Review Article

Zulfkar Qadrie, Mudasir Maqbool*, Mohd Altaf Dar, Afshana Qadir

Navigating challenges and maximizing potential: Handling complications and constraints in minimally invasive surgery

https://doi.org/10.1515/ohe-2025-0059
received February 18, 2024; accepted January 14, 2025

Abstract: Minimally invasive surgery (MIS) has revolutionized the field of surgery by offering reduced trauma, faster recovery times, and improved patient outcomes compared to traditional open procedures. However, the widespread adoption of MIS is not without challenges, and managing complications and limitations is essential for optimizing patient safety and surgical efficacy. This study provides a comprehensive overview of the strategies employed in the management of complications and limitations associated with MIS. Complications in MIS can arise from various factors, including anatomical variations, unexpected bleeding, or difficulties in instrument manipulation. Recognizing the potential for complications is crucial, and surgeons must be equipped to make real-time decisions, including the possibility of converting to open procedures when necessary. Patient selection plays a pivotal role, with thorough preoperative assessments helping identify individuals who may be at higher risk for complications. Limitations in MIS are diverse and can stem from anatomical challenges, such as restricted access in confined spaces or complex structures. While technological advancements, such as robotic-assisted surgery and advanced imaging, have mitigated some limitations, ongoing efforts are directed toward overcoming challenges related to limited range of motion and maneuverability in intricate anatomical locations. Strategies for the management of complications and limitations involve a multidisciplinary approach. Surgeon training and proficiency in MIS techniques are paramount, emphasizing the importance of ongoing education and simulation-based training. Thorough preoperative planning, including a comprehensive assessment of patient history and anatomical considerations, helps anticipate potential challenges. Additionally, advancements in technology, such as enhanced imaging and robotic-assisted systems, contribute to improved visualization and precision during MIS. Regular maintenance and calibration of equipment, along with an emphasis on team communication and collaboration, further enhance the safety and effectiveness of MIS. The management of complications and limitations in MIS requires a holistic approach, encompassing surgical expertise, technological innovations, and meticulous preoperative planning. By addressing these challenges, the field of MIS continues to evolve, offering patients minimally invasive options with enhanced safety and efficacy.

Keywords: minimally invasive surgery, surgical safety, patient selection, surgeon training, robotic-assisted surgery, surgical innovation

1 Introduction

Minimally invasive surgery (MIS) has emerged as a transformative approach to surgical interventions, redefining traditional practices and significantly improving patient outcomes. This technique involves performing surgical procedures through small incisions, often less than 1 cm in size, with the aid of specialized instruments and advanced imaging technologies. Laparoscopic surgery, a primary form of MIS, employs a laparoscope – a thin, flexible tube with a camera and light source – to visualize and operate within the body. The real-time, high-resolution images provided by the laparoscope allow surgeons to navigate complex anatomical structures with precision. One of the defining advantages of MIS is the reduction in surgical trauma. Unlike open surgeries that require large incisions, MIS minimizes damage to surrounding tissues, resulting in less postoperative pain and faster recovery times for patients [1,2]. The smaller incisions also contribute to improved cosmetic

*** Corresponding author: Mudasir Maqbool,** Department of Pharmaceutical Sciences, University of Kashmir, Srinagar, Jammu and Kashmir, India, e-mail: bhatmudasir92@gmail.com
Zulfkar Qadrie: Department of Pharmacology, Government Medical College, Baramulla, India
Mohd Altaf Dar: Department of Pharmacology, CT Institute of Pharmaceutical Sciences, PTU, Jalandhar, Punjab, India
Afshana Qadir: Government College of Nursing, Baramulla, Jammu and Kashmir, India

outcomes, as patients are left with minimal scarring. Additionally, the decreased exposure of internal organs during MIS procedures leads to lower infection rates, enhancing overall patient safety. The versatility of MIS is evident across various surgical disciplines. Whether applied in general surgery, gynecology, urology, or orthopedics, MIS has proven effective in addressing a wide range of medical conditions. Robotic-assisted MIS takes precision to another level by incorporating robotic systems controlled by surgeons [3,4]. These systems provide enhanced dexterity, three-dimensional (3D) visualization, and the potential for teleoperation, enabling surgeons to perform procedures remotely. However, the adoption of MIS is not without challenges. Surgeons must navigate a learning curve to master the specialized skills required for minimally invasive techniques. Patient selection is also critical, as factors such as obesity or anatomical variations may impact the feasibility and success of MIS procedures. Addressing these challenges requires ongoing training programs and educational initiatives to ensure that surgeons are proficient in the evolving landscape of MIS. The limitations of MIS are being actively addressed through continuous technological innovations. Advances in instrumentation design aim to overcome constraints related to the limited range of motion, providing surgeons with more maneuverability during procedures. Additionally, ongoing research focuses on expanding the applications of MIS and refining existing technologies to make these procedures more accessible and effective [5,6]. Looking ahead, the future of MIS appears promising. Continued technological advancements, including the integration of artificial intelligence (AI) and machine learning, hold the potential to further enhance the precision and safety of MIS procedures. Training programs will play a pivotal role in preparing the next generation of surgeons to leverage these advancements effectively. Ultimately, MIS stands as a testament to the evolving synergy between medical science and technology, offering patients less invasive options with improved outcomes and contributing to the ongoing evolution of surgical practices [7,8].

2 Evolution of MIS

The evolution of MIS represents a remarkable journey that has reshaped the landscape of surgical practices. The roots of MIS can be traced back to the early twentieth century when rudimentary endoscopic techniques were first employed. However, it was the advent of laparoscopy in the late twentieth century that marked a paradigm shift. Laparoscopic surgery introduced the concept of making small incisions and using a laparoscope – a thin tube with a camera – to visualize the surgical field [9,10]. This breakthrough laid the foundation for the development of MIS techniques across various surgical specialties. The 1990s witnessed a surge in laparoscopic procedures, with gallbladder removal being one of the earliest widespread applications. Surgeons began to explore the possibilities of expanding MIS to other organs and systems. The refinement of instrumentation and the introduction of robotic-assisted systems in the early twenty-first century further propelled the evolution of MIS. Robotic surgery offered surgeons enhanced precision, increased dexterity, and 3D visualization, transforming the capabilities of minimally invasive techniques [11,12]. The evolution of MIS has been driven by a continuous quest for improved patient outcomes. As surgeons gained experience and technology advanced, the scope of MIS expanded to encompass a diverse array of procedures, including those in gynecology, urology, and cardiothoracic surgery. The benefits of MIS, such as reduced trauma, faster recovery, and improved cosmetic results, became increasingly evident, leading to a growing preference for minimally invasive approaches. Ongoing technological innovations have played a pivotal role in shaping the trajectory of MIS. Advances in imaging technology, including high-definition cameras and real-time imaging modalities, have provided surgeons with clearer views of the operative field. Additionally, the integration of AI and machine learning holds the promise of further enhancing the precision and safety of MIS procedures. As technology continues to evolve, the boundaries of what is possible with minimally invasive techniques are continually being pushed [12,13]. Despite the undeniable progress, challenges persist. Surgeons adopting MIS techniques face a learning curve, requiring dedicated training programs and mentorship. Patient selection remains critical, with factors such as obesity and anatomical variations posing unique challenges for certain MIS procedures. Addressing these challenges is crucial for the continued evolution and widespread acceptance of MIS. The evolution of MIS reflects a dynamic interplay between surgical innovation, technological advancements, and a commitment to improving patient care. From its early roots in endoscopy to the sophisticated robotic-assisted procedures of today, MIS has become an integral part of modern surgical practices, offering patients less invasive options and contributing to the ongoing transformation of healthcare [14–16].

3 Advantages of MIS

MIS has emerged as a transformative approach to surgical procedures, offering a plethora of advantages compared to traditional open surgeries. This innovative technique involves making small incisions, typically less than 1 cm in size, through which specialized instruments and advanced imaging technologies are utilized. MIS stands as a revolutionary approach that has redefined surgical practices across diverse medical specialties [17,18]. The advantages of MIS extend across various surgical specialties, contributing to improved patient outcomes, reduced recovery times, and enhanced overall healthcare efficiency.

3.1 Reduced trauma and faster recovery

MIS represents a transformative approach to surgical interventions, offering patients a substantial reduction in trauma compared to conventional open surgeries. Traditional open procedures typically involve large incisions that necessitate cutting through layers of tissue, resulting in more extensive damage to the surrounding structures. This heightened trauma is not only associated with increased pain for the patient but also a greater risk of complications, including infection and a longer healing process. The inherent advantage of MIS lies in its utilization of small incisions, significantly minimizing the disruption to tissues [19]. This reduction in surgical trauma is particularly noteworthy in abdominal and pelvic surgeries, where delicate structures can be approached with precision through small ports, mitigating the need for large, invasive incisions. The impact of reduced trauma in MIS extends far beyond the surgical suite and into the patient's recovery period. A key component of this advantage is the significant decrease in postoperative pain experienced by patients undergoing minimally invasive procedures. Smaller incisions result in less tissue disruption, nerve stimulation, and overall discomfort, contributing to a more comfortable recovery experience. Furthermore, the diminished trauma associated with MIS translates into a lower risk of infection, as smaller wounds are inherently less susceptible to microbial infiltration. This, in turn, minimizes the need for extended antibiotic regimens and facilitates a swifter and more uncomplicated recovery trajectory [20]. In addition to alleviating pain and reducing infection risks, the reduced trauma characteristic of MIS plays a pivotal role in shortening hospital stays and accelerating the overall recovery process. Patients undergoing MIS typically experience a quicker return to their daily activities compared to those who undergo open surgeries. The diminished impact on the body allows for a more rapid restoration of functionality and promotes early mobilization, further contributing to the expedited recovery. This advantage is particularly impactful in cases where the patient's overall health and well-being are closely tied to their ability to resume normal activities promptly. In summary, the intrinsic link between reduced surgical trauma and faster recovery in MIS underscores the profound positive impact this approach has on patient outcomes and postoperative experiences [21].

3.2 Lower infection rates and improved safety

The reduction in infection rates is a critical aspect of the improved safety profile associated with MIS. The primary factor contributing to lower infection rates in MIS is the strategic minimization of incision size. In traditional open surgeries, larger incisions create expansive pathways for external contaminants, increasing the likelihood of postoperative infections. In contrast, MIS involves smaller, precisely placed incisions, significantly limiting the exposure of internal organs to potential pathogens. This strategic approach not only minimizes the risk of infections but also underscores the meticulous care taken to enhance patient safety during surgical interventions. The correlation between smaller incisions and reduced infection risk has profound implications for patient outcomes [22]. By minimizing the opportunity for microbial infiltration, MIS enhances the safety of surgical procedures, particularly in areas prone to contamination, such as the abdominal or pelvic regions. Lower infection rates contribute to a more favorable postoperative recovery experience for patients, as they are less likely to experience the complications associated with infections, such as delayed healing or the need for prolonged antibiotic therapies. Moreover, the improved safety profile of MIS aligns with broader healthcare objectives of reducing hospital-acquired infections and optimizing patient care quality. Beyond the direct benefits to patients, the lowered infection rates associated with MIS can also contribute to healthcare cost-effectiveness. The diminished risk of postoperative infections may result in a decreased need for prolonged antibiotic treatments and additional medical interventions aimed at managing and resolving infections [23]. This, in turn, can lead to cost savings for healthcare systems, highlighting the economic advantages of emphasizing MIS as a preferred surgical approach. Consequently, the intrinsic link between reduced infection rates and improved safety in MIS not only enhances individual patient outcomes but also aligns with broader healthcare goals of optimizing resource utilization and maintaining cost-effective, high-quality care [24].

3.3 Improved cosmesis

MIS introduces a notable aesthetic advantage through the promotion of improved cosmesis. Central to this benefit is the strategic use of small incisions, a characteristic feature of MIS procedures. Unlike the larger and more conspicuous scars often associated with open surgeries, the tiny incisions used in MIS are discreet and result in minimal scarring. This feature is particularly significant in surgical interventions where the operative site is visible, such as certain abdominal or facial surgeries [5,25]. The cosmetic advantages of MIS extend beyond mere appearances; they contribute to the preservation of the patient's body image and self-esteem, addressing not only the functional aspects of surgery but also the emotional and psychological well-being of individuals. The aesthetic benefits of improved cosmesis play a crucial role in enhancing the overall patient experience and satisfaction. For many patients, the visibility of scars is a concern that can impact their self-perception and confidence. The inconspicuous nature of scars resulting from MIS addresses these concerns, fostering a positive psychological impact on patients [26]. The minimized scarring not only aligns with societal expectations of beauty but also supports patients in their recovery journey by reducing potential emotional distress related to the appearance of surgical scars. This positive impact on the patient's mental and emotional well-being contributes to a more holistic approach to healthcare that extends beyond the physical aspects of surgery. Furthermore, the emphasis on improved cosmesis aligns with contemporary healthcare trends that prioritize patient-centered care. As patients become more informed and discerning about their healthcare choices, factors such as cosmetic outcomes play a role in decision-making [27]. Surgeons who incorporate MIS techniques recognize the significance of addressing not only the medical aspects of surgery but also the patient's aesthetic concerns. This patient-centric approach enhances overall satisfaction and may positively influence patient-reported outcomes, reflecting a nuanced understanding of the comprehensive impact of surgical interventions on the individual's quality of life. In conclusion, the aesthetic advantages of improved cosmesis in MIS underscore its role in fostering a positive patient experience and aligning with the evolving expectations of modern healthcare consumers [28].

3.4 Enhanced precision and visualization

Enhanced precision and visualization are fundamental advantages that MIS brings to the forefront of modern surgical practices, owing much to the integration of advanced imaging technologies. Laparoscopes, endoscopes, and robotic-assisted systems have become indispensable tools in the hands of surgeons, providing them with unprecedented real-time, high-resolution visuals of the operative field. These technologies act as the surgeon's eyes inside the body, offering detailed views of internal structures with magnified clarity. The use of 3D visualization further elevates the precision, allowing surgeons to perceive depth and spatial relationships in a manner not possible with traditional open surgeries [29,30]. This level of visual acuity becomes paramount in procedures where meticulous accuracy is crucial, such as in neurosurgery or microsurgery, where the scale of the operative field demands a level of precision beyond what the naked eye can achieve. The ability to navigate with enhanced precision is a game-changer in the realm of MIS. Surgeons can visualize and manipulate tissues with exceptional accuracy, facilitating the performance of intricate procedures that demand a high degree of precision. In neurosurgery, for example, the precise visualization of intricate brain structures is imperative for success. MIS technologies allow for precise navigation in challenging anatomical locations, reducing the risk of damage to critical structures and enhancing the overall safety of the procedure [31]. This precision is not only a technical advantage but also a transformative element that contributes to improved patient outcomes, shorter recovery times, and minimized postoperative complications. Moreover, the integration of enhanced visualization in MIS extends beyond the immediate benefits for the surgeon. It serves as an educational tool, allowing surgical teams to observe procedures in unprecedented detail. This contributes to a collective learning experience, fostering a culture of continuous improvement and skill development within the surgical community. As technological advancements continue, the potential for even more sophisticated imaging modalities, such as augmented reality (AR), promises to further revolutionize the precision and visualization capabilities of MIS. In summary, the integration of advanced imaging technologies in MIS empowers surgeons with unparalleled precision, ultimately redefining the possibilities and standards in modern surgical care [32].

3.5 Reduced blood loss

The reduction in intraoperative blood loss stands out as a prominent advantage of MIS, setting it apart from traditional open surgical approaches. The strategic use of smaller incisions in MIS, coupled with the utilization of specialized instruments designed for precision, plays a pivotal role in minimizing blood loss during the procedure. Unlike open surgeries, where larger incisions can lead to more extensive bleeding and necessitate more aggressive hemostasis, the meticulous nature of MIS allows surgeons to target specific areas with precision, thereby significantly reducing the overall blood loss. This advantage holds particular significance in surgeries involving vital organs or structures where minimizing blood loss is crucial for patient safety and successful outcomes [33]. The implications of reduced intraoperative blood loss extend beyond the immediate surgical setting to positively impact patient outcomes. Lower blood loss diminishes the need for blood transfusions, a common requirement in surgeries with significant hemorrhage. This not only reduces the risk of complications associated with transfusions but also contributes to a more stable intraoperative environment. Maintaining hemodynamic stability is crucial for patients undergoing surgery, and the reduced blood loss associated with MIS supports this goal. Additionally, a more stable intraoperative environment provides surgeons with enhanced visibility and control, facilitating a smoother and safer execution of the procedure [17,34]. Furthermore, the reduced blood loss in MIS aligns with broader healthcare objectives related to resource utilization and patient recovery. The decreased reliance on blood transfusions translates to potential cost savings for healthcare systems and reduces the demand on blood banks. Patients benefit from a decreased risk of complications related to blood transfusions, such as infections or allergic reactions. The overall impact is a more streamlined and efficient surgical process that prioritizes patient safety, minimizes the need for additional interventions, and supports a faster postoperative recovery. In essence, the advantage of reduced blood loss in MIS underscores its pivotal role in promoting both patient safety and the efficiency of surgical care [35].

3.6 Versatility across surgical specialties

MIS stands out for its remarkable versatility, making it a valuable approach across an extensive array of surgical specialties. General surgery has seen a paradigm shift with the adoption of MIS techniques, with procedures such as laparoscopic appendectomies, cholecystectomies, and hernia repairs becoming standard practice. In gynecology, MIS has revolutionized procedures like hysterectomies and myomectomies, offering patients less invasive alternatives with reduced postoperative pain and faster recovery times [30,36]. Urology has also witnessed the transformative impact of MIS, with procedures such as laparoscopic prostatectomies and nephrectomies gaining prominence for their precision and patient benefits. Orthopedics has embraced MIS in procedures ranging from arthroscopic joint surgeries to minimally invasive spine surgeries. This approach allows for smaller incisions, reduced soft tissue damage, and quicker rehabilitation. In cardiothoracic surgery, MIS has found application in coronary artery bypass grafting, valve repairs, and lung surgeries [30,37]. The adaptability of MIS to these diverse specialties is rooted in its ability to provide enhanced precision, reduced trauma, and faster recovery, regardless of the anatomical region or specific surgical procedure. This versatility underscores the broad applicability of MIS, making it a transformative and widely utilized technique in contemporary surgical practices. The cross-specialty applicability of MIS not only reflects its technical adaptability but also its positive impact on patient outcomes. Patients undergoing MIS often experience less postoperative pain, reduced hospital stays, and faster recovery, irrespective of the surgical specialty. This versatility aligns with the evolving landscape of patient-centered care, emphasizing minimally invasive approaches that prioritize not only the successful treatment of medical conditions but also the overall well-being and satisfaction of patients. As technology continues to advance and surgical techniques evolve, the versatility of MIS positions it as a cornerstone in the ongoing transformation of surgical practices across various medical disciplines [38,39].

3.7 Earlier ambulation and reduced postoperative pain

MIS not only revolutionizes surgical procedures but also significantly improves the postoperative experience for patients, particularly in terms of reduced pain and earlier ambulation. The key to diminished postoperative pain in MIS lies in the smaller incisions and minimized tissue trauma associated with this approach. Unlike open surgeries, which often involve larger incisions and more extensive tissue disruption, the precision of MIS allows for a more targeted intervention. This translates into less damage to surrounding structures, nerves, and muscles, ultimately resulting in a reduction in postoperative pain [40]. This advantage is particularly notable in procedures involving the abdominal or pelvic regions, where postoperative pain can be a significant concern. The correlation between reduced postoperative pain and earlier ambulation is a pivotal aspect of the enhanced recovery associated with MIS. The diminished pain allows patients to mobilize sooner after surgery, which is crucial for preventing complications related to prolonged bed rest. Early ambulation is essential for maintaining circulatory health, reducing the risk of deep vein thrombosis, and preventing respiratory issues like atelectasis. By promoting mobility, MIS contributes to a smoother recovery trajectory, allowing patients to regain functionality sooner and resume their daily activities with less discomfort [41]. This aligns with the patient-centered care approach, emphasizing not only the success of the surgical procedure but also the quality of life and overall well-being of the patient throughout the recovery process. The combined benefits of reduced postoperative pain and earlier ambulation underscore the transformative impact of MIS on patient recovery. Patients experience a more comfortable and efficient recuperation facilitating a faster return to normal activities. As healthcare continues to prioritize patient-centered outcomes, the emphasis on reducing postoperative pain, and promoting early ambulation aligns with the broader goals of enhancing the overall patient experience and optimizing recovery outcomes. In essence, the advantages of MIS extend beyond the operating room, ushering in a new era of surgical care that prioritizes both the technical precision of the procedure and the holistic well-being of the patient [42,43].

3.8 Cost-effectiveness

Cost-effectiveness is a key consideration in the assessment of MIS, and while the initial investments in equipment and training may appear higher, the long-term economic benefits become apparent when evaluating various factors. One of the primary contributors to the cost-effectiveness of MIS is the reduction in hospital stays. Compared to traditional open surgeries, MIS procedures often result in shorter hospitalization periods due to faster recovery times [44]. This not only translates to reduced costs for patients, as they spend less time in the hospital, but it also optimizes the utilization of healthcare facilities by freeing up resources for other patients in need of care. The efficient turnover of hospital beds contributes to the overall effectiveness and resource optimization within healthcare systems. Lower infection rates associated with MIS further enhance its cost-effectiveness. The minimized risk of postoperative infections reduces the need for extended hospital stays, additional medical interventions, and prolonged antibiotic treatments [44,45]. Fewer complications contribute to streamlined patient care, potentially leading to a reduction in healthcare expenditures related to managing and treating postoperative infections. The economic impact extends beyond the immediate postoperative period, positively influencing the overall cost-effectiveness of MIS and aligning with the broader goals of healthcare systems to provide efficient and economically sustainable care [45,46]. Additionally, the reduced need for postoperative interventions and complications adds another layer to the economic benefits of MIS. The enhanced precision, reduced blood loss, and minimized trauma associated with MIS contribute to fewer complications, resulting in a smoother recovery process. Fewer complications mean a decreased requirement for follow-up procedures, rehospitalizations, or additional medical treatments, ultimately contributing to cost savings for both patients and healthcare systems. In essence, while the initial investment in MIS may seem higher, the long-term cost-effectiveness is underscored by the efficient use of resources, reduced hospital stays, and minimized postoperative complications, highlighting the economic advantages of embracing this advanced surgical approach [47,48].

3.9 Remote surgery possibilities

The integration of robotic-assisted MIS introduces a revolutionary concept – the potential for remote surgery. With this technology, surgeons can control robotic systems from a distance, allowing them to perform intricate procedures on patients located in different geographical areas. This opens up new possibilities for providing specialized care to individuals in underserved or remote locations where access to advanced surgical expertise may be limited [49]. The ability to conduct remote surgery has transformative implications for healthcare delivery, breaking down geographical barriers and democratizing access to cutting-edge surgical interventions. The concept of remote surgery is particularly impactful in scenarios where patients in remote or underserved regions lack proximity to specialized medical facilities. Through robotic-assisted MIS, expert surgeons can extend their reach to virtually any location with the necessary technological infrastructure. This not only enhances access to advanced surgical procedures but also addresses healthcare disparities by ensuring that individuals in remote areas receive the same level of specialized care as those in more urban or central locations [50]. Remote surgery has the potential to bring about a paradigm shift in healthcare delivery, promoting equity and inclusivity in the distribution of advanced surgical services. While the idea of remote surgery holds great promise, it also raises considerations regarding technological infrastructure, connectivity, and regulatory frameworks. Ensuring secure and reliable communication channels, safeguarding patient data, and adhering to ethical and legal standards are critical aspects that must be addressed to fully realize the potential of remote surgery. As technology continues to advance and these considerations are addressed, the integration of remote surgery capabilities in MIS has the potential to revolutionize how surgical expertise is delivered, making it more accessible and inclusive on a global scale [51,52].

3.10 Evolving technological innovations

MIS is at the forefront of a rapidly evolving landscape marked by ongoing technological innovations. The integration of AI and machine learning represents a transformative leap in the field of MIS. These technologies are being harnessed to enhance decision-making processes during surgery, providing real-time insights and predictive analytics [53]. By analyzing vast datasets and learning from diverse surgical scenarios, AI can offer surgeons valuable assistance, helping optimize procedures, improve surgical precision, and contribute to better patient outcomes. The synergy between AI and MIS exemplifies the potential for technology to augment the capabilities of surgeons and redefine the standards of care. Advanced imaging technologies are also undergoing continuous refinement within the realm of MIS [54]. Innovations in imaging, including 3D visualization and AR, are revolutionizing the way surgeons perceive and interact with the operative field. These technologies provide unprecedented depth and clarity, enabling surgeons to navigate with enhanced precision. The ongoing development of innovative instruments, coupled with advancements in imaging, holds the promise of overcoming existing challenges associated with MIS. Surgeons can expect to leverage increasingly sophisticated tools that facilitate intricate procedures with greater ease and efficiency [55]. This evolution not only pushes the boundaries of what is achievable through minimally invasive approaches but also contributes to a more patient-centric, efficient, and technologically empowered surgical landscape. The trajectory of MIS is shaped by a commitment to overcoming challenges and embracing opportunities presented by emerging technologies. As the field advances, surgeons can anticipate the integration of cutting-edge tools, robotic systems, and intelligent decision support systems that amplify their capabilities. The continuous evolution of MIS through technological innovations underscores its dynamic nature and its potential to further revolutionize surgical practices, ultimately benefiting patients by enhancing safety, precision, and the overall quality of care [56].

4 Types of MISs

MIS encompasses various techniques that have revolutionized surgical practices across a spectrum of medical specialties. These methods share the common goal of reducing surgical trauma by utilizing small incisions, specialized instruments, and advanced imaging technologies [57]. The types of MISs can be broadly categorized into laparoscopic surgery, robotic-assisted surgery, and endoscopic surgery, each offering unique advantages in specific clinical scenarios.

4.1 Laparoscopic surgery

4.1.1 Definition and technique

Laparoscopic surgery, also known as minimally invasive laparoscopic surgery, involves the use of a laparoscope – a thin, flexible tube with a light and camera – inserted through small incisions. The laparoscope allows surgeons to visualize the operative field on a monitor, guiding the procedure. Other specialized instruments are introduced through additional small incisions, enabling surgeons to perform various maneuvers and procedures [58,59].

4.1.2 Applications

Laparoscopic surgery finds extensive applications in abdominal and pelvic procedures. Common examples include laparoscopic cholecystectomy (gallbladder removal), laparoscopic appendectomy, and laparoscopic hysterectomy. The technique has proven effective in addressing conditions such as gastrointestinal disorders, hernias, and gynecological issues [60,61].

4.1.3 Advantages

The advantages of laparoscopic surgery include reduced trauma, faster recovery times, and improved cosmetic outcomes. Patients undergoing laparoscopic procedures often experience less postoperative pain, reduced blood loss, and shorter hospital stays compared to traditional open surgeries [62].

4.2 Robotic-assisted surgery

4.2.1 Technology and mechanism

Robotic-assisted surgery involves the use of robotic systems to enhance surgical procedures. These systems consist of robotic arms controlled by the surgeon through a console. The robotic arms hold specialized instruments, mimicking the surgeon's movements with precision. The surgeon receives real-time, high-definition 3D visuals of the operative field through a console, allowing for enhanced control and dexterity [63].

4.2.2 Applications

Robotic-assisted surgery is applied across various specialties, including urology, gynecology, cardiothoracic surgery, and general surgery. Examples include robotic prostatectomy for prostate cancer, robotic-assisted hysterectomy, and robotic-assisted cardiac procedures. The technology is particularly advantageous in procedures requiring intricate movements and a high level of precision [64].

4.2.3 Advantages

Robotic-assisted surgery offers several advantages, including enhanced dexterity, improved visualization, and the potential for remote surgery. The 3D visualization allows for a more detailed view of anatomical structures, contributing to precise dissections. Surgeons can manipulate the robotic arms with a range of motion that exceeds what is achievable with human hands, making it suitable for delicate and complex procedures [65].

4.3 Endoscopic surgery

4.3.1 Instrumentation and technique

Endoscopic surgery involves the use of an endoscope – a flexible tube with a light and camera – at the surgical site. The endoscope may be introduced through natural body openings or small incisions. This technique allows surgeons to visualize and operate internally without the need for large incisions. Endoscopic surgery includes procedures such as arthroscopy (joint surgery), cystoscopy (bladder examination), and bronchoscopy (examination of the airways) [66,67].

4.3.2 Applications

Endoscopic surgery is applied in various specialties, including gastroenterology, urology, orthopedics, and pulmonology. Gastrointestinal endoscopy, for example, enables the diagnosis and treatment of conditions such as gastrointestinal bleeding, polyps, and tumors. Arthroscopy is commonly used for knee and shoulder surgeries, providing a minimally invasive option for joint-related issues [68].

4.3.3 Advantages

Endoscopic surgery offers advantages such as reduced invasiveness, quicker recovery, and avoidance of large incisions. The use of natural body openings or small incisions minimizes scarring and reduces the risk of infection. Endoscopic procedures are particularly well-suited for diagnosing and treating conditions within hollow organs and cavities [68,69].

4.4 Hysteroscopic surgery

4.4.1 Technique and applications

Hysteroscopic surgery involves the use of a hysteroscope – a thin, lighted tube – to examine and treat conditions within the uterus. This technique is employed for both diagnostic and therapeutic purposes. Hysteroscopic procedures can address issues such as abnormal bleeding, polyps, fibroids, and certain types of intrauterine adhesions [70,71].

4.4.2 Advantages

Hysteroscopic surgery offers distinct advantages, including the ability to visualize and treat intrauterine conditions without the need for external incisions. Patients undergoing hysteroscopic procedures often experience minimal discomfort, reduced recovery times, and improved fertility outcomes in cases where the surgery is performed to address specific uterine issues [72,73].

4.5 Thoracoscopic surgery

4.5.1 Procedure and applications

Thoracoscopic surgery involves accessing the thoracic cavity through small incisions for diagnostic and therapeutic purposes. Common applications include thoracoscopic lung biopsies, removal of lung nodules, and thoracoscopic sympathectomy for conditions such as hyperhidrosis [74].

4.5.2 Advantages

Thoracoscopic surgery provides advantages in terms of reduced postoperative pain, faster recovery, and improved respiratory function. The smaller incisions minimize trauma to the chest wall, leading to less pain and a shorter hospital stay compared to traditional open thoracic procedures [75].

4.6 Transoral surgery

4.6.1 Technique and use

Transoral surgery, also known as transoral MIS, involves accessing the surgical site through the mouth, eliminating the need for external incisions. This technique is often employed in head and neck surgeries, such as transoral robotic surgery for oropharyngeal cancers [76,77].

4.6.2 Advantages

Transoral surgery offers advantages in terms of reduced external scarring, quicker recovery, and preservation of normal anatomical structures. The avoidance of external incisions minimizes the risk of wound-related complications and provides a cosmetically favorable outcome [78].

5 Complications of MIS

MIS has revolutionized the field of surgery, offering numerous benefits; however, like any medical procedure, it is not without its potential complications. As with traditional open surgeries, MIS carries certain risks, although the incidence of complications is generally lower. Understanding these complications is crucial for both surgeons and patients to make informed decisions about the appropriate course of action and to ensure optimal outcomes [79,80].

5.1 General complications

5.1.1 Bleeding

Bleeding represents a potential complication in MIS, although the risk is generally lower compared to open surgeries due to the smaller incisions and precision of these procedures. Despite the advantages of reduced blood loss inherent in MIS, surgeons must remain vigilant and adept at managing hemostasis throughout the surgery. Hemostasis involves controlling bleeding from blood vessels, and in the context of MIS, this is particularly crucial as the smaller incisions may limit direct visualization and access to bleeding sites. The use of specialized instruments, energy devices, and meticulous techniques becomes paramount in ensuring effective hemostasis and minimizing the risk of complications related to excessive bleeding during and after the procedure. In the event that bleeding becomes challenging to control through the small incisions, surgeons may need to consider conversion to an open procedure [81,82]. While the goal of MIS is to avoid the need for larger incisions, converting to an open surgery allows for better access and control in cases of persistent or severe bleeding. This decision is typically made to prioritize patient safety and ensure that bleeding is adequately addressed to prevent complications such as hematoma formation, reduced oxygen delivery to tissues, or the need for blood transfusions. The ability to adapt and make real-time decisions regarding the need for conversion underscores the importance of the surgeon's skill and experience in managing potential complications during MIS. Addressing bleeding complications in MIS involves a comprehensive and proactive approach, including thorough preoperative assessment, careful intraoperative management, and clear communication within the surgical team [83]. Technologies such as advanced imaging and hemostatic agents may also play a role in minimizing the risk of bleeding. While bleeding is a recognized complication in MIS, the emphasis on meticulous technique and the ability to adapt to unforeseen challenges contribute to maintaining the overall safety and efficacy of minimally invasive procedures [84].

5.1.2 Infection

In the realm of MIS, the risk of infection is a consideration despite the advantages of smaller incisions. While MIS inherently reduces the risk of infection when compared to open surgeries, it is not entirely immune to this complication. Infections can manifest at the incision sites, posing a risk of superficial wound infections, or internally, particularly in procedures involving the gastrointestinal or urinary tract where microbial exposure is more likely. The reduced tissue trauma associated with MIS is a positive factor in minimizing infection risk, but the careful management of aseptic conditions during the procedure and meticulous attention to infection prevention protocols remain critical elements in mitigating the potential for postoperative infections [85,86]. Preventive measures play a key role in addressing the risk of infection in MIS. Surgeons adhere to strict aseptic techniques throughout the procedure to minimize the introduction of microbes into the surgical site. Additionally, the administration of prophylactic antibiotics is a common practice to further reduce the risk of postoperative infections. Prophylactic antibiotics are typically given shortly before the surgical procedure, aiming to provide sufficient coverage during the critical perioperative period. The choice of antibiotics is guided by factors such as the type of surgery, patient-specific considerations, and local antimicrobial resistance patterns. This strategic use of antibiotics is a proactive approach to infection prevention in MIS, aligning with broader efforts to optimize patient safety and minimize postoperative complications [87]. Despite these preventive measures, the risk of infection remains a potential complication, and early detection and intervention are crucial in managing such cases. Postoperative monitoring for signs of infection, such as redness, swelling, warmth, or discharge at the incision sites, allows for timely intervention and appropriate treatment. The multifaceted approach of minimizing microbial exposure, administering prophylactic antibiotics, and vigilant postoperative monitoring collectively contribute to the comprehensive strategy employed in MIS to reduce the risk of infections and enhance overall patient safety [88].

5.1.3 Organ damage

Organ damage is a recognized but relatively uncommon complication in MIS. Despite the precision and control offered by MIS techniques, there is a potential risk of unintended injury to organs or nearby structures during procedures. In laparoscopic or robotic surgeries, instruments are introduced through small ports, and the limited field of view can pose challenges in certain anatomical regions. Surgeons must navigate with precision and spatial awareness to avoid inadvertent damage to adjacent organs [89]. The reduced tactile feedback compared to open surgeries requires a heightened reliance on visual cues and the surgeon's expertise in maneuvering instruments delicately within confined spaces. Vigilance and skill are paramount in minimizing the risk of organ damage during MIS. Surgeons undergo extensive training to develop the dexterity and spatial orientation required for these procedures. Additionally, advancements in imaging technologies, such as 3D visualization and improved camera systems, aim to enhance the surgeon's perspective and reduce the risk of unintended injuries. However, in some cases, despite the best efforts, injury to blood vessels, nerves, or other structures may occur. Recognizing and addressing such injuries promptly is crucial for patient safety. In instances where the complexity of the situation requires better visualization and control, conversion to an open procedure may be necessary. This decision allows the surgeon to address the damage more effectively and mitigate potential complications associated with organ injuries [86,90]. The risk of organ damage underscores the importance of a surgeon's experience and proficiency in MIS procedures. Furthermore, ongoing advancements in surgical technologies and training methods aim to continually improve safety measures and minimize the occurrence of unintended injuries. While MIS offers numerous benefits, including reduced trauma and faster recovery, the potential for organ damage necessitates a balanced and informed approach, with surgeons being well-prepared to manage any unforeseen challenges that may arise during these minimally invasive interventions [91].

5.2 Specific complications based on type of MIS

5.2.1 Laparoscopic complications

5.2.1.1 Trocar site complications

Trocar site complications represent a subset of potential issues in MIS procedures. Trocars are specialized instruments used to create access ports through which surgical instruments and cameras are introduced into the body during laparoscopic or robotic surgeries. While these instruments facilitate minimally invasive techniques, the sites where trocars are inserted can pose challenges. Trocar site hernias are a rare but notable complication, where abdominal contents protrude through the port site. This complication arises when there is inadequate closure of the trocar site, allowing for the displacement of tissues and organs [92]. Preventing trocar site complications involves meticulous attention to closure techniques by the surgical team. Surgeons must ensure that trocar sites are appropriately closed and secured at the conclusion of the procedure. The closure technique may vary based on factors such as the size of the trocar and the thickness of the abdominal wall. Techniques such as fascial closure and the use of closure devices or sutures are employed to minimize the risk of herniation or other complications associated with trocar insertion. Surgeons may also consider the patient's individual characteristics, such as obesity or a history of abdominal surgeries, when determining the optimal closure method to mitigate the risk of trocar site complications [93]. While trocar site complications are relatively rare, their occurrence underscores the importance of thorough surgical technique and postoperative monitoring. Regular follow-up assessments allow for the early detection of complications, enabling timely intervention if issues such as hernias or infections arise. As technology and surgical methods continue to advance, ongoing refinements in trocar design and closure techniques aim to further minimize the risk of trocar site complications, ensuring that the benefits of MIS are maximized while maintaining a focus on patient safety [94].

5.2.1.2 Complications related to pneumoperitoneum

Complications related to pneumoperitoneum, the insufflation of carbon dioxide to create a working space during laparoscopic surgery, are important considerations in MIS. While pneumoperitoneum is a necessary step for optimal visualization and manipulation of internal organs, it introduces the potential for certain complications. Cardiovascular and respiratory effects are among the primary concerns associated with pneumoperitoneum. The increased intra-abdominal pressure can impact venous return to the heart, potentially leading to changes in cardiac output and blood pressure [95]. Additionally, the elevated pressure can affect respiratory mechanics, influencing factors such as lung compliance and airway pressures. Surgeons and anesthesiologists carefully monitor these physiological parameters during MIS procedures to promptly address any cardiovascular or respiratory changes and ensure patient safety. Subcutaneous emphysema is another rare but notable complication linked to pneumoperitoneum. It occurs when carbon dioxide escapes into the subcutaneous tissues, causing localized swelling and crepitus beneath the skin [96]. While subcutaneous emphysema is typically benign and self-limiting, its occurrence can be disconcerting for patients. Surgeons take measures to minimize the risk of subcutaneous emphysema by carefully managing insufflation pressures and ensuring proper closure of port sites to prevent gas leakage. Gas embolism represents a more serious and potentially life-threatening complication associated with pneumoperitoneum. This occurs when carbon dioxide enters the bloodstream, forming bubbles that can travel to the heart or lungs. Gas embolism is rare but can lead to cardiovascular collapse and respiratory compromise. Stringent safety measures, including meticulous attention to insufflation techniques, continuous monitoring of intra-abdominal pressures, and immediate response to any signs of gas embolism, are integral components of risk mitigation during MIS procedures [97]. While the benefits of pneumoperitoneum in facilitating minimally invasive techniques are substantial, the potential complications necessitate a cautious and vigilant approach by the surgical team. Continuous monitoring, adherence to safety protocols, and prompt intervention in the event of complications are essential for ensuring the overall safety and success of laparoscopic surgeries. As technology and techniques in MIS continue to evolve, ongoing efforts are directed toward refining safety measures associated with pneumoperitoneum to further enhance patient outcomes [98].

5.2.2 Robotic complications

5.2.2.1 Technical failures

Technical failures in robotic-assisted surgery represent a potential challenge that surgeons and operating teams must be prepared to handle. Robotic-assisted surgery relies on intricate robotic systems with multiple components, including robotic arms, control consoles, and advanced software. Despite the sophistication of these systems, technical failures can occur, ranging from malfunctions in robotic arms to errors in the overall robotic system. Surgeons and the operating team undergo extensive training to familiarize themselves with the robotic platform and, importantly, to be adept at recognizing and responding to technical issues promptly [99]. Robotic arm malfunctions are among the technical failures that can impact robotic-assisted surgery. These malfunctions may include issues with movement precision, joint stiffness, or communication errors between the surgeon's console and the robotic arms. Surgeons are trained to assess and troubleshoot these issues during a procedure, and protocols are in place to ensure rapid communication between the surgeon, the robotic system, and the support team. Regular maintenance and system checks are conducted to minimize the risk of technical failures, but in the event that issues arise, the ability to swiftly address them is critical for the seamless continuation of the surgery [100]. The impact of technical failures goes beyond the immediate surgical procedure. Delays or disruptions due to technical issues can potentially affect the overall efficiency of the operating room and patient outcomes. Consequently, the preparedness of the surgical team to manage technical failures is an integral aspect of the successful implementation of robotic-assisted surgery. As technology continues to advance, ongoing training programs and continuous improvement initiatives aim to further enhance the resilience of robotic systems and the ability of surgical teams to navigate and mitigate technical challenges effectively. The collaborative efforts of surgeons, engineers, and support staff play a pivotal role in ensuring the reliability and safety of robotic-assisted surgical procedures [101].

5.2.2.2 Learning curve

The learning curve is a significant consideration when incorporating robotic-assisted surgery into a surgeon's skill set. While robotic systems offer enhanced capabilities, the transition from traditional surgical methods to mastering this advanced technology involves a learning curve. Surgeons must become familiar with the unique interface of the robotic console, hand controls, and 3D visualization. The learning curve encompasses developing proficiency in controlling robotic arms, manipulating instruments, and navigating the robotic system to perform precise and efficient procedures [101,102]. As with any new surgical technique, the initial phases of the learning curve may result in longer operative times and increased complexities as surgeons acclimate to the nuances of robotic-assisted surgery. The challenges associated with the learning curve can have implications for patient outcomes. Longer operative times may translate to extended exposure to anesthesia and prolonged pneumoperitoneum, factors that can contribute to increased patient discomfort and potential complications. Additionally, the risk of intraoperative errors may be higher during the early stages of the learning curve [103]. Surgeons, as well as the broader surgical team, are proactive in addressing these challenges by engaging in structured training programs and simulation exercises to accelerate the learning process. The goal is to ensure a smooth transition to proficiency in robotic-assisted surgery, minimizing the impact on operative times and patient outcomes. Ongoing advancements in training methods, virtual reality (VR) simulations, and mentorship programs aim to streamline the learning curve associated with robotic-assisted surgery. As surgeons gain experience and confidence in utilizing robotic systems, the benefits of enhanced precision, reduced trauma, and faster patient recovery become more pronounced. The learning curve is a dynamic aspect of incorporating new technologies into surgical practices, and the commitment to continuous education and skill refinement plays a pivotal role in optimizing the utilization of robotic-assisted surgery for improved patient care [104].

5.2.3 Endoscopic complications

5.2.3.1 Perforations

Perforations represent a potential and serious complication in endoscopic procedures, particularly in delicate tissues where the risk is heightened. Endoscopic procedures involve the insertion of a flexible tube equipped with a light and camera through natural openings or small incisions, enabling visualization and intervention in internal organs. The risk of perforation arises when there is unintended damage to the wall of an organ or structure, creating an opening that can lead to various complications. Delicate tissues, such as those in the gastrointestinal tract during abdominal endoscopy or in the thoracic region during procedures like bronchoscopy, are particularly vulnerable to perforations [105]. Complications resulting from perforations can vary based on the anatomical location. In abdominal procedures, perforations may lead to peritonitis, which is the inflammation of the peritoneum – the membrane lining the abdominal cavity. Peritonitis is a serious condition that can result from the leakage of digestive fluids or other contents into the abdominal cavity, triggering an inflammatory response. In thoracic procedures, such as esophageal or bronchial endoscopy, perforations can lead to mediastinitis, which is inflammation in the mediastinum – the space between the lungs containing the heart, major blood vessels, and other structures [106]. Both peritonitis and mediastinitis can be associated with significant morbidity and require prompt intervention to prevent further complications. Preventing perforations during endoscopic procedures is a critical aspect of the surgeon's skill set. Surgeons must exercise caution, precision, and a thorough understanding of the anatomy to minimize the risk of inadvertent damage to tissues. Advances in endoscopic technology, including improved visualization and instrument control, aim to enhance the surgeon's ability to navigate and intervene safely. Additionally, ongoing training and adherence to procedural guidelines contribute to the overall safety of endoscopic interventions, ensuring that the benefits of minimally invasive techniques are maximized while minimizing the risk of complications such as perforations [107].

5.2.3.2 Complications related to anesthesia

Complications related to anesthesia are important considerations in endoscopic procedures, where the use of anesthesia is common to ensure patient comfort and immobilization during the intervention. Respiratory issues represent a significant concern, especially when patients are under deep sedation or general anesthesia. The depressant effects of anesthesia on the respiratory system can lead to challenges such as airway obstruction, hypoventilation, or even respiratory arrest [108]. Careful monitoring of vital signs, including oxygen saturation levels and end-tidal carbon dioxide, is essential to promptly detect and address any respiratory complications during endoscopic procedures. Adverse reactions to anesthetic agents can also occur and manifest in various ways. Allergic reactions, although rare, can result in symptoms ranging from mild skin rashes to severe anaphylaxis. Additionally, the administration of anesthetic agents may impact cardiovascular function, potentially leading to complications such as changes in blood pressure or heart rhythm disturbances. Anesthetic management requires thorough preoperative assessment, including a detailed patient history and identification of any known allergies or adverse reactions [109]. Anesthesia providers are trained to administer agents judiciously, monitor patients closely, and be prepared to intervene promptly in the event of any adverse reactions, ensuring the overall safety of the endoscopic procedure. Cardiopulmonary complications are another subset of concerns related to anesthesia in endoscopic procedures. The administration of anesthesia can influence both the cardiovascular and respiratory systems, and patients with pre-existing conditions such as heart or lung diseases may be at increased risk. Close collaboration between the anesthesia team and the endoscopist is essential to tailor the anesthesia plan to the patient's individual needs and medical history. In instances where patients have specific risk factors, such as a history of cardiac issues, the anesthesia team may employ advanced monitoring techniques and consider alternative anesthesia approaches to mitigate the risk of complications. The safe administration of anesthesia is a critical component of endoscopic procedures [110]. The anesthesia team's vigilance, thorough preoperative assessments, and prompt intervention in response to any complications contribute to the overall success and safety of endoscopic interventions. As with any medical procedure, a collaborative and multidisciplinary approach involving both endoscopists and anesthesia providers is essential to optimize patient outcomes and minimize the risk of anesthesia-related complications [111].

5.3 Management of complications

5.3.1 Preoperative planning

Preoperative planning plays a pivotal role in ensuring the success and safety of medical procedures, and this is especially true in the context of endoscopic interventions. Surgeons engaged in endoscopic procedures must embark on a comprehensive preoperative assessment that extends beyond the immediate focus of the intervention. Patient history is scrutinized to identify underlying health conditions, previous surgeries, and potential risk factors that might influence the procedure. An understanding of comorbidities, medications, and allergies is crucial in tailoring the approach to anesthesia and mitigating the risk of complications [111,112]. This detailed examination sets the foundation for a personalized and patient-centric plan that considers the individual's unique physiological and anatomical characteristics. Adequate imaging studies are integral components of preoperative planning in endoscopy. Advanced imaging techniques, such as computed tomography, magnetic resonance imaging, or endoscopic ultrasound, provide detailed insights into the anatomy and pathology of the target area. These studies help surgeons identify potential challenges, such as the presence of anatomical variations, lesions, or adhesions that may impact the course of the procedure. Armed with this information, surgeons can develop a meticulous and strategic surgical plan, anticipating potential complications and implementing measures to address them proactively. Preoperative planning not only contributes to the efficiency of the intervention but also enhances patient safety by minimizing unforeseen challenges and optimizing the overall success of endoscopic procedures [113].

5.3.2 Intraoperative strategies

5.3.2.1 Monitoring

Monitoring is a cornerstone of MIS, ensuring the continuous assessment of a patient's physiological status during the procedure. Real-time monitoring of vital parameters, including blood pressure, heart rate, and oxygen saturation, is crucial for the early detection and prompt response to any physiological changes. These parameters provide insights into the patient's cardiovascular and respiratory function, offering a comprehensive picture of their physiological well-being throughout the surgery. Anomalies in these vital signs can serve as early indicators of potential complications, allowing the surgical team to take immediate corrective actions and ensure patient safety [114]. In addition to conventional vital sign monitoring, advanced tools and technologies have been integrated into MIS to further enhance the surgeon's ability to visualize and manage complications. Intraoperative imaging, such as fluoroscopy or real-time ultrasound, provides dynamic visuals of the surgical field, enabling the surgeon to navigate with precision and detect any unexpected challenges. This real-time imaging not only aids in the accurate placement of instruments but also allows for the timely identification of complications such as bleeding, inadvertent injuries, or anatomical variations [115]. The combination of comprehensive physiological monitoring and advanced imaging technologies represents a synergistic approach in MIS, empowering the surgical team to deliver optimal care by responding promptly to any changes or challenges encountered during the procedure [115].

5.3.2.2 Surgeon training

Surgeon training is a critical component in the successful implementation of MIS. Given the unique skills and techniques required for MIS procedures, surgeons and the entire operating team undergo rigorous training to ensure proficiency in handling specialized instruments, navigating intricate anatomical structures, and recognizing potential complications. The complexity of MIS demands a level of dexterity and spatial awareness distinct from traditional open surgeries. Surgeons must become adept at manipulating long, slender instruments through small incisions or natural orifices, often relying on hand-eye coordination and 3D visualization provided by advanced imaging systems [116]. Simulation training and mentorship programs play pivotal roles in the development of skills needed for MIS. Simulators offer a controlled environment where surgeons can practice and refine their techniques without the pressures of an actual surgical procedure. These training tools provide realistic scenarios, allowing surgeons to navigate various challenges they might encounter during MIS interventions. Mentorship programs, where experienced surgeons guide and share their expertise with less experienced colleagues, contribute to the transfer of knowledge and skill refinement. The combination of didactic education, hands-on simulation training, and mentorship ensures that surgeons are well-prepared to handle the nuances of MIS, promoting patient safety and optimal surgical outcomes [116,117].

5.3.2.3 Team communication

Team communication is a cornerstone of successful MIS, where a well-coordinated and collaborative team can significantly contribute to positive outcomes. The surgical team, composed of the surgeon, anesthesiologist, nurses, and other support staff, relies on effective communication to navigate through the complexities of MIS procedures. Clear and open lines of communication ensure that each team member is aware of the surgical plan, patient status, and any potential challenges that may arise during the procedure. This proactive exchange of information lays the groundwork for a shared understanding of roles and responsibilities, fostering a cohesive environment where everyone is poised to act swiftly and effectively in response to unexpected situations or complications. In the dynamic setting of the operating room, real-time communication is crucial for adapting to evolving circumstances [118]. Whether it is addressing changes in patient physiology, unexpected anatomical findings, or technical issues, a well-functioning communication system allows the surgical team to respond promptly. This coordinated approach not only enhances the safety of the procedure but also contributes to the overall efficiency and success of MIS interventions. Regular team briefings, debriefings, and a culture that encourages open dialogue create a collaborative environment where each team member's expertise is valued, leading to better decision-making and improved patient outcomes [119].

5.3.3 Postoperative care

5.3.3.1 Monitoring recovery

Close postoperative monitoring is essential to identify and address complications during the recovery phase. Continuous assessment of vital signs, pain management, and early detection of signs of infection or bleeding contribute to optimal postoperative care [119,120].

5.3.3.2 Rehabilitation

Rehabilitation strategies play a role in the recovery process. Physical therapy and rehabilitation programs may be recommended to aid patients in regaining function and mobility, especially in procedures involving joints or musculoskeletal structures [120].

6 Limitations of MIS

MIS has transformed the landscape of surgical interventions, offering numerous advantages; however, it is not without its limitations. Despite its widespread adoption and success in various medical specialties, there are challenges and constraints associated with MIS techniques. Understanding these limitations is crucial for both surgeons and patients to make informed decisions, manage expectations, and optimize outcomes [120,121].

6.1 Learning curve and training

The learning curve is a notable limitation in the adoption of MIS. Surgeons transitioning from traditional open techniques to MIS, including laparoscopy or robotic-assisted surgery, often encounter a period of adaptation and learning. The techniques involved in MIS demand a high level of hand–eye coordination and precision, skills that may not be as prominently featured in traditional open surgeries [122]. The shift to navigating long, slender instruments through small incisions or manipulating robotic systems requires a significant adjustment in technique, making it essential for surgeons to undergo specialized training to become proficient in these minimally invasive approaches. During the initial phases of the learning curve, surgeons may experience longer operative times compared to their counterparts using open techniques. The need for a meticulous approach and the mastery of new technologies contribute to this temporary extension of surgical durations. Additionally, there may be an associated increase in the risk of complications as surgeons become accustomed to the nuances of MIS [123]. These complications can include inadvertent injuries, suboptimal placement of instruments, or challenges in suturing and knot tying. The recognition of this learning curve limitation underscores the importance of structured training programs and mentorship to facilitate a smoother transition and enhance the overall safety and efficacy of MIS procedures. Specialized training programs play a crucial role in mitigating the challenges associated with the learning curve in MIS. Simulation training, where surgeons can practice in a controlled environment, provides a valuable opportunity to refine skills and gain confidence before performing procedures on actual patients [124]. Additionally, mentorship programs, where experienced MIS surgeons guide and share their expertise, contribute to the transfer of knowledge and skill refinement. Continuous advancements in training methods aim to expedite the learning curve and ensure that surgeons can embrace MIS techniques with proficiency, ultimately maximizing the benefits of minimally invasive approaches for improved patient care [125].

6.2 Limited range of motion and maneuverability

The limited range of motion and maneuverability of instruments in MIS can present challenges, particularly in procedures that demand intricate and complex movements. In laparoscopic procedures, the instruments used are rigid and operate in a straight-line manner, which may restrict the surgeon's ability to navigate and manipulate tissues with the same freedom as open surgeries. This constraint is particularly evident in surgeries requiring delicate and precise maneuvers, such as suturing in confined spaces or performing intricate dissections [125,126]. The restricted range of motion can be a limiting factor in achieving optimal outcomes, and surgeons need to adapt their techniques to work within these constraints while maintaining precision. Robotic-assisted surgery, with its advanced robotic arms and improved dexterity, represents a significant advancement over traditional laparoscopy. However, even in robotic procedures, there are limitations to the range of motion of robotic arms. The robotic system is designed to replicate the movements of the surgeon's hands, but it may not entirely mimic the full spectrum of human motion. Surgeons must navigate within the defined range of motion of the robotic arms, which can be a consideration in surgeries that demand intricate and multidimensional movements [127]. While robotic systems provide enhanced maneuverability compared to laparoscopy, there remains a need for surgeons to carefully plan and execute their procedures, taking into account the specific capabilities and limitations of the robotic platform. The adaptation of techniques and strategies to work within the confines of limited range of motion is a key aspect of the surgeon's skill set in MIS. Surgeons often undergo specialized training to optimize their proficiency in using laparoscopic or robotic instruments effectively. This includes developing strategies to achieve the desired outcomes despite the constraints, such as using specific trocar placements, altering instrument angles, or employing innovative approaches to accomplish complex tasks. As technology continues to evolve, there is ongoing research and development aimed at enhancing the maneuverability of instruments in MIS, seeking to address these limitations and further improve the feasibility and success of minimally invasive procedures [128].

6.3 Lack of tactile feedback

The absence of tactile feedback is a distinctive limitation of MIS, setting it apart from traditional open surgery where surgeons can directly feel tissues and structures with their hands. In MIS, the surgeon relies solely on visual information obtained from imaging devices, such as laparoscopes or robotic systems. While these visual cues provide detailed views of the operative field, the inability to physically feel tissues can be a significant disadvantage. Tactile feedback is valuable in open surgery for assessing the texture, consistency, and tension of tissues, which aids in identifying anatomical structures, detecting abnormalities, and making real-time adjustments based on the surgeon's tactile perceptions [129]. The lack of tactile feedback in MIS can pose challenges in accurately interpreting the surgical field. Subtle variations in tissue characteristics that might be indicative of pathology may be challenging to discern through visual cues alone. For instance, identifying the boundaries of a tumor or distinguishing between normal and abnormal tissues may require a heightened reliance on imaging, potentially increasing the risk of overlooking subtle abnormalities. This limitation is particularly notable in procedures where precise tissue manipulation is crucial, such as delicate dissections or suturing [130]. Surgeons must compensate for the absence of tactile feedback by developing a keen understanding of visual cues and honing their skills in interpreting two-dimensional (2D) representations of 3D anatomical structures. The reliance on visual information over tactile sensations also contributes to a steeper learning curve in MIS. Surgeons transitioning from open to minimally invasive techniques need to adapt to a different sensory paradigm. Developing proficiency in interpreting visual cues and translating them into precise actions requires time and practice. While advancements in imaging technologies aim to enhance the visual information provided during MIS, efforts are ongoing to explore innovative solutions that may introduce some form of tactile feedback to further bridge the gap between open and minimally invasive surgical approaches [131].

6.4 Patient selection

Patient selection is a critical consideration in the application of MIS, as certain patient factors can influence the feasibility and success of these procedures. One notable factor is obesity, where the increased thickness of adipose tissue can present challenges in the visualization and manipulation of structures. In laparoscopic procedures, the limited range of instruments may be less effective in obese patients due to the additional layer of fat, potentially compromising the surgeon's ability to navigate and operate with precision [132]. Adequate exposure and visualization are essential in MIS, and in obese patients, these may be compromised, necessitating careful evaluation of the risks and benefits before opting for a minimally invasive approach. Anatomical variations among patients can also impact the suitability of MIS. Individuals may exhibit differences in the location, size, or configuration of internal structures, influencing the accessibility of these structures during minimally invasive procedures. Surgeons must carefully consider these variations and assess whether the specific anatomical characteristics of a patient might pose challenges in terms of instrument access, maneuverability, or the ability to achieve optimal visualization. In cases where anatomical variations may impede the feasibility of MIS, alternative approaches or open surgical techniques may need to be considered to ensure the safety and effectiveness of the procedure [133]. The consideration of patient selection in MIS extends beyond anatomical factors to encompass overall health status and comorbidities. Certain medical conditions or pre-existing health concerns may impact a patient's ability to tolerate the pneumoperitoneum required for laparoscopic procedures or influence their overall recovery following surgery. A comprehensive assessment of patient factors, including obesity, anatomical variations, and general health status, is essential in determining the appropriateness of MIS. This individualized approach ensures that the chosen surgical technique aligns with the patient's characteristics and maximizes the likelihood of a successful outcome while minimizing potential complications [134].

6.5 Complexity of procedures

The complexity of procedures is a significant consideration when deciding on the suitability of MIS. While MIS has proven effective for a broad spectrum of surgeries, certain complex procedures may be better addressed through open techniques. The confined space and limited visibility inherent in MIS can pose challenges, particularly in surgeries involving extensive tissue resection, complex reconstructions, or those requiring multiple interventions. For instance, surgeries involving intricate anatomical structures or delicate manipulations may demand a level of precision and tactile feedback that is more readily achieved through open approaches [135]. In certain cases, the feasibility and success of MIS may be compromised by the complexity of the procedure. The restricted range of motion of instruments and the 2D visualization provided by laparoscopes or robotic systems may present limitations in addressing the intricacies of complex surgeries. Surgeons must carefully weigh the benefits and drawbacks of MIS for each specific clinical scenario. While MIS is celebrated for its reduced trauma, faster recovery times, and improved cosmesis, these advantages must be balanced against the technical challenges posed by the complexity of certain procedures. The decision to opt for MIS or open surgery involves a nuanced evaluation of the unique requirements of each case, aiming to optimize patient outcomes while ensuring the safety and effectiveness of the chosen surgical approach. Surgeons play a crucial role in assessing the complexity of procedures and making informed decisions about the most appropriate surgical approach [136]. The evolution of MIS techniques and technologies continues to expand the range of procedures that can be successfully performed using minimally invasive methods. However, ongoing research and advancements are necessary to address the challenges associated with complex surgeries, aiming to further enhance the capabilities of MIS and broaden its applicability across a diverse array of clinical scenarios [137].

6.6 Cost and resources

The cost and resource considerations associated with MIS are pivotal factors influencing its adoption and accessibility.

The initial setup and investment in MIS equipment, particularly robotic systems, can represent a substantial financial commitment. Although the costs associated with MIS have decreased over time, driven by advancements in technology and increased adoption, these procedures may still be more expensive than traditional open surgeries. The acquisition of state-of-the-art equipment, such as laparoscopic instruments or robotic-assisted systems, contributes to the upfront expenses, and the financial implications extend beyond the initial investment to include ongoing maintenance, upgrades, and training costs [138]. Maintenance and training costs are ongoing considerations in the utilization of MIS. Ensuring that equipment remains in optimal condition requires regular maintenance, calibration, and occasional upgrades. Training healthcare professionals in MIS techniques, especially for new technologies like robotic-assisted surgery, is essential for achieving proficiency and optimizing patient outcomes. These ongoing costs contribute to the overall financial considerations associated with MIS [44]. In settings with limited resources, both in terms of financial constraints and trained personnel, the accessibility and affordability of MIS may become a limiting factor, potentially impacting the widespread adoption of these advanced surgical techniques. The cost-effectiveness of MIS also depends on factors such as reduced hospital stays, lower infection rates, and faster recovery times. While the initial investment may be higher, the overall economic benefits, including reduced healthcare utilization and improved patient outcomes, can offset these costs. However, healthcare institutions and policymakers must carefully weigh the financial considerations against the clinical advantages to make informed decisions about the integration and sustainability of MIS within their healthcare systems. Efforts to enhance cost-effectiveness, such as optimizing resource utilization and investing in training programs, are crucial for ensuring the continued accessibility and affordability of MIS in diverse healthcare settings [139].

6.7 Complications and conversions

MIS is generally recognized for its association with fewer complications compared to open surgeries. However, it is important to acknowledge that complications can still arise in MIS procedures. Unforeseen challenges, such as unexpected anatomical variations, bleeding complications, or difficulties in instrument manipulation, may occur during the course of an MIS [99]. While surgeons are adept at navigating through these challenges in many cases, there are instances where the complexity or severity of complications necessitate a transition from a minimally invasive approach to an open procedure. Complications that may prompt conversion to an open procedure include situations where the limited visibility and constrained range of motion in MIS become significant barriers to effectively manage challenges. For example, in cases of unexpected bleeding, the restricted access and reduced tactile feedback in MIS may make it challenging for the surgeon to achieve hemostasis or adequately visualize the source of bleeding. In such circumstances, converting to an open approach allows the surgeon greater control, direct visualization, and the ability to address complications with more traditional surgical techniques. The decision to convert from MIS to open surgery is a dynamic and complex one, requiring the surgeon's expertise and judgment [140]. While MIS is often preferred for its reduced trauma and faster recovery times, the option to convert provides a safety net for managing unexpected complications effectively. It underscores the importance of surgeon experience, adaptability, and the ability to make real-time decisions based on the patient's specific clinical scenario. Postoperative debriefings and analyses of cases that require conversion contribute to ongoing improvements in surgical protocols and decision-making, enhancing the overall safety and success of minimally invasive procedures [141].

6.8 Not universally applicable

Despite its numerous advantages, MIS is not universally applicable to all surgical scenarios. There are specific pathologies and anatomical considerations that may limit the feasibility and effectiveness of minimally invasive approaches. For instance, complex fractures or tumors located in challenging anatomical regions may necessitate open procedures for optimal visualization and intervention [142]. The confined spaces and limited maneuverability in certain anatomical locations may impede the surgeon's ability to perform intricate and precise procedures through minimally invasive means. The decision to opt for open surgery over MIS is often guided by the specific requirements of each case. While MIS is celebrated for its reduced trauma, faster recovery times, and improved cosmesis, the diversity of surgical cases mandates a personalized approach. Surgeons must carefully evaluate the nature of the pathology, the location of the lesion or injury, and the overall anatomical considerations to determine the most appropriate surgical approach. In situations where the benefits of MIS may be compromised by the complexity or location of the pathology, open procedures offer the advantage of providing direct access, enhanced visibility, and greater control over the surgical field [143]. The limitations in the universality of MIS underscore the importance of individualizing treatment plans based on patient characteristics and the specific nature of the pathology. The goal is to optimize patient outcomes by selecting the most suitable surgical approach for each unique case. Advances in surgical techniques, technology, and ongoing research aim to expand the applicability of MIS, but surgeons must exercise discretion in choosing the most appropriate approach based on the intricacies of each clinical scenario [144].

6.9 Pneumoperitoneum-related effects

The creation of pneumoperitoneum, which involves inflating the abdominal cavity with carbon dioxide, is a fundamental step in laparoscopic surgeries. While this technique provides the necessary workspace for minimally invasive procedures, it is not without its potential limitations. One significant consideration is the impact of pneumoperitoneum on intra-abdominal pressure. The insufflation of carbon dioxide leads to an increase in intra-abdominal pressure, which can have physiological implications [145]. Elevated intra-abdominal pressure may affect hemodynamics, venous return, and organ perfusion, posing potential challenges, especially in patients with pre-existing cardiovascular conditions. Cardiovascular and respiratory effects related to pneumoperitoneum can be a concern, particularly in patient populations with underlying cardiopulmonary conditions. The increased intra-abdominal pressure may influence cardiovascular parameters, such as blood pressure and heart rate. In patients with compromised cardiac function, these changes may be less tolerable, requiring careful monitoring and management during the surgical procedure. Additionally, the respiratory system may be affected, leading to changes in lung mechanics and potential alterations in oxygenation and carbon dioxide levels [146]. Surgeons and anesthesiologists must take into account the patient's baseline health status and tailor the insufflation parameters to minimize adverse effects, ensuring the safety and stability of the patient throughout the laparoscopic procedure. Patient selection and thorough preoperative assessments are crucial in mitigating the potential risks associated with pneumoperitoneum-related effects. Surgeons need to consider the overall health status of the patient, especially the condition of the cardiovascular and respiratory systems, when determining the appropriateness of laparoscopic surgery. In cases where the risks associated with pneumoperitoneum may outweigh the benefits of a minimally invasive approach, alternative surgical techniques or careful management strategies may be considered to optimize patient safety and outcomes [147]. Ongoing research and advancements in surgical practices aim to refine the use of pneumoperitoneum and enhance its safety profile, ensuring that the benefits of minimally invasive procedures can be realized across a broad spectrum of patients [148].

6.10 Limited access in challenging anatomy

MIS encounters limitations in scenarios where anatomical access becomes challenging. Certain anatomical locations present inherent difficulties for MIS due to their confined spaces or complex structures. Accessing structures in densely vascular areas or regions with intricate anatomical features can be particularly demanding. For example, procedures involving the pelvis, where vital structures such as blood vessels, nerves, and pelvic organs are closely situated, may pose challenges in achieving optimal access and visualization [149]. The limited range of motion and reduced maneuverability of instruments in MIS can become pronounced in such anatomical contexts, potentially compromising the surgeon's ability to navigate and manipulate tissues with precision. In cases of challenging anatomy, the limitations in access during MIS may impact the surgeon's capacity to perform complex procedures. Regions with intricate anatomical structures, such as the head and neck or certain areas within the abdominal cavity, require meticulous and precise maneuvers. The confined spaces in these anatomical locations may limit the range of motion of laparoscopic instruments or robotic arms, making it challenging to achieve the necessary degree of dexterity [150]. Surgeons must carefully assess the specific anatomical challenges posed by each case and weigh the benefits of MIS against the potential limitations. In instances where access proves to be a limiting factor, open surgical approaches may provide the necessary direct access and visibility for optimal intervention. Advancements in surgical technologies and techniques aim to address the challenges associated with limited access in challenging anatomy. The development of more flexible and articulating instruments, as well as innovations in imaging technologies, contributes to overcoming some of the constraints imposed by anatomical complexities. However, the decision to pursue MIS in challenging anatomical locations remains a nuanced one, requiring a thorough understanding of the specific anatomical nuances and potential trade-offs between the benefits of minimally invasive approaches and the need for optimal access and maneuverability [151].

6.11 Prolonged recovery times

Although MIS is frequently associated with quicker recovery, some cases contradict this trend. Complications such as undetected internal bleeding, infections, or delayed wound healing can prolong recovery. These issues may arise because the smaller incisions in MIS make it harder to detect and address such complications early. Studies have shown that for certain complex procedures, traditional open surgeries may offer more predictable recovery trajectories [100].

6.12 Longer operative times

MIS, particularly robotic-assisted surgeries, often requires extended operative times due to the complexity of the setup, equipment handling, and surgeon familiarity. The learning curve for MIS is steep, and during the initial phase, this can lead to increased operative durations and potentially higher complication rates [101].

6.13 Risks of complications

While the incidence of bleeding, infection, and organ damage is generally lower in MIS than in open surgeries, these risks are not negligible. For example, the lack of tactile feedback during MIS can increase the likelihood of inadvertent damage to adjacent structures. Additionally, managing complications in MIS can be more challenging due to the confined visual field and limited access [102].

6.14 Cost and accessibility

The financial burden associated with MIS remains a significant barrier, particularly in underfunded or rural healthcare settings. Robotic-assisted systems, while offering enhanced precision, are prohibitively expensive for many institutions. The costs extend beyond the initial purchase to include maintenance, upgrades, and specialized training for surgeons and staff. This has created disparities in access, with many patients in remote areas unable to benefit from MIS due to the lack of infrastructure and expertise [103].

MIS offers several advantages, such as less trauma, quicker recovery, and better cosmetic results. However, it is also important to consider the downsides and challenges of these techniques. In some cases, MIS can lead to longer recovery times compared to traditional open surgeries. For instance, while laparoscopic procedures usually reduce pain after surgery, some patients might face delayed recovery due to complications like internal bleeding or infections, which are harder to detect because the surgery is less invasive. In such cases, the benefit of smaller incisions may be outweighed by the difficulty in closely monitoring the surgical site afterward [100]. Another major challenge is the **high cost** of MIS, particularly when robotic-assisted systems are used. These systems require significant investment in equipment, ongoing maintenance, and specialized training for surgeons and staff. The high upfront and operational costs make it hard for many healthcare centers, especially those in rural or underfunded areas, to adopt these technologies. For example, robotic-assisted surgery is often too expensive for hospitals in rural areas, worsening the healthcare access gap between urban and rural populations [101]. Additionally, there are **risks of injury to nearby organs** during MIS because surgeons do not get the tactile feedback they do in open surgeries. Instead of feeling the tissues, MIS relies on visual feedback from cameras, which may not always be precise enough. This can increase the risk of accidentally damaging nearby structures, such as blood vessels or nerves, especially during complex procedures like gallbladder or prostate surgery. These issues can lead to complications such as bleeding, infections, or damage to organs, which may require a shift to traditional open surgery for better control [80–85].

Furthermore, hospitals in remote areas face additional **challenges in adopting MIS** due to a lack of advanced technology and the high level of expertise needed. Many hospitals in rural or underdeveloped regions cannot afford the specialized equipment or training required for MIS. Maintaining this equipment and keeping highly trained surgeons is also difficult, especially since robotic systems need regular maintenance and skilled operators, which may not be feasible in low-resource settings. This creates a significant barrier to widespread adoption of MIS in these areas [111]. To overcome these issues, several **solutions** are being explored. Efforts are being made to create **more affordable MIS technologies**, so the benefits of these advanced surgeries can be more accessible. In addition, remote training programs and **simulation-based education** are helping to increase the number of skilled surgeons, even in under-resourced areas. Some healthcare systems are also looking into **mobile surgical units** equipped with MIS technology that can be used in remote locations, helping to make these advanced surgeries more widely available [112].

7 Gaps in the literature

While MIS has made significant advancements in recent years, several gaps in the current literature remain, highlighting areas where further research is needed. One of the most prominent challenges is the high cost associated with robotic-assisted surgery and the lack of access to advanced MIS technologies, particularly in remote or under-resourced regions. This limitation underscores the need for more cost-effective solutions and technologies that can be adapted for wider deployment, ensuring equitable access to MIS across different healthcare settings [35–37]. Another critical area that requires further exploration is the lack of tactile feedback in MIS procedures. Unlike traditional open surgery, where surgeons rely heavily on tactile sensations to guide their actions, MIS largely depends on visual information provided by cameras and robotic systems. The absence of this tactile feedback can complicate delicate procedures, particularly those involving intricate anatomical structures. Future research should focus on developing advanced haptic feedback systems that could simulate the sense of touch during MIS, potentially improving the precision and safety of these procedures. Surgeon training is another domain that demands continuous improvement [112–115]. The learning curve for mastering MIS techniques, particularly robotic-assisted surgery, remains steep. While current training programs are effective, there is a need for more sophisticated simulation-based education, possibly incorporating VR and AR technologies. Such innovations could provide more realistic and immersive training environments, helping surgeons to develop the necessary skills more efficiently and safely. Additionally, there is a shortage of comprehensive, long-term studies on the outcomes of MIS across various surgical disciplines. While the short-term benefits of MIS, such as reduced trauma and quicker recovery times, are well-documented, more research is needed to evaluate the long-term efficacy and safety of these procedures, particularly in specialized fields such as neurosurgery and cardiothoracic surgery [152].

Compared to open surgery, MIS offers patients better cosmetic results, a shorter recovery time, and less trauma. MIS has completely changed the medical landscape. Nevertheless, in spite of these benefits, MIS still has unsolved issues that restrict its usefulness and increase the room for further innovation. The absence of tactile input in robotic-assisted surgery is one of the biggest drawbacks. In contrast to open surgery, where surgeons use their tactile sense to assess tissue tension, texture, and resilience, MIS – especially robotic-assisted MIS – removes this vital sense, making it more difficult to manipulate tissue accurately and raising the risk of inadvertent damage to nearby structures. For instance, the lack of tactile input during robotic-assisted prostatectomy makes it more difficult for the surgeon to accurately feel the borders between the prostate and nearby nerves [110–115]. This restriction raises the possibility of unintentionally harming these vital structures, which could result in erectile dysfunction or urine incontinence as postoperative consequences. Similar to this, while performing a laparoscopic myomectomy to remove uterine fibroids, the surgeon must only use visual cues to differentiate the fibroid tissue from the surrounding uterine tissue. This can be difficult because the two types of tissue may appear similar on imaging. This absence of haptic perception can make precise excision more difficult, raising the possibility of insufficient removal or undue harm to healthy tissue [110,111].

Continued research into creating sophisticated haptic feedback methods is crucial for overcoming these constraints. For example, by incorporating pressure-sensitive sensors into robotic tools, tactile data might be transmitted in real time, enabling surgeons to remotely “feel” the properties of tissue. This could potentially restore a crucial layer of sensory input in robotic-assisted MIS by simulating the feel of tactile feedback. Additionally, a possible way to make up for this shortcoming is using AI [120–125]. Real-time tissue interactions might be analyzed by an AI system included into robotic tools, which could then adaptively modify tool reaction according to tissue type or give the surgeon visual and aural feedback. Even in the absence of direct touch, a system trained on large datasets from comparable surgeries, for instance, may warn the surgeon if an excessive amount of force is being applied, preventing tissue damage. Filling in these gaps highlights the need for additional empirical study on these AI-enhanced and haptic technologies. Research aimed at evaluating and confirming these developments in clinical settings may open the door to MIS that is safer and more efficient. By expanding the applicability of MIS and improving its precision, this line of study makes these cutting-edge surgical techniques safer for a variety of patient demographics and complex operations [140–145].

MIS is not suitable for all patients. Obesity, anatomical variations, and pre-existing comorbidities can complicate procedures and increase the risk of complications. Furthermore, the cost of MIS technology and the need for highly trained personnel make it less accessible in remote or underfunded areas. Facilities in these regions often lack the resources to acquire and maintain advanced MIS equipment, further exacerbating healthcare disparities [125–127]. The transition from traditional open techniques to MIS is accompanied by a steep learning curve. Surgeons must develop new skills, such as interpreting 2D imaging and operating without tactile feedback. This process requires extensive training and simulation, which not all institutions can afford. During the early stages of adoption, the increased risk of complications and extended operative times are well-documented concerns [130–132].

8 Future directions

MIS has witnessed remarkable advancements over the years, and its future directions hold tremendous promise for further innovations, technological integrations, and improved patient outcomes. As technology continues to evolve, several key areas are likely to shape the future of MIS [153].

8.1 Advanced imaging and visualization

The integration of advanced imaging technologies is poised to revolutionize the field of MIS. High-resolution imaging modalities, such as AR and VR, have the potential to enhance the surgeon's visualization capabilities. These technologies can provide 3D views of the operative field, allowing for more precise navigation and manipulation of anatomical structures. AR and VR may also facilitate better preoperative planning, enabling surgeons to simulate procedures and anticipate challenges [153].

8.2 Robotics and AI

The role of robotics in MIS is expected to expand significantly. Robotic-assisted surgery has already demonstrated enhanced precision and dexterity, and future developments are likely to focus on improving robotic systems' autonomy and adaptability. Integrating AI into robotic platforms can enable real-time decision support, allowing robots to analyze data, anticipate potential issues, and even learn from the surgeon's actions. AI-driven assistance could enhance the safety and efficiency of MIS procedures [154].

8.3 Telemedicine and remote surgery

The convergence of MIS with telemedicine technologies opens the door to remote surgery. Surgeons may be able to perform procedures on patients located in different geographical areas, especially in regions with limited access to specialized healthcare. Remote surgery holds the potential to democratize healthcare, providing expert surgical care to underserved populations. However, ensuring the security and reliability of telemedicine platforms is a critical consideration for widespread adoption [155].

8.4 Nanotechnology and microbots

Advancements in nanotechnology are paving the way for the development of microbots – tiny robotic devices that can navigate within the body for diagnostic and therapeutic purposes. In MIS, microbots could be designed to deliver targeted treatments, perform precise interventions, or provide real-time diagnostics at the cellular or molecular level. This opens new possibilities for minimally invasive procedures with minimal impact on surrounding tissues [156].

8.5 Smart instruments and instrumentation

The instruments used in MIS are likely to become smarter and more adaptable. Integration of sensors into surgical instruments can provide real-time feedback on factors like tissue characteristics, temperature, and blood flow. Smart instruments may enable surgeons to make more informed decisions during procedures, enhancing the overall safety and efficacy of MIS [157].

8.6 Enhanced ergonomics

Surgeon ergonomics is a critical factor in the success of MIS procedures. Future developments may focus on creating more ergonomic platforms and instruments, reducing the physical strain on surgeons during long and complex surgeries. This includes the design of robotic consoles and interfaces that promote comfort and minimize fatigue, ultimately contributing to better outcomes [158].

8.7 Innovations in energy sources

Advances in energy sources used in MIS are anticipated to improve the efficiency and safety of procedures. The development of more precise energy devices, such as advanced electrosurgical and ultrasonic instruments, can contribute to reduce thermal damage to surrounding tissues and enhance the overall precision of energy-based interventions [159].

8.8 Integration of augmented intelligence

The synergy between human expertise and AI, termed augmented intelligence, is poised to play a significant role in MIS. AI algorithms can analyze vast datasets, providing insights into patient-specific factors, predicting outcomes, and assisting in personalized treatment plans. This integration has the potential to improve preoperative planning, optimize intraoperative decision-making, and enhance postoperative care [160].

8.9 Patient-centric innovations

Future directions in MIS will likely prioritize patient-centric innovations. This includes the development of less invasive techniques, reduced recovery times, and further improvements in cosmetic outcomes. Tailoring procedures to individual patient characteristics, such as anatomy and genetics, may become more common, leading to personalized and optimized treatment approaches [161].

8.10 Education and training

The future of MIS will require a robust focus on education and training. Simulated environments, VR training modules, and immersive learning experiences will become integral components of surgical education. Surgeons will need continuous training to stay abreast of evolving technologies and techniques, ensuring proficiency in the dynamic landscape of MIS [162].

9 Challenges and considerations

MIS has transformed the field of surgery, offering numerous benefits; however, it is not without its challenges and considerations. Technical hurdles present a formidable obstacle, as the adoption of MIS techniques requires surgeons to navigate a steep learning curve. Mastery of new technologies, such as laparoscopy or robotic-assisted surgery, demands dedicated training, and staying abreast of evolving instrumentation adds to the complexity. Patient selection becomes a critical factor, with factors like obesity and anatomical variations posing challenges to the feasibility of MIS procedures. Ethical and regulatory considerations add another layer of complexity [163]. Informed consent becomes paramount, necessitating clear communication about the learning curve and the potential for conversions to open procedures. The integration of technology raises concerns about data security and privacy, requiring stringent measures to protect patient information. Regulatory approval and standardization are essential to ensure the safety and efficacy of MIS devices and techniques, adding a layer of scrutiny to the adoption of new technologies. Economic factors play a role in the widespread adoption of MIS [164]. The upfront costs of acquiring and maintaining advanced MIS technologies, including robotic systems, can strain healthcare budgets. Training costs for surgical teams to become proficient in MIS techniques add to the economic considerations. Access and disparities further complicate the landscape, with geographic and socioeconomic factors influencing who has access to advanced MIS procedures. Bridging these disparities requires strategic efforts, including telemedicine initiatives and educational programs in underserved regions. In navigating these challenges and considerations, a comprehensive and multidimensional approach is crucial to ensuring the ethical, equitable, and successful integration of MIS into surgical practices [165].

10 Conclusion

The management of complications and limitations in MIS involves a multifaceted approach that encompasses both preoperative planning and intraoperative vigilance. Surgeons must be well-versed in recognizing and addressing potential challenges associated with MIS, such as bleeding, organ damage, and technical difficulties. Thorough preoperative assessments help identify patient-specific factors that may contribute to complications, allowing for careful patient selection and personalized surgical plans. Intraoperatively, continuous monitoring of vital signs and real-time feedback aids in early detection and management of complications. Additionally, maintaining open lines of communication within the surgical team is crucial for prompt decision-making and potential conversion to open procedures if needed. Postoperatively, vigilant monitoring of patients for signs of complications, such as infections or delayed healing, is essential. The development of robust training programs for surgical teams, incorporating simulation and ongoing education, addresses the learning curve associated with MIS and enhances proficiency. Embracing technological advances, such as augmented intelligence and improved instrumentation, contributes to minimizing limitations. Overall, a comprehensive and adaptive approach to the management of complications and limitations in MIS ensures patient safety, optimal outcomes, and continued progress in the field.

Acknowledgements: We are sincerely grateful to the authors whose unwavering review articles and invaluable contributions played a pivotal role in successfully completing this review article.

Funding information: Authors state no funding involved.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and consented to its submission to the journal, reviewed all the results and approved the final version of the manuscript. Z.Q. and M.M. were involved in study design, data interpretation, drafting of the article, and critical revision of the manuscript. M.A.D. and A.Q. handled data collection and analysis.

Conflict of interest: Authors state no conflict of interest.

Informed consent: Not applicable.

Ethical approval: Not applicable.

Data availability statement: Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

References

[1] Robinson T, Stiegmann G. Minimally invasive surgery. J Endosc. 2004;36(1):48–51.
[2] Palep JH. Robotic-assisted minimally invasive surgery. J Minim Access Surg. 2009;5(1):1–7.
[3] Fuchs K. Minimally invasive surgery. J Endosc. 2002;34(2):154–9.
[4] Jaffray B. Minimally invasive surgery. Ann R Coll Surg Engl. 2005;90(5):537–42.
[5] Darzi A, Munz Y. The impact of minimally invasive surgical techniques. Annu Rev Med. 2004;55:223–37.
[6] Keller DS, Tahilramani RN, Flores-Gonzalez JR, Mahmood A, Haas EM. Transanal minimally invasive surgery: Review of indications and outcomes from 75 consecutive patients. J Am Coll Surg. 2016;222(5):814–22.
[7] Omisore OM, Han S, Xiong J, Li H, Li Z, Wang L. A review on flexible robotic systems for minimally invasive surgery. IEEE Trans Syst Man Cybern Syst. 2020;52(1):631–44.
[8] Yoon JW, Wang MY. The evolution of minimally invasive spine surgery: JNSPG 75th Anniversary Invited Review Article. J Neurosurg Spine. 2019;30(2):149–58.
[9] Del Vecchio JJ, Ghioldi ME. Evolution of minimally invasive surgery in hallux valgus. Foot Ankle Clin. 2020;25(1):79–95.
[10] Momin AA, Steinmetz MP. Evolution of minimally invasive lumbar spine surgery. World Neurosurg. 2020;140:622–6.
[11] Porter J, Blau E, Gharagozloo F, Martino M, Cerfolio R, Duvvuri U, et al. Society of robotic surgery review: Recommendations regarding the risk of COVID-19 transmission during minimally invasive surgery. BJU Int. 2020;126(2):225–34.
[12] Hanly EJ, Talamini MA. Robotic surgery: Past, present, and future. Surg Endosc. 2004;18(5):845–53.
[13] Hegarty NJ, Desai MM. Laparoendoscopic single-site surgery (LESS) in urology: Initial experience. J Endourol. 2008;22(4):783–7.
[14] Bhandarkar DS, Mittal G, Shah RS, Katara AN, Udwadia TE. Robotic surgery: Past, present, and future. J Minim Access Surg. 2010;6(1):1–10.
[15] Lorenz K, Backert S, Schmidbauer S, Klink C, Schemmer P. Current trends in minimally invasive surgery: Robotic-assisted surgery and endoscopic techniques. Zentralbl Chir. 2017;142(6):604–13.
[16] Barbaros U, Dinççağ A. Minimally invasive surgery: Laparoscopic and robotic surgery. JSLS. 2010;14(3):407–11.
[17] Baik SH, Lee WJ, Rha KH, Lee SH. Robotic total mesorectal excision for rectal cancer: A preliminary experience. Surg Endosc. 2008;22(3):2557–61.
[18] Hagen ME, Meehan JJ, Inan I, Morel P. Minimally invasive surgery: How much more? Dig Surg. 2011;28(1):53–8.
[19] Ballantyne GH. Robotic surgery, telerobotic surgery, telepresence, and telementoring. Surg Endosc. 2002;16(10):1389–402.
[20] Herrell SD, Smith Jr JA. Robotic-assisted laparoscopic prostatectomy: What is the learning curve? Urology. 2005;66(5 Suppl):105–7.
[21] Hemal AK, Menon M. Robotics in urology. Curr Opin Urol. 2004;14(2):89–93.
[22] Cuschieri A. Evolution of minimal access surgery and its future. World J Surg. 1995;19(1):9–15.
[23] Rassweiler JJ, Teber D, Ketan M, Rassweiler MC. Robotics and telesurgery: Future trends. Minerva Urol Nefrol. 2006;58(2):127–40.
[24] Giulianotti PC, Coratti A, Angelini M, Sbrana F, Cecconi S, Bianchi PP, et al. Robotics in general surgery: Personal experience in a large community hospital. Arch Surg. 2003;138(7):777–84.
[25] Lanfranco AR, Castellanos AE, Desai JP, Meyers WC. Robotic surgery: A current perspective. Ann Surg. 2004;239(1):14–21.
[26] Dulucq JL, Wintringer P, Mahajna A. Robotic-assisted laparoscopic colorectal surgery. Surg Endosc. 2006;20(10):1521–5.
[27] Melvin WS, Needleman BJ, Krause KR, Wolf RK, Michler RE, Kohmoto T, et al. Computer-enhanced robotic telesurgery. Minim Invasive Ther Allied Technol. 2000;9(5):317–23.
[28] Parini S, Carlucci M, DeLorenzo F, Veronesi P. Minimally invasive surgery and cancer: A step forward. J Cancer Res Ther. 2020;16(Suppl):112–7.
[29] Wang Z, Wang P, Li H, Zeng H, Shi Y, Chen Z, et al. Robotic-assisted laparoscopic pancreaticoduodenectomy versus open pancreaticoduodenectomy: A meta-analysis and systematic review. J Gastrointest Surg. 2018;22(10):1837–47.
[30] Cunningham JD, Alemozaffar M, Crea D, Talamini M, Horgan S. Robotic surgery in general surgical practice: A single institution's experience of 433 cases. Surg Endosc. 2011;25(12):3858–62.

[31] Moore MD, Bennett N. Telerobotic surgery: An update. Curr Urol Rep. 2008;9(2):126–9.

[32] Buchs NC, Pugin F, Morel P. Robotic general surgery: Current practice, evidence, and perspective. Minerva Chir. 2011;66(1):15–33.

[33] Sbrana F, Linares A, Bianchi PP, Sensi B, Pesi B, Roviello F. Robotic gastric surgery. Surg Oncol Clin N Am. 2020;29(4):683–91.

[34] Boggi U, Vistoli F, Signori S, Perrone VG, Coppelli A, Marchetti P, et al. Robotic pancreatic surgery: An appraisal of its current value and future perspectives. Pancreatology. 2011;11(4):332–8.

[35] Cerfolio RJ, Bryant AS. The role of robotic-assisted thoracic surgery in the modern management of lung cancer. Clin Lung Cancer. 2011;12(3):165–70.

[36] Huang JJ, Kang CH, Cheng YT, Chou TY, Huang MS, Liu HP. Robotic-assisted thoracic surgery. Chang Gung Med J. 2010;33(3):248–54.

[37] Morgan JA, Lombardi JV, Cronin B, Brooks AG, Argenziano M. Robotic surgery in cardiothoracic surgery. J Cardiovasc Transl Res. 2008;1(3):290–304.

[38] Wilson TG. Laparoscopic radical prostatectomy. Curr Opin Urol. 2001;11(3):217–22.

[39] Smith AL, Rodriguez LV, Raz S. The role of robotic-assisted laparoscopic surgery in female urology. Curr Opin Urol. 2006;16(1):49–53.

[40] Hung AJ, Teh BS. Robotic radiation surgery. Urol Oncol. 2007;25(6):531–5.

[41] Chandra A, Levchenko A. Nanomedicine for minimally invasive surgery. Wiley Interdiscip Rev Nanomed Nanobiotechnol. 2017;9(5):223–8.

[42] Forcione DG. Endoscopic resection of large colorectal polyps. Gastroenterol Hepatol (N Y). 2007;3(9):694–9.

[43] Primrose JN. Minimally invasive liver surgery. Ann R Coll Surg Engl. 2011;93(3):184–9.

[44] Asbun HJ, Stauffer JA. Laparoscopic surgery of the pancreas. J Hepatobil Pancr Sci. 2011;18(5):520–5.

[45] Giulianotti PC, Buchs NC, Addeo P, Bianco FM. Robot-assisted surgery: State of the art and future perspectives. Minerva Chir. 2009;64(3):237–49.

[46] Burgess A, Ramsey-Stewart G. Challenges of laparoscopy in remote locations: Performing minimally invasive surgery in the Antarctic. ANZ J Surg. 2021;91(6):1089–93.

[47] Chang M, Shang Z, Huang W, Xue L. Advances and challenges in telemedicine and robotic surgery: A comprehensive review. Telemed J E Health. 2020;26(4):453–63.

[48] Finley DS, Aron M, Eldefrawy A, Canes D, Desai M, Gill IS. Robotic adrenalectomy: Indications and technique. Urol Clin North Am. 2008;35(2):297–308.

[49] Yoo Y, Jeong S, Choi Y, Jang Y. A review of autonomous surgical robots for laparoscopic surgery. IEEE Trans Biomed Eng. 2018;65(11):2349–61.

[50] Rajmohan S, Rajasekaran RB, Rebekah G, Mohankumar S. Minimally invasive surgery for pelvic fractures. J Clin Orthop Trauma. 2020;11(Suppl 1):7–11.

[51] Ahmed K, Khan MS, Vats A, Nagpal K, Priest O, Patel V, et al. Current status of robotic-assisted pelvic surgery and future developments. Int J Surg. 2009;7(5):431–40.

[52] Gavriilidis P, Roberts KJ, Sutcliffe RP, Hodson J, Marudanayagam R, Isaac J, et al. Robotic vs laparoscopic distal pancreatectomy: A systematic review and meta-analysis. Eur J Surg Oncol. 2017;43(11):1806–17.

[53] Chen L, Li K, Su X, Liang Y, Zhang X, Cai L, et al. Comparison of perioperative outcomes between laparoscopic and robotic hepatectomy: A meta-analysis of studies from 2011 to 2020. Cancer Manag Res. 2021;13:197–207.

[54] Allaf ME, Bhayani SB, Shrivastava A, Kavoussi LR. Complications of robotic-assisted laparoscopic surgery. J Endourol. 2004;18(5):572–5.

[55] Aron M, Haber GP, Gill IS. Laparoscopic radical prostatectomy versus robotic-assisted radical prostatectomy: The debate is still on. J Endourol. 2008;22(4):819–24.

[56] Van Velthoven RF, Hoffmann P, Borghesi M. Robotic-assisted laparoscopic radical prostatectomy: Is it a new gold standard? J Endourol. 2006;20(6):485–9.

[57] Hamilton BH, Whiting R, Clemente L. Cost analysis of robotic-assisted versus traditional laparoscopic surgery for colorectal cancer: A multi-institutional review. J Surg Res. 2018;226:95–103.

[58] Yamashita K, Shimizu K, Hamano K. Current status and future perspectives of robotic surgery in general thoracic surgery. Ann Thorac Cardiovasc Surg. 2020;26(2):65–72.

[59] Schauer PR, Ikramuddin S, Gourash W, Ramanathan R, Luketich J. Outcomes after laparoscopic Roux-en-Y gastric bypass for morbid obesity. Ann Surg. 2000;232(4):515–29.

[60] Kendrick ML, Cusati D. Total laparoscopic pancreaticoduodenectomy: Feasibility and outcomes in an early experience. Arch Surg. 2010;145(1):19–23.

[61] Pasic RP, Rafiq A. Robotic-assisted laparoscopic hysterectomy. Surg Technol Int. 2008;17:203–8.

[62] Park A, Lee G, Seagull FJ, Meenaghan N, Dexter D. Patients benefit while surgeons suffer: An impending epidemic. J Am Coll Surg. 2010;210(3):306–13.

[63] Li K, Sun Y, Hu Y, Zhao W, Cheng N. Comparison of robotic-assisted and laparoscopic surgery in the treatment of colorectal cancer: A meta-analysis. Eur J Surg Oncol. 2020;46(5):848–56.

[64] Powell AG, Smith BJ, Majmudar N, Williams NR, Paterson-Brown S. Robotic versus laparoscopic colorectal resection: A cost-effectiveness study. Colorectal Dis. 2012;14(8):1124–31.

[65] Gumbs AA, Gayet M, Gayet B. Current status of robotic pancreatic surgery. J Hepatobil Pancr Sci. 2011;18(6):749–56.

[66] Vigneswaran Y, Prachand VN, Alverdy JC. Minimally invasive surgery: Past, present, and future. Surg Clin North Am. 2016;96(3):491–512.

[67] Horgan S, Vanuno D. Robots in laparoscopic surgery. J Laparoendosc Adv Surg Tech A. 2001;11(6):415–9.

[68] Meyer L, Papanikolaou IG, Skorek M, Mallia A, Fountas K. Surgical technologies in minimally invasive spine surgery. Neurosurg Rev. 2020;43(3):767–80.

[69] Berguer R. Surgical technology and the ergonomics of laparoscopic instruments. Surg Endosc. 1998;12(5):458–62.

[70] Prasad A, Wallace DJ, Shin S, Goyeneche AA, Isakov R, Petrusa E, et al. Ergonomics in the operating room. J Am Coll Surg. 2017;224(2):194–202.

[71] Earle DB, Roth JS. Laparoscopic versus open ventral hernia repair: Cost analysis. Hernia. 2012;16(2):193–9.

[72] Tewari AK, Peabody JO, Fisher H, Menon M, Vallancien G. Critical evaluation of the learning curve for laparoscopic and robotic-assisted radical prostatectomy. J Urol. 2003;170(1):238–44.

[73] Ström P, Nyman CR, Magnusson B, Norlén BJ, Lantz B, Wretenberg P, et al. Learning curve and preliminary results of robot-assisted laparoscopic radical cystectomy with intracorporeal urinary diversion. BJU Int. 2011;108(5):825–32.

[74] Ballantyne GH. Robotic surgery, telerobotic surgery, telepresence, and telementoring: Review of early clinical results. Surg Endosc. 2002;16(10):1389–402.

[75] Guillonneau B, Vallancien G. Laparoscopic radical prostatectomy: The Montsouris experience. J Urol. 2000;163(2):418–22.

[76] DiGiorgi PL, Gonzalez-Stawinski GV, Rice TW, Stewart RW. Robotic-assisted esophagectomy for esophageal cancer. Surg Endosc. 2006;20(11):1876–81.

[77] Simorov A, Ranade A, Parcells JP, Hill C, Shaligram A, Shostrom V, et al. Emergence of robotic-assisted surgery in colorectal procedures. Surg Endosc. 2013;27(8):2972–80.

[78] Cadier B, Tyson-Capper A, Caddick M. Minimally invasive pancreatic surgery: Current status and future directions. Surg Oncol. 2020;35:33–40.

[79] Deng Y, Su Q, Tang W, Zhao J, Li Y. Robotic surgery for rectal cancer: A systematic review and meta-analysis based on randomized controlled trials. Surg Endosc. 2017;31(11):4621–30.

[80] Ielpo B, Duran H, Diaz E, Fabra I, Malave L, Caruso R, et al. Robotic versus laparoscopic rectal resection: Is there any real difference? A comparative single center study. Int J Med Robot. 2014;10(4):366–70.

[81] Mirnezami R, Mirnezami AH, Chandrakumaran K, Sasapu K, Sagar P, Finan P. Increased local recurrence and reduced survival from minimally invasive colorectal cancer surgery: A systematic review and meta-analysis. Ann Surg. 2010;252(1):45–56.

[82] Pedrazzani C, Cassini D, Ruzzenente A, Conci S, Allegrini V, Campagnaro T, et al. Minimally invasive surgery in gastric cancer treatment: Current status and future perspectives. World J Gastroenterol. 2016;22(2):571–89.

[83] Waters JA, Al-Haddad M, El Chafic AH, Rosemurgy AS. Robotic-assisted pancreatic surgery: Ready for prime time? Minerva Chir. 2012;67(1):45–57.

[84] Willems LH, Konsten JL, De Hingh IH. Robotic versus conventional laparoscopic pancreatoduodenectomy: A systematic review. Eur J Surg Oncol. 2020;46(4):403–7.

[85] Piozzi GN, Orsenigo E, Sicoli F, Finazzi R, Bona S, Rosati R. Minimally invasive techniques for colorectal cancer: A literature review. Minerva Chir. 2018;73(3):338–50.

[86] Kim JY, Lee SE, Kim JY, Baek SE, Kim HJ. Robotic surgery for gastric cancer: Technical overview and comparative outcomes. J Gastric Cancer. 2012;12(3):129–38.

[87] Pakula AM, Wasielewski NJ, Polk Jr HC. Minimally invasive surgery for the acute abdomen. J Trauma Acute Care Surg. 2015;79(5):823–8.

[88] Hanly EJ, Talamini MA. Robotic surgery in oncology. Cancer J. 2008;14(4):215–8.

[89] Carlucci JR, Cain JS, Randazzo BP, Rudari DM. Surgical management of gallbladder cancer: Minimally invasive approaches. Surg Clin North Am. 2019;99(2):343–59.

[90] Howard R, Chao GF, Yang J, Thumma J, Chhabra K, Arterburn DE, et al. Comparative safety of sleeve gastrectomy and gastric bypass up to 5 years after surgery in patients with severe obesity. JAMA Surg. 2021 Dec;156(12):1160–9.

[91] Seo HJ, Lee NR, Son SK, Kim DK, Rha KH, Lee SH. Comparison of robot-assisted radical prostatectomy and open radical prostatectomy outcomes: a systematic review and meta-analysis. Yonsei Med J. 2016 Sep;57(5):1165–77.

[92] Rassweiler JJ, Autorino R, Klein J, Mottrie A, Goezen AS, Stolzenburg JU, et al. Future of robotic surgery in urology. BJU Int. 2017 Dec;120(6):822–41.

[93] Rabinovich A. Minimally invasive surgery for endometrial cancer. Curr Opin Obstet Gynecol. 2015 Aug;27(4):302–7.

[94] Sutherland J, Aboumarzouk O, Sweeney M. Robotic-assisted laparoscopic surgery for the management of esophageal cancer: A systematic review and meta-analysis. Surg Oncol. 2019;29:13–9.

[95] Zhou JY, Xin C, Mou YP, Xu XW, Zhang MZ, Zhou YC, et al. Robotic versus laparoscopic distal pancreatectomy: a meta-analysis of short-term outcomes. PLoS One. 2016 Mar;11(3):e0151189.

[96] Momin AA, Steinmetz MP. Evolution of minimally invasive lumbar spine surgery. World Neurosurg. 2020 Aug;140:622–6. doi: 10.1016/j.wneu.2020.05.071. Epub 2020 May 17. PMID: 32434014.

[97] Targarona EM, Balagué C, Martínez C, Pernas JC, Trias M. Single-incision laparoscopic surgery (SILS) in general surgery: a current update. Langenbecks Arch Surg. 2021 Dec;406(8):2677–89.

[98] Lacy AM, García-Valdecasas JC, Delgado S, Castells A, Taurá P, Piqué JM, et al. Laparoscopy-assisted colectomy versus open colectomy for treatment of non-metastatic colon cancer: a randomised trial. Lancet. 2002 Jun;359(9325):2224–9.

[99] Teoh JY, Yip SK. Robotic surgery: The evolving role of robotics in urology. Urology. 2016;94:9–15.

[100] Lee SY, Kim SW, Nam BY, Choi SJ, Park YH, Jeong CW. Robot-assisted vs laparoscopic partial nephrectomy for T1 renal tumors: a meta-analysis. Eur J Surg Oncol. 2021 Feb;47(2):307–16.

[101] Moore JA, Koch MO. Robotic-assisted laparoscopic prostatectomy: Where do we go from here? BJU Int. 2015;116(5):674–5.

[102] Barin A, Yildirim G, Ozdemir A. The role of robotic surgery in urology: A review. Int Urol Nephrol. 2018;50(12):2135–41.

[103] Li H, Wei Q, Wang Y, Du F, Zhu J, Feng M, et al. Robotic versus laparoscopic hysterectomy for endometrial cancer: a systematic review and meta-analysis. J Obstet Gynaecol Res. 2021 Apr;47(4):1345–55.

[104] Jung SH, Ha US, Kim ME, Hong SH, Lee JY, Kim SH, et al. Comparison of robotic surgery to laparoscopic and open surgeries in the treatment of rectal cancer: systematic review and meta-analysis. Ann Surg Treat Res. 2017 Jul;93(1):8–16.

[105] Vela C, De La Vega M, Sernam D. Robotic-assisted laparoscopic surgery for kidney tumors: A comprehensive review. Eur Urol Focus. 2020;6(3):526–33.

[106] Yang C, Chen C, Wang X. Robotic-assisted laparoscopic surgery for endometrial cancer: A systematic review. Surg Oncol. 2020;34:76–81.

[107] AlJabri B, Khan MF, Brown B, Agarwal A. Outcomes of robotic vs laparoscopic colorectal surgery: systematic review and meta-analysis. Dis Colon Rectum. 2020 Dec;63(12):1664–72.

[108] Weber S, Gass M, von Flüe M, Hahnloser D. Minimally invasive surgery for rectal cancer: current status and future perspectives. World J Gastroenterol. 2016 May;22(18):5262–75.

[109] Dasari BVM, McKay A, Gardner-Thorpe J, Rees J, Lobo DN. Systematic review and meta-analysis of laparoscopic vs. open distal pancreatectomy for pancreatic cancer. Br J Surg. 2015 Jul;102(8):843–51.

[110] Lee SY, Kim SW, Kim YJ, Choi SJ, Choi JW. Robot-assisted surgery for rectal cancer: comparison of oncological and functional outcomes with laparoscopic surgery. Int J Colorectal Dis. 2017 Dec;32(12):1701–11.

[111] Park IJ, You YN, Skibber JM, Rodriguez-Bigas MA, Eng C. Minimally invasive surgery for colon cancer in elderly patients. Ann Surg. 2017 Feb;265(2):372–8.

[112] Bozkurt T, Braun U, Kunz R, Fiegel H. Minimally invasive vs open surgery for colorectal cancer: a systematic review of meta-analyses. Surg Endosc. 2021 Aug;35(8):4406–19.

[113] Son GM, Yun H, Lee JH, Lee SI, Hur H. Current Status and Future Perspectives of Laparoscopic Surgery for Gastric Cancer. World J Gastroenterol. 2016 Mar 14;22(10):2424–33.

[114] Shida D, Takasu A, Hasegawa H, Tsukamoto S, Kanemitsu Y. Current status and future perspectives of robotic surgery in colorectal cancer. J Anus Rectum Colon. 2019 Apr;3(2):99–107.

[115] Fischer CP, Lidor AO, Steele SR. Evolution of minimally invasive surgery: a review. JAMA Surg. 2019 Jun;154(6):541–8.

[116] Guerrini GP, Lauretta A, Rompianesi G, Tarantino G, De Rosa V, Giovagnoni A, et al. Robotic versus laparoscopic liver resections: A systematic review and meta-analysis. HPB (Oxf). 2021 Jul;23(7):1019–30.

[117] Liu Z, Zhang P, Ma Y, Chen H, Zhou Y, Zhao Q, et al. Laparoscopic versus open total mesorectal excision for middle and low rectal cancer: a systematic review and meta-analysis of randomized controlled trials. J Gastrointest Surg. 2017 Apr;21(4):648–62.

[118] Binder J, Kramer W. Robotically-assisted laparoscopic radical prostatectomy. BJU Int. 2001 May;87(6):408–10.

[119] Baik SH, Kwon HY, Kim YH, Lee YJ, Lee SE, Lee J, et al. Robotic versus laparoscopic low anterior resection of rectal cancer: short-term outcome of a prospective comparative study. Ann Surg Oncol. 2009 Jun;16(6):1480–7.

[120] Yamashita S, Sheth RA, Aloia TA, Chun YS, Vauthey JN, Conrad C. Robotic versus laparoscopic liver resection: What is the best minimally invasive approach? J Hepatol. 2020 Apr;72(4):589–91.

[121] Kudsi OY, McCarty JC, Paluvoi N, DuCoin C, Crespin OM. Robotic versus laparoscopic cholecystectomy: a matched cohort study. Surg Endosc. 2017 Sep;31(9):3878–84.

[122] Hoh BL, Velat GJ, Wilmer EN, McDougall CG, Albuquerque FC. Advances in minimally invasive intracranial surgery. Neurosurgery. 2014 Feb;74(Suppl 1):S1–2.

[123] Lee SY, Kim JH, Lee NR, Kim KH. The role of robotic surgery in esophageal cancer: A comprehensive review. Thorac Cancer. 2022 May;13(9):1253–63.

[124] Sylla P, Rattner DW, Delgado S, Lacy AM. NOTES transanal rectal cancer resection using transanal endoscopic microsurgery and laparoscopic assistance. Surg Endosc. 2010 May;24(5):1205–10.

[125] Cheung HY, Lee F, Leung AC, Chung MS, Yip SK, Hou SM, et al. Robot-assisted versus conventional laparoscopic total mesorectal excision for mid and low rectal cancer: a prospective randomised trial. Surg Endosc. 2009 Dec;23(12):2798–804.

[126] Khatri VP, Stukenborg GJ. Current state of minimally invasive pancreatic surgery: A review of systematic reviews. J Surg Oncol. 2019 Dec;120(8):1457–65.

[127] Porpiglia F, Fiori C, Bertolo R, Manfredi M, De Cillis S, Angheben A, et al. Five-year outcomes for a prospective randomised controlled trial comparing laparoscopic and open partial nephrectomy. Eur Urol. 2017 May;71(5):908–18.

[128] Kim J, Shin JH, Kim JY. A review of robotic distal pancreatectomy: Updates on surgical techniques and outcomes. Int J Med Robot. 2020 Dec;16(6):e2158.

[129] Adamina M, Kehlet H, Tomlinson GA, Senagore AJ, Delaney CP. Enhanced recovery pathways optimize health outcomes and resource utilization: a meta-analysis of randomized controlled trials in colorectal surgery. Surgery. 2011 Jun;149(6):830–40.

[130] Solaini L, Perna M, Mulatti GC, Graziosi L, Vasquez G, Percalli L. Robotic vs laparoscopic pancreaticoduodenectomy: An up-to-date meta-analysis. World J Gastrointest Oncol. 2020 Jun;12(6):625–42.

[131] Ceccarelli G, Patriti A, Bartoli A, Biancafarina A, Bellochi R, Spaziani A, et al. Robotic and laparoscopic surgery for rectal cancer: a prospective comparative study. Surg Endosc. 2012 May;26(5):1177–85.

[132] Kasherman L, Munz Y. The role of robotics in minimally invasive surgery. Surg Endosc. 2019;33(1):51–61.

[133] Morelli L, Palmeri M, Furbetta N, Gianardi D, Guadagni S, Di Franco G, et al. Robot-assisted approach for gallbladder cancer: a single institution experience and systematic review. Int J Med Robot. 2016 Sep;12(3):482–8.

[134] Costantino FA, Diana M, Wall J, Mutter D, Marescaux J. Minimal invasive surgery for liver tumors. World J Hepatol. 2015 Apr;7(8):1118–31.

[135] Hasegawa H, Shida D, Miyake H, Hamaguchi T, Kanemitsu Y. Robotic colorectal surgery for elderly patients: Current evidence and future perspective. J Anus Rectum Colon. 2020 Jul;4(3):85–93.

[136] Velanovich V, Morton JM. Advantages and disadvantages of minimally invasive surgery. Surg Clin North Am. 2020 Jun;100(3):561–76.

[137] Lee SW, Leu SY, Son T, Hyung WJ. Minimally invasive surgery for gastric cancer. J Surg Oncol. 2017 Jan;115(5):634–46.

[138] Guerron AD, Ali MR, Arnell TD, Awaiz A, Parra-Davila E. Current role of robotic surgery for rectal cancer. Surg Oncol Clin N Am. 2020 Apr;29(2):259–74.

[139] Chen K, Pan Y, Cai JQ, Xu XW, Wu D. Totally laparoscopic versus open total gastrectomy for gastric cancer: a case-matched study about short-term outcomes. Med (Baltim). 2017 May;96(21):e6872.

[140] Cho MS, Baek SJ, Hur H, Min BS, Baik SH, Kim NK. The impact of robotic surgery for mid and low rectal cancer: a propensity score-matched analysis of oncological outcomes and morbidity between robotic and laparoscopic surgery. Dis Colon Rectum. 2015 Feb;58(2):193–201.

[141] Jayne DG, Pigazzi A, Marshall H, Croft J, Corrigan N, Copeland J, et al. Effect of robotic-assisted vs conventional laparoscopic surgery on risk of conversion to open laparotomy among patients undergoing resection for rectal cancer: the ROLARR randomized clinical trial. JAMA. 2017 Oct 24;318(16):1569–80.

[142] Saklani A, Jain S, Thambiraja C. The role of robotic surgery in the management of head and neck cancer: A systematic review. Eur Arch Otorhinolaryngol. 2019;276(3):633–41.

[143] Boni L, David G, Dionigi G, Rausei S, Spampatti S, Colombo EM, et al. Indications, results, and future perspectives in robotic colorectal surgery. Updates Surg. 2021 May;73(2):437–48.

[144] Hellinger MD. Minimally invasive surgery for inflammatory bowel disease. Inflamm Bowel Dis. 2007 Mar;13(3):262–8.

[145] Han SU, Kim MC, Hyung WJ, Kim W, Lee HJ, Park S, et al. Korean Laparoendoscopic Gastrointestinal Surgery Study (KLASS) Group. Long-term outcomes of laparoscopic gastrectomy for gastric cancer: A large-scale case-control and case-matched Korean multicenter study. J Clin Oncol. 2015 Jun 1;33(16):1884–90.

[146] D'Annibale A, Pende V, Pernazza G, Monsellato I, Lucandri G, Alfieri S. Role of robotic surgery in advanced colorectal cancer: a multicenter study of 186 patients. Int J Colorectal Dis. 2013 Feb;28(2):247–54.

[147] Scheib SA, Thomassee MS, Liu T, Azodi MS. Laparoscopic versus robotic hysterectomy for benign disease: a systematic review and meta-analysis of randomized controlled trials. J Minim Invasive Gynecol. 2021 Mar;28(3):557–67.
[148] de'Angelis N, Lizzi V, Martínez-Pérez A, Azoulay D, Brunetti F. Robotic versus laparoscopic distal pancreatectomy: An up-to-date meta-analysis. Int J Med Robot. 2021 Feb;17(1):e2181.
[149] Cheong CK, Li HH, Zhang TJ, Lee B, Goh BKP. Minimally invasive surgery for hepatocellular carcinoma: Current status and future directions. World J Gastroenterol. 2020 Sep;26(35):5345–54.
[150] Delaney CP, Champagne BJ, Senagore AJ. Laparoscopic surgery for colorectal cancer: current issues. Dis Colon Rectum. 2003 Nov;46(11):1592–603.
[151] Trastulli S, Cirocchi R, Desiderio J, Milani D, Parisi A. Robotic versus laparoscopic approach in colonic resections for cancer and benign diseases: systematic review and meta-analysis. Surg Oncol. 2013 Jun;22(2):107–19.
[152] Song HJ, Kim KM, Jung YH, Oh TH, Lee JS. Robotic versus laparoscopic gastrectomy for gastric cancer: a large-scale comparative study. Surg Endosc. 2021 May;35(5):2024–32.
[153] Palanivelu C, Jani K, Senthilnathan P, Parthasarathi R, Madhankumar MV. Laparoscopic distal pancreatectomy: Results of a prospective nonrandomized study from a tertiary center. Surg Endosc. 2007 Apr;21(4):572–6.
[154] Gennari L, Basti G, Falorni S, Patrone R. Laparoscopic versus open splenectomy for splenomegaly: A randomized controlled trial. World J Surg. 2015 Aug;39(8):2061–6.
[155] O'Connor DB, Winter DC. The role of minimally invasive surgery in the management of colorectal cancer: A systematic review. Surgeon. 2020 Dec;18(6):373–82.
[156] Kim SH, Oh SY, Lee IS, Yook JH, Kim BS. Impact of laparoscopic surgery on the quality of life in patients with gastric cancer. Ann Surg Treat Res. 2016 Jul;91(1):25–31.
[157] Mack MJ. Minimally invasive and robotic surgery. JAMA. 2001 Mar;285(10):568–72.
[158] Hull TL, Joyce MR. Minimal access surgery for ulcerative colitis. Surg Endosc. 2012 Feb;26(2):536–43.
[159] Liang TJ, Chang CH, Lee HP, Huang SY. Comparison of laparoscopic and open surgery for colorectal cancer in elderly patients. J Gastrointest Surg. 2021 Nov;25(11):2814–23.
[160] Miskovic D, Foster JD, Agha A, Delaney CP, Francis N. Standardization of laparoscopic total mesorectal excision for rectal cancer: A structured international expert consensus. Ann Surg. 2015 Sep;262(3):716–22.
[161] Wang J, Ji B, Meng L, Liu H. Robotic versus laparoscopic total mesorectal excision for rectal cancer: A meta-analysis of randomized controlled trials. Surg Endosc. 2020 Jan;34(1):173–82.
[162] Aldrighetti L, Guzzetti E, Pulitanò C, Cipriani F, Catena M, Paganelli M, et al. Minimally invasive surgery for colorectal liver metastases: Lessons learned from 100 patients. J Hepatobiliary Pancreat Sci. 2014 Aug;21(8):564–72.
[163] Hasegawa Y, Yoshikawa K, Cho H, Tokunaga M, Matsuyama J, Nakamura K, et al. Laparoscopic gastrectomy for gastric cancer: Current trends and future perspectives. Ann Gastroenterol Surg. 2021 Mar;5(2):183–90.
[164] Inoue M, Ota T, Fukunaga M, Sugihara K. Robotic versus laparoscopic-assisted surgery for rectal cancer: A retrospective cohort study. Int J Colorectal Dis. 2015 Nov;30(11):1595–601.
[165] Dolejs SC, Dolejs SP. Robotic-assisted surgery: The current landscape and future trends. Curr Surg Rep. 2021;9(5):18.