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Evolving Paradigms in Video-Assisted Thoracoscopic Surgery for Lung Cancer: Techniques, Outcomes, and Emerging Technologies

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ABSTRACT

Background: Video-Assisted Thoracoscopic Surgery (VATS) has transformed lung cancer management by enabling minimally invasive approaches with improved perioperative outcomes. However, rapid advancements in surgical techniques and integration with emerging technologies necessitate a comprehensive synthesis of current evidence. **Objectives:** This review aims to evaluate the evolving paradigms of VATS in lung cancer, including comparisons between uniportal and multiportal techniques, assessment against robotic-assisted thoracic surgery (RATS), and analysis of clinical outcomes and technological innovations. **Methods:** A narrative review was conducted using a structured literature search across major databases, including retrospective studies, prospective trials, meta-analyses, and consensus reports published over the past two decades. Relevant studies were selected based on predefined inclusion criteria and analyzed qualitatively. **Results and Discussions:** Evidence indicates that uniportal VATS is increasingly adopted, offering reduced postoperative pain, shorter hospital stays, and comparable oncological outcomes to multiportal VATS and open surgery. RATS demonstrates enhanced surgical precision and improved lymph node dissection with favorable recovery profiles, although associated with higher costs and technical demands. Overall, minimally invasive approaches reduce perioperative complications and improve recovery, but limitations persist regarding technical complexity, cost-effectiveness, and long-term outcomes. **Conclusion:** VATS continues to evolve as a safe and effective modality in lung cancer surgery. Integration with advanced technologies enhances surgical performance; however, further standardized protocols and high-quality studies are required to optimize clinical implementation.

Keyword: lung cancer, minimally invasive surgery, robotic-assisted thoracic surgery, surgical outcomes, VATS

ABSTRAK

Latar Belakang: Video-Assisted Thoracoscopic Surgery (VATS) telah merevolusi penatalaksanaan kanker paru melalui pendekatan invasif minimal yang memberikan hasil perioperatif yang lebih baik. Namun, perkembangan teknik bedah dan integrasi teknologi baru menuntut sintesis bukti yang komprehensif. **Tujuan:** Tinjauan ini bertujuan untuk mengevaluasi perkembangan VATS dalam kanker paru, termasuk perbandingan teknik uniportal dan multiportal, evaluasi terhadap robotic-assisted thoracic surgery (RATS), serta analisis luaran klinis dan inovasi teknologi. **Metode:** Literature review dilakukan melalui pencarian terstruktur pada berbagai database yang mencakup studi retrospektif, uji prospektif, meta-analisis, dan laporan konsensus dalam dua dekade terakhir. Studi yang relevan dipilih berdasarkan kriteria inklusi dan dianalisis secara kualitatif. **Pembahasan:** Uniportal VATS menunjukkan peningkatan penggunaan dengan keunggulan berupa nyeri pascaoperasi lebih rendah, lama rawat lebih singkat, serta luaran onkologis yang sebanding dengan teknik multiportal dan operasi terbuka. RATS memberikan presisi bedah yang lebih tinggi dan diseksi kelenjar getah bening yang lebih optimal, namun dengan biaya lebih tinggi dan kebutuhan pelatihan khusus. Secara keseluruhan, pendekatan invasif minimal menurunkan komplikasi perioperatif dan mempercepat pemulihan, meskipun masih terdapat keterbatasan dalam kompleksitas teknik, efektivitas biaya, dan data jangka panjang.

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Kesimpulan: VATS merupakan metode yang aman dan efektif dalam pembedahan kanker paru yang terus berkembang. Integrasi teknologi meningkatkan performa bedah, namun diperlukan standarisasi protokol dan penelitian berkualitas tinggi untuk optimalisasi implementasi klinis.
Kata kunci: bedah invasif minimal, kanker paru, luaran bedah, RATS

Practice Points

1. Minimally invasive approaches, particularly uniportal VATS, provide reduced postoperative pain and shorter hospital stay compared to conventional thoracotomy.
2. Robotic-assisted thoracic surgery (RATS) enhances surgical precision and lymph node dissection but requires higher costs and specialized training.
3. Integration of advanced imaging and emerging technologies improves surgical planning and intraoperative accuracy in lung cancer treatment.
4. Comparative outcomes between VATS, RATS, and open surgery remain dependent on surgeon expertise and institutional resources.
5. Standardization of protocols and long-term evidence are needed to optimize clinical decision-making in minimally invasive thoracic surgery.

1. Introduction

Lung cancer remains the leading cause of cancer-related mortality worldwide, highlighting the urgent need for effective and less invasive treatment strategies).[1,2] Video-Assisted Thoracoscopic Surgery (VATS) has emerged as a cornerstone in the surgical management of lung cancer by reducing surgical trauma and improving postoperative recovery compared to conventional thoracotomy.[3,4] Since its introduction more than three decades ago, VATS has evolved from multiportal to uniportal approaches and has become widely adopted, particularly for early-stage non-small cell lung cancer (NSCLC) management.[5-7] The adoption of minimally invasive techniques, including robotic-assisted thoracic surgery (RATS), has further transformed thoracic oncology by enhancing surgical precision, visualization, and perioperative outcomes.[8] These developments have important clinical and economic implications, as minimally invasive approaches are associated with shorter hospital stays, faster recovery, and improved quality of life.[3,4]

Despite these advancements, several challenges remain in optimizing minimally invasive approaches for lung cancer. Ongoing debates persist regarding the comparative effectiveness, safety, and cost-effectiveness of uniportal versus multiportal VATS, as well as their relative advantages compared to robotic-assisted approaches.[7,9] While uniportal VATS has demonstrated potential benefits in reducing postoperative pain and improving recovery, evidence comparing it with multiportal VATS and RATS remains heterogeneous and inconclusive.[10] Furthermore, the expanding role of VATS in advanced-stage NSCLC, particularly following neoadjuvant therapy, and the emergence of non-intubated VATS techniques introduce additional complexity in clinical decision-making.[8,11] The lack of high-quality randomized controlled trials and long-term oncological data continues to contribute to uncertainty regarding optimal surgical strategies.[12]

Current literature often focuses on isolated aspects of VATS, such as technical comparisons or short-term outcomes, without integrating surgical evolution, technological innovation, and multidimensional clinical outcomes into a unified perspective. This fragmentation highlights a critical gap in the literature, particularly in understanding how emerging technologies, including robotic systems and advanced imaging, influence both surgical performance and patient-centered outcomes.[8,13] Therefore, this review aims to evaluate the evolving paradigms of VATS in lung cancer by synthesizing evidence on surgical techniques, comparative effectiveness, perioperative and oncological outcomes, and emerging technological innovations. By addressing these gaps, this review seeks to provide a comprehensive perspective to inform clinical decision-making and guide future research in minimally invasive thoracic surgery.[7]

2. Method

2.1 Study Design and Data Sources

This study use a narrative literature review design to synthesize current evidence on advancements and trends in Video-Assisted Thoracoscopic Surgery (VATS) for lung cancer. A structured literature search was conducted using major electronic databases, including PubMed, Scopus, and Europe PMC.

2.2 Eligibility Criteria

The inclusion criteria for the reviewed studies were as follows:

1. Articles published in English
2. Studies published within the last 5 years (2019–2025)
3. Studies focusing on VATS, uniportal and multiportal approaches, or robotic-assisted thoracic surgery (RATS) in lung cancer
4. Studies reporting perioperative outcomes, oncological outcomes, cost-effectiveness, or quality of life

Exclusion criteria included:

1. Non-research articles (e.g., editorials, letters, case reports)
2. Studies not relevant to lung cancer surgical management
3. Articles with inaccessible full text

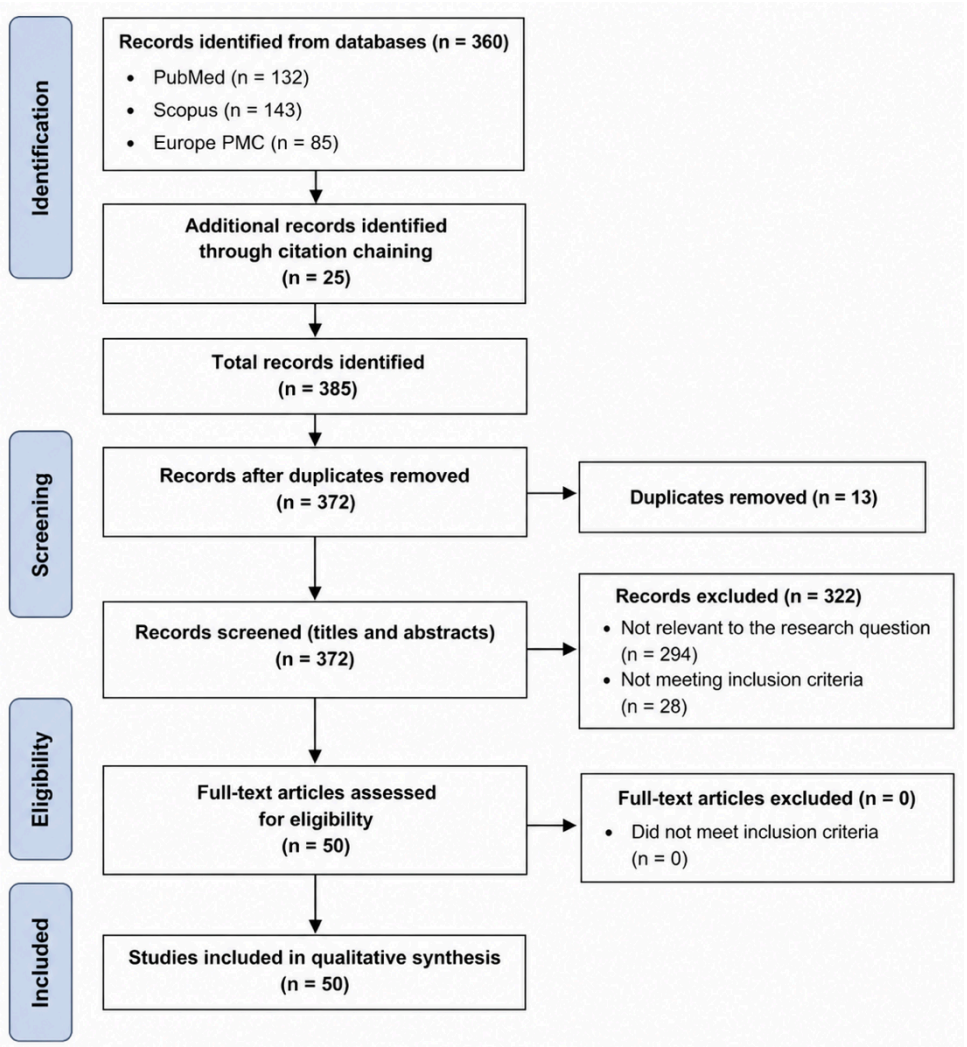
2.3 Search Strategy and Study Selection

The literature search was conducted using combinations of keywords and Boolean operators across selected electronic databases, including PubMed, Scopus, and Europe PMC, to identify relevant studies on Video-Assisted Thoracoscopic Surgery (VATS) for lung cancer. The search strategy incorporated terms related to surgical techniques, disease condition, and clinical outcomes, including: “Video-Assisted Thoracoscopic Surgery” OR “VATS”, “lung cancer” OR “non-small cell lung cancer”, “robotic-assisted thoracic surgery” OR “RATS”, and “minimally invasive surgery”, combined with outcome-related terms such as “perioperative outcomes”, “oncological outcomes”, and “quality of life”.

The search syntax was adapted for each database to optimize retrieval based on their respective indexing systems. The initial search yielded a total of 360 records across the three databases. To enhance the comprehensiveness of the review, additional studies were identified through citation chaining, including backward and forward reference tracking, resulting in 25 additional records.

All identified records were compiled and duplicates were removed prior to screening. The remaining studies were screened based on titles and abstracts according to predefined inclusion and exclusion criteria. Studies that did not meet the criteria were excluded. Subsequently, full-text articles of potentially relevant studies were assessed for eligibility.

In total, 385 records were identified, of which 372 remained after duplicate removal. Following the screening process, 50 studies were considered highly relevant and included in the final qualitative synthesis. The study selection process is illustrated in Figure 1.



3. Result and Discussion

3.1 Descriptive Characteristics of Included Studies

A total of 50 studies were included in this review following the literature selection process (Figure 1). The included studies consisted of retrospective cohorts, prospective trials, meta-analyses, and consensus reports published within the last five years. These studies evaluated surgical techniques, perioperative outcomes, oncological efficacy, patient recovery, and economic considerations in minimally invasive thoracic surgery.

The literature encompassed a broad spectrum of clinical contexts, including early-stage and advanced lung cancer, with increasing attention to the transition from multiportal to uniportal VATS and the integration of robotic-assisted thoracic surgery (RATS). This diversity of study designs and clinical settings provides a comprehensive overview of current surgical practices and evolving trends in thoracic oncology.[3,5]

3.2 Definition and Conceptual Scope of Uniportal VATS

A major area of ambiguity in modern thoracic literature is the exact definition and boundary of uniportal VATS. Conceptually, uniportal VATS is defined as a minimally invasive surgical technique wherein both the thoracoscope (video camera) and all active surgical instruments are introduced simultaneously through a single, small intercostal incision (typically 3 to 5 cm) without any rib spreading.[7] This represents a profound geometric departure from conventional multiportal VATS, which utilizes 2 to 4 separate incisions (ports) to isolate the visual axis from the instrumental axes.[1,7] In uniportal VATS, the visual axis of the thoracoscope is parallel to the working instruments, mimicking the direct line of sight experienced in open thoracotomy, thereby providing a familiar sagittal view for the operator.[10] Crucially, a clear clinical distinction must be maintained between uniportal VATS and medical thoracoscopy (also referred to as pleuroscopy). Although both modalities utilize a single incision, they represent entirely distinct clinical entities: Medical Thoracoscopy/Pleuroscopy: Typically performed under local anesthesia or conscious sedation in an endoscopy suite by pulmonologists. It relies on a single rigid or semi-flexible pleuroscope primarily for basic diagnostic interventions (e.g., parietal pleural biopsy, visual inspection of the pleural space) or basic

palliative procedures (e.g., fluid aspiration, talc poudrage pleurodesis). It does not involve pulmonary parenchymal dissection or formal lymphadenectomy. Uniportal VATS: A highly complex therapeutic surgical procedure performed in a major operating theater under general anesthesia with double-lumen endotracheal intubation or specialized non-intubated protocols utilizing one-lung ventilation.[21] Conducted exclusively by thoracic surgeons, it involves sophisticated anatomical resections (such as lobectomy, segmentectomy, sleeve resections) and formal mediastinal lymph node dissection using articulable endo-surgical instruments and staplers.

3.3 Evolution of Surgical Techniques in VATS

The findings of this review reflect a significant paradigm shift in lung cancer surgery, transitioning from conventional open thoracotomy to minimally invasive approaches, including multiportal VATS, uniportal VATS, and robotic-assisted thoracic surgery (RATS). This evolution is driven not only by the goal of reducing surgical trauma but also by the integration of emerging technologies that enhance surgical precision, patient outcomes, and overall treatment strategies.

The evolution of VATS techniques reflects a paradigm shift toward minimizing surgical trauma while maintaining oncological effectiveness. Early studies focused on validating the safety and feasibility of multiportal VATS compared to open thoracotomy. More recent evidence highlights the increasing adoption of uniportal VATS, which offers reduced postoperative pain, shorter hospital stays, and improved cosmetic outcomes.[1,14]

Furthermore, the integration of robotic-assisted thoracic surgery (RATS) represents a significant technological advancement. RATS enhances surgical precision, dexterity, and visualization, particularly in complex resections and lymph node dissection. However, its adoption remains influenced by cost, learning curve, and resource availability.[13,15]

3.4 Comparative Clinical Outcomes

3.4.1 Perioperative Outcomes

Minimally invasive approaches, including VATS and RATS, consistently demonstrate improved perioperative outcomes compared to open thoracotomy. These include reduced postoperative pain, shorter hospital stay, lower complication rates, and faster recovery. Uniportal VATS, in particular, has been associated with decreased surgical trauma and enhanced patient comfort.[3,16]

However, variability exists depending on surgeon experience and institutional factors. Some studies report longer operative times in robotic-assisted procedures, reflecting the technical complexity and learning curve associated with these approaches.[9]

3.4.2 Oncological Outcomes

Evidence suggests that VATS and RATS achieve comparable oncological outcomes to open surgery, including similar survival rates, margin status, and adequacy of lymph node dissection. Several studies indicate that robotic-assisted approaches may facilitate more extensive lymph node retrieval due to enhanced visualization.[3,17]

Despite these findings, long-term oncological outcomes remain limited, particularly for newer techniques such as uniportal VATS. Variability in study design and follow-up duration contributes to ongoing uncertainty regarding oncological equivalence.[18,19]

3.4.3 Patient-Centered Outcomes

Patient-reported outcomes demonstrate improved quality of life following minimally invasive surgery. Reduced postoperative pain, earlier mobilization, and shorter recovery times contribute to better functional outcomes and patient satisfaction.[20,21]

Nevertheless, some studies highlight inconsistencies in short-term pain outcomes, particularly when comparing uniportal and multiportal techniques, suggesting that patient selection and perioperative management may influence results.[22]

3.4.4 Comparative Clinical Evaluation of Uniportal and Multiportal VATS

To accurately appreciate the strengths and limitations of minimally invasive thoracic surgery, a comprehensive multi-dimensional comparison between uniportal and multiportal VATS is required.[1,7] In terms of operative time, multiportal VATS traditionally features a more standardized and stabilized timeline globally.[3,9] Uniportal VATS, while achieving comparable duration once surgical proficiency is established, can exhibit slightly prolonged times during early institutional adoption due to the increased technical

difficulty of operating within a single axis.[7,14] This technical constraint stems from instrument crowding ("fencing") and the loss of traditional counter-traction triangulation angles, making anatomical dissection more complex.[7,10] Consequently, the learning curve for uniportal VATS is steeper, typically requiring 50–60 cases to stabilize, whereas multiportal VATS proficiency is generally achieved within 30–50 cases.[6,14] From a patient-centered perspective, postoperative pain represents the primary clinical advantage of the uniportal approach.[1,12] By strictly limiting surgical manipulation and intercostal compression to a single intercostal space, uniportal VATS significantly reduces acute pain scores and minimizes long-term intercostal neuralgia compared to the multi-site nerve involvement seen in multiportal VATS.[1,22] Both approaches demonstrate excellent profiles regarding intraoperative blood loss and overall postoperative complications, yielding significantly lower morbidity than conventional open surgery.[3,4] The length of hospital stay (LOS) is frequently shorter in patients undergoing uniportal VATS, a benefit directly facilitated by accelerated mobilization and reduced reliance on heavy opioid analgesia.[4,20] The conversion rate to open thoracotomy due to calcified hilar nodes or vascular injury remains statistically equivalent between both approaches.[3,19] However, multiportal access provides a slightly more flexible angle for rapid troubleshooting.[7,22] Regarding surgical clearance, formal lymph node dissection requires higher advanced skill in a uniportal setting to achieve proper subcarinal exposure.[13,18] Nonetheless, current literature demonstrates that both techniques achieve an oncologically adequate node count, resulting in identical long-term oncological outcomes, including 3-year and 5-year overall survival curves for non-small cell lung cancer (NSCLC).[3,18] Finally, regarding cost considerations, both surgical tracks are highly cost-effective, though uniportal VATS occasionally yields marginal financial savings through a reduced consumption of specialized surgical access ports.[4,9]

3.5 Technological Advancements and Innovation

Technological innovation has played a crucial role in the advancement of minimally invasive thoracic surgery. The integration of robotic systems, three-dimensional imaging, and enhanced instrumentation has improved surgical precision and expanded the feasibility of complex procedures.[8,13]

Robotic-assisted thoracic surgery offers advantages in ergonomics, dexterity, and visualization, which may contribute to improved surgical outcomes. However, these benefits are counterbalanced by increased costs, longer setup times, and the need for specialized training, which may limit widespread implementation.[9,15]

3.6 Economic Considerations and Implementation Challenges

Economic considerations remain a critical factor in the adoption of minimally invasive techniques. While VATS is generally associated with cost savings due to shorter hospital stays and reduced complications, RATS is consistently linked to higher procedural costs.[4,22]

Implementation challenges include variability in surgeon expertise, institutional resources, and access to advanced technologies. These factors contribute to heterogeneity in outcomes and may influence the generalizability of study findings.[1,12]

3.7 Critical Synthesis of Evidence

Overall, the evidence supports the efficacy and safety of minimally invasive thoracic surgery, particularly VATS, in lung cancer management. These approaches consistently demonstrate improved perioperative outcomes while maintaining comparable oncological effectiveness to open surgery.

However, this review also highlights several limitations within the current body of literature. These include the predominance of retrospective studies, heterogeneity in study design, and limited long-term data, particularly for emerging techniques. Additionally, cost-effectiveness and accessibility remain significant barriers to the widespread adoption of advanced technologies such as RATS.

Taken together, the findings emphasize the need for standardized protocols and high-quality randomized controlled trials to validate emerging innovations and optimize surgical strategies in lung cancer treatment.[23,24]

Table 1. Comprehensive multi-dimensional operational matrix of surgical approaches for lung cancer.

Parameter	Uniportal VATS	Multiportal VATS	Robotic-Assisted (RATS)	Open Thoracotomy
Surgical Access	Single 3–5 cm incision; no rib spreading.[7]	2–4 separate small incisions; no rib spreading. [1,7]	4–5 small incisions; no rib spreading.[4]	Large posterolateral/axillary incision; mechanical rib spreading.[3]
Visualization	2D/3D scope; parallel sagittal view (direct line of sight).[10]	2D/3D scope; triangulation view (angled perspective).[7]	High-definition 3D stereoscopic; magnified, stable console control. [8,13]	Direct, naked-eye binocular visualization; restricted depth in deep recesses.[3]
Postoperative Pain	Minimal; strictly limited to a single intercostal space. [1,22]	Low; multi-site intercostal involvement.[1,12]	Low; multi-site but mitigated by precise robotic arm pivoting. [12,22]	Severe; prolonged due to extensive muscle division and rib retraction.[3]
Operative Time	Moderate; comparable to multiportal after competency.[7]	Moderate; highly standardized and efficient globally. [3,9]	Prolonged; driven by mandatory system docking and calibration setup.[4,9]	Shortest; unhindered direct rapid exposure baseline.[9]
Blood Loss	Low; equivalent to multiportal approach.[3]	Low; significantly lower than open surgery.[3,4]	Minimal; optimal due to high-precision micro-dissection. [3,17]	Highest; secondary to extensive soft-tissue division.[3]
Hospital Stay (LOS)	Shortest; accelerated by minimal pain scores.[4,20]	Short; highly optimized discharge tracks. [4]	Short; comparable to VATS modalities.[3,4]	Prolonged; secondary to trauma and chest tube duration.[3]
Lymph Node Dissection	Adequate; requires high skill for deep subcarinal stations.[18]	Adequate; well-established standardized clearance.[3,18]	Excellent; superior wrist dexterity allows extensive harvest.[13,17]	Excellent; traditional gold-standard reference baseline. [17]
Complication Rate	Low; reduced long-term chronic chest neuralgia.[1,18]	Low perioperative morbidity profiles.[3,16]	Low; excellent safety profile. [3,19]	Highest; elevated cardiopulmonary morbidity.[3]
Oncological Outcomes	Equivalent; validated 3-5 year survival curves. [7,18]	Equivalent; standard reference for early NSCLC. [5,7]	Equivalent; proven long-term efficacy. [3,17]	Traditional standard; equivalent survival across stages.[3]
Learning Curve	Steep; requires high endo-coplanar instrument control.[6,14]	Moderate; structured global training pathways.[6]	Moderate; highly intuitive but system-dependent. [9,15]	Shortest; foundational surgical training block.[6]
Financial Cost	Highly cost-effective; low consumable use. [1,4]	Cost-effective; standard institutional framework.[4,9]	Very High; high capital overhead and disposable costs.[4,9]	Low initial instrument cost; higher post-op bed cost.[4]
Primary Advantages	Unmatched pain reduction; excellent patient cosmetics.[1,7]	Modular instrument triangulation; low conversion risk. [7,22]	7 degrees of instrument freedom; superior ergonomics.[8,15]	Tactile feedback; rapid control of major vascular events.[3]
Primary Limitations	Instrument crowding/fencing; single axis traction.[7,10]	Multiple intercostal nerve involvements. [1,22]	High cost; complete loss of tactile sensation. [9,15]	Severe surgical trauma; high chronic post-thoracotomy pain.[3]
Ideal Indications	Early-stage NSCLC; peripheral nodules; fit patients.[7,14]	Standard anatomical lung resections across stages I-III.[5,6]	Complex hilar dissections; segmentectomy; sleeve resections. [13,17]	T4 advanced tumors; central infiltration; salvage resections. [3]

4. Conclusion

This comprehensive review demonstrates that Video-Assisted Thoracoscopic Surgery (VATS) has definitively shifted the paradigm of lung cancer management from open thoracotomy toward sophisticated minimally invasive platforms. While uniportal VATS, multiportal VATS, and robotic-assisted thoracic surgery (RATS) deliver strictly equivalent long-term oncological outcomes and survival curves for early-stage non-small cell lung cancer (NSCLC), they present distinct operational and perioperative trade-offs. Uniportal VATS stands out for its unmatched reduction in surgical trauma, achieving the lowest acute postoperative pain, minimal long-term intercostal neuralgia, and accelerated hospital discharge by confining access to a single intercostal space. However, it introduces technical difficulties such as instrument crowding ("fencing") and a steeper learning curve, making it ideally suited for early-stage NSCLC and peripheral anatomical resections. Multiportal VATS remains a globally established and highly reliable surgical standard, offering flexible instrument triangulation and stable operative times across routine stage I–III resections. RATS represents a major technological advancement, offering superior 3D stereoscopic visualization and 7 degrees of instrument articulation that enhance complex hilar dissections and deep mediastinal lymph node retrieval. Nevertheless, its widespread clinical implementation remains constrained by substantial capital acquisition costs, high disposable instrument expenses, and a complete loss of haptic feedback. Conventional open thoracotomy, while associated with higher surgical trauma, remains an essential fallback option for complex T4 tumors, severe central chest infiltration, and acute vascular control. Ultimately, the selection among these surgical techniques should be individually tailored by balancing patient-specific clinical characteristics, surgeon mastery, and institutional economic resources.

5. Recommendations

Future research should prioritize large-scale, high-quality randomized controlled trials to establish standardized protocols and evaluate long-term oncological outcomes of minimally invasive techniques, particularly uniportal VATS and robotic-assisted approaches.

In addition, further studies are needed to assess cost-effectiveness and accessibility, especially in resource-limited settings, to ensure equitable implementation of advanced surgical technologies.

From a clinical perspective, the adoption of minimally invasive thoracic surgery should be accompanied by structured training programs and competency-based evaluation to address the learning curve associated with advanced techniques such as RATS.

Moreover, integration of emerging technologies, including advanced imaging and surgical navigation systems, should be further explored to enhance precision and patient-centered outcomes in lung cancer surgery.

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