The Cardiothoracic Surgeon

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Cost minimization analysis by Monte Carlo simulation in spontaneous versus mechanical ventilation thoracoscopic surgery

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Abstract

Background Spontaneous ventilation video-assisted thoracic surgery (SV-VATS) represents an additional step ahead within the evolution of minimally invasive thoracic surgery and has been shown to be associated with reduced morbidity and hospitalization times in selected cohorts. Nevertheless, the economic implications of this strategy are still under-investigated.

Aim of this study was to perform a cost-minimization analysis in order to compare SV- versus mechanical ventilation (MV) VATS across different surgical scenarios. Costs computation included non-device-related costs and costs related to management of post-operative complications.

Results We compared SV-VATS (group A) versus MV-VATS (group B) through a cost-minimization analysis. Costs included in the analysis were hourly operating room expenses, daily costs for hospitalization, and costs related to post-operative complications. Economic evaluation was made using Monte Carlo simulation modeling. Two different scenarios were investigated: lung volume reduction surgery for emphysema and wedge resection for lung metastasectomy. Input data about operative room time, hospital stay, and morbidity were retrieved from 2 of our previously published comparative studies. In the first scenario about lung volume reduction surgery, group A presented significantly lower estimated mean costs (€6238.9 ± 2430.9 versus €11,874.1 ± 3529.1 for group B, $p < 0.001$). The analysis of cost distribution revealed that group B was associated with a wider and higher range of costs, suggesting greater financial variability. Evaluation of cost differences distribution showed that group B was associated with higher costs in 90.8% of simulations, with an expected mean cost saving of €5635.2 ± 4309.5 per patient by adopting SV. In the second scenario about wedge resection, group A confirmed lower estimated mean costs (€3199.8 ± 1074.2 versus €4538.7 ± 2405.4 of group B, $p < 0.001$) and a narrower cost distribution, reflecting a more predictable economic profile. Distribution of cost difference indicated that patients in group B presented higher costs in 65.8% of simulations, with an expected mean cost saving of €1338.9 ± 2629.9 by choosing SV.

Conclusions SV-VATS was associated with lower overall costs compared to MV-VATS in different clinical scenarios, suggesting a lower in-hospital financial burden. These findings support the role of this strategy not only as clinically advantageous, but also as a cost-minimizing strategy in healthcare resource management.

Keywords Cost-minimization analysis, Monte Carlo simulation, Spontaneous ventilation video-assisted thoracic surgery, Healthcare management, Thoracic surgery

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Background

Video-assisted thoracic surgery (VATS) has emerged as a less invasive approach for most thoracic surgical procedures and has been associated with less pain, shorter hospitalization, and equivalent oncologic outcomes as compared with thoracotomy [1–3]. In a health economic perspective, VATS is characterized by more expensive equipment with consequent increased costs [4]. However, these expenses are counterbalanced by significant cost savings thanks to shorter length of stay and fewer complications, which makes VATS economically advantageous compared to open surgery [4].

Spontaneous ventilation VATS (SV-VATS), which avoids double-lumen intubation and mechanical ventilation (MV) by preserving physiological breathing, represents a further step ahead within the evolution of minimally invasive thoracic surgery. This strategy is aimed at reducing anesthesia-related adverse effects including airway traumas, ventilator-induced lung injuries, impaired cardiac function and post-operative gastrointestinal symptoms [5]. As a result, the lower risk of peri-operative complications may reflect in a faster recovery and discharge, in particular when dealing with selected cohorts with an impaired pulmonary function [6, 7]. Despite potential clinical advantages, the economic implications of SV-VATS are still under-investigated. Few studies have addressed this topic, revealing lower costs for SV-VATS anesthesia [8, 9] and shorter hospitalization [10–12] as compared to MV-VATS. Unfortunately, no data has been provided about a deeper subgroup analysis and the impact of post-operative complications on the final expense. Therefore, a comprehensive economic evaluation of SV-VATS compared to MV-VATS is still lacking.

The aim of this study was to perform a cost-minimization analysis comparing SV- and MV-VATS across different surgical scenarios [13, 14] using a Monte Carlo modeling and incorporating non-device-related costs including those related to management of post-operative complications.

Methods

Cost analysis

In order to compare SV- (group A) versus MV-VATS (group B), we have adopted a cost-minimization analysis that is an economic evaluation method in which costs of alternative healthcare interventions are compared under the assumption that their outcomes are equivalent. The rationale is that when clinical effectiveness does not differ between the two options and the health outcome is expected to be equivalent, the analysis is exclusively focused on identifying the intervention associated with the lowest cost [15]. This approach was selected since the surgical procedure was identical and differed only in the anesthesiologic strategy. Consequently, long-term outcomes were assumed to be equivalent and quality-adjusted life years were deemed to be comparable between groups. In this setting, peri-operative variables such as complications and length of stay were considered as drivers of hospital resources utilization rather than effectiveness outcomes.

With reference to the costs included in the study, material costs were not considered for the analysis for the following reasons:

1) A previous cost-effectiveness study [16] comparing SV- and MV-VATS reported no significant difference in total material costs between the two strategies.
2) In our routine clinical practice, the same devices are used during surgery regardless of the anesthesia strategy.
3) Ventilatory equipment and anesthetic medications are routinely prepared also for SV-VATS to allow immediate emergency conversion to double-lumen intubation if required. Consequently, potential differences in anesthesia-related materials and medications between groups were considered negligible.

The analysis was then based on hourly operating room costs, daily costs for length of stay and costs for possible post-operative complications and associated procedures. Costs concerning operating room and hospitalization were retrieved by our hospital administration and amounted to €800 per hour and €750 per day, respectively. Costs related to complications were estimated according to national diagnosis-related groups reimbursement rates. They were all expressed in Euros and referred to the same price year for all inputs.

Monte Carlo simulation and clinical scenarios

Economic evaluation was performed through the adoption of a Monte Carlo simulation model with 10,000 iterations. Monte Carlo simulation is a statistical tool widely used in health economics to explore uncertainty in costs and outcomes by generating multiple hypothetical patient scenarios in which parameters are randomly sampled from real-world probability distributions, resulting in a distribution of total cost estimates rather than a single point estimate [17]. This approach allows comparison of cost distributions between alternative clinical strategies.

For the present study, we have chosen two different clinical scenarios, and data about operating room time, length of stay, and complications were retrieved from previous studies published by our group. The first scenario

Table 1 Input parameters retrieved from the literature for Monte Carlo simulation

Lung volume reduction surgery [13]		
Variable	**Group A (SV-VATS) *n* = 30**	**Group B (MV-VATS) *n* = 30**
Operating room time (min), mean ± SD	133 ± 37	377 ± 104
Hospital stay (days), mean ± SD	5.5 ± 2.4	8.9 ± 4.4
Complication rate, %	3.33%	9.99%
Wedge resection for metastasectomy [14]		
Variable	**Group A (SV-VATS) *n* = 45**	**Group B (MV-VATS) *n* = 13**
Operating room time (min), median (IQR)	66 (51–78)	78 (60–96)
Hospital stay (days), median (IQR)	3 (2–4)	3.7 (1–6)
Complication rate, %	2.22%	15.38%

IQR, interquartile range; *MV*, mechanical ventilation; *SD*, standard deviation; *SV*, spontaneous ventilation; *VATS*, video-assisted thoracic surgery

involved lung volume reduction surgery for emphysema [13] whereas the second one was about wedge resection for lung metastasectomy, which constitutes two common indications for SV-VATS at our center [14]. Both studies were designed as retrospective ones: in the former, patients were divided into SV- versus MV-VATS based on the time period of treatment, whereas in the latter, patients who refused SV-VATS were allocated in the MV group. In the study about lung volume reduction surgery, patients undergoing SV-VATS were sedated with propofol and remifentanil or dexmedetomidine, monitored using bispectral index, and received additional oxygen through a laryngeal mask [13]. Patients of the SV group in the wedge resection study also had target control sedation with bispectral index but received additional oxygen through a ventimask [14]. Input parameters are summarized in Table 1. Regarding lung volume reduction surgery, the operative time reported in the study also included weaning and recovery room time. Conversely, for wedge resection metastasectomy, recovery room time was not considered. With reference to post-operative complications, Clavien-Dindo I complications, such as prolonged air leaks not requiring any intervention and usually reflecting only into a prolonged hospitalization (as occurred in the lung volume reduction study), were not considered within the economic assessment. Complications retrieved by the studies and included in the Monte Carlo model were atrial fibrillation, pneumonia, and wound infection requiring debridement. All a priori assumptions of the study are summarized in Table 2.

Operating room time and length of stay were simulated using normal distributions. When the studies used for input data reported mean ± standard deviation (SD), these values were used directly; when only median and interquartile range (IQR) were reported, SD was approximated as IQR/1.35, and the distribution was centered on the median. To avoid unrealistic values, times were truncated at a lower bound (≥ 1 min for operating room time, ≥ 1 day for hospitalization). Post-operative complications were modeled as Bernoulli trials using reported probabilities. Total costs were calculated by multiplying resource use and complications by unit costs, generating right-skewed cost distributions reflecting variability across patients.

Economic and statistical analysis

Economic and statistical analysis was performed using Jupyter Notebook (Project Jupyter version 7.3.2), running Python (version 3) (see Supplementary material). Continuous variables were reported as mean ± standard deviation (SD), and a Student *t* test was applied for descriptive analysis. A *p*-value less than 0.050 was considered statistically significant. Mean cost components were displayed using bar charts, while tornado plots were used to show cost variability across components. Cost distributions were represented using both boxplots and kernel density

Table 2 Summary of a priori assumptions of the study

Summary of a priori assumptions
1) Long-term outcomes and quality-adjusted life years were considered comparable between groups
2) Differences in material costs between groups were considered negligible and were not included
3) Only complications reported in previously published study were included in Monte Carlo model
4) Clavien-Dindo I complications were excluded by Monte Carlo model
5) No conversion to general anesthesia or open thoracotomy was included in Monte Carlo model

estimate plots. Finally, the distribution of cost differences across simulations and the expected mean cost saving per patient were illustrated using bar charts.

Results

First clinical scenario: lung volume reduction surgery

The comparison between group A and group B after Monte Carlo simulation showed significantly lower estimated mean costs for the former group (€6238.9 ± 2430.9, 95% confidence interval (CI) €2304–€14,084 for group A versus €11,874.1 ± 3529.1, 95% CI €5037–€18,861 for group B, $p < 0.001$). In both groups, hospital stay proved the main contributor to mean cost (Fig. 1A) followed by operating room time and complications. Hospital stay also accounted for the largest share of cost variability in the tornado plots (Fig. 1B), whereas the second most influential component differed between groups, being post-operative complications for group A and operating room time for group B.

The analysis of cost distribution (Fig. 2) showed that group B was associated with a wider and overall higher

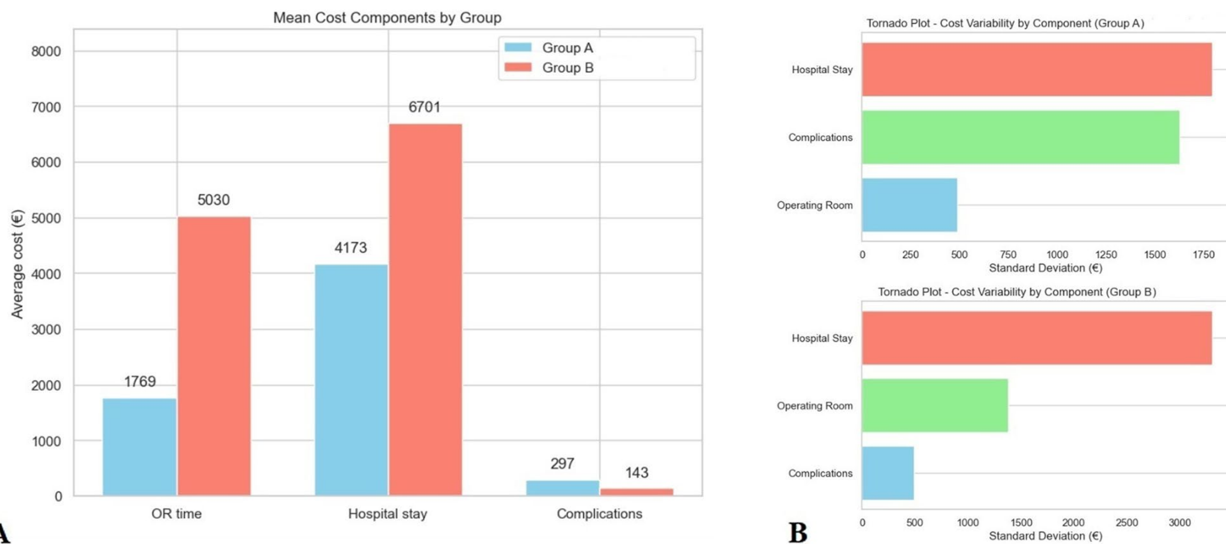

Fig. 1 **A** Bar chart showing mean cost components by group in lung volume reduction surgery scenario; **B** tornado plot showing cost variability by component in lung volume reduction surgery scenario

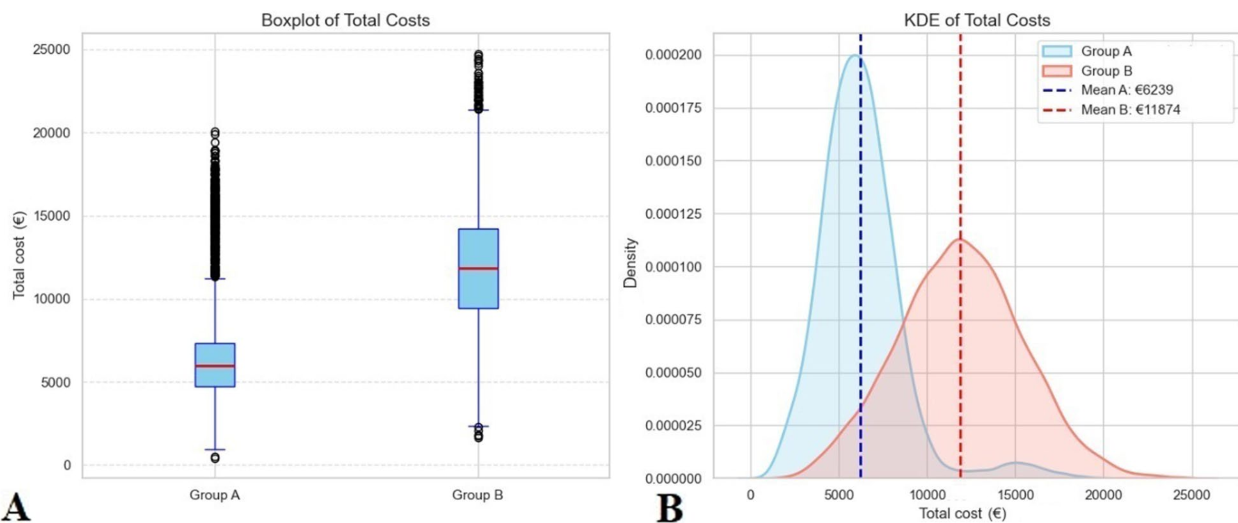

Fig. 2 **A** Boxplot of total costs in lung volume reduction surgery scenario; **B** kernel density estimate (KDE) plot of total costs in lung volume reduction surgery scenario

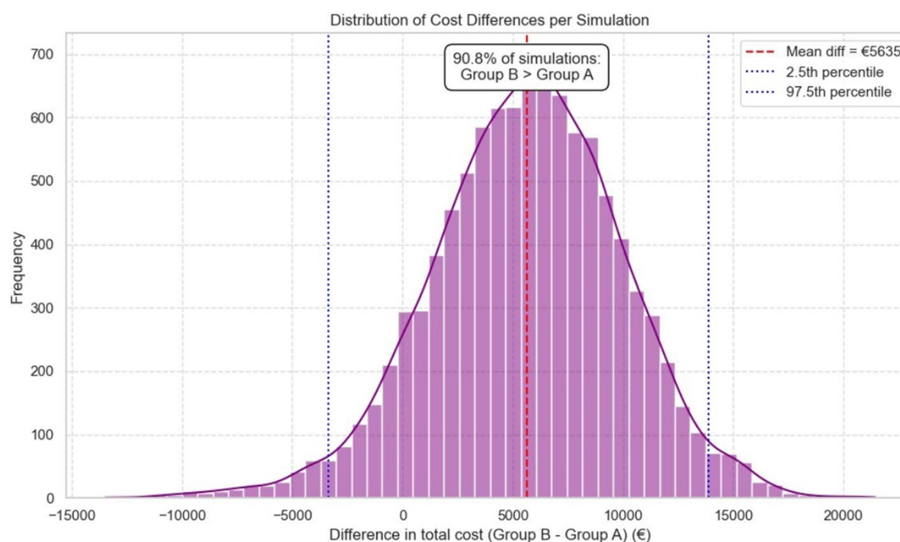

Fig. 3 Distribution of cost difference per simulation in lung volume reduction surgery scenario

range of costs, indicating greater financial variability and less predictable expenditure. Conversely, group A showed a narrower distribution with lower estimated costs, reflecting a more stable and predictable economic profile.

Evaluation of cost differences distribution between the two anesthesia strategies across the 10,000 simulated patients (Fig. 3) has shown a distribution shifted toward positive values, indicating that group B was more costly than group A in the majority of simulations. Specifically, group B was associated with higher costs in 90.8% of simulations, with an expected mean cost saving of €5635.2 ± 4309.5 (95% CI € −3391 – €13,666) per patient when SV-VATS was adopted. The 95th percentile of the cost difference, reflecting the potential magnitude of tail risk in extreme scenarios, was €12,492.

In sensitivity analyses varying the operating room time hourly costs and hospitalization daily costs by ± 30%, the findings remained robust. Mean total costs for group A ranged from € 4449 (– 30% costs) to €8026 (+ 30% costs), while mean costs group B ranged from €8360 to €15,353. The mean cost difference varied between €3911 and €7327, and the probability group A to be cost-saving remained consistently high (90.0–91.1%).

Second scenario: wedge resection

Monte Carlo simulation demonstrated significantly lower estimated costs for patients in group A compared to group B, with mean total costs of €3199.8 ± 1074.2, 95% CI €1449–€5418 versus €4538.7 ± 2405.4, 95% CI €1360–€9786, respectively ($p < 0.001$). Hospital stay remained the main driver of mean total cost (Fig. 4A) and the component contributing most to cost variability (Fig. 4B). Unlike lung volume reduction surgery, the tornado plot revealed that the second most influential component was operating room time for group A and post-operative complications for group B.

Cost distribution analysis (Fig. 5) confirmed group A as a financially safer option, with lower and more stable costs, whereas group B exhibited greater variability. Furthermore, group B also showed a right-skewed tail, suggesting occasional very high-cost cases.

Examination of the distribution of cost difference (Fig. 6) indicated that patients from group B incurred higher costs in 65.8% of simulations compared to group A, with an expected mean cost saving of €1338.9 ± 2629.9 (95%CI € −2948 – €7044) by choosing SV-VATS and a 95th percentile of cost difference of €6111.

When costs for operating room time and length of stay were varied by ± 30%, mean total costs for group A ranged from €2243 to €4161, while mean costs for group B ranged from €3215 to €5736. The mean cost difference remained positive (ranging from €972 to €1575), and the probability of cost-saving for group A changed only slightly (63.6–64.6%).

Discussion

Results of this study have shown that SV-VATS could be not only a beneficial strategy for selected cohorts but also a cheaper and more stable option than MV-VATS from an economic health perspective. Indeed, in both simulations, SV-VATS resulted in lower indirect and non-device-related total costs than MV-VATS. Moreover, by SV-VATS, less variance in cost distribution was observed, with consequent reduced financial risk.

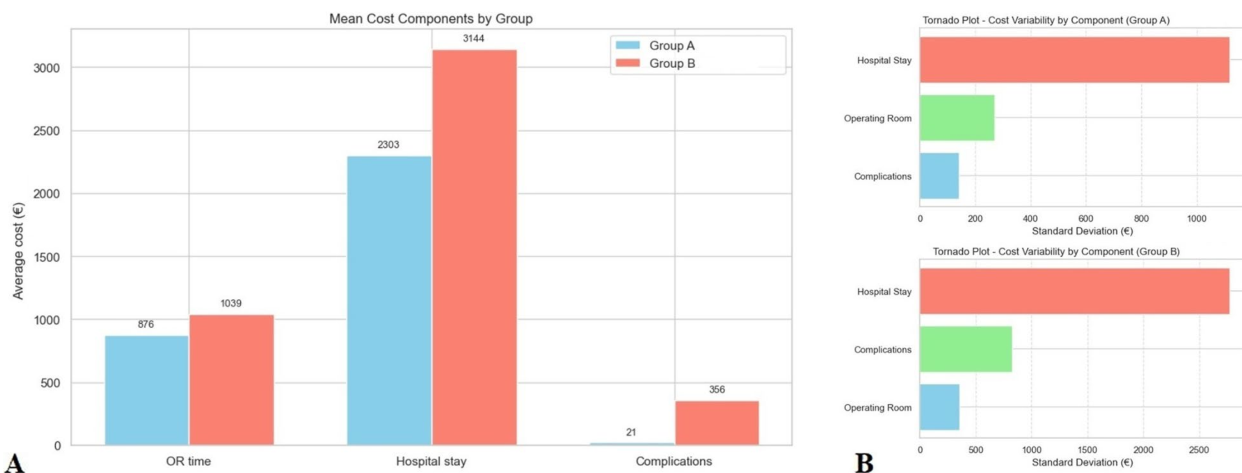

Fig. 4 **A** Bar chart showing mean cost components by group in wedge resection scenario; **B** tornado plot showing cost variability by component in wedge resection scenario

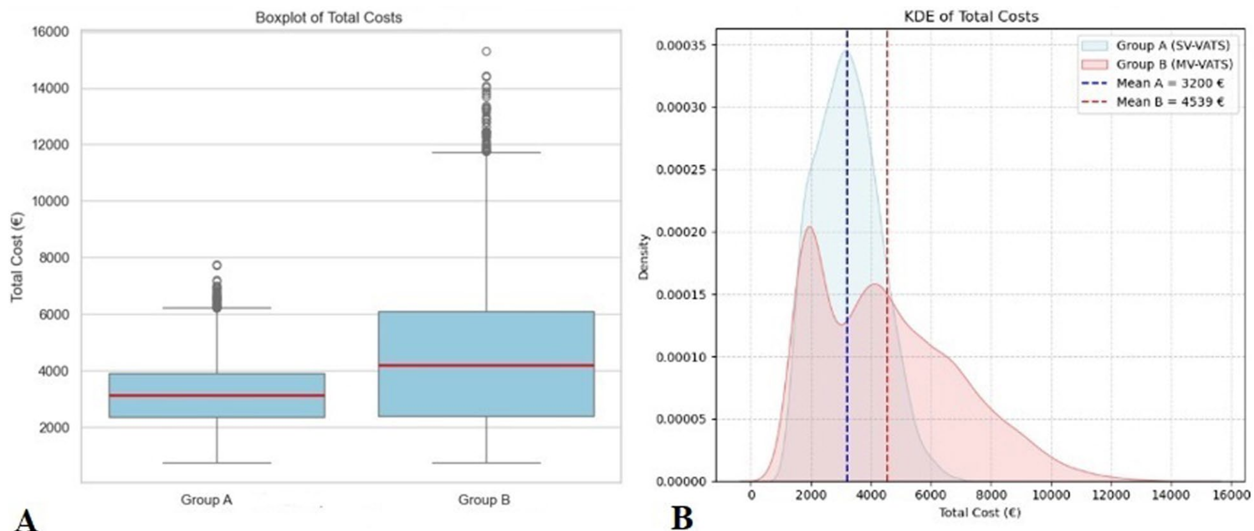

Fig. 5 **A** Boxplot of total costs in wedge resection scenario; **B** kernel density estimate (KDE) plot of total costs in wedge resection scenario

VATS has progressively established itself over open thoracotomy for selected surgical procedures showing better recovery with fewer complications [3], together with comparable long-term results for oncological diseases [18, 19]. In addition, several studies have shown that VATS may prove more advantageous from an economic standpoint. Cho et al. reported that the total hospital cost was lower for VATS if compared to open surgery for lobectomies [20]. Mafé et al. demonstrated that VATS is more cost-effective at one year compared to open lobectomy since it provided equivalent clinical outcomes at lower costs, remaining below commonly accepted willingness-to-pay thresholds [21]. Similar results were obtained by Fang et al. who found that VATS was potentially cost-effective in the short term within the common willingness-to-pay levels in Taiwan [22]. Finally, Bendixen et al. performed the first randomized trial about cost-utility analysis for stage I non-small-cell lung cancer undergone VATS versus open lobectomy and underlined VATS as cost-effective, with better economical outcomes as measured by quality-adjusted life years and lower overall costs [23].

The SV approach may be considered a further step forward within evolutionary changes of minimally invasive thoracic surgery, as it eliminates risks of tracheal traumatism and ventilator-induced injuries [24], preserves diaphragmatic movements, and facilitates maintenance of hemodynamic stability [25]. Evidence from

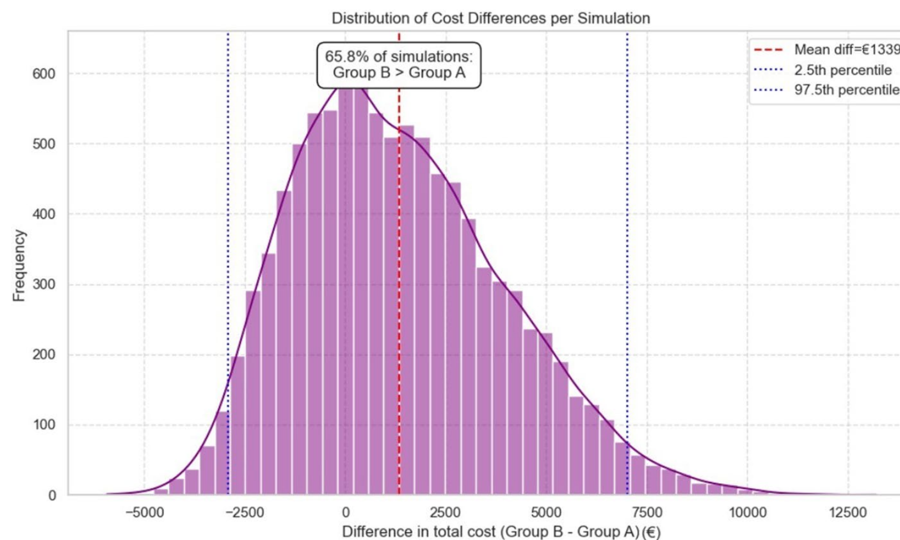

Fig. 6 Distribution of cost difference per simulation in wedge resection scenario

the literature suggests that these changes can be associated with a lower incidence of post-operative complications and a shorter recovery time [26, 27].

Despite the multiple potential clinical benefits related to SV-VATS, this strategy is still poorly investigated under a public health perspective and few studies evaluated if it also offers economic advantages. Indeed, the economic aspect was just marginally addressed in the literature. Caviezel et al., in their study about bilateral uniportal sympathectomy, stated that, compared to MV-VATS, SV-VATS could be performed as an outpatient procedure with consequent lower expenses [11]. Liu et al., in their randomized trial about SV versus MV-VATS for spontaneous pneumothorax, found that anesthesia costs were significantly lower in the SV group ($297.81 vs $399.81; $p < 0.001$) [9]. Xu et al. also stated that SV-VATS has generally lower costs compared to MV [28]. The only study focused on costs comparison between SV- and MV-VATS was published by Wang et al. [16]. In this retrospective study, it has been shown that, even if the SV-VATS group had lower costs related to anesthesia materials and medications, no difference in the total costs was found when including also diagnostic, surgical, and other material expenses. However, also in the analysis of Wang et al., indirect and non-device-related costs, including those related to operating room time, hospitalization, and complication-related additional procedures were not included.

To the best of our knowledge, the current analysis is the first specifically comparing SV and MV-VATS from an economic perspective focusing on indirect and organizational costs, such as length of hospital stay, operating room time, and post-operative complications. We believe that these cost components are likely to represent the main drivers of overall expense, as the surgical scenarios chosen for the analysis included surgical procedures, which were identical in each group and routinely performed using the same devices, regardless of the type of anesthesia. Moreover, in daily clinical practice, anesthetic equipment and medications for MV are usually prepared even in SV-VATS to allow immediate emergency conversion whenever required, making differences in material and anesthesia-related costs marginal and thus negligible.

By contrast, variations in post-operative course and complication rates may differ and substantially affect total costs, eventually revealing particularly relevant aspects from a health economics perspective. To explore these aspects, we adopted a Monte Carlo model, a simulation approach already widely used in health economics to evaluate uncertainty and variability in clinical and cost parameters [29, 30]. This tool allows the generation of a significant number of plausible scenarios, providing a more robust estimation of cost distributions compared with point estimates alone.

This study has some limitations. Only two surgical procedures were included. As clinical inputs were retrieved from previous studies conducted by our group, in which there were no conversions to thoracotomy or general anesthesia, potential additional costs related to conversion were not evaluated during the simulation. Moreover, operating room time was calculated differently between the two source studies. Furthermore, the analysis was based on modeled assumptions, which might not completely reflect real-world variability, and was conducted from a hospital perspective without considering indirect

social costs (i.e., absence from work or caregiver burden). The simulation model uses means and SD retrieved from published studies as fixed inputs. While patient-level stochastic variability was modeled, we did not incorporate uncertainty in the parameter estimates themselves, which may slightly underestimate the overall uncertainty in cost outcomes. Complication costs were based on diagnosis-related groups tariffs, which may not exactly reflect the true hospital expenditures per patient. Additionally, in our Monte Carlo model, post-operative complications were assumed independent of length of stay. This simplification was necessary due to the lack of patient-level data to model conditional distributions. We are perfectly aware that this may under- or overestimate the variability of total costs, and future studies with detailed clinical datasets could allow modeling these dependencies more accurately. Finally, due to the cost-minimization setting and the assumption of equivalent long-term outcomes between the investigated strategies, quality-adjusted life years and long-term expenses were not included.

Conclusions

In this study, SV-VATS was associated with lower overall costs compared with MV-VATS in different clinical scenarios, and the reduced variability in cost distribution suggested a lower in-hospital financial burden. These findings support the role of SV-VATS not only as clinically advantageous in selected cohorts, but also as a cost-minimizing strategy in thoracic surgery and healthcare resource management. Further studies, including a broader range of procedures and clinical settings, are warranted to confirm these preliminary but encouraging results.

Abbreviations

CI	Confidence interval
IQR	Interquartile range
MV	Mechanical ventilation
SD	Standard deviation
SV	Spontaneous ventilation
VATS	Video-assisted thoracic surgery

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43057-026-00197-1.

Supplementary Material 1. Jupyter Notebook codes for analysis.

Acknowledgements

Presented at "Hot Parade in Thoracic Surgery, 4th Hybrid Workshop", Monte Porzio Catone, Rome, Italy, 24 October 2025.

Authors' contributions

Conceptualization, EP; methodology, EP and AP; software, AP; formal analysis, EP and AP; investigation, SAB and AP; data curation, AP and SAB; writing—original draft preparation, EP and AP; writing—review and editing, FT, SE, VA, and EP; visualization, EP; and supervision, VA and EP

Funding

This research received no external funding.

Data availability

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

Declarations

Ethics approval and consent to participate

Ethical approval was not required for this study. Consent to participate was not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 26 February 2026 Accepted: 26 March 2026
Published online: 06 April 2026

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