [39]	University of Pisa, Italy (2006–2012)	P	High surgical risk	<5 cm	IGTA (RFA)	62 (27.4%)	NA	49.5%
Ambrogi (2015) [39]	Ormaweb Surgical Database (2006–2012)	R	High surgical risk	<5 cm	SLR (wedge)	59 (22%)	NA	47%
Hu (2021) [36]	Shanghai Tertiary Academic Center, China (2014–2018)	R	Mixed surgical risk	<3 cm	IGTA (MWA)	68 (35.3%)	NA	63%
Hu (2021) [36]	Shanghai Tertiary Academic Center, China (2014–2018)	R	Mixed surgical risk	<3 cm	SLR (wedge)	155 (33.5%)	NA	71%
Iguchi (2020) [35]	Okayama University Hospital, Japan (2002–2014)	R	Mixed surgical risk	<5 cm	SBRT (48GyX4 or 60GyX8)	58 (20.6%)	Mean 1.63 L	NA
Iguchi (2020) [35]	Okayama University Hospital, Japan (2002–2014)	R	Mixed surgical risk	<5 cm	SLR (wedge/ segmentectomy)	193 (47.6%)	Mean 2.12 L	NA
Iguchi (2020) [35]	Okayama University Hospital, Japan (2002–2014)	R	Mixed surgical risk	<5 cm	IGTA (RFA)	38 (42.1%)	Mean 1.47 L	NA
Zemlyak (2010) [43]	Stony Brook University Database, USA (2003–2008)	R	High surgical risk	<3 cm	SLR (wedge/ segmentectomy)	25 (64%)	NA	65%

(*continued on next page*)

cardiopulmonary reserve or significant comorbidities [5,6]. In such cases, sublobar resection (SLR), including segmentectomy or wedge resection, is commonly offered as a parenchyma-sparing surgical alternative that allows for both tumor margin assessment and pathological staging [3,4]. Recent randomized trials have further refined the role of SLR, demonstrating that in carefully selected patients, particularly those with peripheral tumors $\leq$ 2 cm, SLR may achieve survival outcomes comparable to lobectomy [7,8].

Stereotactic body radiotherapy (SBRT) delivers ablative doses of ionizing radiation, with recommended biologically effective dose (BED) exceeding 100 Gy, in one to five fractions for peripheral tumors [4]. Prospective trials have demonstrated 3-year local control rates approaching 90%, with favorable survival outcomes [9,10]. Although concerns regarding regional nodal recurrence persist [10], SBRT is established as the standard of care for patients with early-stage NSCLC who are medically inoperable or decline surgery [3,4].

Independently, image-guided thermal ablation (IGTA) techniques, including radiofrequency ablation (RFA), microwave ablation (MWA), and cryoablation, have been utilized for the treatment of peripheral primary lung malignancies [11]. These minimally invasive modalities enable targeted tumor destruction while minimizing parenchyma loss [12], and can be repeated in case of local recurrence, making them particularly applicable in patients with compromised pulmonary function who are poor candidates for both surgery and radiotherapy [13]. Although prospective data remains limited, retrospective studies report acceptable local tumor control and survival outcomes in carefully selected patients [14].

For patients who are not candidates for lobectomy, current guidelines generally favor SLR over non-surgical modalities when feasible [3,4]. Nevertheless, the comparative effectiveness of SLR versus SBRT or IGTA remains controversial [14]. To date, no randomized controlled trial has been completed to compare these modalities. Previous attempts, such as the ACOSOG Z4099 trial, were prematurely terminated due to insufficient patient accrual [15]. Consequently, the available comparative evidence is derived primarily from retrospective studies and is therefore susceptible to substantial treatment-selection bias, as surgical candidates typically have more favorable baseline health [16].

Given these limitations, the benefits and risks associated with SLR, SBRT, and IGTA remain a subject of debate, with current treatment decisions relying largely on retrospective data and institutional preferences [17,18]. To address this issue, this study aims to systematically evaluate the survival outcomes of the locoregional treatment strategies for patients with early-stage NSCLC when lobectomy is not a viable option.

2. Methods

2.1. Study design and registration

This study was conducted within the framework of the Systems Education Program at Semmelweis University [19] and the Translational Medicine (TM) Cycle Framework of the Academia Europaea [20]. The systematic review and *meta*-analysis was performed and reported in accordance with the PRISMA 2020 guidelines [21], and the recommendations of the Cochrane Handbook for Systematic Reviews of Interventions [22]. The study protocol was registered in PROSPERO (CRD42024609071). The PRISMA checklist is provided in Supplementary Table S4.

2.2. Information sources and search strategy

A systematic search was performed in MEDLINE (via PubMed), Embase, and CENTRAL on April 20, 2026. The search strategy included three domains and is detailed in Supplementary Methods S1. Citation tracking of the included studies was performed using Citation Chaser [23].

2.3. Eligibility criteria

Comparative studies evaluating treatment outcomes in patients with early-stage NSCLC treated with surgical versus non-surgical modalities, including radiotherapy or thermal ablation, were considered eligible.

Table 1 (*continued*)

Author (year)	Data Source (Years)	Study Design	Patient Risk Status	Tumor size	Intervention	Number of Patients (Female %)	FEV_1 (L), Reported	FEV_1 (% Predicted)
Zemlyak (2010) [43]	Stony Brook University Database, USA (2003–2008)	R	High surgical risk	<3 cm	IGTA (RFA)	12 (44%)	NA	64%
Zemlyak (2010) [43]	Stony Brook University Database, USA (2003–2008)	R	High surgical risk	<3 cm	IGTA (cryoablation)	27 (60%)	NA	64%
Liu (2022) [40]	Shandong Provincial Hospital, China (2014–2018)	R	Mixed surgical risk	<3 cm	IGTA (MWA)	35 (54.3%)	NA	NA
Liu (2022) [40]	Shandong Provincial Hospital, China (2014–2018)	R	Mixed surgical risk	<3 cm	SLR (wedge/ segmentectomy)	35 (57.1%)	NA	NA
Safi (2015) [31]	Heidelberg University Hospital, Germany (2009–2013)	R	High surgical risk	<5 cm	IGTA (RFA)	25 (28%)	NA	67.1%
Safi (2015) [31]	Heidelberg University Hospital, Germany (2009–2013)	R	High surgical risk	<5 cm	SLR (wedge/ segmentectomy)	42 (36%)	NA	69.4%
Grills 2010 [34]	William Beaumont Hospital, USA (2003–2009)	R	High surgical risk	<5 cm	SLR (wedge)	69 (62%)	Mean 1.39 L	61%
Motono (2016) [42]	Kanazawa Medical University, Japan (2009–2015)	R	High surgical risk	<3 cm	SLR (wedge)	20 (35%)	Mean 1.93 L	74.8%
Dong (2020) [46]	Zhejiang Cancer Hospital, China (2012–2016)	R	High surgical risk	<5 cm	SLR (wedge/ segmentectomy)	121 (46%)	NA	NA

Abbreviations: SBRT, stereotactic body radiation therapy; SLR, sublobar resection; RFA, radiofrequency ablation; MWA, microwave ablation; IGTA, image-guided thermal ablation; NA, not available; FEV_1, forced expiratory volume in 1 s, P, prospective; R, retrospective.

Following study selection, the research team recognized that a more precise specification was necessary for a sufficiently homogeneous quantitative analysis. After discussions with the broader research team, which included methodology and statistical experts, additional criteria were applied for inclusion in the *meta*-analysis. Studies were required to include patients with pathologically confirmed early-stage NSCLC, defined as (T1-T2b, N0, M0) with tumor size < 5 cm, based on the 8th edition AJCC TNM classification [24]. Intervention of interest were SLR including wedge or segment resection, while SBRT or IGTA including RFA, MWA or cryoablation served as comparator treatments. The primary outcomes were overall survival (OS) and cancer-specific survival (CSS), and the secondary outcomes were progression-free survival (PFS).

To stay in accordance with the registered protocol, all otherwise eligible papers were still collected and analyzed as part of the qualitative analysis.

2.4. Study selection

The selection process was performed by three independent reviewers (SA, AA, and TB). After duplicate records were removed, the three reviewers screened titles and abstracts, followed by full-text reviews. Inter-rater agreement was assessed using Cohen's kappa coefficient ($\kappa = 0.824$ for title and abstract screening and $\kappa = 0.843$ for full-text review). Disagreements at any stage were resolved through discussion and consensus. Records identified through citation chasing were subjected to the same two-stage screening and full-text review.

2.5. Data extraction

Data extraction was performed independently by two reviewers (SA and AA) using a predefined pilot extraction form (Microsoft Excel). Extracted variables included study characteristics, patient demographics, tumor size, disease stage, treatment modalities, and survival outcomes. Extracted data were cross-verified by the primary investigator (SA), and discrepancies were resolved through discussion and consensus.

The primary effect size measure was hazard ratio (HR) with corresponding 95% confidence interval (CI). Information on HR was collected from the study manuscript, and when not reported, HR was estimated from the corresponding Kaplan-Meier (KM) curve.

2.6. Risk of bias and certainty evidence

Risk of bias was assessed independently by two reviewers (SA and AA), and disagreements were resolved by consensus. The ROBINS-I tool [25] was used for comparative PSM analysis, and the Joanna Briggs Institute (JBI) checklist was used for the single-arm analysis [26]. The results were visualized using the ROBVIS web application [27]. Certainty of evidence for each outcome was graded using the grade framework in GRADE pro and was evaluated separately for comparative and single-arm analysis [28].

2.7. Statistical analysis

Formal *meta*-analyses were conducted for outcomes that were comparable across studies with the necessary number of available published articles (defined as minimum of three studies).

In the single-arm analysis, the effect size measure was the pooled mean survival probability at 12, 24, 36, and 48 months, based on individual patient data (IPD) from reconstructed KM-curves, each with the corresponding 95% confidence interval (CI).

When both matched and unmatched cohorts were reported, the KM curve for the unmatched cohort was preferentially used to maximize the available sample size. Furthermore, pooled survival functions for each intervention were estimated using a distribution-free random effects method and presented on summary survival curves, as described by Combescure et al. [29].

Only studies with propensity score matching (PSM) were included in the comparative head-to-head analysis to combat any underlying bias between the intervention and the control groups. The effect size measure used was HR with corresponding 95% CI.

Both study-specific HRs and mean survival probabilities effect sizes, with their corresponding 95% CIs, were log-transformed and analyzed within an inverse-variance random-effects *meta*-analysis model framework with a REML tau estimator and Hartung-Knapp adjustment. Absolute between-study heterogeneity was assessed using τ^2, and relative between-study heterogeneity was assessed using I^2 measure. Both study-level and pooled HR as well as survival estimate at specific time points were visualized using forest plots.

Publication bias was visually assessed using funnel plots, with asymmetry indicating the presence of small study publication bias. Leave-one-out sensitivity analyses were performed to account for potential outliers and influential studies.

Studies not suitable for quantitative synthesis due to substantial clinical heterogeneity were summarized qualitatively using structured systematic review tables, provided in Supplementary Table S1.

As part of the systematic analysis, a clinically relevant subset of studies reporting OS in PSM cohorts was additionally analyzed in a directionality plot, displaying the direction of the favored treatment on a two-sided p-value scale with the corresponding (logarithmized) sample. The results are provided in Supplementary Fig. S1.

Detailed statistical analyses are provided in the Supplementary Method S2.

3. Results

The systematic literature search identified 10,363 records. After removal of duplicates and screening of titles, abstracts, and full-text articles, 147 studies met the inclusion criteria. An additional six studies were identified through citation chaser, resulting in a total of 153 included studies. Of these, 17 comparative studies [30–46] were eligible for quantitative *meta*-analysis, as they provided methodologically and clinically comparable cohorts evaluating outcomes between SLR and SBRT or IGTA in patients with pathologically confirmed NSCLC (<5 cm, T1-T2b, N0, M0).

The remaining 136 studies were included in the qualitative analysis due to heterogeneity in surgical approach, radiation modality, ablation technique, or outcome reported. A systematic review table including the reason for their exclusion from the quantitative analysis is provided in Supplementary Table S1. The study selection process is summarized in the PRISMA flow diagram (Fig. 1).

3.1. Propensity score matching comparative analysis: SLR vs SBRT

Seven retrospective studies [30,32,33,37,41,44,45] reported propensity score-matched (PSM) comparisons between SLR and SBRT. Matching variables commonly included age, sex, tumor size, histology, pulmonary function parameters, and comorbidity indices. Baseline characteristics of the matched cohorts are detailed in Supplementary Table S2.

3.1.1. Overall survival

All seven studies [30,32,33,37,41,44,45] reported OS, including 2,109 patients treated with SBRT and 2,109 patients treated with SLR. In pooled analysis, SLR was associated with improved OS compared with SBRT (HR 1.51 95% CI: 1.18–1.93; Fig. 3A).

3.1.2. Cancer-specific survival

Five studies [30,32,37,41,44] reported CSS, including 484 patients treated with SBRT and 484 patients treated with SLR. No statistically significant difference in CSS was observed between the groups (HR 1.08 95% CI: 0.48–2.45; Fig. 3B).

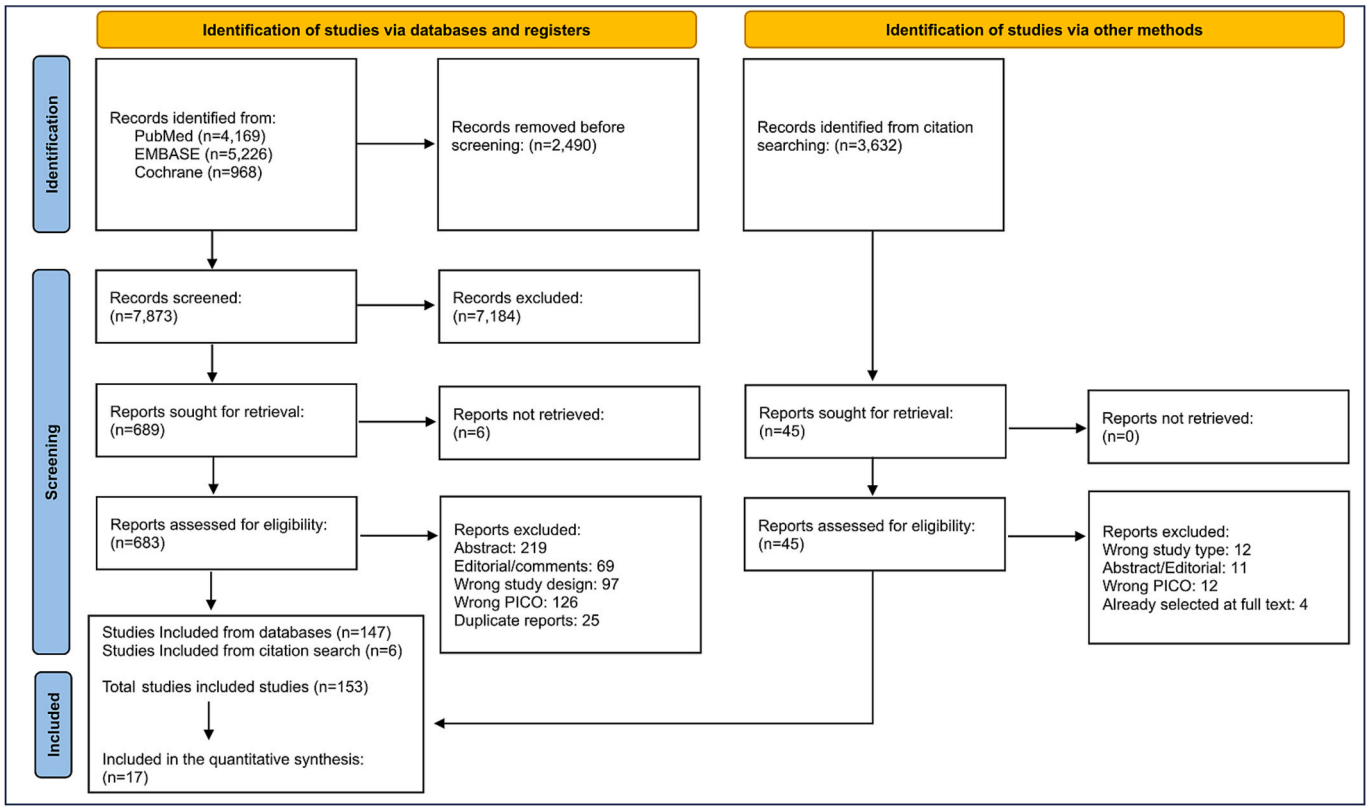

Fig. 1. PRISMA 2020 flowchart representing the study selection process.

3.2. Single-arm pooled survival analysis

3.2.1. Overall survival

Sixteen studies [30–45] contributed to the single-arm pooled analysis of OS. Across the follow-up, pooled survival estimates were consistently higher for SLR than for SBRT and IGTA, which demonstrated similar survival estimates with overlapping confidence intervals (Fig. 2).

The estimated OS rates at 1, 2, and 3 years for SLR were 0.98 (95% CI: 0.96–0.99), 0.91 (95% CI: 0.87–0.94), and 0.80 (95% CI: 0.75–0.86), respectively. Corresponding OS rates for SBRT were 0.92 (95% CI: 0.89–0.95), 0.77 (95% CI: 0.72–0.84), and 0.64 (95% CI: 0.56–0.73). For IGTA, the estimated OS rates were 0.95 (95% CI: 0.93–0.98), 0.84 (95% CI: 0.75–0.94), and 0.64 (95% CI: 0.48–0.86) (Supplementary Figs. S3-5).

3.2.2. Cancer-specific survival

Nine studies [30,32,34,37–39,41,43,44] reported CSS. The pooled survival curves for SLR and SBRT were closely aligned, with overlapping confidence intervals throughout follow-up. The IGTA curve demonstrated a more pronounced early decline, with wide confidence intervals overlapping those of the other treatment modalities (Fig. 4B).

For SLR, the estimated CSS rates at 1, 2, and 3 years were 1.00 (95% CI: 1.00–1.00), 0.94 (95% CI: 0.91–0.97) and 0.88 (95% CI: 0.84–0.92), respectively. For SBRT, they were 1.00 (95% CI: 1.00–1.00), 0.90 (95% CI: 0.85–0.94) and 0.84 (95% CI: 0.82–0.87). For IGTA, they were 0.97 (95% CI: 0.88–1.07), 0.83 (95% CI: 0.63–1.09) and 0.76 (95% CI: 0.50–1.14) (Supplementary Figs. S6-8).

3.2.3. Progression-free survival

Nine studies [30,31,35,36,42,43,45,46] reported PFS. The pooled survival curve for SLR remained higher across follow-up compared with SBRT and IGTA, whereas SBRT and IGTA demonstrated closely aligned curves with overlapping confidence intervals (Fig. 4A).

For SLR, the estimated PFS rates at 1, 2, and 3 years were 0.95 (95% CI: 0.92–0.99), 0.85 (95% CI: 0.75–0.96), and 0.79 (95% CI: 0.68–0.91), respectively. For SBRT, they were 0.84 (95% CI: 0.65–1.08), 0.65 (95% CI: 0.41–1.03), and 0.50 (95% CI: 0.35–0.70). For IGTA, they were 0.85 (95% CI: 0.80–0.89), 0.70 (95% CI: 0.62–0.80), and 0.62 (95% CI: 0.54–0.73). (Supplementary Figs. S9-11).

3.3. Subset analysis

We conducted a subset analysis restricted to cohorts with tumor size < 3 cm, including eight studies [30,32,33,36,38,40,42,44]. Across the follow-up, SLR demonstrated higher pooled survival estimates compared with SBRT and IGTA, which demonstrated closely aligned survival curves, with overlapping confidence intervals (Supplementary Figs. S2B).

The estimated OS rates at 1, 2, and 3 years for SLR were 0.97 (95% CI: 0.94–1.00), 0.90 (95% CI: 0.83–0.97) and 0.81 (95% CI: 0.72–0.90), respectively. For SBRT, they were 0.91 (95% CI: 0.84–0.97), 0.76 (95% CI: 0.61–0.95), and 0.62 (95% CI: 0.44–0.88). For IGTA, they were 0.95 (95% CI: 0.88–1.03), 0.84 (95% CI: 0.63–1.13) and 0.63 (95% CI: 0.15–2.59) (Supplementary Figs. S12-14).

A subset analysis was also conducted on cohorts identified as high-risk surgical candidates, based on criteria reported by the authors in each study. Eight studies [31,32,34,37,39,41–43] reported OS including high-risk patients. SLR demonstrated higher survival probability curve; however, the confidence intervals for all three modalities largely overlapped with one another, limiting the statistical power of the results (Supplementary Figs. S2A).

The estimated OS rates at 1, 2, and 3 years for SLR were 1.00 (95% CI: 1.00–1.00), 0.91 (95% CI: 0.87–0.95), and 0.79 (95% CI: 0.68–0.92), respectively. For SBRT, they were 0.95 (95% CI: 0.88–1.02), 0.84 (95% CI: 0.68–1.03) and 0.74 (95% CI: 0.50–1.10). For IGTA, they were 0.92 (95% CI: 0.86–0.98), 0.79 (95% CI: 0.52–1.22) and 0.55 (95% CI: 0.16–1.87) (Supplementary Figs. S15-17).

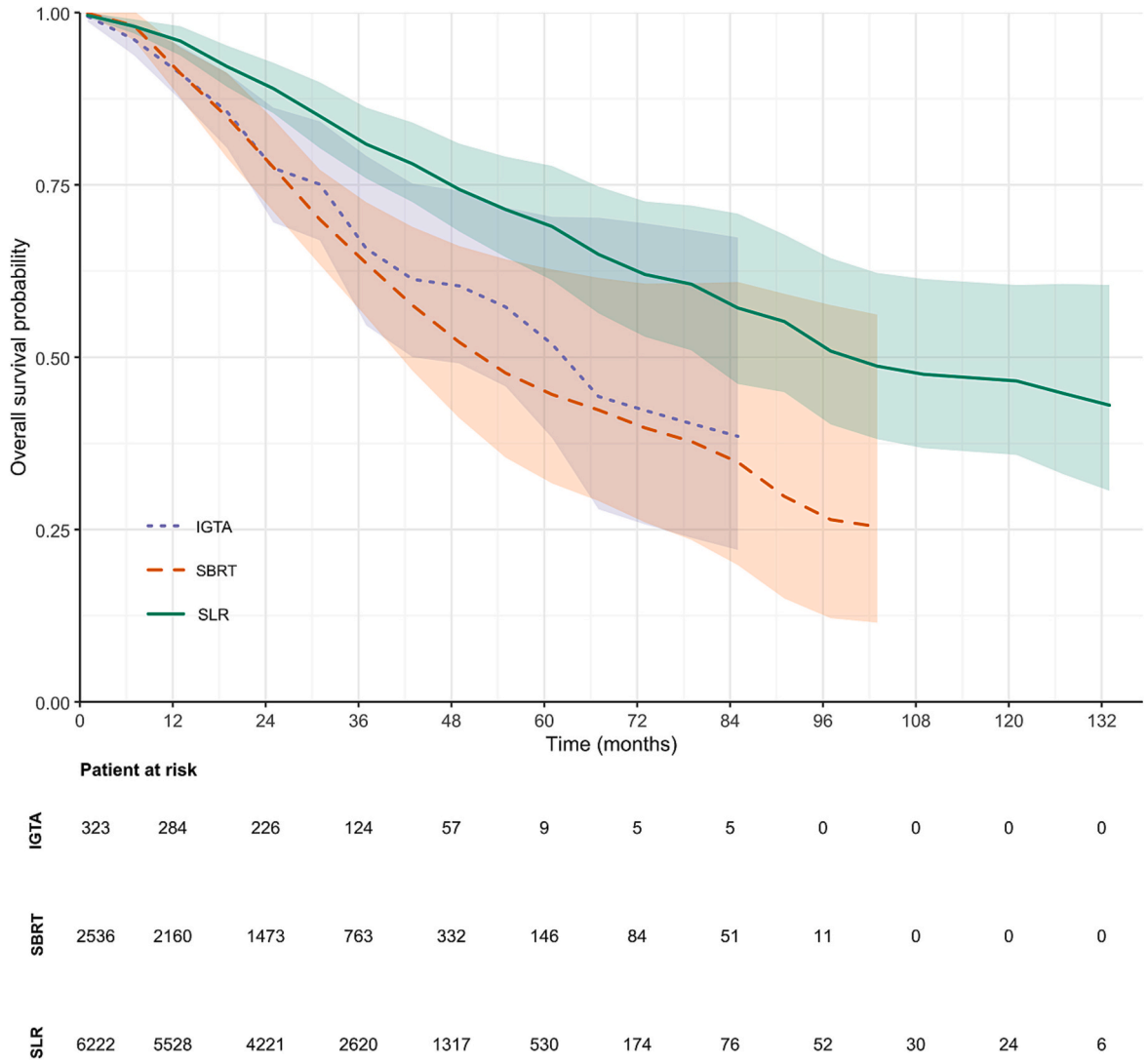

Fig. 2. Pooled single-arm probability curve of overall survival for patients with pathologically confirmed early-stage NSCLC (with tumor size < 5 cm) treated with SLR, SBRT and IGTA. Shaded regions around the central estimates represent the 95% CI for each intervention. The table below represents the number of patients at risk at each time point. Abbreviations: SBRT, stereotactic body radiotherapy; HR, hazard ratio; CI, confidence interval; NSCLC, non-small cell lung cancer; SLR, sublobar resection; IGTA, image guided thermal ablation.

3.4. Heterogeneity and publication bias assessment

3.4.1. Heterogeneity

In the PSM analysis, we estimated moderate heterogeneity for both OS and CSS outcomes, with I^2 values of 23% (95% CI: 0–66%) and 53% (95% CI: 0–83%), respectively. This is likely due to variation in patient inclusion criteria across the studies. Several studies explicitly defined their cohorts as high-risk or medically inoperable patients, whereas others included surgically eligible patients without stratification by baseline health status.

3.4.2. Risk of bias

In our PSM analysis, four studies [30,32,37,41] were assessed as having an overall moderate risk of bias (ROB), mainly due to the lack of pathological nodal staging in the SBRT cohort (ROBINS-I domain 6). Three studies [33,44,45] were assessed as having an overall serious ROB due to baseline imbalances between the treatment groups (ROBINS-I domain 3).

In our single-arm analysis, uncertainty regarding the treatment selection criteria (JBI domain 1), as well as incomplete reporting of baseline patient characteristics (JBI domain 2), were the main factors influencing ROB. In addition, the majority of SBRT and IGTA cohorts lacked adequate reporting of lymph node evaluation (JBI domain 3), thereby introducing selection bias. Visualization of the ROB assessment for both PSM and single-arm analyses is provided in Supplementary Figs. S18-21.

3.4.3. Certainty of evidence

In the comparative PSM *meta*-analysis, the overall certainty of evidence was rated as moderate to serious. Although all included studies were retrospective, the use of propensity score matching and restriction to directly comparable cohorts mitigated but did not eliminate confounding. Residual confounding, particularly related to unmeasured frailty and staging differences, remains possible and may influence effect estimates.

In the pooled single-arm analyses, the certainty of evidence was also rated as moderate to serious, primarily due to imprecision and heterogeneity, especially within the IGTA cohorts, characterized with small sample size, and wide confidence intervals. Detailed certainty of evidence assessment is included in Supplementary Table S3.

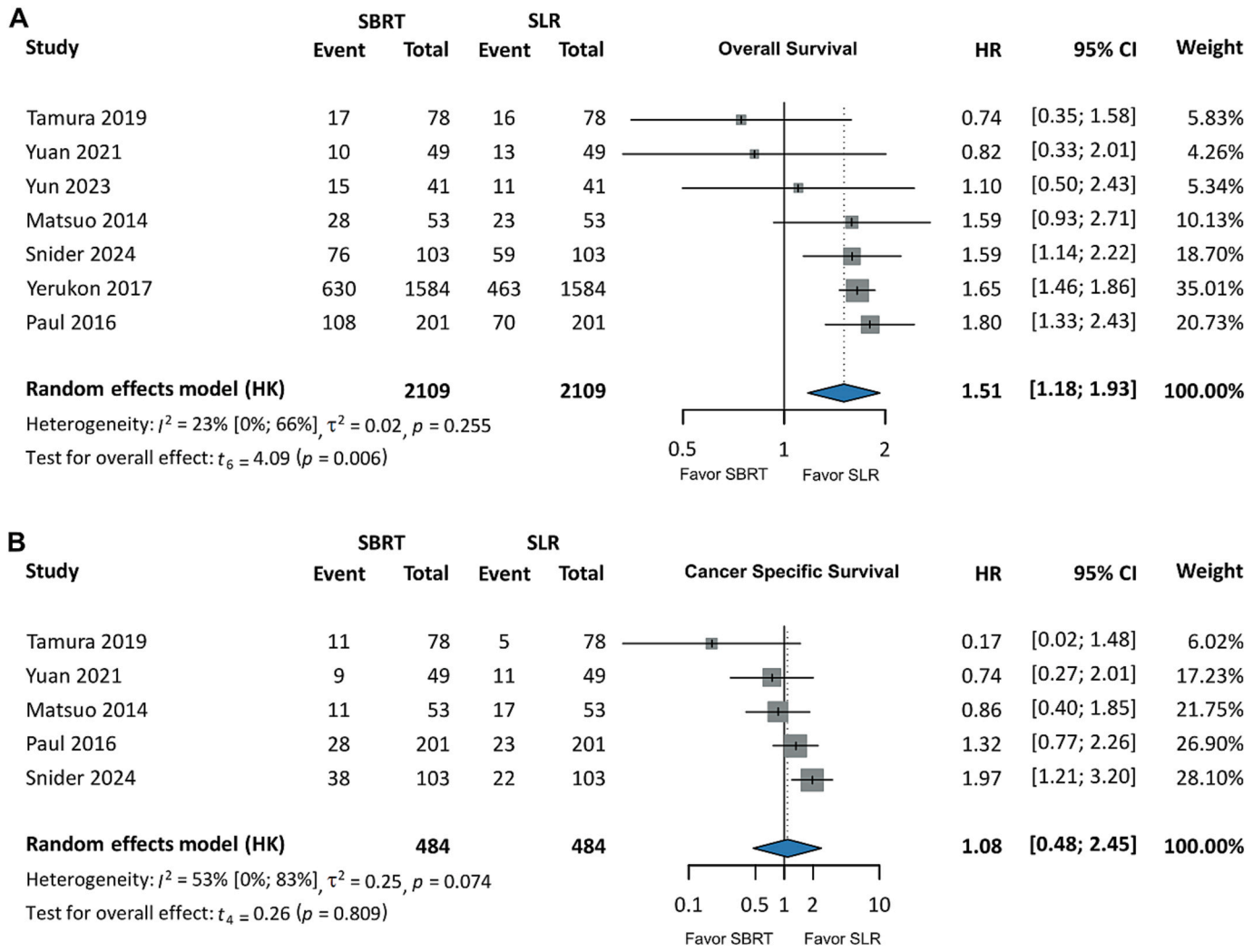

Fig. 3. Forest plots demonstrating the overall survival (A) and cancer-specific survival (B) in propensity scored-matched patients with pathologically confirmed early-stage NSCLC, and tumor size under 5 cm, treated with SBRT and SLR. Abbreviations: SBRT, stereotactic body radiotherapy; HR, hazard ratio; CI, confidence interval; NSCLC, non-small cell lung cancer; SLR, sublobar resection.

4. Discussion

Our findings suggest that SLR is associated with better OS compared with SBRT and IGTA, whereas our analysis of CSS did not differ significantly among the treatment modalities (Figs. 2 and 4B). This divergence between OS and CSS may reflect systematic differences in baseline patient health rather than pure treatment-effect difference [47]. Since current clinical guidelines consistently recommend surgical resection for eligible patients, surgical cohorts are populated by patients deemed fit for surgery, whereas SBRT and IGTA cohorts inevitably include a substantial proportion of medically inoperable patients with a higher burden of competing, non-cancer-related mortality [3,4]. This imbalance, inherent to treatment allocation based on surgical candidacy, is difficult to fully neutralize, even within PSM analyses.

The impact of competing non-cancer mortality is further highlighted by real-world data from SBRT-treated cohorts reporting five-year all-cause and cancer-specific mortality rates of 57.7% and 25.3%, respectively [48]. Thus, more than half of the observed deaths in these cohorts appear to be attributable to non-cancer causes.

To further mitigate confounding related to baseline comorbidity, we performed a subset analysis restricted to cohorts in which all patients were classified as high-risk surgical candidates due to significant comorbidities (Supplementary Figs. S2A). Within this subset, the OS advantage of SLR compared to the broader cohort was attenuated, and the confidence intervals across all three modalities overlapped substantially. The impact of patient operability is further demonstrated by the JCOG0403 trial [49], in which patients receiving identical SBRT regimens demonstrated higher three-year OS in the operable subgroup compared with inoperable subgroup (76.5% vs 59.9%), despite comparable tumor characteristics. Collectively, these findings further emphasize the influence of baseline health status on survival outcomes and underscore the importance of multidisciplinary team-based decision-making for individualized treatment selection [50]. Importantly, the overlapping confidence intervals should not be interpreted as therapeutic equivalence; they reflect statistical uncertainty, and suggest, rather than confirm, that SBRT and IGTA may achieve outcomes comparable to SLR, in carefully selected patients.

Progression-free survival (PFS) provides an additional aspect for comparing treatment modalities, as it reflects both tumor control and mortality. In this analysis, higher PFS estimates were observed following SLR compared with SBRT and IGTA (Fig. 4A). This observation should be interpreted in light of the fundamental differences between the modalities. Surgical resection offers the opportunity for intraoperative assessment of hilar and mediastinal lymph nodes, and pathologic detection of occult nodal disease may guide adjuvant therapy, thereby improving tumor control [51]. In routine clinical practice, however, this advantage is frequently attenuated, particularly among patients at high risk for lobectomy. A large national cancer database (NCDB) analysis of

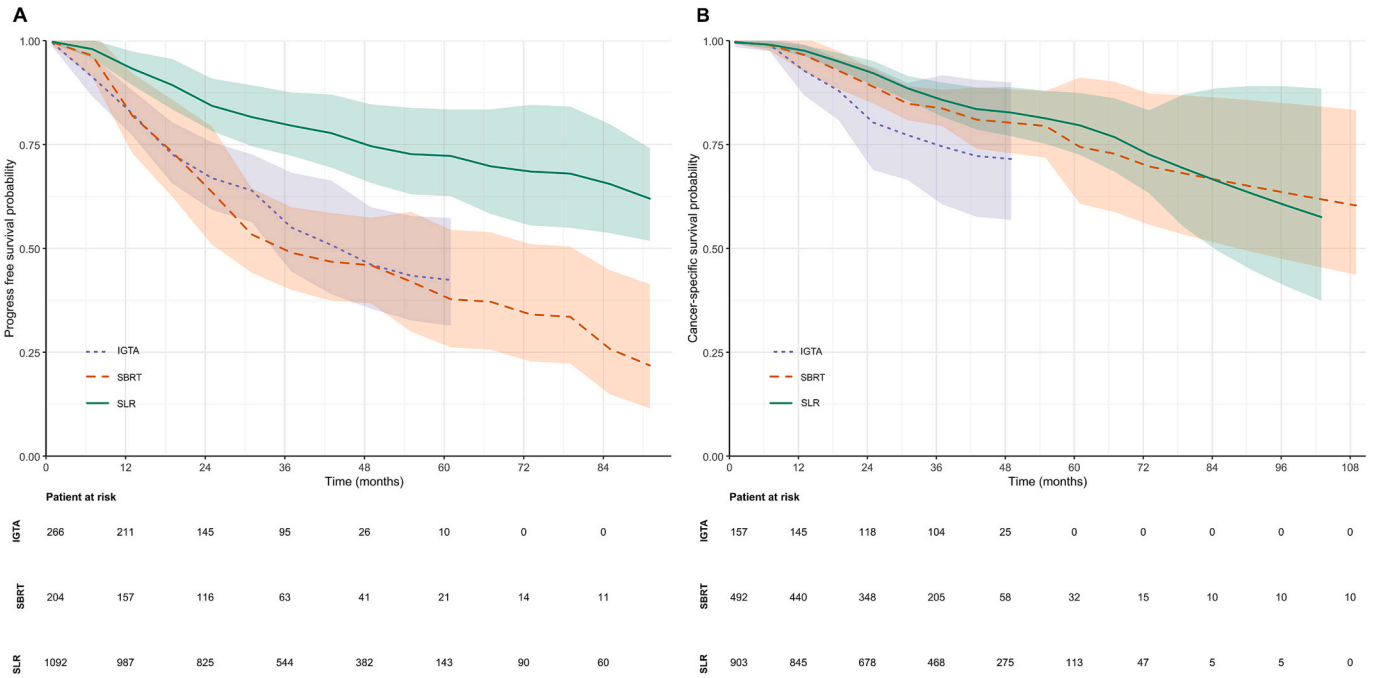

Fig. 4. Pooled single-arm probability curve of PFS (A) and CSS (B) for patients with pathologically confirmed early-stage NSCLC (tumor size < 5 cm) treated with SLR, SBRT and IGTA. Shaded regions around the central estimates represent the 95% CI for each intervention. The table below represents the number of patients at risk at each time point. Abbreviations: SBRT, stereotactic body radiotherapy; NSCLC, non-small cell lung cancer; SLR, sublobar resection; IGTA, image-guided thermal ablation.

patients with stage IA NSCLC showed that 21% of those treated with SLR did not undergo any invasive lymph node evaluation, compared with 2% of those treated with lobectomy [52]. Moreover, even when nodal disease is identified, subsequent adjuvant therapy is not consistently delivered; in the *meta*-analysis by Chen, pathological nodal upstaging occurred in 15.6% of surgically treated patients, yet only 11.4% of upstaged patients ultimately received adjuvant treatment [47].

For patients treated with SBRT or IGTA, invasive lymph node staging is infrequently performed, likely because of the same comorbidities that contraindicate surgery. Consequently, these cohorts rely largely on imaging-based staging, which is less sensitive for occult nodal disease and may result in under-staging, suboptimal treatment, and higher recurrence rates [5,53]. Reflecting this, Ajmani [54] reported that only 0.7% of patients treated with SBRT received adjuvant therapy, compared with 64.7% of patients undergoing wedge resection with lymph node assessment. Similarly, Razi [55] demonstrated that up to 15% of patients undergoing surgery with invasive lymph node evaluation had unsuspected nodal disease and subsequently received adjuvant therapy, which significantly improved their overall survival. Notably, patients treated with either surgery or SBRT without invasive lymph node evaluation demonstrated comparable survival. Collectively, these findings suggest that the PFS advantage of SLR may reflect, at least in part, differences in the accuracy of nodal staging rather than the treatment modality alone.

Another key difference lies in the assessment of completeness of treatment. Surgical resection allows intraoperative margin assessment and the immediate extension of resection when necessary, thereby ensuring the complete removal of the tumor [5]. For patients treated with SBRT, treatment completeness is verified by confirming accurate delivery to the intended target, using daily pre-treatment volumetric imaging, with optional intra-fraction monitoring [56]. Nevertheless, pathological confirmation of complete tumor eradication is not feasible [51]. The MISSILE trial highlighted this limitation, reporting that among patients with T1-2N0M0 NSCLC treated with SBRT, only 60% achieved complete pathological tumor response [57]. For IGTA, early post-procedural imaging may demonstrate the ablation zone but cannot reliably exclude microscopic residual viable tumor at the treatment margin [58]. Cryoablation represents a partial exception within this group, as it allows real-time visualization of the ice-ball during the procedure, which can improve procedural precision and tumor coverage [14]. In addition, emerging navigation systems for CT-guided interventions may further improve the efficiency and safety of IGTA by enabling more precise applicator placement [59].

In subset analyses restricted to tumors smaller than 3 cm, the results were consistent with the overall cohort, with SLR demonstrating higher OS estimates across follow-up (Supplementary Figs. S2B). Importantly, pooled single-arm analyses of IGTA showed numerically improved survival outcomes for smaller lesions compared with analyses including tumors up to 5 cm. Prior studies support this size-dependent effect. Dupuy reported a two-year OS of 69.8%, which increased to 83% when the analysis was restricted to patients with tumors smaller than 2 cm [60]. Similarly, Yim found no significant differences in OS or CSS between IGTA and wedge resection when the analysis was restricted to tumors smaller than 1 cm, whereas wedge resection remained superior for larger tumors [61]. Collectively, these findings suggest that tumor size may be a critical factor of IGTA effectiveness, with improved performance in smaller lesions. Nonetheless, further evidence is needed to define optimal size thresholds for treatment selection.

Previous *meta*-analyses focused primarily on pairwise comparisons and have consistently demonstrated improved survival with surgery compared with SBRT [47,62] and IGTA [63]. Notably, Chen attributed the apparent survival advantage of surgery primarily to residual imbalance in baseline characteristics, reflecting the limits of statistical adjustment [47]. This interpretation is supported by the pooled analysis of the STARS and ROSEL which suggested improved survival with SBRT compared with lobectomy in operable early-stage NSCLC [10]. Although the combined sample size was small (58 patients) and both trials were closed prematurely, substantially limiting statistical power, this finding demonstrates that when selection bias is eliminated through randomization, the survival advantage conventionally attributed to surgery is no longer evident.

In contrast to previous pairwise analyses, we incorporates all three

locoregional treatment modalities within a single analytical framework. Moreover, we restricted inclusion to pathologically confirmed malignancies and focused on clinically homogeneous subpopulations. This approach reduces selection bias and enhances the interpretation of our results in the context of real-world clinical practice [64].

5. Strengths and limitations

To our knowledge, this study is the first to evaluate all locoregional modalities within a single analytical framework. We conducted both a pooled single-arm analysis and a head-to-head comparison for the PSM group, increasing the applicability of our results. The strict inclusion criteria we applied focused on treatment strategies commonly used in patients unable to tolerate lobectomy, including SLR, SBRT, and IGTA, reflecting clinically relevant real-world decision-making. Our *meta*-analysis has limitations. While PSM aims to reduce imbalance in measured variables, it cannot account for unmeasured or unobservable confounders; therefore, fundamental differences in baseline health status between surgical and non-surgical candidates remain a structural limitation. In addition, the relatively small number of studies comparing IGTA with surgery, especially those using PSM analysis, limits the statistical power of our analysis. Lastly, heterogeneity in the definitions of the reported outcomes (such as recurrence pattern, complications), as well as the lack of clear definition for high-risk patients, limit the number of outcomes and subsets amenable to formal *meta*-analyses.

6. Conclusion

Treatment selection for patients with early-stage NSCLC who are unsuitable for lobectomy is complex and should be systematically evaluated by a multidisciplinary team that considers patient-related factors, and tumor characteristics. Based on the current results, SLR should generally be favored when technically and clinically feasible. SBRT and IGTA remain viable alternatives for patients who are medically inoperable or who decline surgery. Nevertheless, high-quality randomized trials are needed to establish definitive evidence-based recommendations, ultimately focusing not only on which technique is superior overall, but rather on which patient is best suited to each technique.

Ethical approval

No ethical approval was required for this systematic review with *meta*-analysis, as all data were already published in peer-reviewed journals. No patients were involved in the design, conduct or interpretation of our study.

The datasets used in this study can be found in the full-text articles included in the systematic review and *meta*-analysis.

Funding

Supported by the Semmelweis University Research, Development and Innovation Fund.

CRediT authorship contribution statement

Shahar Adar: Writing – original draft, Investigation, Conceptualization. **Alexandra Ádám:** Writing – original draft, Investigation, Conceptualization. **Tamara Balogh:** Data curation, Investigation. **Mátyás Rédei:** Investigation, Data curation. **Karen Krisztina Fazekas:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Mátyás Paczkó:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Nina Galdzytska:** Writing – review & editing, Methodology, Conceptualization. **Marie Anne Engh:** Writing – review & editing, Methodology, Conceptualization. **András Bibok:** Writing – review & editing, Data curation, Conceptualization. **Gábor Zoltán Duray:** Writing – review & editing, Conceptualization. **Péter Hegyi:** Writing – review & editing, Project administration, Conceptualization. **Dénes Balázs Horváthy:** Supervision, Project administration, Conceptualization, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

None to declare.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lungcan.2026.109467.

References

[1] J. Zhou, Y. Xu, J. Liu, L. Feng, J. Yu, D. Chen, Global burden of lung cancer in 2022 and projections to 2050: incidence and mortality estimates from GLOBOCAN, Cancer Epidemiol. 93 (2024) 102693.
[2] American Cancer Society, Cancer Facts & Figures 2025, American Cancer Society; 2025.
[3] A. Zer, M.J. Ahn, F. Barlesi, L. Bubendorf, D. De Ruysscher, P. Garrido, et al., Early and locally advanced non-small-cell lung cancer: ESMO clinical practice guideline for diagnosis, treatment and follow-up, Ann. Oncol. 36 (11) (2025) 1245–1262.
[4] National Comprehensive Cancer Network, NCCN Clinical Practice Guidelines in Oncology: Non-Small Cell Lung Cancer, Version 2.2026, Plymouth Meeting, PA: National Comprehensive Cancer Network, 2026.
[5] A. Pennathur, M. Lanuti, R.E. Merritt, A. Wolf, H. Keshavarz, B.W. Loo jr., Treatment selection for the high-risk patient with stage i non-small cell lung cancer: sublobar resection, stereotactic ablative radiotherapy or image-guided thermal ablation? Semin. Thorac. Cardiovasc. Surg. 37 (1) (2024) 114–121.
[6] A. Brunelli, G. Hardavella, R.M. Huber, T. Berghmans, A. Frille, M. Rodriguez, et al., European respiratory society and european society of thoracic surgeons clinical practice guideline on fitness for curative intent treatment of lung cancer, Eur. Respir. J. 66 (5) (2025).
[7] N. Altorki, X. Wang, D. Kozono, C. Watt, R. Landrenau, D. Wigle, et al., Lobar or sublobar resection for peripheral stage IA non-small-cell lung cancer, N. Engl. J. Med. 388 (6) (2023) 489–498.
[8] H. Saji, M. Okada, M. Tsuboi, R. Nakajima, K. Suzuki, K. Aokage, et al., Segmentectomy versus lobectomy in small-sized peripheral non-small-cell lung cancer (JCOG0802/WJOG4607L): a multicentre, open-label, phase 3, randomised, controlled, non-inferiority trial, Lancet 399 (10335) (2022) 1607–1617.
[9] R. Timmerman, R. Paulus, J. Galvin, J. Michalski, W. Straube, J. Bradley, et al., Stereotactic body radiation therapy for inoperable early stage lung cancer, JAMA 303 (11) (2010) 1070–1076.
[10] J.Y. Chang, S. Senan, M.A. Paul, R.J. Mehran, A.V. Louie, P. Balter, et al., Stereotactic ablative radiotherapy versus lobectomy for operable stage I non-small-cell lung cancer: a pooled analysis of two randomised trials, Lancet Oncol. 16 (6) (2015) 630–637.
[11] S.J. Genshaft, R.D. Suh, F. Abtin, M.O. Baerlocher, A.J. Chang, S.R. Dariushnia, et al., Society of interventional radiology multidisciplinary position statement on percutaneous ablation of non-small cell lung cancer and metastatic disease to the lungs: endorsed by the canadian association for interventional radiology, the cardiovascular and interventional radiological society of europe, and the society of interventional oncology, J. Vasc. Interv. Radiol. 32 (8) (2021), 1241.e1-.e12.
[12] A. Mačionis, I. Balčiūnaitė, G. Galnaitienė, R. Dubeikaitė, G. Maziliauskienė, I. Dimienė, et al., Dynamics of pulmonary perfusion and function following radical treatment for lung tumors: a prospective comparative study of surgery, radiotherapy, and thermal ablation, Cancers 18 (8) (2026) 1213.
[13] E.C. Bartlett, S. Rahman, C.A. Ridge, Percutaneous image-guided thermal ablation of lung cancer: what is the evidence? Lung Cancer 176 (2023) 14–23.
[14] D.S. Buchberger, R. Khurana, M. Bolen, G.M.M. Videtic, The treatment of patients with early-stage non-small cell lung cancer who are not candidates or decline surgical resection: the role of radiation and image-guided thermal ablation, J. Clin. Med. 13 (24) (2024).
[15] H. Fernando, R. Timmerman, American College of Surgeons Oncology Group Z4099/Radiation Therapy Oncology Group 1021: a randomized study of sublobar resection compared with stereotactic body radiotherapy for high-risk stage I non-small cell lung cancer, J. Thorac. Cardiovasc. Surg. 144 (3) (2012) S35–S38.
[16] H.S. Park, F.C. Detterbeck, D.C. Madoff, B.C. Bade, U. Kumbasar, V.J. Mase Jr, A guide for managing patients with stage I NSCLC: deciding between lobectomy, segmentectomy, wedge, SBRT and ablation—part 4: systematic review of evidence involving SBRT and ablation, J. Thorac. Dis. 14 (6) (2022).
[17] J. Howington, L.H. Souter, D. Arenberg, J. Blasberg, F. Detterbeck, F. Farjah, et al., Management of patients with early-stage non-small cell lung cancer: an American college of chest physicians clinical practice guideline, Chest 168 (3) (2025) 810–827.
[18] A. Pennathur, A. Brunelli, G.J. Criner, H. Keshavarz, P. Mazzone, G. Walsh, Definition and assessment of high risk in patients considered for lobectomy for stage I non-small cell lung cancer: the American association for thoracic surgery

expert panel consensus document, J. Thorac. Cardiovasc. Surg. 162 (6) (2021), 1605–18.e6.
[19] P. Hegyi, A. Varró, Systems education can train the next generation of scientists and clinicians, Nat. Med. 30 (12) (2024) 3399–3400.
[20] P. Hegyi, O.H. Petersen, S. Holgate, B. Erőss, A. Garami, Z. Szakács, Academia Europaea position paper on translational medicine: the cycle model for translating scientific results into community benefits, J. Clin. Med. 9 (5) (2020).
[21] M.J. Page, J.E. McKenzie, P.M. Bossuyt, I. Boutron, T.C. Hoffmann, C.D. Mulrow, et al., The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, BMJ 372 (2021) n71.
[22] J.P.T. Higgins, J. Thomas, J. Chandler, M. Cumpston, T. Li, M.J. Page, et al., Cochrane Handbook for Systematic Reviews of Interventions, Version 6.5 (updated August 2024) ed: Cochrane, 2024.
[23] N.R. Haddaway, M.J. Grainger, C.T. Gray, citationchaser: an R package for forward and backward citations chasing in academic searching, 0.0.3 ed2021.
[24] P. Goldstraw, K. Chansky, J. Crowley, R. Rami-Porta, H. Asamura, W.E. Eberhardt, et al., The IASLC lung cancer staging project: proposals for revision of the TNM stage groupings in the forthcoming (eighth) edition of the TNM classification for lung cancer, J. Thorac. Oncol. 11 (1) (2016) 39–51.
[25] J.A. Sterne, M.A. Hernán, B.C. Reeves, J. Savović, N.D. Berkman, M. Viswanathan, et al., ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions, BMJ (2016:) i4919.
[26] JBI Manual for Evidence Synthesis. Adelaide: Joanna Briggs Institute; 2020.
[27] L.A. McGuinness, J.P.T. Higgins, Risk-of-bias visualization (robvis): an R package and Shiny web app for visualizing risk-of-bias assessments, Res. Synth. Methods 12 (1) (2021) 55–61.
[28] U. McMaster, Evidence Prime I. GRADEpro GDT: GRADEpro Guideline Development Tool, Evidence Prime, 2024.
[29] C. Combescure, Y. Foucher, D. Jackson, Meta-analysis of single-arm survival studies: a distribution-free approach for estimating summary survival curves with random effects, Stat. Med. 33 (15) (2014) 2521–2537.
[30] M. Snider, J.K. Salama, M. Boyer, Survival and recurrence rates following SBRT or surgery in medically operable stage I NSCLC, Lung Cancer 197 (2024) 107962.
[31] S. Safi, G. Rauch, op den Winkel J, J. Kunz, T. Schneider, M. Bischof, Sublobar resection, radiofrequency ablation or radiotherapy in stage I non-small cell lung cancer, Respiration 89 (6) (2015) 550–557.
[32] M. Tamura, I. Matsumoto, Y. Tanaka, D. Saito, S. Yoshida, S. Kakegawa, Comparison between stereotactic radiotherapy and sublobar resection for non-small cell lung cancer, Ann. Thorac. Surg. 107 (5) (2019) 1544–1550.
[33] B.A. Yerokun, C.F.J. Yang, B.C. Gulack, X. Li, M.S. Mulvihill, L. Gu, A national analysis of wedge resection versus stereotactic body radiation therapy for stage IA non–small cell lung cancer, J. Thorac. Cardiovasc. Surg. 154 (2) (2017), 675–86.e4.
[34] I.S. Grills, V.S. Mangona, R. Welsh, G. Chmielewski, E. McInerney, S. Martin, et al., Outcomes after stereotactic lung radiotherapy or wedge resection for stage I non-small-cell lung cancer, J. Clin. Oncol. 28 (6) (2010) 928–935.
[35] T. Iguchi, T. Hiraki, Y. Matsui, T. Mitsuhashi, N. Katayama, K. Katsui, et al., Survival outcomes of treatment with radiofrequency ablation, stereotactic body radiotherapy, or sublobar resection for patients with clinical stage I non-small-cell lung cancer: a single-center evaluation, J. Vasc. Interv. Radiol. 31 (7) (2020) 1044–1051.
[36] H. Hu, B. Zhai, R. Liu, J.C. Chi, Microwave ablation versus wedge resection for stage I non-small cell lung cancer adjacent to the pericardium: propensity score analyses of long-term outcomes, Cardiovasc. Intervent. Radiol. 44 (2) (2021) 237–246.
[37] X.S. Yuan, W.C. Chen, Q.R. Lin, Y.J. Liu, Y.Y. Zhu, X.J. Sun, A propensity-matched analysis of stereotactic body radiotherapy and sublobar resection for stage I non-small cell lung cancer in patients at high risk for lobectomy: the results in a chinese population, J. Thorac. Dis. 13 (3) (2021) 1822–1832.
[38] E.S. Alexander, J.T. Machan, T. Ng, L.D. Breen, T.A. DiPetrillo, D.E. Dupuy, Cost and effectiveness of radiofrequency ablation versus limited surgical resection for stage I non-small-cell lung cancer in elderly patients: is less more? J. Vasc. Interv. Radiol. 24 (4) (2013) 476–482.
[39] M.C. Ambrogi, O. Fanucchi, P. Dini, F. Melfi, F. Davini, M. Lucchi, et al., Wedge resection and radiofrequency ablation for stage I nonsmall cell lung cancer, Eur. Respir. J. 45 (4) (2015) 1089–1097.
[40] J. Liu, C. Wang, W. Yi, H. Zheng, A. Zheng, A retrospective comparative study of microwave ablation and sublobectomy in the treatment of early subpleural nonsmall cell lung cancer, Int. J. Hyperthermia 39 (1) (2022) 1379–1386.
[41] Y. Matsuo, F. Chen, M. Hamaji, A. Kawaguchi, N. Ueki, Y. Nagata, et al., Comparison of long-term survival outcomes between stereotactic body radiotherapy and sublobar resection for stage I non-small-cell lung cancer in patients at high risk for lobectomy: a propensity score matching analysis, Eur. J. Cancer 50 (17) (2014) 2932–2938.
[42] N. Motono, M. Tanaka, Y. Machida, S. Maeda, K. Usuda, H. Toga, et al., The therapeutic strategy for clinical stage IA non-small cell lung cancer patients who are ineligible for lobectomy, Japanese J. Lung Cancer. 56 (3) (2016) 183–188.
[43] A. Zemlyak, W.H. Moore, T.V. Bilfinger, Comparison of survival after sublobar resections and ablative therapies for stage I non-small cell lung cancer, J. Am. Coll. Surg. 211 (1) (2010) 68–72.
[44] S. Paul, P.C. Lee, J. Mao, A.J. Isaacs, A. Sedrakyan, Long term survival with stereotactic ablative radiotherapy (SABR) versus thoracoscopic sublobar lung resection in elderly people: national population based study with propensity matched comparative analysis, BMJ (2016) i3570.
[45] J. Yun, J.H. Cho, T.H. Hong, K. Yang, Y.C. Ahn, H.K. Kim, Sublobar resection versus stereotactic body radiation therapy for clinical stage I non-small cell lung cancer: a study using data from the korean nationwide lung cancer registry, Cancer Res. Treat. 55 (4) (2023) 1171–1180.
[46] B. Dong, X. Zhu, J. Jin, Y. Chen, H. Ying, Y. Chen, et al., Comparison of the outcomes of sublobar resection and stereotactic body radiotherapy for stage T1-2N0M0 non-small cell lung cancer with tumor size $\leq$ 5 cm: a propensity score matching analysis, J. Thorac. Dis. 12 (10) (2020) 5934–5954.
[47] H. Chen, J.M. Laba, R.G. Boldt, C.D. Goodman, D.A. Palma, S. Senan, et al., Stereotactic ablative radiation therapy versus surgery in early lung cancer: a meta-analysis of propensity score studies, Int. J. Radiat. Oncol. Biol. Phys. 101 (1) (2018) 186–194.
[48] P. Rai, S. Zhang, Y. Song, C. Gao, A. Jiang, J. Li, et al., Real-world clinical outcomes and biopsy patterns of older patients with unresected non-small-cell lung cancer treated with primary stereotactic body radiotherapy, J. Clin. Med. 14 (23) (2025) 8604.
[49] Y. Nagata, M. Hiraoka, T. Shibata, H. Onishi, M. Kokubo, K. Karasawa, et al., Prospective trial of stereotactic body radiation therapy for both operable and inoperable T1N0M0 non-small cell lung cancer: Japan clinical oncology group study JCOG0403, Int. J. Radiat. Oncol. Biol. Phys. 93 (5) (2015) 989–996.
[50] B.J. Schneider, M.E. Daly, E.B. Kennedy, M.B. Antonoff, S. Broderick, J. Feldman, et al., Stereotactic body radiotherapy for early-stage non–small-cell lung cancer: American society of clinical oncology endorsement of the American society for radiation oncology evidence-based guideline, J. Clin. Oncol. 36 (7) (2018) 710–719.
[51] C.M. Maxwell, C. Ng, H.C. Fernando, Stereotactic body radiation therapy versus ablation versus surgery for early-stage lung cancer in high-risk patients, Thorac. Surg. Clin. 33 (2) (2023) 179–187.
[52] J.H. Rodriguez-Quintero, M.K. Kamel, R. Jindani, M. Vimolratana, N.P. Chudgar, B.M. Stiles, Sublobar resection is associated with less lymph nodes examined and lower delivery of adjuvant therapy in patients with 1.5- to 2.0-cm clinical IA2 non-small-cell lung cancer: a retrospective cohort study, Eur. J. Cardiothorac. Surg. 65 (1) (2024).
[53] Á.D. Tárnoki, D.L. Tárnoki, M. Dąbrowska, M. Knetki-Wróblewska, A. Frille, H. Stubbs, et al., New developments in the imaging of lung cancer, Breathe (Sheff.) 20 (1) (2024) 230176.
[54] G.S. Ajmani, C.-H. Wang, K.W. Kim, J.A. Howington, S.B. Krantz, Surgical quality of wedge resection affects overall survival in patients with early-stage non–small cell lung cancer, J. Thorac. Cardiovasc. Surg. 156 (1) (2018) 380–391.
[55] S.S. Razi, K. Kodia, A. Alnajar, M.I. Block, F. Tarrazzi, D. Nguyen, et al., Lobectomy versus stereotactic body radiotherapy in healthy octogenarians with stage I lung cancer, Ann. Thorac. Surg. 111 (5) (2021) 1659–1665.
[56] M. Guckenberger, N. Andratschke, K. Dieckmann, M.S. Hoogeman, M. Hoyer, C. Hurkmans, et al., ESTRO ACROP consensus guideline on implementation and practice of stereotactic body radiotherapy for peripherally located early stage non-small cell lung cancer, Radiother. Oncol. 124 (1) (2017) 11–17.
[57] D.A. Palma, T.K. Nguyen, A.V. Louie, R. Malthaner, D. Fortin, G.B. Rodrigues, et al., Measuring the integration of stereotactic ablative radiotherapy plus surgery for early-stage non–small cell lung cancer: a phase 2 clinical trial, JAMA Oncol. 5 (5) (2019) 681–688.
[58] S.H. Blackmon, R.M. Sterner, P.W. Eiken, T.J. Vogl, B.B. Pua, J.L. Port, et al., Technical and safety performance of CT-guided percutaneous microwave ablation for lung tumors: an ablate and resect study, J. Thorac. Dis. 13 (12) (2021) 6827–6837.
[59] M. Rédei, P. Sólymos, C. Turan, B. Szabó, A. Ádám, I.-I. Rezuș, et al., Navigation systems significantly improve the efficiency and safety of CT-guided interventions, Life 16 (3) (2026) 431.
[60] D.E. Dupuy, H.C. Fernando, S. Hillman, T. Ng, A.D. Tan, A. Sharma, et al., Radiofrequency ablation of stage IA non–small cell lung cancer in medically inoperable patients: results from the American college of surgeons oncology group Z4033 (alliance) trial, Cancer 121 (19) (2015) 3491–3498.
[61] S. Yim, W.C. Lin, J.S. Liu, M.H. Yen, Survival after thermal ablation versus wedge resection for stage I non-small cell lung cancer $<$ 1 cm and 1 to 2 cm: evidence from the US SEER database, Cancer Imaging 24 (1) (2024) 91.
[62] C. Cao, D. Wang, C. Chung, D. Tian, A. Rimner, J. Huang, et al., A systematic review and meta-analysis of stereotactic body radiation therapy versus surgery for patients with non-small cell lung cancer, J. Thorac. Cardiovasc. Surg. 157 (1) (2019), 362–73.e8.
[63] Y. Li, F. Yang, Y.Y. Huang, T. Wang, Sublobar resection versus ablation for stage I non-small-cell lung cancer: a meta-analysis, J. Cardiothorac. Surg. 17 (1) (2022) 17.
[64] P. Hegyi, B. Erőss, F. Izbéki, A. Párniczky, A. Szentesi, Accelerating the translational medicine cycle: the Academia Europaea pilot, Nat. Med. 27 (8) (2021) 1317–1319.