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RESEARCH

Robotic vs thoracoscopic vs open lobectomy and segmentectomy for lung cancer: a multicenter cohort study in the ATS of Milan

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Abstract
The study aimed at comparing the effectiveness of open thoracotomy (OT), video-assisted thoracoscopic surgery (VATS), and robot-assisted thoracic surgery (RATS) for anatomical lung resection in early-stage non–small cell lung cancer. We conducted a multicenter cohort study across eight hospitals in the Milan health authority, including patients undergoing lobectomy or segmentectomy in 2016–2021 (retrospective) and 2023–2025 (prospective). Inverse probability weighting was used to estimate average treatment effects. Primary outcomes were postoperative complications, 30-day readmission, and conversion to thoracotomy; secondary outcomes were operative time, postoperative length of stay (PO-LOS), 180-day mortality, and overall survival. The analytic cohort included 1,605 patients (647 OT, 653 VATS, 305 RATS). Adjusted odds ratios (ORs) of conversion were higher with VATS than with RATS (OR 2.47, 95% CI 1.43–4.24). Adjusted overall survival was unfavorable for OT vs. RATS (hazard rate 1.51 95% CI 1.11–2.05). Adjusted PO-LOS was longer with OT and VATS versus RATS (OR 3.38, 95% CI 2.62–4.37; and 1.90, 1.47–2.44). OT had shorter operative time and higher frequency of complications than minimally invasive approaches. VATS had longer operative time than RATS. Thirty-day readmission and 180-day mortality were similar across approaches. RATS was associated with shorter hospitalization and fewer conversion than VATS and with better adjusted survival than OT; early mortality and readmission were similar across approaches.

Keywords Video-assisted thoracoscopic surgery (VATS) · Robotic-assisted thoracoscopic surgery (RATS) · Open thoracotomy (OT) · Lung cancer · Multicentric cohort study

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Introduction

Surgical resection remains the cornerstone of curative-intent treatment for early-stage non–small cell lung cancer (NSCLC), and the increasing detection of small peripheral lesions has renewed interest in parenchyma-sparing strategies. In this scenario, anatomical segmentectomy has progressively moved from a "selected cases" procedure to a mainstream option for appropriately staged tumors.

Segmentectomy achieved oncologic outcomes at least comparable to lobectomy in trials focusing on small peripheral NSCLC and peripheral stage IA disease [1, 2].

Systematic syntheses focusing on VATS segmentectomy versus VATS lobectomy for stage I NSCLC have reported broadly comparable perioperative and oncologic outcomes. Importantly, the clinical boundaries of segmentectomy are still evolving, as illustrated by the STEP UP trial [3]. As segmentectomy becomes more frequent, it becomes clinically relevant to assess whether the surgical approach robotic, thoracoscopic or open meaningfully influences perioperative outcomes and downstream endpoints.

Minimally invasive thoracic surgery has challenged open thoracotomy (OT) as the reference approach for anatomical lung resections due to greater surgical trauma, postoperative pain, and potentially slower functional recovery.

Robot-assisted thoracic surgery (RATS) has expanded rapidly within the spectrum of minimally invasive techniques thanks to its ability to provide more precise dissection in confined spaces and potentially improve performance in complex procedures, including anatomical segmentectomy.

Nevertheless, the clinical "added value" of RATS over VATS remains debated and meta-analytic evidence heterogeneous. Some studies suggested lower conversion rates, shorter hospital stay, and a modest increase in lymph node harvest for RATS than VATS in lobectomies or segmentectomies [4–7], whereas survival endpoints appear broadly similar and costs higher [8–10].

Very recent systematic reviews have emphasized that the total volume of data from randomized controlled trials remains limited and that certainty across outcomes varies [11, 12]. Persistent uncertainty is also reflected in the Cochrane protocol [13] comparing RATS, VATS, and OT. A recent Bayesian network meta-analysis comparing open, VATS, and RATS segmentectomy suggested no major differences in key short-term endpoints, while also highlighting heterogeneity and limitations in the underpinning evidence [14].

Beyond clinical effectiveness, RATS adoption has implications on operating room time and resource utilization when comparing robotic to thoracoscopic lobectomy [15]. A recent systematic review suggests that RATS is frequently associated with higher costs, with variability in methods and conclusions across indications and health systems [16].

The key gap in the literature is the scarcity of contemporary, multicenter studies based on data reflecting routine clinical practice, collected within a defined health system and analyzed with robust confounding control for head-to-head comparisons of RATS, VATS, and OT, especially when considering both lobectomy and segmentectomy, and focusing on meaningful endpoints such as postoperative complications, readmissions, conversion to thoracotomy, and survival.

Within the Agency for Health Protection of Milan (ATS), the statutory mandate includes health system planning, performance monitoring, and health technology assessment (HTA) analyses to support evidence-informed decision-making. In this context, the coexistence within the same health authority of multiple high-volume hospitals adopting all currently available surgical approaches for anatomical lung resection (OT, VATS, and RATS) provided an opportunity to conduct a comparative effectiveness evaluation in the routine clinical practice. Leveraging routinely collected administrative data integrated with clinical and oncologic information, ATS promoted the development of a multicenter study aimed at assessing whether different surgical platforms translate into measurable differences in clinical outcomes beyond patient selection and case mix.

Accordingly, the primary objective of this multicenter observational study was to compare postoperative complications, 30-day all-cause hospital readmission, and conversion to thoracotomy among RATS, VATS, and OT for lobectomy and segmentectomy within the ATS of Milan, using robust adjustment strategies to account for baseline differences. Secondary objectives were to compare operative time, postoperative length of stay (PO-LOS), 180-day mortality, and long-term survival across surgical approaches.

Materials and methods

Study design and setting

This multicenter cohort study included patients with primary lung cancer treated at eight hospitals with dedicated thoracic surgery units in the ATS of Milan area, including both private and public individual centers accredited to provide healthcare services within the Italian National Healthcare System. In 2024, six hospitals performed more than 150 surgical procedures for primary and secondary lung cancer, whereas the remaining two hospitals performed more than 50 surgical procedures in the same year. At study start, three hospitals had an available robotic surgical platform; an additional center acquired it during the study period.

The study consisted of a retrospective cohort including patients who underwent surgery between 2016 and 2021 and a prospective cohort including patients operated on between 1 March 2023 and 16 September 2025.

Cohort assembly

Retrospective patients were initially identified through routinely collected administrative data and subsequently confirmed by participating centers. Prospective patients were enrolled by clinicians at participating centers.

Variables and data sources

Clinical information, surgery and tumor related data were uploaded onto a dedicated portal developed by the ATS Epidemiologic Unit. Routinely collected data were used to derive information on comorbidities and preoperative healthcare utilization (the number of hospital admissions, outpatient visits, Emergency Room accesses, and prescribed drugs in the period from 395 to 30 days before surgery).

The Charlson Comorbidity Index (CCI) was computed by adapting the algorithm proposed by Quan et al. [17] Information on index hospitalization and subsequent hospitalizations, vital status and date of death, and comorbidities was derived from routinely collected healthcare databases (Online Resource 1).

Study samples and outcomes

A first descriptive analysis included all ATS residents with complete information on surgical approach, smoking status, type of resection, and cancer stage.

Given the limited number of RATS procedures in other resection categories and to improve clinical comparability, the effectiveness analyses were restricted to patients undergoing lobectomy or segmentectomy.

Primary and secondary outcomes are those reported in the introduction. Definitions and categorization of postoperative complications and conversion in thoracotomy are reported in Online Resource 1.

Statistical analysis

Baseline characteristics were summarized by surgical approach. Operative time and postoperative LOS were categorized into four classes using quartiles of the overall study sample.

Associations between surgical approach and binary outcomes were estimated using logistic regression models. Quartile-based outcomes were analyzed using ordinal logistic regression. Overall survival was analyzed using Cox proportional hazards models, with follow-up starting at the date of surgery; the end of follow-up was set at 25 September 2025. For all models, OT was used as the reference category; contrasts were used to directly compare VATS and RATS.

To adjust for baseline differences among treatment groups, all outcome models were fitted using inverse probability weighting (IPW) to estimate the average treatment effect. The probability of receiving each surgical approach was estimated using a multinomial model with the following predictors: sex, age, smoking status, period of surgery, type of resection, cancer stage, presence of chronic obstructive pulmonary disease (COPD), CCI, and preoperative healthcare utilization indicators. Period of surgery was included in the IPW model as an adjustment variable to account for secular changes in surgical practice, technology diffusion, coding, and perioperative pathways; it was categorized as 2016–2018, 2019–2021, and 2023–2025 to avoid sparse annual categories, with the last period corresponding to the prospective cohort. Weights were calculated as the inverse of the estimated probability of receiving the observed surgical approach and were subsequently stabilized and truncated.

Covariate balance across surgical approaches after weighting was evaluated as proposed by McCaffrey et al. [18] (Online Resource 2).

Statistical significance was evaluated at a two-sided level of 0.05 Confidence intervals are at the 95% level. A sensitivity analysis was conducted restricting the dataset to retrospective patients only. Data management and statistical analyses were performed using SAS version 9.4 (SAS Institute Inc.).

The study was registered on ClinicalTrials.gov (NCT05674227). Study reporting STROBE guidelines for cohort studies where applied (Online Resource 3).

Data availability statement

The data underlying this article cannot be shared publicly for the privacy of individuals that participated in the study. The aggregated data will be shared on reasonable request to the corresponding author.

Results

Study population

Overall, 2001 patients were confirmed (retrospective) or enrolled (prospective) by the participating centers. Of these, 1921 patients had complete information on surgical approach, smoking status, type of resection, and cancer stage and were included in the descriptive analyses.

Surgical approach distribution and procedures

Among the 1921 patients, OT and VATS were the most frequently adopted approaches (42.4% and 41.0%, respectively), while RATS was less performed (16.6%). RATS was used predominantly for anatomical resections (Online Resource 1). Specifically, within segmentectomies ($n = 198$) the distribution was 48.8% OT, 37.4% VATS, and 14.6% RATS, while within lobectomies ($n = 1407$) the distribution was 39.2% OT, 41.2% VATS, and 19.6% RATS (Table 1).

Comparative cohort and baseline characteristics

Patients undergoing lobectomy or segmentectomy were 1605 (40.3% OT, 40.7% VATS, and 19.0% RATS). Baseline characteristics of the comparative cohort are shown in Table 1. The mean age was 69.2 years (SD 8.6) and did not differ across groups. Men were significantly more frequently treated with OT (59.0%) than with VATS (52.2%) or RATS (52.8%). Smoking status differed across techniques, with a higher proportion of never-smokers in the RATS group (22.6%) compared with VATS (18.1%) and OT (14.1%).

Patients treated with OT showed a higher comorbidity burden (mean CCI: 3.8 (SD 2.1) OT, 3.2 (SD 1.9) VATS, 3.3 (SD 1.9) RATS); a CCI$\geq$6 was more frequent in OT (29.1%) than in VATS (15.6%) and RATS (17.4%). Selected cardiovascular comorbidities were also more prevalent in OT, including heart failure (9.4% OT; 5.5% VATS; 5.6% RATS) and other cardiological conditions (17.9% OT; 12.6% VATS; 12.5% RATS). COPD/asthma prevalence was similar across groups.

Tumor characteristics differed markedly by approach. OT patients presented more advanced stages (stage I: 47.6% OT, 69.4% VATS, 72.1% RATS) and larger tumors (median size: 27 mm (IQR 18–45) OT, 21 mm (IQR 15–30) VATS, 19 mm (IQR 13–27.5) RATS). Tumor size was missing in 148 patients overall (66 OT, 81 VATS, 1 RATS). Histology also differed, with a higher proportion of squamous cell carcinoma in OT (21.0%) compared with VATS (13.3%) and RATS (10.8%), and a higher proportion of carcinoids in RATS (11.2%) compared with OT (5.9%) and VATS (6.9%).

Follow-up and crude outcome rates

Mean follow-up was 1635 days (SD 910.7) and was similar across surgical techniques; 50 patients (3.1%) were lost to follow-up. During follow-up, 527 patients (32.8%) died, with marked crude differences across approaches (41.9% OT, 29.9% VATS, 20.0% RATS). Within 180 days after surgery, 49 deaths (3.2%) were observed (4.5% OT, 2.6% VATS, 1.7% RATS).

Overall postoperative complications occurred in 439 patients (27.4%) and were more frequent after OT (31.7%) than after VATS (25.7%) and RATS (21.6%). Unplanned 30-day hospital readmissions occurred in 63 patients (3.9%), with similar crude proportions in OT (4.2%) and RATS (4.6%) and slightly lower proportions in VATS (3.4%). Conversion to thoracotomy occurred in 12.7% of VATS cases and 4.1% of RATS cases.

Operative time and PO-LOS differed by approach. Median operative time was 133 min for OT, 193 for VATS, and 174 for RATS; median PO-LOS was 6, 5, and 4 days, respectively.

IPW-adjusted comparisons across surgical approaches

After weighing, a good balance of baseline characteristics across surgical approaches was reached (Online Resource 2).

Raw and IPW-adjusted estimates for seven outcomes are reported in Fig. 1 and Online Resource 1.

OT showed higher mortality when compared with RATS (HR 1.51, CI 1.11–2.05). A tendency towards higher mortality was suggested for VATS compared with RATS (HR 1.33, CI 0.98–1.82; $p = 0.0717$), and to a lesser extent for OT versus VATS (HR 1.13, CI 0.93–1.38). No statistically significant differences were observed in IPW-adjusted 180-day mortality or in 30-day readmissions.

The IPW-adjusted estimates showed higher odds for postoperative complications after OT compared with RATS (OR 1.55, CI 1.14–2.11) and with VATS (OR 1.35, CI 1.06–1.81), while VATS and RATS were similar (OR 1.15, CI 0.84–1.57). VATS was associated with higher conversion to OT compared with RATS (OR 2.47, CI 1.43–4.24).

PO-LOS showed consistent differences across all comparisons, with longer stays in OT and VATS compared with RATS (VATS vs. RATS OR 1.90, CI 1.47–2.44; OT vs. RATS OR 3.38, 2.62–4.37) and longer stays in OT compared with VATS (OR 1.78, CI 1.46–2.17).

Operative time was shorter in OT compared with minimally invasive approaches (OT vs. RATS OR 0.21, CI 0.16–0.27; OT vs. VATS OR 0.15, CI 0.12–0.19). The comparison between VATS and RATS showed longer operative time for VATS (OR 1.40, CI 1.09–1.78).

Margins and mediastinal lymph node dissection

Margin status and mediastinal lymph node counts are reported in Online Resource 1. Among patients with available margin assessment, microscopic positive margins were

Table 1 Patients' baseline characteristics and time-period distribution

		Total 1605	OT 647	VATS 653	RATS 305	*P*-value[a]
Sex	M	883 − 55.0%	381 − 59.0%	341 − 52.2%	161 − 52.8%	0.04
Age	*Median(I.R.)*[b]	70(64–75)	71(64–75)	70(64–76)	70(63–75)	0.64
Smoking status	*Smoker*	441 − 27.5%	193 − 29.8%	176 − 27.0%	72-23.6%	**0.009**
	Ex-smoker	724 − 45.1%	306 − 47.3%	281 − 43.0%	137 − 44.9%)	
	Never smoke	278 − 17.3%	91-14.1%	118 − 18.1%	69-22.6%	
	Unknown	162 − 10.1%	57 − 8.8%	78-11.9%	27 − 8.9%	
CCI	*Mean-±s.d.*[c]	3.5 ± 2.0%	3.8 ± 2.1	3.2 ± 1.9	3.3 ± 1.9	
	0–2	750 − 46.7%	261 − 40.3%	335 − 51.3%	154 − 50.5%	**< 0.001**
	3–5	512 − 31.9%	198 − 30.6%	216 − 33.1%	98-32.1%	
	6+	343 − 21.4%	188 − 29.1%	102 − 15.6%	53-17.4%	
Comorbidities	*Diabetes*	259 − 16.1%	114 − 17.6%	99-15.2%	46-15.1%	0.41
	Hypercholesterolemia	486 − 30.3%	199 − 30.8%	192 − 29.4%	95-31.2%	0.81
	Hypertension	918 − 57.2%	371 − 57.3%	358 − 54.8%	189 − 62%	0.11
	Ischemic cardiovascular	212 − 13.2%	94-14.5%	88-13.5%	30 − 9.8%	0.13
	Heart failure	114 − 7.1%	61 − 9.4%	36 − 5.5%	17 − 5.6%	**0.01**
	Arrhythmias	214 − 13.3%	94-14.5%	84-12.9%	36-11.8%	0.46
	Non-arrhythmic cardiovascular	139 − 8.7%	68-10.5%	48 − 7.4%	23 − 7.5%	0.10
	Other cardiological	236 − 14.7%	116 − 17.9%	82-12.6%	38-12.5%	**0.01**
	Cerebrovascular	90 − 5.6%	45 − 7.0%	28 − 4.3%	17 − 5.6%	0.12
	BPCO/Asma	501 − 31.2%	217 − 33.5%	196 − 30.0%	88-28.9%	0.24
	BPCO	198 − 12.3%	88-13.6%	72 − 11.0%	38-12.5%	0.37
Histological type	*Small cell carcinoma*	10 − 0.6%	8-1.2%	0–0%	2-0.7%	**< 0.001**
	Adenocarcinoma	1165 − 72.6%	442 − 68.6%	498 − 76.3%	225 − 73.8%	
	Carcinoid	117 − 7.3%	38 − 5.9%	45 − 6.9%	34-11.2%	
	Squamous cell carcinoma	255 − 15.9%	135 − 21.0%	87-13.3%	33-10.8%	
	Large cell carcinoma	15 − 0.9%	5-0.8%	7-1.1%	3 − 1.0%	
	Other, specified	40 − 2.5%	16 − 2.5%	16 − 2.5%	8-2.6%	
	Missing	3	3	0	0	
Stage	*I*	981 − 61.1%	308 − 47.6%	453 − 69.4%	220 − 72.1%	**< 0.001**
	II	334 − 20.8%	166 − 25.7%	111 − 17.0%	57-18.7%	
	III	269 − 16.8%	162 − 25.0%	81-12.4%	26 − 8.5%	
	IV	21 − 1.3%	11 − 1.7%	8-1.2%	2-0.7%	
Tumor size (mm)	*Median(I.R.)*	23(15–35)	27(18–45)	21(15–30)	19 (13-27.5)	**< 0.001**
	Missing	148	66	81	1	
Previous hospital admissions	*0*	794 − 49.5%	309 − 47.8%	330 − 50.5%	155 − 50.8%	0.39
	1	519 − 32.3%	213 − 32.9%	201 − 30.8%	105 − 34.4%	
	2+	292 − 18.2%	125 − 19.3%	122 − 18.7%	45-14.8%	
Previous out-patient visits	*0–3*	485 − 30.2%	215 − 33.2%	161 − 24.7%	109 − 35.7%	**0.008**
	4–6	419 − 26.1%	160 − 24.7%	184 − 28.2%	75-24.6%	
	7–10	378 − 23.6%	142 − 22.0%	170 − 26.0%	66-21.6%	
	11+	323 − 20.1%	130 − 20.1%	138 − 21.1%	55 − 18.0%	
Previous Emergency Room accesses	NO	1006 − 62.7%	400 − 61.8%	412 − 63.1%	194 − 63.6%	0.83
	YES	599 − 37.3%	247 − 38.2%	241 − 36.9%	111 − 36.4%	
Drugs	*0*	230 − 14.3%	113 − 17.5%	81-12.4%	36-11.8%	**0.001**
	1–5	598 − 37.3%	211 − 32.6%	276 − 42.3%	111 − 36.4%	
	6+	777 − 48.4%	323 − 49.9%	296 − 45.3%	158 − 51.8%	
Time-period	*2016–2018*	510 − 31.8%	235 − 36.3%	172 − 26.3%	103 − 33.8%	**< 0.001**
	2019–2021	904 − 56.3%	387 − 59.8%	386 − 59.1%	131 − 43.0%	
	2023–2025	191 − 11.9%	25 − 3.9%	95-14.5%	71-23.3%	

[a]Chi-square and Kruskal-Wallis test according to variable nature; [b]Interquartile range; [c]Standard deviation

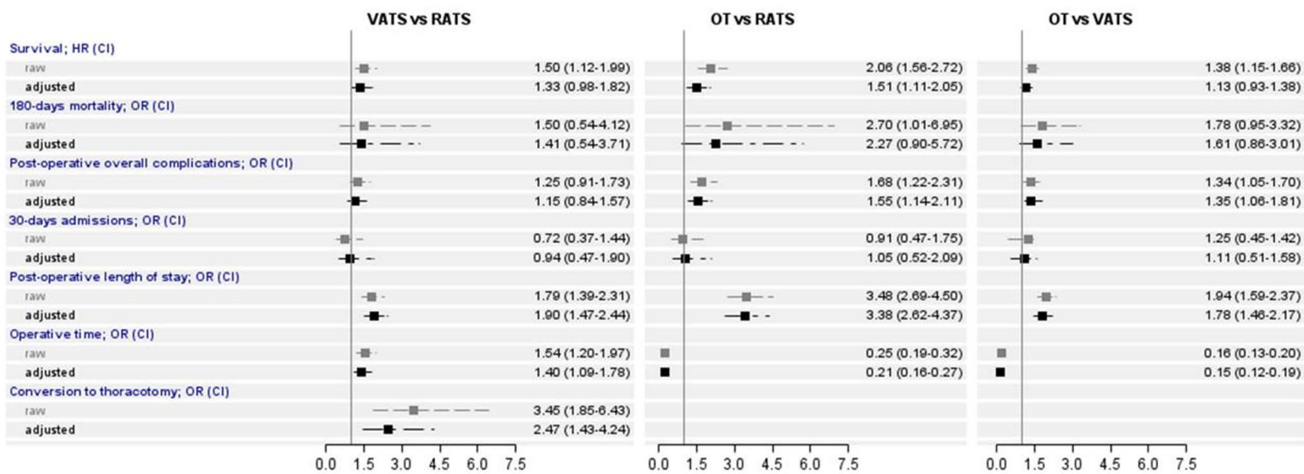

Fig. 1 Impact of surgical technique on outcomes in terms of hazard ratio for survival and of odds ratio for all the others; raw and IPW-adjusted estimates

uncommon (1.4% OT, 1.1% VATS, 1.0% RATS), while macroscopic positive margins were observed only in OT (0.4%). The number of dissected mediastinal lymph nodes differed across approaches, with higher counts in OT and RATS compared with VATS (median 6 (IQR 3–11), 5 (IQR 3–7), and 6 (IQR 4–10), respectively).

Sensitivity analysis

The sensitivity analysis restricted to retrospective patients included 1414 individuals (Online Resource 1). Overall findings were consistent with the main analysis, with two notable exceptions: (i) the IPW-adjusted HR for overall survival comparing VATS with RATS became significantly different from 1 (HR 1.43, CI 1.04–1.96), and (ii) the association between OT and RATS for postoperative complications was attenuated (OR 1.29, CI 0.92–1.82).

Discussion

In this multicenter study, comparing outcomes for lobectomy and segmentectomy in the routine clinical practice, we identified three main findings. First, case mix differed substantially across approaches, with OT being more frequently used in patients with a higher comorbidity burden and more advanced stage disease. Second, after IPW-adjustment, RATS showed the most favorable perioperative recovery profile, with shorter PO-LOS than VATS and OT, lower conversion to thoracotomy, fewer complications than OT, and better survival than OT. Third, 30-day readmission and 180-day mortality did not differ materially across approaches after adjustment. Margin positivity was low across techniques, and mediastinal lymph node counts were higher with OT and RATS than with VATS in unadjusted comparisons.

The relatively high proportion of OT should be interpreted in light of case mix, platform availability, and referral patterns. RATS was not available across all centers during the entire study period, and acquisition of robotic platforms in public hospitals is influenced by regional authorization, budget constraints, and HTA considerations. Moreover, early robotic activity in hospitals equipped with robots often focused on urologic surgery, partly because of regional reimbursement rules. At the same time, patients treated with OT had a higher comorbidity burden, more advanced stage disease, and larger tumors; higher OT use was concentrated in national referral centers, suggesting that case complexity and local practice patterns, rather than simple reluctance to adopt minimally invasive surgery, contributed to the observed OT rate.

Our finding that minimally invasive approaches are associated with improved postoperative recovery aligns with high-quality randomized evidence comparing VATS with OT [19]. Even without direct pain measures, the observed reduction in PO-LOS with VATS and particularly RATS fits the broader construct that reduced access trauma can translate into faster recovery and earlier discharge.

The relative performance of RATS and VATS remains debated. The most robust adjusted difference in our analysis was conversion to thoracotomy, which was significantly more frequent with VATS than RATS. This finding is consistent with the direction of effect reported in the meta-analysis by Ma and colleagues [4]. Conversion is a clinically meaningful endpoint, often associated with increased complications, prolonged length of stay, and higher costs. Robotic instrumentation may facilitate dissection and exposure, but conversion also depends on surgeon thresholds, institutional practice patterns, and case selection.

RATS showed the shortest PO-LOS compared with both VATS and OT. Published syntheses report heterogeneous differences between RATS and VATS, suggesting that perioperative pathways and center experience may moderate any platform effect [6–14].

Operative time in our study followed an expected pattern, with shorter operative time for OT than for minimally invasive techniques after adjustment. However, we observed longer VATS operative times than RATS in the adjusted ordinal model, a pattern that diverges from some contemporary reports. For example, a large contemporary observational analysis [15] highlighted that robotic-assisted lobectomy may require more operating room time compared with VATS. Similarly, Catelli and colleagues [9] reported shorter operative time with VATS compared with RATS in a prospective randomized trial. Discrepancy may reflect differences in how operative time is measured (skin-to-skin vs. total room time), in the distribution of complex cases between platforms, and potential learning-curve or standardization effects across centers. It is also plausible that, in a network where robotic programs are concentrated in high-throughput units with standardized docking workflows, the effective time penalty of robotics diminishes, while VATS may be more broadly applied across centers with wider variability in experience and case complexity. Importantly, because operative time was categorized into quartiles, small absolute differences may translate into category shifts; therefore, this signal should be interpreted as hypothesis-generating rather than definitive.

In our adjusted analyses we observed higher postoperative complication rates after OT compared with other approaches. This pattern is compatible with the broader literature supporting a perioperative benefit of minimally invasive access, although differences between RATS and VATS have been inconsistent across studies [4, 6]. Notably, in our sensitivity analysis, the association between OT and RATS for complications was attenuated, reinforcing that inferences about complications are more fragile than those about PO-LOS and conversion in this dataset.

Survival and oncologic outcomes remain the critical reference point when evaluating durable benefit. In our analysis, adjusted hazard ratios suggested better survival with RATS compared with OT. This finding adds to the existing literature, although survival comparisons should be interpreted cautiously because of residual confounding. Tasoudis et al. [5] and Catelli et al. [9] found equivalent overall and disease-free survival between RATS and VATS lobectomy. More broadly, recent systematic reviews focusing on randomized evidence have emphasized that the available trials are still limited in number and size, and that certainty across several outcomes remains variable [11, 12]. The Cochrane protocol underscores that definitive comparative-effectiveness conclusions remain a work in progress [13].

The oncologic adequacy of segmentectomy and sublobar resections deserves special attention because the technical demands of anatomical sublobar surgery may amplify any platform-related differences. Very low margin positivity across approaches is reassuring; unadjusted lymph node counts were higher with OT and RATS than VATS, consistent with modestly higher nodal harvest with RATS, but unadjusted comparisons warrant caution.

Our study also sits within a clinical landscape where the target population for segmentectomy continues to expand. Trials such as STEP UP [3] are exploring whether anatomical segmentectomy can be extended to larger (IA3) pure-solid tumors. Population-based evidence underscores tailoring resection to patient factors such as age and frailty, while weighing platform benefits against system costs [20].

From a health service and HTA perspective, our results inform the value discussion around robotic programs in a regional network. Shorter PO-LOS and fewer conversions with RATS may reduce downstream resource use, while operating room time and capital costs remain key drivers of robotic expense. Although direct costs were unavailable, these clinical parameters can inform future economic modeling in the Italian setting.

The principal strength of this study is its pragmatic, multicenter design within a defined health authority network, linkage of clinical and administrative data for follow-up and the use of IPW with balance diagnostics to address baseline differences.

To carry out its institutional tasks, the ATS in Milan has access to health and social-health data routinely collected for administrative purposes on all residents within its territorial scope. Available data include demographic registries, hospital discharge records, outpatient services, drug prescriptions, and co-payment exemptions. The quality and completeness of the data are ensured by regional and local level checks, which are also carried out for reimbursement purposes. Moreover, the Epidemiology Unit of the ATS of Milan manages the Cancer Registry on residents, which is validated according to the quality standards provided by the International Agency for Research on Cancer (IARC). These linked data allow reconstruction of patient's medical history, comorbidities, healthcare utilization, vital status, and follow-up within the regional health-care system.

Limitations of the sudy include residual confounding, the mixed retrospective/prospective design, and heterogeneous diffusion of RATS across centers. Robotic adoption was heterogeneous across centers, and surgeon- and center-level learning curves could not be fully modeled because of the limited number of RATS procedures and the incomplete overlap of surgical approaches across hospitals. Therefore, the estimates should be interpreted as the average performance of surgical approaches within a regional health-care network, rather than as purely technology-specific effects independent of center experience. A limitation of the available data is the lack of specific clinical information; for example, pulmonary function variables such as FEV1 and DLCO were not available and could not be included in the adjustment models. Although COPD/asthma, comorbidity burden, smoking status, procedure type, stage, and preoperative healthcare utilization were included in the IPW model, these variables are only partial proxies for functional status. Residual confounding related to pulmonary reserve and frailty cannot be excluded.Limitations also include a small number of unexpected postoperative histology/stage retained to avoid selection bias.

Information on neoadjuvant and adjuvant oncologic treatments was not systematically collected. This limitation is particularly relevant to the interpretation of long-term survival and to the higher proportion of stage III disease among OT patients. Although cancer stage was included in the IPW model and may partially account for measured disease extent, it cannot replace direct adjustment for preoperative therapy, postoperative oncologic treatment, treatment intent, or pTNM versus ypTNM classification. Residual confounding related to multimodal treatment pathways cannot be excluded.

Surgeon-level data, including individual procedure volume, seniority, platform-specific experience, and onboarding of new surgeons, were not available; therefore, the influence of surgeon learning curves and team experience on outcomes could not be quantified.

Among the study population a small number of patients were ultimately diagnosed with small cell lung cancer or pathological stage IV disease. These findings reflect unexpected intraoperative or postoperative histological and staging results, despite preoperative clinical assessment. Given the observational nature of the study, these patients were not excluded to avoid selection bias. However, their presence may have partially influenced postoperative outcomes and survival analyses, and this should be considered when interpreting the results.

The results should therefore be interpreted as network-level comparative-effectiveness estimates that include the influence of organizational context, platform diffusion, team experience, and learning curves, rather than as estimates of a technology effect isolated from surgeon and center experience.

The findings support the use of minimally invasive platforms in routine practice and suggest that, in a regional network, RATS may provide incremental perioperative advantages over VATS, particularly in recovery and conversion—while long-term outcomes appear broadly comparable. Future work should integrate surgeon-level learning curves, procedure-specific stratification (lobectomy vs. segmentectomy), and formal economic evaluation to inform high-value diffusion of robotic programs in health systems.

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Declarations

Conflict of interest Mario Nosotti reports financial support was provided by Fondazione IRCCS Ca' Granda Ospedale Maggiore Policlinico.Other authors declare that they have no relevant financial or non-financial interests to disclose.

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Consent to participate Written informed consent was obtained from the participants.

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