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EDITORIAL

Risk and management of adverse events in minimally invasive esophagectomy

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Abstract

Minimally invasive esophagectomy (MIE) has transformed esophageal surgery by reducing morbidity, accelerating recovery, and improving postoperative outcomes compared to traditional open esophagectomy. By utilizing techniques such as laparoscopic, thoracoscopic, and robotic-assisted approaches, MIE mini-mizes surgical trauma while maintaining oncological thoroughness. However, it also presents unique challenges, including risks of complications such as ana-stomotic leakage, pulmonary complications, and atrial fibrillation. Zhong *et al* developed and validated a risk stratification model for predicting surgical adverse events after MIE, enhancing preoperative assessment and patient management. This editorial further examines the advantages of MIE, its comparable oncological and long-term outcomes, as well as the incidence and contributing factors of post-operative complications. Emerging technologies, including machine learning models, intraoperative nerve monitoring, and robotic-assisted surgery, are high-lighted as innovative solutions for risk prediction and prevention. Strategies such as enhanced recovery after surgery protocols and multidisciplinary collaboration are emphasized for their critical roles in minimizing complications and optimizing patient outcomes. By addressing these aspects, this editorial provides guidance to surgical teams in maximizing the benefits of MIE while effectively managing its associated risks.

Key Words: Minimally invasive esophagectomy; Anastomotic leakage; Enhanced recovery after surgery; Robotic-assisted surgery; Surgical adverse events

Core Tip: Minimally invasive esophagectomy (MIE) offers significant benefits, including reduced morbidity, faster recovery, and comparable oncological outcomes to open esophagectomy. This study highlights key complications such as anastomotic leakage, pulmonary issues, and atrial fibrillation, while identifying risk factors including high body mass index and comorbidities. Emerging technologies like machine learning, intraoperative nerve monitoring, and robotic-assisted surgery enhance risk prediction and surgical precision. Strategies like enhanced recovery after surgery protocols and multidisciplinary approaches are emphasized for their role in minimizing complications and optimizing recovery. This editorial guides surgical teams in maximizing MIE's benefits while effectively managing associated risks.

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INTRODUCTION

Minimally invasive esophagectomy (MIE) has transformed esophageal surgery by offering significant benefits, including reduced morbidity, faster recovery, and improved postoperative outcomes compared to traditional open esophagectomy (OE)[1]. These advantages are achieved through techniques such as laparoscopic, thoracoscopic, and robotic-assisted approaches, which minimize surgical trauma while maintaining oncological thoroughness[2]. However, MIE is not without challenges, as it presents unique risks and technical complexities.

Studies from multiple regions and healthcare systems consistently demonstrate that MIE offers significant reductions in postoperative pulmonary complications and wound infections compared to OE, with complication rates lowered by up to 4.29 times in some high-risk populations, such as the elderly and patients with preexisting pulmonary conditions[3,4]. Moreover, region-specific analyses indicate that high-volume centers consistently achieve better outcomes with MIE, highlighting the importance of institutional expertise. For example, a multicenter study from Europe reported significantly shorter hospital stays and reduced mortality rates with MIE, while a study from Asia highlighted its applicability even in low-resource settings with proper training and technology[5,6].

In addition to these benefits, MIE demonstrates comparable oncological outcomes to OE, including similar lymph node harvest rates and five-year survival outcomes. These results underscore the reliability of MIE as a cancer treatment modality. Furthermore, patients undergoing MIE experience faster recovery times, enhanced quality of life, and lower healthcare costs due to reduced hospital stays and fewer postoperative complications.

This editorial provides an in-depth exploration of the benefits of MIE, the incidence and causes of complications, the role of emerging technologies in risk reduction, and strategies for optimizing patient outcomes. By addressing these aspects, the editorial aims to guide surgical teams in maximizing the benefits of MIE while effectively managing its associated risks.

BENEFITS OF MIE

Reduced postoperative complications

MIE substantially lowers the risk of postoperative complications compared to OE, particularly for pulmonary and wound-related issues (Table 1). Pulmonary complications, a leading concern in esophageal surgery, are significantly reduced with MIE. This is attributed to the smaller thoracic incisions, which minimize disruption to the chest wall and respiratory mechanics. Studies indicate that MIE reduces the likelihood of pulmonary complications by up to 4.29 times compared to OE[7]. This advantage is especially beneficial for high-risk populations, such as elderly patients and those with preexisting pulmonary conditions, who otherwise face heightened risks of pneumonia, atelectasis, and respiratory failure after surgery[3,5].

Additionally, wound infections and other surgical site complications are significantly less frequent with MIE. The smaller incisions required for MIE reduce the risk of bacterial contamination, promote faster healing, and lower the odds ratio for wound infections to 0.31 compared to OE[4]. The cumulative reduction in complications leads to improved overall outcomes and a smoother recovery process.

Enhanced recovery and shorter hospital stays

Patients undergoing MIE consistently experience shorter hospital stays compared to those undergoing OE (Table 1). This is due to the minimally invasive nature of MIE, which reduces intraoperative blood loss, tissue trauma, and postoperative pain. A meta-analysis reported that MIE patients had hospital stays that were several days shorter on average compared to OE patients, reflecting a more efficient recovery process[8]. The quicker return to bowel function and reduced reliance on intensive postoperative monitoring further contribute to reduced hospitalization durations.

Moreover, MIE allows for earlier mobilization and resumption of daily activities. Patients report faster recovery timelines, with earlier initiation of oral diets and ambulation, compared to the prolonged recovery associated with OE[9].

Table 1 Comparison of key outcomes between minimally invasive esophagectomy and open esophagectomy

Parameter	Minimally invasive esophagectomy	Open esophagectomy
Pulmonary complications	Lower incidence due to reduced surgical trauma and improved respiratory mechanics	Higher incidence due to larger thoracic incisions and greater disruption of respiratory structures
Anastomotic leak rate	Comparable rates with optimized techniques and better visualization during surgery	Slightly higher rates in some studies due to technical challenges with large incisions
Wound infections	Significantly reduced risk due to smaller incision size and less exposure to contamination	Higher risk associated with larger incision size and longer healing times
Postoperative recovery	Faster recovery with shorter hospital stays and quicker return to daily activities	Slower recovery due to greater surgical stress and longer hospitalization
Oncological outcomes	Comparable lymph node harvest and survival rates	Equivalent oncological efficacy with traditional surgical thoroughness
Technological requirements	Requires advanced equipment and surgeon training (*e.g.*, robotic systems, IONM)	Requires fewer technological resources but depends heavily on surgical expertise

IONM: Intraoperative nerve monitoring.

These benefits not only improve patient quality of life but also reduce healthcare costs and resource utilization.

Comparable oncological and long-term outcomes

MIE has demonstrated oncological outcomes comparable to OE, ensuring that its minimally invasive nature does not compromise cancer treatment efficacy (Table 1). The number of lymph nodes harvested during MIE is equivalent to that in OE, maintaining the surgical thoroughness required for accurate staging and effective treatment[6]. Five-year survival rates for MIE patients are also comparable to those for OE patients, indicating its reliability as a cancer treatment modality[10].

In terms of long-term outcomes, MIE offers additional advantages due to its association with a reduced surgical stress response. Patients undergoing MIE exhibit better-preserved immune function and superior intestinal barrier integrity, which contribute to improved long-term survival and reduced postoperative morbidity[9,11].

INCIDENCE AND CAUSES OF POSTOPERATIVE COMPLICATIONS

Common complications

Despite its benefits, MIE is associated with certain complications that can impact recovery and long-term outcomes. Anastomotic leaks, pulmonary complications, and atrial fibrillation (AF) are the most frequently reported issues. Anastomotic leaks, occurring in 7.7%-14.8% of cases, are critical complications that increase the risk of sepsis and negatively affect survival rates[12,13]. Pulmonary complications, such as pneumonia and respiratory failure, are also common, although their incidence is lower in MIE compared to OE[14].

Postoperative AF is observed in approximately 25.6% of MIE patients, contributing to extended hospital stays and an increased risk of thromboembolic events. While transient in most cases, AF requires prompt management to prevent further complications[15].

Contributing factors

Multiple factors influence the incidence of complications in MIE, including patient characteristics, surgical techniques, and institutional expertise. High body mass index and preexisting conditions such as diabetes or chronic obstructive pulmonary disease are significant risk factors that predispose patients to complications like anastomotic leaks and respiratory issues[16].

In addition to comorbidities, individual patient characteristics such as age, gender, and genetic predispositions also play a critical role in determining outcomes and complications in MIE. For example, elderly patients often face increased risks of postoperative pulmonary complications due to reduced respiratory reserve and slower recovery times. Male patients have been noted in some studies to have a higher incidence of anastomotic leaks compared to females, potentially linked to anatomical or hormonal differences. Genetic predispositions, such as variations in inflammatory or healing-related genes, may also impact the likelihood of complications like sepsis or delayed wound healing. Recognizing these individual factors is essential for tailoring preoperative risk assessments and postoperative management strategies.

To mitigate these risks, individualized treatment strategies should be implemented. For elderly patients, prehabilitation programs focusing on improving physical fitness and optimizing nutrition can enhance surgical outcomes. Smokers may benefit from preoperative smoking cessation programs, which have been shown to significantly reduce pulmonary complications. Patients with complex comorbidities require a multidisciplinary approach, incorporating cardiology, pulmonology, and nutritional expertise to ensure comprehensive risk management and support throughout the perioperative period. By addressing the unique needs of these patient groups, surgical teams can improve the safety and effectiveness of MIE.

The technical complexity of MIE, particularly in performing intrathoracic anastomosis, adds to the risk. Studies have shown that less experienced surgical teams report higher rates of leaks and other complications[17]. In contrast, high-volume centers with experienced surgical teams consistently achieve better outcomes, highlighting the importance of institutional expertise in minimizing complications[18].

EMERGING TECHNOLOGIES FOR RISK PREDICTION AND PREVENTION

Predictive tools and machine learning

Zhong *et al*[19] developed and validated a risk stratification model for predicting surgical adverse events after MIE, significantly improving preoperative assessment and patient management. This model serves as a foundation for developing tools that identify high-risk patients and enable tailored perioperative strategies to minimize complications.

Machine learning (ML) models have further advanced these efforts by integrating clinical and imaging data to generate risk predictions with high accuracy. For example, neural networks and support vector machines are commonly used ML algorithms that analyze large datasets, identifying complex patterns and correlations that traditional statistical methods may overlook. One study demonstrated that advanced ML models achieved an area under the ROC curve of 0.87 for predicting anastomotic leaks, outperforming conventional predictive models[20].

Despite these promising results, the clinical adoption of ML models faces several challenges. Firstly, the quality and consistency of input data are critical for model accuracy, and discrepancies in data collection across institutions can limit generalizability. Secondly, integrating ML models into clinical workflows requires user-friendly interfaces and seamless interoperability with existing electronic health record systems, which often necessitate significant technological investment. Thirdly, the "black box" nature of some ML algorithms raises concerns about interpretability, making clinicians hesitant to rely solely on these tools for decision-making. Addressing these issues through improved data standardization, user-centered design, and transparent algorithm development will be essential for broader implementation.

Despite these challenges, ML models offer distinct advantages in MIE. By providing real-time risk assessments, these tools enable proactive interventions that can prevent complications and optimize patient outcomes. Furthermore, the ability of ML to analyze high-dimensional data makes it particularly suited for personalized risk stratification, allowing for tailored surgical and postoperative strategies based on individual patient profiles.

Intraoperative technologies

Intraoperative nerve monitoring (IONM) is a technique used during surgery to reduce the risk of nerve damage by providing real-time feedback on the functional integrity of nerves. During MIE, IONM is employed to monitor the recurrent laryngeal nerve, which is susceptible to injury during esophagectomy. This technology uses electrical stimulation to detect nerve responses, enabling surgeons to avoid accidental damage. Studies have shown that the use of IONM significantly decreases the incidence of vocal cord paralysis and respiratory complications, enhancing surgical safety and patient outcomes[21]. AI-assisted navigation systems further support surgical precision by providing real-time identification of critical structures, reducing intraoperative risks[22].

Robotic-assisted surgery

Robotic-assisted surgery (RAS) is a cutting-edge technology that enhances surgical precision, dexterity, and visualization through robotic systems controlled by surgeons. In the context of MIE, RAS offers unmatched accuracy during complex procedures, such as intrathoracic anastomosis, by providing a magnified 3D view of the surgical field and enabling precise instrument movement. This technology is particularly beneficial in challenging cases where traditional laparoscopic techniques may be less effective. While robotic systems involve higher upfront costs and training requirements, they have demonstrated improved patient outcomes, such as reduced postoperative complications and shorter recovery times[23].

Despite these advantages, the long-term effectiveness and cost-effectiveness of RAMIE and other emerging technologies require further exploration. For example, while RAMIE has demonstrated reduced complication rates in high-volume centers, its outcomes in low-resource settings or smaller institutions remain underreported. The high initial costs of robotic systems and the associated training requirements also pose challenges to their widespread adoption. Moreover, data on the long-term oncological outcomes of RAS compared to traditional MIE approaches is still limited, particularly in diverse healthcare settings. Addressing these gaps through multicenter studies and cost-benefit analyses will provide valuable insights into the broader applicability and sustainability of these technologies.

STRATEGIES FOR PREVENTION AND MANAGEMENT

Prevention strategies

Enhanced recovery after surgery (ERAS) protocols are evidence-based perioperative care pathways designed to improve surgical outcomes and accelerate patient recovery. In the context of MIE, ERAS protocols include key elements such as preoperative patient education, optimized nutritional support, multimodal pain management, and early mobilization. These measures collectively reduce surgical stress, shorten hospital stays, and minimize complications. For instance, prehabilitation programs focusing on improving patients' physical fitness and respiratory function before surgery have been shown to reduce postoperative pulmonary complications. Early initiation of oral nutrition postoperatively supports faster recovery of gastrointestinal function, while structured pain management strategies limit the use of opioids, thereby reducing the risk of respiratory depression. ERAS has been widely adopted in high-volume centers, demonstrating a significant reduction in morbidity and improved overall recovery trajectories for MIE patients[4].

Effective management

Prompt detection and management of complications are critical for improving outcomes. Early identification of anastomotic leaks through routine contrast studies allows for timely intervention, either through endoscopic or surgical means. Pulmonary complications can be mitigated with aggressive physiotherapy, respiratory support, and careful monitoring[18].

CONCLUSION

MIE offers significant advantages over traditional open surgery, including reduced complications, faster recovery, and comparable oncological outcomes. However, its success requires meticulous planning, advanced technology, and skilled surgical teams. Emerging tools, such as ML, IONM, and RAS, are transforming risk prediction and complication management, while multidisciplinary approaches and standardized care pathways enhance patient outcomes. To further optimize results, future research should focus on how patient-specific factors, such as age, comorbidities, and genetic predispositions, influence complications. These insights can enable personalized treatment strategies and enhance decision-making. Additionally, multicenter studies and cost-benefit analyses are necessary to evaluate the feasibility and long-term effectiveness of technologies like RAS and AI in diverse healthcare settings. Clinicians are encouraged to integrate advanced tools and tailored protocols to address individual risks, reduce technical complexity, and improve outcomes. Training programs should emphasize robotic and AI-assisted techniques to ensure safe adoption of emerging innovations. Refining ERAS protocols and fostering collaboration among specialists are crucial for optimizing perioperative care, particularly for high-risk populations. As technology evolves, ongoing research and education will be essential to expand access to MIE and maximize its benefits for all patients.

FOOTNOTES

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