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Non-intubated robot-assisted anatomic lung resection under spontaneous ventilation: a single center initial experience

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Abstract

Background Non-tracheally intubated (NTI) robot-assisted thoracic surgery (RATS) for lung cancer resection has been only anecdotally reported, and evidence regarding feasibility is still lacking. This study aims at evaluating feasibility of NTI-RATS anatomic lung resection for early-stage lung cancer.

Results This retrospective single-institution feasibility study of prospectively collected data included patients undergoing anatomic NTI-RATS lung resections. The study was approved by our institutional ethical committee. All procedures included careful patient selection, thoracic epidural anesthesia, temporary phrenic and vagal nerve blocks and 4-port RATS approach. Feasibility was defined as the possibility to accomplish the whole procedure by RATS without need of conversion to open-surgery or trachealintubation with double lumen intubation according to predefined criteria. Perioperative blood gases and cerebral oxygen saturation were evaluated at predefined time points whereas recovery time was calculated according to standardized criteria. Post-operative protocol allowed to start feeding and mobilizing within 4 h after surgery. Between January and July 2026, 15 consecutive NTI-RATS anatomic lung resections were performed (12 lobectomies and 3 segmentectomies) with only one conversion to general anesthesia due to excessive mediastinal movement. We documented a median intra-operative $PaCO_2$ increment (+56.1% p<0.001), which returned close to baseline values 30 minutes after awakening. No patient met the criteria for cerebral desaturation throughout the procedure despite a slight median decrement (-10.1%, p<0.001) at the onset of surgical pneumothorax. Resection with free margins was achieved in all cases. Early feeding and mobilization were possible in all instances. There was no 30-day mortality and only one minor postoperative morbidity due to atrial fibrillation.

Conclusions NTI-RATS anatomic lung resection proved feasible in the vast majority (93.3%, 14/15, 95% confidence interval 68.1%-99.8%) in a highly selected population of patients with early-stage NSCLC.

Keywords Non-intubated thoracic surgery, RATS, Spontaneous ventilation, Minimally invasive, Thoracic surgery

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Background

Anatomic pulmonary resection with systematic lymph node dissection is the standard surgical treatment for patients with early-stage non-small cell lung cancer (NSCLC). Over the past decades, thoracic surgery has undergone a remarkable evolution toward progressively less invasive approaches as video-assisted thoracic surgery (VATS) and robotic-assisted thoracic surgery (RATS). These techniques have reduced post-operative pain and hospital stay, accelerated functional recovery, and improved patients' quality of life [1], maintaining oncological outcomes comparable to those of open surgery [2]. Ultimately, RATS is gaining popularity because of technical advantages over VATS, including high-definition three-dimensional visualization, articulated instruments with seven degrees of freedom, tremor filtration and improved surgeon ergonomics [3, 4].

In parallel with the evolution of surgery methods, thoracic anesthesia also has witnessed significant advances in recent years, most notably with the introduction of non-tracheally intubated (NTI) strategies with maintenance of spontaneous ventilation [5]. The rationale for NTI thoracic surgery is the avoidance of tracheal intubation, neuromuscular blockade and mechanical ventilation-related adverse effects including airway damage, barotrauma, volutrauma and atelectrauma [6] as well as an accelerated post-operative recovery [7]. These changes have been suggested to prove particularly helpful in selected categories of fragile patients with compromised cardiopulmonary function [8].

More recently NTI-VATS started to be adopted in more complex procedures, including anatomic lung resections, with encouraging results in terms of post-operative recovery, complications and oncological radicality [9, 10]. Comparison with mechanical ventilation VATS reported similar or even better outcomes, supporting the concept that intubation and mechanical ventilation may not always be mandatory for anatomic lung resection [11].

Despite encouraging results for VATS, the adoption of NTI-RATS remains uncertain. The use of carbon dioxide insufflation, the limited access to the patient after robotic docking, and the need to maintain an immobile operative field to avoid robotic arms-related injuries have traditionally reinforced the belief that general anesthesia and one-lung mechanical ventilation are indispensable during RATS procedures [12]. Consequently, the available literature about NTI-RATS anatomic lung resection is extremely limited. Robust evidence regarding its feasibility and safety is therefore still lacking.

The present study aims to evaluate for the first time the initial results, in terms of feasibility and peri-operative outcomes, of a single-institution NTI-RATS program entailing anatomic lung resection for early-stage NSCLC.

Methods

This retrospective single-institution feasibility study of prospectively collected data included patients undergoing NTI-RATS anatomic lung resection between January and July 2026. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki and was approved by our institutional ethical committee before the first surgery. Written informed consent for both surgery and spontaneous ventilation, as well as to the use of anonymized clinical data for research purposes, was obtained from all patients. The study is reported according to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines. The completed STROBE checklist is provided as Supplementary Material.

All surgical procedures were performed according to a predefined multidisciplinary protocol specifically developed for NTI-RATS. The protocol was jointly designed by thoracic surgeons and anesthesiologists and included standardized patient selection, regional anesthesia, intraoperative airway management, physiological monitoring and predefined conversion criteria.

Inclusion criteria were age ≥ 18 years, a diagnosis of early-stage NSCLC (up to clinical stage IIA, with no clinical lymph node involvement), and surgical indication for lobectomy or segmentectomy. Exclusion criteria were: history of previous ipsilateral thoracic surgery, severe obesity, known allergy to local anesthetics, presence of any absolute or relative contraindication to epidural anesthesia (i.e. infection at the catheter insertion site, a history of coagulopathy, obstructive cardiomyopathy, anatomic spinal abnormalities, inability to maintain positioning for epidural placement [13]), predicted difficult intubation in case of emergency conversion (i.e. Mallampati IV, reduced cervical motility, previous cervical radiotherapy, a history of previous difficult intubation), and absence of patient consent for spontaneous ventilation surgery.

Anesthesia management

The anesthesia team was always the same and included anesthesiologists with previous validated experience with NTI-VATS. Before surgery, a 16-G peripheral venous catheter and a 20-G radial arterial catheter were inserted under local anesthesia. Baseline arterial blood gas analysis was obtained while the patient was awake in the pre-operative holding area.

Thoracic epidural analgesia was established under ultrasound guidance at the T4–T5 interspace using an 18-G epidural catheter. Following confirmation of correct catheter placement, a bolus of 5 ml ropivacaine 0.5% was administered. Surgery was started after an adequate sensory block extending from T3 to T9 had been confirmed by cold sensation testing, approximately 15–30

min after the bolus. The expected duration of this block at this dose is approximately 4 h. No other epidural infusion was required during surgery. To reduce diaphragmatic excursion during spontaneous ventilation, an ultrasound-guided (high-frequency linear probe) phrenic nerve block was performed only on the side ipsilateral to surgery through an interscalene approach using mepivacaine 1% 10 ml before induction with the patient in supine position [14]. The phrenic nerve was identified on the anterior surface of the anterior scalene muscle, and the anesthetic was injected around the nerve under real-time ultrasound visualization of local spread. The block was always performed unilaterally, and no contralateral block was performed. The low volume of a short-to-intermediate acting local anesthetic was chosen to limit unintended spread and to restrict the duration of hemidiaphragmatic paresis. Successful diaphragmatic paresis was ultrasonographically confirmed before induction of sedation.

After positioning the patient in lateral decubitus, standard intra-operative monitoring was established, including continuous electrocardiography, invasive arterial pressure, pulse oximetry, respiratory rate and entropy monitoring. Sedation was achieved using target-controlled infusion of propofol (2-3.5 mcg/ml) combined with continuous remifentanil infusion (0.1–0.3 mcg/kg/min). Sedation depth was adjusted to maintain entropy values between 50 and 70 while preserving spontaneous ventilation. Once the target level of sedation had been achieved, a second-generation supraglottic airway device (i-gel®, Intersurgical Ltd., Wokingham, UK) was inserted without administration of neuromuscular blocking agents. Throughout the procedure, spontaneous ventilation was maintained and supplemental oxygen was administered through the anesthesia workstation with a FiO2 between 40% and 70% to maintain peripheral oxygen saturation above 90%.

At the completion of surgery, assisted ventilation through the supraglottic airway was temporarily applied whenever necessary to facilitate carbon dioxide elimination before removal of the airway device if $PaCO_2$ was > 60 mmHg and pH < 7.20. Patients were then awakened and transferred to the recovery room.

Surgical technique

All procedures were performed using a standardized 4-port RATS approach by the same thoracic surgical team using da Vinci Xi system. All the members of the surgical team had completed the curriculum recommended by Intuitive® and had previous consolidated experience with lobectomies and segmentectomies performed by RATS under general anesthesia and mechanical ventilation. Port mapping was based on a 3 cm utility port at the 6th intercostal space, along with three additional ports for robotic trocars, placed under thoracoscopic vision, two in the 9th intercostal space and one at the 8th one. No artificial capnothorax was adopted during any procedure. Following robotic docking and pleural exploration, the mediastinal pleura was opened and the ipsilateral vagus nerve was identified. Approximately 5 mL of lidocaine 1% were infiltrated around the vagus nerve under direct robotic vision to abolish the cough reflex before hilar dissection [15]. A possible additional dose of 5 ml was permitted if the cough reflex returned during the procedure.

Standard lobectomy or anatomical segmentectomy was subsequently performed, using robotic staplers. Particularly, segmentectomy was reserved for peripheral lesions measuring ≤ 1.5 cm without extension across the intersegmental plane. Lymph node assessment consisted of dissection of hilar, interlobar and mediastinal stations, including the subcarinal station (7), with the same approach in lobectomy and segmentectomy. Conversion to general anesthesia with double-lumen intubation was considered at any stage of the procedure in the presence of persistent oxygen desaturation, uncontrolled bleeding, excessive mediastinal movement compromising surgical safety, or any other condition considered unsafe by either the surgeon or the anesthesiologist. Specific precautions were adopted to allow prompt conversion to tracheal intubation with a double-lumen tube. First, all surgeries were performed with the attendance of an anesthesiologist experienced in double-lumen tube intubation in the lateral decubitus position. Second, a double-lumen tube, neuromuscular blocking agents and a fiberoptic bronchoscope were always available at the anesthesia workstation throughout surgery. Third, the da Vinci Xi patient-side cart was always docked so as to preserve unobstructed access to the patient's airway for the anesthesiologist. In case of conversion, the protocol included the rapid removal of the robotic instruments and undocking of the robotic arms, in order to prevent patient injury from any movement during intubation in lateral decubitus.

Intra- and post-operative monitoring

Physiological assessment extended beyond routine hemodynamic monitoring. Serial arterial blood gas analyses were performed at three predefined time points and evaluated with the same analyzer:

- T1: awake patient before induction of anesthesia on room air;
- T2: during the final phase of surgery after the extraction from pleural cavity of the lobe/segment with patient still sedated and under spontaneous ventilation through supraglottic device;
- T3: 30 min after awakening on room air or with supplementary oxygen through Venturi mask if required.

Heart rate, invasive arterial pressure, peripheral oxygen saturation and respiratory parameters were continuously monitored throughout the procedure. Regional cerebral oxygen saturation (rSO_2) was assessed by near-infrared spectroscopy at four predefined time points:

- T1: awake patient before induction of anesthesia (baseline);
- T2: immediately after surgical opening of the pleural cavity;
- T3: completion of pulmonary resection;
- T4: 30 min after awakening.

For descriptive purposes, the following commonly accepted clinical thresholds were adopted to describe physiologic extremes: pH < 7.20, SaO_2<90%, PaO_2<60 mmHg, lactate > 2 mmol/L, and a decrease in rSO_2>20% from baseline or an absolute value < 50%.

Post-operative management

Following surgery, all patients were transferred to the recovery room before returning to the ward. Recovery was assessed using the modified Aldrete score [16]. Patients were considered dischargeable from recovery room after achieving an Aldrete score ≥ 9. After reaching the ward, all patients were allowed to start feeding and active mobility.

All patients performed chest X-ray during the first post-operative day and possible elevation of the hemidiaphragm was assessed by a radiologist blinded to the phrenic nerve block. Post-operative pain was assessed by the patient using the Visual Analogue Scale (VAS) from 0 to 10 on postoperative day 1 and 3 during the morning round and reported to the clinical record by the physician. Analgesic regimen was based on acetaminophen 1 g three times a day and ketorolac 30 mg twice a day during the first two post-operative days. Data about pleural drainage volume during postoperative day 1, post-operative air leak, chest tube duration, post-operative complications (according to Clavien-Dindo classification) and length of hospital stay were also recorded. Chest tube was removed, according to our institutional practice, when daily pleural effusion was < 200 ml with no air leaks.

Study endpoints

The primary endpoint was the feasibility of NTI-RATS anatomic lung resection, defined as the successful completion of the planned RATS procedure without surgical- or anesthesia related adverse effects requiring conversion to general anesthesia and double-lumen tube intubation with or without thoracotomy.

Secondary endpoints included intra-operative physiological stability, post-operative recovery, recovery room stay, post-operative pain, post-operative complications, post-operative elevation of ipsilateral hemidiaphragm at chest X-ray, length of stay. Oncological outcomes were assessed as resection margin status and extent of nodal assessment (number of retrieved lymph nodes and stations).

Statistical analysis

Statistical analysis was performed using SPSS Statistics version 26.0 (IBM Corp. Released 2016. IBM SPSS Statistics, Armonk, NY, USA: IBM Corp.). Continuous variables were reported as median with interquartile range (IQR), whereas categorical variables as frequencies and percentages. The variables and time points of the physiologic assessment were predefined in the clinical protocol, whereas the statistical analysis plan was not prespecified and was defined after data collection. Comparison of the variables across the fixed time points, due to the limited number of patients, was performed using the non-parametric Friedman test for repeated measures. When a statistically significant result was found, post-hoc pairwise comparisons (i.e. T1 vs. T2, T2 vs. T3, T1 vs. T3) were performed using the Wilcoxon signed-rank test for paired data, with Bonferroni correction applied for multiple comparisons (corrected significance threshold: $\alpha = 0.0167$ for all comparisons with three time points; $\alpha = 0.0083$ if four time points). Given the exploratory and descriptive nature of the study, no further correction was applied across physiologic parameters. Moreover, several parameters were physiologically correlated, which would make a Bonferroni correction across all outcomes overly conservative. Furthermore, changes in each variable across the study time points were graphically represented using line plots, illustrating the trend over time for each parameter. These graphs were obtained using Jupyter Notebook (Project Jupyter version 7.3.2), running Python (version 3).

Results

Clinical and demographic characteristics

A total of 15 consecutive patients was included in this study. A flow diagram reporting the number of patients originally assessed and the reasons for exclusion is displayed in Fig. 1. Median age was 62 years (IQR 51–76 years old), and 7/15 patients (46.7%) were male. A positive history of smoking was recorded in 9/15 patients (60.0%). Thirteen out of 15 patients (86.7%) had an American Society of Anesthesiologists (ASA) score of 3 while the remaining 2 patients (13.3%) were ASA 2. Median pre-operative forced expiratory volume during the 1st second (FEV1) was 2.41 L (IQR 1.53–2.94), whereas median Diffusing Capacity of the Lungs for Carbon Monoxide (DLCO) was 92.0% (IQR84.0%-99.0%) of the predicted value.

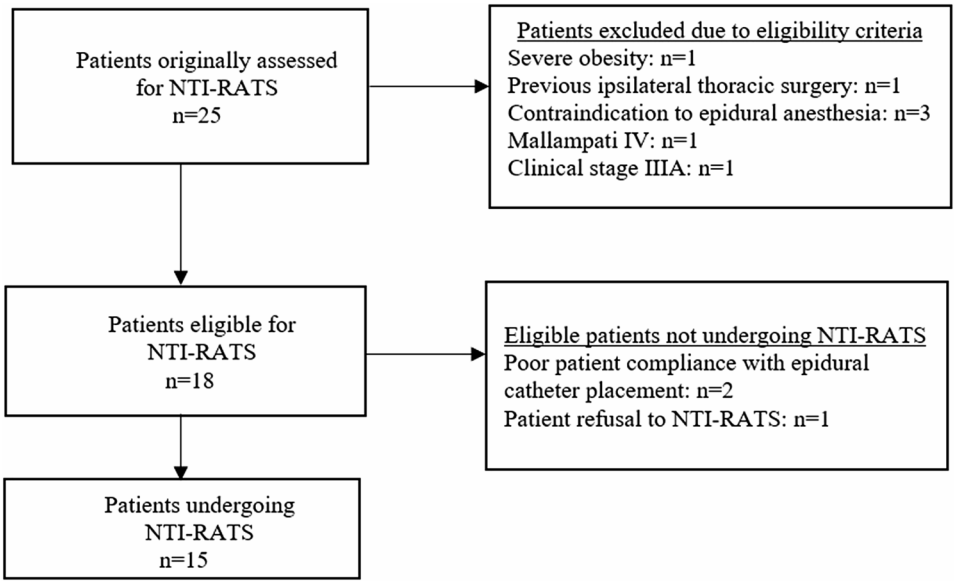


Fig. 1 Flow diagram showing patients originally assessed for non-tracheally intubated robotic assisted thoracic surgery (NTI-RATS) and reasons for exclusion

Operative and pathological outcomes

Twelve patients (80.0%) underwent lobectomy while the remaining 3 patients (20.0%) underwent segmentectomy. Particularly, among lobectomies, 4/12 (33.3%) involved right upper lobe, 2/12 (16.7%) middle lobe, 3/12 (25.0%) right lower lobe, 1/12 (8.3%) left upper lobe, and 2/12 (16.7%) left lower lobe. As regards segmentectomies, we performed one left upper lobe trisegmentectomy, one lingulectomy and one right lower lobe S6 segmentectomy. Median total operative time was 206 (IQR 181–213) minutes, and median console time was 127 (IQR 120–163) minutes. With reference to nodal dissection, a median of 10 lymph nodes (IQR 7–12) from 3 nodal stations (IQR 3–5) were removed.

Conversion to general anesthesia and double-lumen intubation was required in 1 patient (6.7%), particularly our second lobectomy (right upper lobe), because of excessive mediastinal movement which was deemed at risk for safety. Conversion was performed approximately 20 min after docking, with removal of the robotic instruments before intubation, and caused no related complications or significant operative delay. No patient required conversion to video-assisted thoracic surgery or thoracotomy. Consequently, feasibility rate calculated per patient on all 15 procedures was 93.3% (14/15; exact binomial 95% confidence interval 68.1%-99.8%). No cases of severe intra-operative desaturation (< 90%), hemodynamic instability or other severe anesthesiologic problems were recorded. Two patients (2/15, 13.3%) required an additional dose of lidocaine for vagal block due to coughing during surgery.

Complete microscopic resection with free margins (at least 2 cm) was achieved in all patients. Final pathologic findings included a diagnosis of adenocarcinoma in 13/15 patients (86.7%) and of squamous cell carcinoma in 2/15 patients (13.3%). Pathological TNM staging was pT1a in 1/15 patient (6.7%), pT1b in 7/15 patients (46.6%), pT1c in 6/15 patients (40.0%), and pT2a in 1/15 patient (6.7%). All patients were classified as pN0. No discrepancy between original clinical TNM and pathological TNM was recorded.

Supplementary video 1 shows one case from this series (left upper lobe trisegmentectomy).

Peri-operative blood gas changes

Comparison of the arterial blood gases across the 3 fixed time points are summarized in Tables 1 and 2 respectively. There were no missing data or arterial blood gas analysis or cerebral rSO_2 obtained outside the predefined windows. Converted patient was included in the analysis.

The pH changed significantly over time ($p < 0.001$), with a significant decrease between T1 and T2 and a subsequent increase between T2 and T3, with values returning to the physiological range, although they did not reach the baseline levels recorded at T1. No patient reached a pH < 7.20 (lowest value 7.20 at T2).

With reference to $PaCO_2$, a significant change was recorded across the three predefined time points ($p < 0.001$). Median $PaCO_2$ increased from 35.1 mmHg (IQR 33.936.3) at T1 to 54.8 mmHg (IQR 47.9–56.8) at T2 (+ 56.1%, $p < 0.001$) and subsequently decreased to 37.6 mmHg (IQR 35.8–39.8) 30 min after awakening. No patient was still hypercapnic 30 min after awakening

Table 1 Arterial blood gas variables at predefined time points, median (IQR); $n = 15$ at each time point

Variable	T1	T2	T3	*p*-value*
pH	7.42 (7.40–7.42)	7.30 (7.23–7.33)	7.37 (7.37–7.40)	**0.000004**
$PaCO_2$ (mmHg)	35.1 (33.9–36.3)	54.8 (47.9–56.8)	37.6 (35.8–39.8)	**0.000003**
PaO_2 (mmHg)	85.9 (80.0–88.5)	98.5 (91.8–100.6)	71.2 (64.3–77.8)	**0.000002**
SaO_2 (%)	96.9 (95.8–97.9)	96.5 (94.5–97.8)	94.6 (92.6–96.5)	**0.002**
Lactate (mmol/L)	0.76 (0.45–0.83)	0.78 (0.73–0.83)	0.86 (0.74–1.02)	0.091
HCO_3^- (mmol/L)	24.7 (23.6–25.2)	24.7 (22.9–25.6)	24.2 (22.7–26.0)	0.45

*Friedman test; p-values in bold are < 0.050

FiO_2: fraction of inspired oxygen; HCO_3^-: bicarbonate; IQR: interquartile range; $PaCO_2$: arterial partial pressure of carbon dioxide; PaO_2: arterial partial pressure of oxygen; SaO_2: arterial oxygen saturation

Table 2 Pairwise comparisons of physiologic variables between time points ($n = 15$)

Variable	Comparison	Median difference (95% CI)†	*p*-value*
pH	T1 vs. T2	−0.13 (−0.17 to −0.08)	**0.0007**
	T2 vs. T3	+0.10 (0.06 to 0.13)	**0.0008**
	T1 vs. T3	−0.04 (−0.06 to −0.01)	**0.008**
$PaCO_2$ (mmHg)	T1 vs. T2	+18.4 (14.8 to 23.1)	**0.0007**
	T2 vs. T3	−16.3 (−22.1 to −11.4)	**0.0007**
	T1 vs. T3	+3.1 (1.0 to 5.2)	**0.011**
PaO_2 (mmHg)	T1 vs. T2	+12.4 (6.6 to 20.3)	**0.002**
	T2 vs. T3	−27.1 (−35.7 to −19.6)	**0.0007**
	T1 vs. T3	−14.5 (−18.7 to −10.4)	**0.0007**
SaO_2 (%)	T1 vs. T2	−0.4 (−1.3 to 0.6)	0.514
	T2 vs. T3	−2.1 (−3.6 to −0.6)	**0.016**
	T1 vs. T3	−2.4 (−3.5 to −1.4)	**0.0007**
Lactate (mmol/L)	T1 vs. T2	+0.09 (−0.06 to 0.22)	0.293
	T2 vs. T3	+0.11 (−0.01 to 0.23)	0.111
	T1 vs. T3	+0.19 (0.07 to 0.34)	**0.005**
rSO_2 (%)	T1 vs. T2	−8.0 (−9.0 to −6.5)	**0.0006**
	T2 vs. T3	+7.5 (6.0 to 8.5)	**0.0006**
	T3 vs. T4	0.0 (−1.0 to 1.0)	0.842
	T1 vs. T3	0.0 (−1.0 to 0.5)	0.796
	T1 vs. T4	0.0 (−1.5 to 1.5)	0.862
	T2 vs. T4	+7.8 (6.0 to 9.5)	**0.0006**

†Hodges-Lehmann median paired difference (later minus earlier time point) with exact 95% confidence interval. *Wilcoxon signed-rank test; p-values in bold are below the Bonferroni-corrected threshold (α = 0.0167 for three time points; α = 0.0083 for rSO_2, four time points)

CI: confidence interval; FiO_2: fraction of inspired oxygen; $PaCO_2$: arterial partial pressure of carbon dioxide; PaO_2: arterial partial pressure of oxygen; rSO_2: regional cerebral oxygen saturation; SaO_2: arterial oxygen saturation

and none of them required temporary assisted ventilation through supraglottic device at the end of surgery to restore $PaCO_2$.

As regards PaO_2 and arterial oxygen saturation (SaO_2), both reached the lowest median values at T3 although no cases of respiratory failure requiring non-invasive ventilation or intubation were reported during recovery room period. FiO_2 was 0.21 in all patients at T1, 0.60 (IQR 0.54–1.00) at T2, and 0.21 in 10 patients and 0.31–0.35 in 5 patients at T3. The PaO_2/FiO_2 ratio decreased from 409 (IQR 381–421) at T1 to 141 (IQR 94–182) at T2 ($p < 0.001$) and recovered to 313 (IQR 222–349) at T3 ($p = 0.001$), while remaining lower than baseline (T1 vs. T3, $p < 0.001$). The lowest SaO_2 (89.6%) and the lowest PaO_2 (57.3 mmHg) were both recorded at T3 in one patient, and SpO_2 promptly improved after increasing FiO_2 from 0.31 to 0.35 and encouraging the patient to expectorate. No other patient had pO2 < 60mmHg or SaO2 < 90%. No significant difference was observed for lactate and $HCO3^-$ levels.

Cerebral rSO_2 varied significantly across the four measurement points ($p < 0.001$). In particular median cerebral saturation decreased from 79% (IQR 78%79%) at T1 to 71% (IQR 69%–72%) at T2 (-10.1%, $p < 0.001$). It subsequently increased up to a median value of 79% (IQR 78%-79%) at T3 ($p < 0.001$) and remained stable (IQR 76%–80%) at T4 ($p = 0.84$). Cerebral oxygenation at T3 ($p = 0.79$) and T4 ($p = 0.86$) did not differ significantly from baseline after correction for multiple comparisons. No patient had a decrease in rSO_2>20% from baseline (largest decrease 13.9%; lowest absolute value 68%).

The temporal trends of pH, $PaCO_2$, PaO_2, and cerebral rSO_2 are shown in Fig. 2.

Post-operative outcomes

The median Aldrete score on admission to the post-operative recovery area was 9 (IQR 9–9), and the median time spent in recovery room before return to the ward was 49 min (IQR 47–54 min). All patients resumed oral fluid intake within 1 h and solid food within 3 h from the end of surgery, and all patients were mobilized within 4 h after returning to the ward. No cases of elevation of hemidiaphragm were highlighted at chest X-ray at post-operative day 1.

Median pain score according to VAS was 3 (IQR 2–4) on post-operative day 1 and 3 (IQR 1–4) on post-operative day 3. Median drainage volume during post-operative day 1 was 250 mL (IQR 170–280 mL). Air leakage was present in 3 patients (20%) on post-operative day 1 and persisted in just 1 patient (6.7%) on post-operative-day 3.

One patient (6.7%) experienced as post-operative complication an atrial fibrillation associated with increased chest-drain output (Clavien-Dindo II). This patient

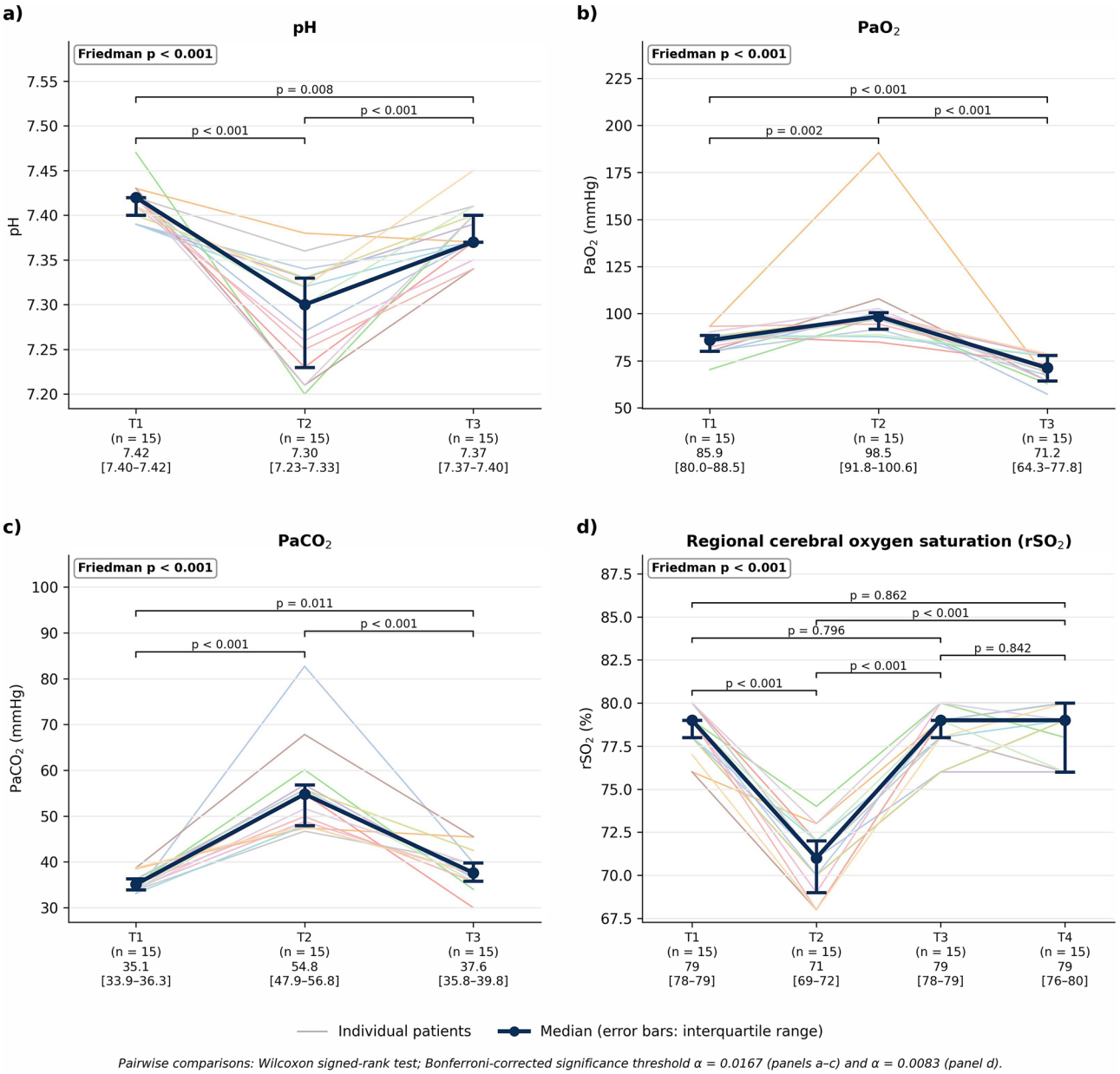


Fig. 2 pH(**a**), PaO2(**b**), PaCO2(**c**), and cerebral oxygenation saturation(**d**) trends over time for each patient (thin lines) and as median value (thick line) with interquartile range (IQR) and p-value after Bonferroni correction

underwent pharmacological cardioversion and was discharged with Heimlich valve on post-operative day 5 with chest tube removal on post-operative day 11. Median hospital stay was 3 days (IQR 2–3 days). No patient was readmitted within 30 days from discharge. No 30-day postoperative mortality was observed. Data about each patient is reported in Supplementary Table S1.

Discussion

The growing interest in NTI thoracic surgery strategies reflects an increasing awareness that many of the physiological adverse effects considered unavoidable during pulmonary resection under general anesthesia, tracheal intubation and one-lung mechanical ventilation might be avoided by less invasive anesthesia protocols [17]. Although VATS and RATS have reduced the surgical trauma of many thoracic surgeries, they have not eliminated the physiological burden related to anesthesia. Consequently, NTI anesthesia methods are emerging as complementary tools aimed at further minimizing the overall peri-operative invasiveness. In this light NTI anesthesia has been initially applied to simple surgical procedures such as lung wedge resection and biopsy, being then adopted in progressively more complex VATS

procedures [18], including lobectomy, by Chen et al. in 2011 [19]. Following this experience, in 2013 Hung et al. described the first cases of NTI-VATS segmentectomies [20]. Despite encouraging results described in VATS, reports about NTI-RATS remain anecdotal, probably because of concerns regarding airway safety, carbon dioxide accumulation, patient movement and the perceived complexity of emergency conversion. Most of the literature about NTI-RATS is focused on tracheal resection [21] and, as far as we know, there is only a recently published case report about NTI-RATS lobectomy [22] and one about a RATS segmentectomy in the same modalities [23].

To the best of our knowledge, our series is the first to report preliminary results of NTI-RATS anatomic lung resection program. It is worth noting that technical feasibility of the procedure was as high as 93.3% (95% confidence interval 68.1%-99.8%), a result which seems in line with those reported by NTI-VATS lobectomy. The only case of conversion occurred early in our experience (second lobectomy), probably reflecting a learning curve effect. Moreover, conversion was not due to an emergency event but rather to the surgeon's decision to convert because of excessive mediastinal movement to assure maximal safety to the patient according to a planned complication-prevention-strategy. In our series we also reported margin-free resection in all patients, with a median of 10 lymph nodes retrieved from at least 3 stations, low peri-operative morbidity, and quick post-operative recovery. At the same time respiratory and acid-base alterations were transient, with no patient reaching a pH below 7.20. Overall, our findings suggest that the feasibility of NTI-RATS relies on the integration of careful patient selection, standardized anesthesia and robotic surgical techniques, detailed intra-operative monitoring, and strict criteria of post-operative recovery room stay.

We believe that the double temporary phrenic and vagus nerves block contributed to facilitating surgical maneuvering under spontaneous ventilation by minimizing unvoluntary movements of the pulmonary hilum and thus making the procedure easier. This may be reflected by the median console time of the present series (127 min), which did not substantially differ from the mean console time of the intubated RATS anatomic lung resections performed by the same surgeon during the last year (111 min, as recorded by the Intuitive® application). Moreover, the phrenic nerve block did not cause any significant post-operative respiratory impairment as suggested by the absence of evident hemidiaphragm elevation 24 h after surgery at the chest X-ray. This is likely due to the short duration of action of the adopted local anesthetic, whose effect is expected to be largely confined to the intra-operative period. Avoidance of capnothorax eliminated an additional source of intrathoracic pressure increase, thereby reducing the potential impact on venous return and respiratory mechanics [24]. An additional feature which enhanced safety of the protocol was the definition of clear conversion criteria before the beginning of each procedure.

One of the principal reasons many surgical teams remain reluctant to adopt NTI-RATS is the perception that conversion to tracheal intubation may become technically difficult or hazardous once the robotic system is docked [25]. In reality, conversion should not be regarded as a procedural failure but as an integral component of the safety strategy [26].

Beyond technical feasibility, this series also reported a favorable post-operative outcome. Patients could return to the ward and start feeding and mobilizing very soon, reported low post-operative pain scores and low morbidity that allowed an early discharge. In this setting our results are consistent with previous literature data from Zhang et al. who reported in a meta-analysis comparing NTI- versus intubated-VATS, a lower incidence of complications and pain as well as a reduced hospitalization time in the former group [11]. It is likely that post-operative recovery cannot be attributed to a single component of the protocol but rather reflects the cumulative effect of multiple peri-operative interventions, including epidural analgesia, preservation of spontaneous ventilation, avoidance of neuromuscular blockade and structured post-operative care. All these factors may have acted synergistically to comply with principles of enhanced recovery after surgery [27].

Regarding blood gas exchange data, some concerns could be raised about the risk of respiratory acidosis and tissue perfusion [28]. Our series showed the development of intra-operative permissive hypercapnia with respiratory acidosis, which however returned to physiological values nearly immediately after surgery. Furthermore, it seems worthy of note that no cases of hypoxia requiring non-invasive ventilation or intubation were recorded, results which seem in line with previously reported data about NTI-VATS [29]. Although previous studies have predominantly investigated shorter surgical procedures, our findings indicate that permissive hypercapnia did not result in clinically relevant adverse events even during longer and more complex surgical procedures such as RATS lobectomies or segmentectomies.

We also investigated the impact of NTI-RATS on cerebral oxygenation. Consistent with previous NTI-VATS data [30], rSO_2 showed only a transient decrease after opening of the pleural cavity, which reversed during surgery, and no patient met the criteria for cerebral desaturation. This early decrease may reflect a phase of hemodynamic and ventilatory adaptation. Previous studies have hypothesized that hypercapnia-induced

cerebral vasodilation might contribute to maintaining cerebral oxygenation during spontaneous ventilation, and even play a protective role, in patients not at risk of intracranial hypertension [30, 31]. However, our data do not allow this hypothesis to be tested. rSO_2 and arterial blood gases were sampled at different intra-operative time points and near-infrared spectroscopy reflects the regional balance between cerebral oxygen supply and demand rather than cerebral perfusion. Future comparative studies with equivalent procedures under tracheal intubation and one-lung mechanical ventilation are needed to clarify this issue.

Several limitations of the present study should be acknowledged. First, this is a single-center analysis including a relatively small number of highly selected patients. This inevitably limits the statistical power and precludes definitive conclusions regarding peri-operative clinical outcomes. Consequently, these results should primarily be interpreted as evidence supporting the feasibility and physiological tolerability of a standardized multidisciplinary approach rather than as proof of superiority over conventional intubated RATS. Another important limitation is the absence of a control group undergoing conventional RATS under mechanical ventilation. As a consequence, the contribution of non-tracheal intubation itself to the observed outcomes cannot be isolated, and no conclusion can be drawn on superiority, general safety or peri-operative advantage over conventional intubated RATS. The relatively short follow-up, together with the relatively small sample size of the population and the lack of more advanced stages of disease, also precludes assessment of long-term oncological outcomes. From a physiological perspective, our study focused on peri-operative arterial blood gas analysis, lactate kinetics and cerebral oxygenation. Although these parameters provide a comprehensive assessment of respiratory adaptation and global tissue perfusion, additional biomarkers, including inflammatory mediators, stress-response biomarkers, diaphragmatic function, post-operative pulmonary mechanics and patient-reported recovery measures, could further improve understanding of the physiological effects of NTI-RATS. Finally, these procedures were performed in a center with consolidated experience in NTI thoracic surgery. These results should therefore not be interpreted as immediately reproducible in all clinical settings.

Conclusions

Results of this study suggest that NTI-RATS anatomic lung resection was completed without conversion in 14 of 15 patients. In addition, in our initial institutional experience, NTI-RATS was associated with margin-free resection, low peri-operative morbidity and rapid post-operative recovery. Some expected physiologic changes including transient permissive hypercapnia with mild respiratory acidosis occurred without evidence of clinically significant tissue hypoperfusion or sustained impairment of cerebral oxygenation.

These results were obtained in a highly selected population with early-stage NSCLC and their applicability to a vast majority of patients remains to be established. Although larger prospective comparative studies are warranted to define clinical advantages of NTI-RATS over equivalent procedures performed by intubation with one-lung mechanical ventilation, the present study provides some interesting insights supporting continued clinical research in this field and promoting further standardized NTI-RATS programs.

Abbreviations

ASA	American society of anesthesiologists
DLCO	Diffusing capacity of the lungs for carbon monoxide
FEV1	Forced expiratory volume during the 1st second
IQR	Interquartile range
NTI	Non-tracheally intubated
NSCLC	Non-small-cell lung cancer
RATS	Robotic-assisted thoracic surgery
VAS	Visual analogue scale
VATS	Video-assisted thoracic surgery

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

Author contributions

SAB: Conceptualization; Data curation; Investigation; Writing- original draft preparation. AP: Formal analysis; Writing- original draft preparation. LCS: Data curation. CC: Data curation. EF: Resources; Supervision. MC: Resources; Data curation. BC: Supervision. SE: Supervision. VA: Supervision; Writing- review & editing. EP: Conceptualization; Methodology; Supervision; Writing- review & editing.

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Data availability

All data generated or analyzed during this study are included in this published article.

Declarations

Ethical approval

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of Tor Vergata University Polyclinic (N. 4.26CS, January 2026). Informed consent was obtained from all individual participants included in the study.

Consent for publication

Informed consent for the use of personal data for scientific purposes was obtained from all subjects involved in this study. Written informed consent for publication of the anonymized intra-operative video (Supplementary Video 1) was obtained from the patient involved.

Competing interests
The authors have no relevant financial or non-financial interests to disclose.

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