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Advancements in Minimally Invasive Surgery: From Laparoscopy to Robotic Precision

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ABSTRACT

Minimally invasive surgery (MIS) has become a dominant surgical paradigm over the last two decades due to its benefits such as less tissue trauma and shorter convalescence for patients. This narrative review presents the progress in MIS from conventional laparoscopic to robotic surgical interventions, highlighting advancements in technology, clinical and educational applications. Early advances in fiber-optic imaging, video-laparoscopy, and creation of corresponding surgical instruments enabled the transition from a purely diagnostic to therapeutic MIS approach and facilitated surgical innovation among many specialties. However, conventional laparoscopy is constrained by several factors, including rigidity of surgical instruments, two-dimensional imaging, and surgical ergonomics.

Recent advances in robotic-assisted surgery have sought to address several of these limitations by providing surgeons with greater dexterity, tremor filtering, motion scaling, improved three-dimensional visualization and enhanced intra-abdominal working space. Early clinical results are promising with evidence suggesting reduced postoperative morbidity in selected complex procedures, although outcomes for robotic and conventional laparoscopic approaches remain comparable for many standard operations. Moreover, MIS is influencing surgical training through the use of surgical simulation models, structured credentialing and performance-based skill assessments.

Although much has been achieved with MIS, there are barriers to its widespread adoption, namely cost and access in less well-resourced surgical environments, as well as concerns relating to equity, accountability and informed patient consent. Moving forward, incorporating emerging technologies such as artificial intelligence, augmented reality and semi-autonomous systems will be pivotal to optimizing MIS. The future of MIS lies in the provision of personalized surgical care as part of an overall vision for precision surgery.

Keywords: Minimally Invasive Surgery (MIS); Laparoscopy; Robotic-Assisted Surgery; Surgical Simulation; Precision Surgery

Introduction

Background and Definition of Minimally Invasive Surgery

Minimally invasive surgery refers to various surgical techniques that accomplish specific therapeutic objectives while keeping tissue damage to a minimum [1]. Traditional open surgery necessitates more tissue damage due to the requirement for larger incisions to provide adequate exposure to the target organs. In contrast to the more traumatic open surgical approach, MIS procedures use smaller incisions, or alternative approaches through natural orifices, utilizing specialized instruments and often with the aid of endoscopic displays that show the surgical site in high resolution, enabling the surgeon to perform precise dissections and repairs accurately. This helps in reducing tissue trauma and shortens the duration of the patient's recuperative period after surgery [2].

Open surgery requires a significant amount of tissue dissection in order to achieve exposure of the target tissue or organs. In contrast, MIS procedures utilize visualization achieved via cameras and high resolution digital imaging. Surgeons gain a highly magnified and detailed view of anatomy far beyond that of the naked eye. Less tissue is damaged, better visualization and more accurate surgical technique all translate to tangible clinical benefit to the patient: less postoperative pain, less postoperative infection, less time spent in the hospital and a more rapid recovery to a normal state of being. All these attributes of the technique have contributed to MIS becoming the preferred approach for many surgical procedures [3,4].

Historical Perspective on Surgical Innovation

Over much of modern history, open surgery has been the conventional method for surgical procedures. The use of large incisions was essential for giving the surgeon a clear view of the operative site and allowing direct handling of the target organ(s) [5]. Although open surgery has made possible the performance of a vast array of lifesaving operations, it is associated with many adverse consequences such as severe postoperative pain, high rates of wound infection, prolonged stay in the hospital, and prolonged rehabilitation period [6]. All these negative aspects are particularly detrimental to the growing geriatric population and to other high-risk patients [7].

The problem of incision related morbidity was a continuing problem for centuries despite considerable efforts to overcome it, and a problem that stimulated significant innovation in the field. Progress in anaesthesia, asepsis and peri-operative care all helped to improve the position of surgery as a safe and effective discipline [8]. However, this had not eradicated the major problem of incisional morbidity. Concurrent technological advancements in the field of optics, imaging and instrumentation provided new ideas, which encouraged the reevaluation of the need for large incisions. Additionally, the trend in healthcare which places increasing emphasis on improvements in patient based endpoints, such as a reduction in number of complications and improved discharge times, further hastened the transition towards less invasive surgical procedures [9].

Rationale and Scope of the Review

Minimally invasive surgery represents a fundamental shift in surgery as we know it. Leaving behind direct anatomical exposure, MIS uses technology to improve the ability of the surgeon while reducing to a minimum the adverse effects on the patient. From basic laparoscopic concepts to the more advanced robotic-assisted surgery, the field of MIS has come a long way, significantly improving the performance of surgery by providing greater dexterity, accuracy and flexibility [10].

This review aims to identify recent advances in the field of minimally invasive surgery (MIS) in the context of its evolution from laparoscopic to robotic surgery. We summarize developments from a technological, clinical and educational point of view. Important achievements and barriers to adoption are highlighted and the evolutionary history of MIS, as well as its clinical benefit and future prospects in different clinical specialties are addressed in subsequent sections.

Methodology

This study was conducted as a narrative literature review aimed at summarizing current advancements in minimally invasive and robotic-assisted surgery. A structured but non-systematic search of the literature was performed using electronic databases, including PubMed, Google Scholar, the Cochrane Library, and ResearchGate.

Search terms included combinations of keywords such as “minimally invasive surgery,” “laparoscopy,” “robotic surgery,” “robotic-assisted surgery,” and “surgical innovation.” Relevant articles were identified through title and abstract screening, and additional sources were retrieved by reviewing the reference lists of selected publications.

Studies were selected based on relevance to the scope of the review, with preference given to peer-reviewed articles, systematic reviews, randomized controlled trials, and high-quality observational studies. No strict date restrictions were applied, although emphasis was placed on contemporary literature to reflect recent technological and clinical developments. Only articles published in English were included.

Given the narrative nature of this review, a formal systematic appraisal or meta-analysis was not conducted.

Evolution of Laparoscopic Surgery

Origins of Laparoscopy

The evolution of laparoscopic surgery came from the desire to visualize the abdominal cavity using the least possible invasion. Diagnostic laparoscopy was developed in the late nineteenth and early twentieth centuries and was commonly practiced in gynecology using a rigid endoscope to view the pelvic organs. The inadequacy of illumination, the limited field of view, and the poor instruments used at that time precluded the performance of surgical procedures and laparoscopy was almost limited to a purely diagnostic use [11,12].

Fiber-optic technology was a major step in the development of laparoscopy. By improving the transmission of light and image quality, it made possible better visualization of the intra-abdominal cavity using endoscopes and enhanced the safety and resolution of the images. It was video-laparoscopy that, more or less, revolutionized laparoscopy as a technique of surgery. Developed in the 1980s, video-laparoscopy was the real turning point of laparoscopy and with it, the surgeon could see an enlarged image on a screen rather than having to observe directly through an eyepiece. This improved the surgeon's working position, promoted a more teamwork oriented approach to the operation and facilitated the learning process for surgical trainees [13,14,15]. The first laparoscopic cholecystectomy was performed by Erich Mühe on September 12, 1985. Widespread clinical adoption followed the independent video-laparoscopic modifications by Mouret (1987) and Dubois (1988), which drew worldwide attention to the technique in the late 1980s. These developments clearly showed that this new method was also applicable to therapeutic procedures and therefore led to the recognition of laparoscopy from a minor diagnostic tool to a major surgical method [16,17].

Key Technological Enablers

The widespread acceptance of laparoscopic surgery depended on several key technological innovations. Firstly, the combination of a high definition camera with a powerful, cold light source enabled high resolution images with excellent depth perception of the field and excellent visualization of the anatomy, thereby enabling better identification and precise location of critical internal anatomy, which enables better and safer surgery [13,14].

Improvements in the insufflation system were also important to the evolution of laparoscopy. With the advent of an automated system for delivery of carbon dioxide, a stable pneumoperitoneum was readily established and maintained. This provided adequate working space with the least possible amount of physiological disturbance. Newer generations of trocar design have contributed to less incisional damage and greater stability of the instrument. Specialized instruments such as grasping forceps, scissors, needle holder, dissectors and other devices have all been designed to mimic the movement of the human hand within the abdominal cavity. Together they made laparoscopy into an extremely reliable and reproducible form of surgery [11,12,13].

Expansion Across Surgical Specialties

The initial success in general surgery with laparoscopic procedures soon translated into other specialties. In general surgery, cholecystectomy and appendectomy replaced open surgery in a large number of institutions. In gynecology, laparoscopic hysterectomy, ovarian cystectomy, and treatment of endometriosis became common. In urology, nephrectomy and prostatectomy also benefited from the advances of laparoscopic techniques [16,17-20].

The progress achieved in minimally invasive surgery was rapidly extended to thoracic and colorectal surgery, and promising results were achieved, even in technically demanding procedures. Over time, laparoscopy evolved into an essential method for both elective and oncologic surgery, thus illustrating the extraordinary versatility and clinical significance in various branches of surgery [18].

Clinical Benefits and Outcome Improvements

The clinical superiority of laparoscopic surgery over open surgery has been demonstrated. Laparoscopic surgery requires smaller incisions; thus patients experience significantly less postoperative pain and less analgesics. They tend to spend fewer days in the hospital, recover faster and have improved quality of life, while incurring lower medical expenses. Furthermore, fewer postoperative wound complications, such as infection and incisional hernia, have been noted [3,18].

The benefits of laparoscopic surgery have been consistently demonstrated in a wide range of surgical procedures and patient populations. Thus, laparoscopy has become the surgical method of choice in situations where it is technically feasible [4].

Limitations of Conventional Laparoscopy

In spite of the significant advantages offered by conventional laparoscopy, it has some inherent limitations. The reduced dexterity at the distal end of the laparoscopic instruments due to their restricted degrees of freedom when compared to the freedom of movements in the human wrist is an important limitation, particularly during delicate and precise tasks like suturing. There is a conflict between hand and eye movements which must be mastered by surgeons, who also have to frequently deal with a two-dimensional visual field. Long-lasting operations cause tiredness and strain for all participants. Furthermore, the significant time that one has to invest to learn advanced skills in laparoscopic surgery has limited its application, particularly in complex surgery. This has motivated the development of robotic-assisted surgery systems, which therefore aim at eliminating many of the constraints inherent to the standard laparoscopic technique [10].

Technological Refinements in Minimally Invasive Surgery

Advanced Imaging and Visualization

Advances in imaging and visualization technology continue to have a positive impact on the safety and efficacy of minimally invasive surgical procedures. Over the years improvements have included upgrading from standard definition to high definition (HD) systems, and more recently to 4K resolution to deliver a superior level of image quality. High definition enables a surgeon to see differences between anatomical planes, to be more confident in their ability to locate smaller vasculature, and to detect fine anatomical and pathological changes in the tissue that they are operating on. These improvements significantly reduce the potential for intraoperative error and improve the accuracy of the procedure [21,22].

Three-dimensional (3D) laparoscopy has addressed the main criticism of 2D laparoscopy, which was lack of depth perception. Restoring stereoscopic vision allows for easier performance of intricate surgical tasks such as intracorporeal suturing and knot tying, thereby potentially shortening surgical time and decreasing the time required for surgeons to become proficient and comfortable with minimally invasive techniques [21,22].

Fluorescence-guided imaging is another innovation that has revolutionized surgical practices. Indocyanine green (ICG) fluorescence allows for the real time assessment of tissue perfusion, as well as biliary anatomy, sentinel lymph nodes and lymphatic channels. Hence ICG fluorescence imaging is a powerful tool for intraoperative identification of structures and vessels in the operating room and is particularly useful during cholecystectomy, colorectal resections, liver surgery and oncology surgeries to avoid surgical pitfalls, promote accurate dissection and minimize surgical complications. Therefore, Fluorescence imaging has become a complementary tool aiding intraoperative decision making in minimally invasive surgery and making it more efficacious [23,24].

Instrumentation and Energy Devices

As well as improvements in visualization, advances in instrumentation have dramatically increased the amount of surgery that can be performed through minimally invasive approaches. To improve on the fixed, linear motion of rigid laparoscopic instruments, articulating instruments offer increased dexterity and more natural wrist-like motion. This provides the ability to perform complex tasks in hard-to-reach or difficult-to-access areas of the body [25].

As well as surgical tools, energy-based devices have undergone a revolution. Sophisticated advanced bipolar and ultrasonic devices provide far more accurate dissection and vessel sealing, with much less collateral thermal spread. These new devices help reduce blood loss, tissue damage and operating time. Also, advancements in stapling and tissue-sealing technology allow for faster performance of key steps in surgery, such as resection of the bowel, haemostasis and anastomosis, particularly in gastrointestinal, bariatric and thoracic surgery [26,27,28].

When taken together, these instrumental advancements afford a wider and more complex set of surgeries that can be performed safely and with reproducibility using minimally invasive approaches.

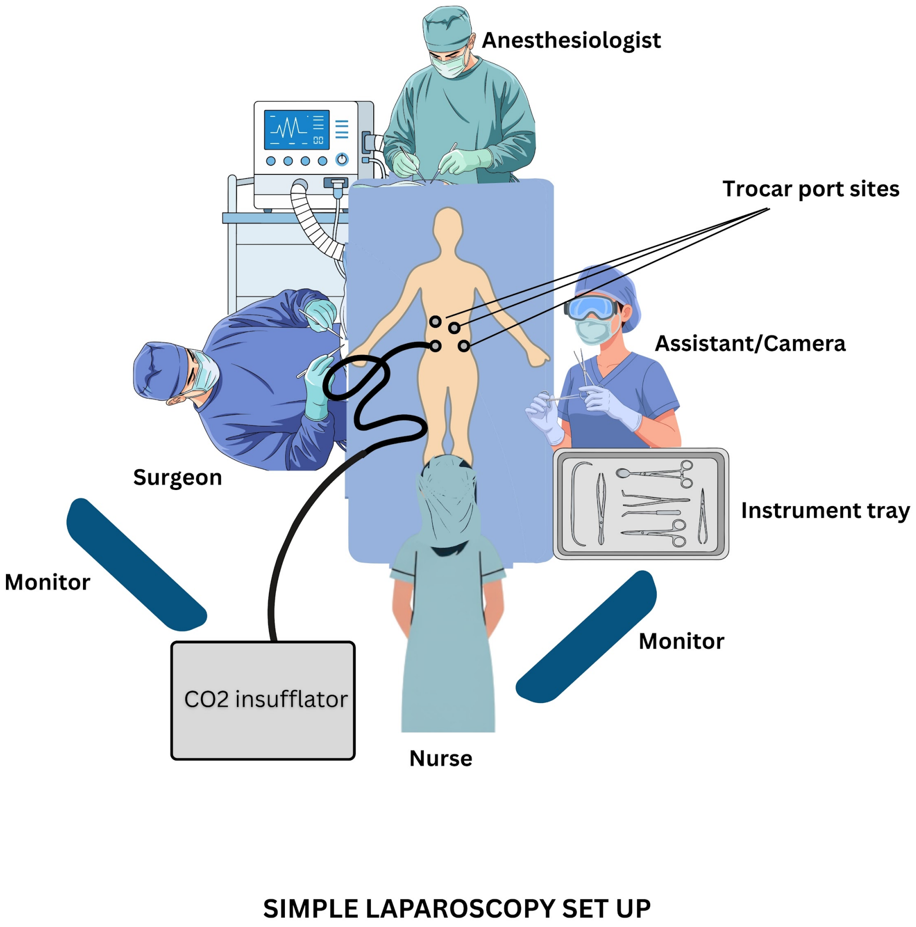
Integration of Digital and Computer-Assisted Systems

Use of digital technologies, computer-assisted techniques represents a significant step towards achieving the goal of true precision surgery. Image-guided navigation involves overlay of preoperative imaging data (CT, MRI, PET, etc) with real-time intraoperative images facilitating accurate surgical intervention in complex anatomy. These systems are now being used commonly in hepatobiliary, pancreatic and oncologic surgeries as well as in spinal surgeries, where the surgery demands great precision in terms of anatomical accuracy [29].

The early adoption of surgical data capture and analytics is beginning to transform the field of minimally invasive surgery. Capturing procedures digitally enables the facilitation of regular performance appraisal, audit, and feedback as well as postoperative debriefing and patient feedback. These learning environments are vital precursors to the adoption of advanced applications of technology such as artificial intelligence-based intraoperative navigation, real time surgical decision support and the use of predictive models to assess pre-operatively the risks and potential for successful outcomes of planned surgical procedures [30,31].

Collectively, advancements in digital and computer-assisted technologies are steadily leading towards more accurate, more precise and safer procedures within the field of minimally invasive surgery. Figure 1 shows a simple laparoscopic set up.

Figure 1: Components of a Basic Laparoscopic Surgical Setup



Emergence of Robotic-Assisted Surgery

Concept and Development of Surgical Robotics

Robotic-assisted surgery was developed because surgeons felt that conventional laparoscopic surgery was limited in certain respects, and that many procedures required skills of a level of precision which human hands were not able to achieve on their own. The technology was based on a number of advances rooted in military and aerospace technology where the purpose of robotics has long been the enhancement of human performance; particularly where tasks require dexterity, accurate movement or are hazardous to humans. The technology was refined for surgical use where accuracy, control and stability are essential [32,33].

The first generation of robotic systems were designed for very simple tasks such as camera guidance for robotic assisted surgery or telesurgery, a long distance remote control surgery. The second generation robots added sophisticated functions that can translate the surgeon's motion accurately and precisely into scaled, tremor-reduced motor actions to perform complex surgical procedures within the body. Key regulatory milestones—most notably FDA clearances in the late 1990s and early 2000s—paved the way for widespread clinical use. Initial adoption was strongest in urology, where robotic-assisted radical prostatectomy quickly demonstrated clear technical superiority over both open and conventional laparoscopic approaches. This success helped establish robotic surgery as a credible and transformative force in modern surgical practice [32,33,34].

Core Components of Robotic Surgical Systems

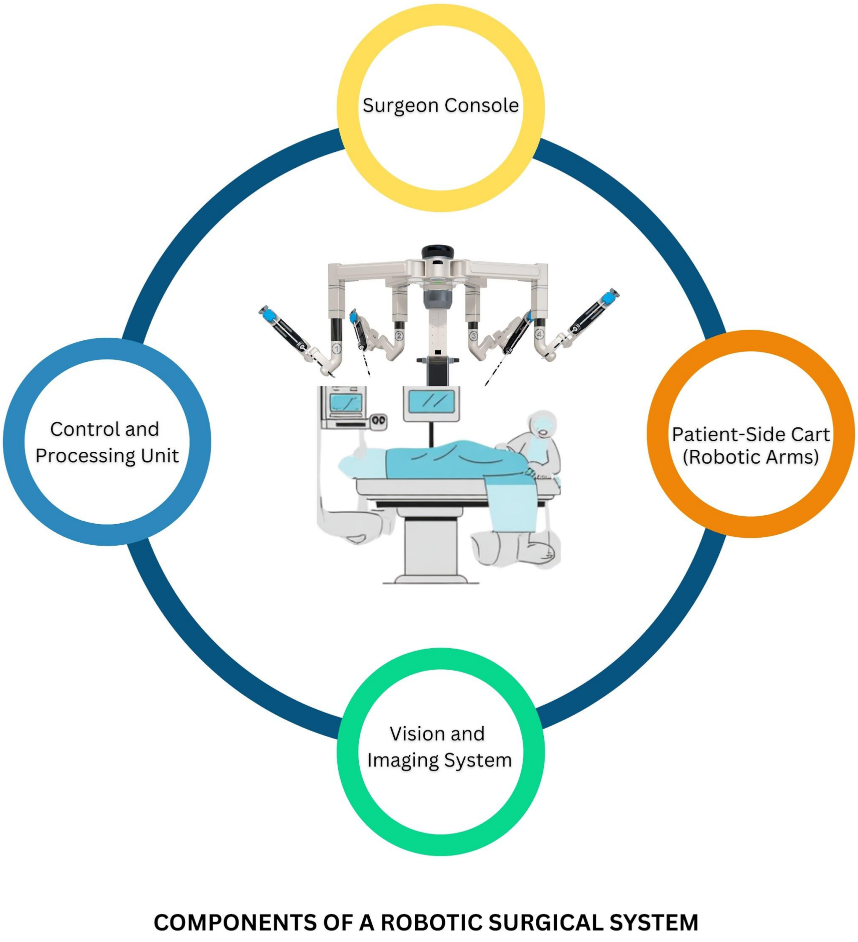
Modern robotic surgical systems have three highly integrated components: the surgeon console, the patient-side cart with robotic arms, and vision and control infrastructure [35].

The surgeon console is the ergonomic command center for the surgical procedure. Seated in the console, the surgeon operates the master controls with both hands and foot pedals, while the robotic surgical instruments are actuated by precise hand and finger movements, similar to performing open surgery. The console design of the robotic surgical system reduces the physical stress and fatigue associated with laparoscopic surgery [35,36,37].

The patient-side robotic arms are located on each side of the operating table. They are controlled by the surgeon and are equipped with wrist-like instruments with several degrees of freedom, enabling them to move dexterously, more so than a human hand and wrist can move. The system also includes a 3D, high definition, stereo vision component that provides highly magnified views of the surgical site, real-time trajectory feedback to help improve the surgeon's understanding of their hand position relative to the target in space, allowing for more precise operation [21,35-37].

Together they provide a highly seamless interface through which extremely delicate and complex surgical tasks can be accurately, stably and consistently performed. Figure 2 highlights the core components of a robotic surgical system.

Figure 2: Key Elements of a Robotic Surgical Setup



Technical Advantages Over Conventional Laparoscopy

Robotic-assisted surgery overcomes several fundamental limitations of conventional laparoscopy through targeted technical improvements.

The primary advantage of wristed robots is improved dexterity. Wristed instruments on newer generation robots offer 7 degrees of freedom as opposed to the 5 degrees available in standard laparoscopic instruments. This extra dexterity allows for better dissection of tissues, improved tissue handling and safer and more reliable intracorporeal suturing within deep, confined and narrow spaces such as the pelvis and mediastinum [35,36,38,39].

Tremor filtration is a functionality that filters out the physiological tremor of the hand allowing for the smoothest and most controlled motion. Motion scaling is a functionality that enables the user to achieve a high degree of precision when operating, as the large hand movements made at the console result in only small movements at the distal ends of the instruments. The combination of these functionalities allows surgeons to have the highest degree of confidence and precision when performing the most delicate surgical tasks [36,38,39].

Surgical robotic systems have finally addressed the issue of ergonomics. With a comfortable seated position and optimal arm and hand position, surgeons can minimize fatigue and strain from the musculoskeletal system, which is often a feature of long periods of awkward posturing required to perform laparoscopic surgery. The overall effect is one of improved surgical technique, better consistency of surgical performance, and reduced damage to surrounding tissues [34,35,36,38].

Expansion of Robotic Surgery Across Specialties

Robot-assisted surgery proved its worth in urology and quickly found its way into other surgical disciplines. In gynecology, robot-assisted surgery has become the mainstay for many procedures, including hysterectomy, myomectomy, sacrocolpopexy and endometriosis surgery, particularly for larger endometriomas and in patients with severe obesity or complex anatomy [40,41-44].

General and colorectal surgery has adopted robotic-assisted technology for colectomy, low anterior resection, rectal cancer surgery and complex ventral hernia repair. The benefits of better exposure and precision of surgery allow for safer dissection and reconstruction in close proximity to vital organs and structures [43].

With the growing trend towards minimally invasive procedures, cardiothoracic and head and neck surgery have begun to incorporate robotic technology into mitral valve repair, thymectomy, lung resection, and transoral surgery in anatomically challenging regions. The expansion into additional surgical specialities reflects the significant applicability and pivotal role of robotics in providing more innovative and patient-friendly minimal access therapies [42,43,44].

Clinical Impact of Robotic Precision

Surgical Accuracy and Precision

One of the many clinical benefits to robotic-assisted surgery is the improved accuracy and precision of surgery. High definition 3-dimensional (3D) visualization and fully wristed instrumentation allow the surgeon to perform intricate, and even more accurate movements, than the human hand can perform. Such dexterity of movement allows for very precise tasks, such as intracorporeal suturing and knot tying, very delicate dissection and intricate reconstruction [21].

Robotic surgery has particular application in constrained or anatomically complex environments. Such environments may include the deep pelvis, mediastinum, or retroperitoneum, where the procedure can be difficult to perform accurately due to limited access and visualization during standard laparoscopy. Robotic surgery filters out tremor, and provides motion scaling, facilitating meticulous dissection around delicate structures, such as nerves, blood vessels, ureters, and other critical tissue to minimize the risk of damage. This improvement in surgical dexterity allows for the performance of more complex surgeries that were previously considered inoperable via traditional minimally invasive approaches and larger open incisions [45,46,47].

Patient Outcomes and Safety

Superior technical precision, possible with robotic surgery has translated into significant benefit for the patient. While studies on robotic versus laparoscopic surgery often show comparable results, or slight improvements in terms of estimated blood loss, complication rate, and length of hospital stay, it was observed that in more complex and technically challenging cases, there was a significant difference in the rate of conversion to open surgery, reflecting the greater control and more confident and dexterous surgery possible with the robotic platform, particularly when dealing with complex and distorted anatomy [48,49,50].

Fewer tissue injuries and a more accurate dissection lead to fewer intraoperative complications. Precision surgery has led to better functional outcomes in a wide range of urological surgeries such as radical prostatectomy. Many high quality series reports show that better nerve sparing is achieved thus a better urinary and sexual function. In oncology, while robotic-assisted surgery may enhance technical precision and facilitate adherence to oncologic principles such as meticulous tumor resection and lymphadenectomy, current evidence indicates that oncologic outcomes—including margin status, lymph node yield, recurrence rates, and overall survival—are largely comparable to those of conventional laparoscopic surgery. High-quality studies, including randomized controlled trials, support the non-inferiority rather than superiority of robotic approaches for most oncologic measures. [48,49,50].

Surgeon Performance and Training

Another significant benefit of robotic-assisted surgery is to the performance and well-being of the surgeon. The ergonomic surgeon console allows surgeons to remain in a natural seated position with arms, hands and neck in optimal configuration which significantly reduces physical strain and fatigue when compared to the uncomfortable and often stooped position that is required to perform conventional laparoscopic procedures. The reduction in physical strain and fatigue enables the surgeon to maintain focus and precision during prolonged and complex procedures [38].

Due to its highly intuitive master - slave concept and high-class visualization, better performance accuracy and consistency, as well as a higher level of reproducibility may be achieved, not only for beginners but also for even experienced surgeons in more complex surgical tasks. In the context of education, robotic surgery provides many benefits in the context of training. These include the option to employ a variety of simulation modules, to carry out proctoring in a dual-console mode, and to use performance metrics that can be evaluated in relation to defined benchmarks and learning objectives. These educational resources promote safe and efficient acquisition of surgical skills, whilst the patient's safety is preserved during the learning process of new skills [51,52].

In the long run, the ergonomic and educational benefits for the surgeon may also have the valuable secondary effects of increasing career duration, reducing the risk of burnout and enabling surgeons to achieve exceptional skill and performance even at later stages in their careers. A technological innovation that enhances surgical performance and quality by the use of robotic precision can therefore be seen as conferring a new dimension of personal achievement to surgeons during their working lives [38,51,52].

Economic, Ethical, and Accessibility Considerations

Cost Implications of Robotic Surgery

While the clinical benefits of robotic-assisted surgery are well-documented, the financial burdens associated with this method of surgery are equally pronounced. Robotic systems are expensive, with the initial purchase price ranging from several million dollars. Add to this the annual maintenance contract, software updates, utilization fees for the sterilization of robotic instruments and single-use consumables and the cost of robotic-assisted surgery is significantly higher than that of conventional laparoscopy. The high initial cost of the robotic system and the relatively high cost per procedure, particularly in low volume centers, make robotic-assisted surgery an expensive option [53,54].

In the early stages of adoption, procedures tend to be longer and therefore more costly. Several analyses have noted partial offsets from the reduction in the incidence of postoperative complications, as well as reductions in hospital length of stay and expedited patient discharge. The long-term cost-effectiveness of robotic-assisted surgery, however, remains in question. The literature currently suggests that cost-effectiveness is highly procedure-dependent and that there is considerable inter-study variability related to the skill of the surgeon, the surgeon's operating volume, and the current reimbursement structure. Thus, conclusions cannot be drawn universally, and this necessitates a clinical context-specific assessment of costs and benefits before reaching conclusions [55,56].

Access and Global Disparities

There is considerable inequity in access to robotic-assisted surgery, both within and between countries. High-income countries and academic or tertiary institutions tend to have the financial resources required to support robotic surgery programs. In low- and middle-income countries, barriers to implementing robotic surgery include high costs of equipment and maintenance, inconsistent global supply of robotic parts and consumables, lack of specialized robotic surgical fellowship training, and insufficient staff to support operations of the robotic system [57,58].

There are many barriers to robotics, from reliable power supply, to adequate imaging modalities and dedicated operating rooms. These are not uncommon barriers for performing surgery in general, but they become compounded when trying to perform surgery in resource poor settings. These inequities raise important questions about fairness in the delivery of new surgical robotics technology. Important questions need to be addressed to ensure that the benefits of surgical robotics technology can reach where they are needed most. Patients in resource poor countries are being left behind. Patients in resource-constrained settings will continue to endure inferior surgical care unless measures are taken to address these inequities. Solutions to bridge the gap and ensure that the delivery of robotic-assisted surgery (RAS) does not further exacerbate existing inequities include developing affordable and locally relevant adaptations of RAS systems, innovative payment structures, development of international training partnerships to build local capacity and networks, and enhanced global partnerships with relevant stakeholders [57,58].

Ethical and Policy Issues

The rapid assimilation of robotics into surgical practice has generated a plethora of ethical and policy issues. Because the use of the robotic system may be dictated by hospital economics rather than medical need, unequal distribution of the technology in different healthcare settings could exacerbate existing healthcare disparities. The promotional campaigns by industry leaders and competitive pressures have also caused the hasty introduction of this technology for a variety of procedures for which there is not robust scientific evidence to suggest that it is the best option for the patient [59].

One of the more contentious ethics issues is informed consent. There are a number of factors that can lead to patients having unjustified elevated expectations of the benefits of robotic surgery. These can include unrealistic media coverage or descriptions of a new high-tech technology, or patients' misunderstanding of what "robotic" is leading them to assume that a robotic approach is always superior to traditional open and laparoscopic surgical techniques. A more balanced and accurate description of the potential benefits, limitations, and risks of robotic-assisted surgery with an accurate discussion of the potential alternatives should be provided by the surgeon and the healthcare institution [60,61].

To ensure that robotic surgery systems are used in a safe and effective manner, there must be a robust policy framework in place that includes independent regulatory review and ongoing comparative effectiveness research to inform wise distribution of the technology. Such a framework will help to ensure that the decisions made by clinicians and institutions to use robotic surgery systems are determined by clinical, quality-of-care considerations, rather than by commercial or institutional self-interest.

Training, Credentialing, and Learning Curves

Surgical Education in the MIS Era

The advent of laparoscopic and robotic-assisted surgery has revolutionized the practice of surgery and as a consequence, surgical education. The centuries old apprenticeship model of open surgical technique has evolved to include formal training in laparoscopic and robotic surgery. Most contemporary residency and fellowship curricula have adapted the curriculum to include formal training in laparoscopic and/or robotic surgery early in the training process, acknowledging that open surgical technique is just one of the many skills that a surgeon may require to perform safely and effectively. The need for a surgeon to be competent in open and minimally invasive surgical techniques is becoming widely accepted as a core competency criteria [51,52].

Simulation-based education is a cornerstone of this evolution. Laparoscopic box trainers and virtual-reality simulators are now widely used to train basic skills such as camera navigation, hand–eye coordination, and endoscopic dissection skills in a safe (low-stakes) environment. Also, console-based robotic simulators provide a highly realistic surgical environment and allow trainees to practice console operation, arm movements and complex surgical tasks, without the risk of injuring a patient. These tools allow trainees to engage in deliberate practice, countless times, with the aid of detailed performance analysis and timely feedback. All of these features lead to efficient acquisition of surgical skills, and thus shortening of the learning curve [62].

Credentialing and Competency Assessment

The Credentialing process for minimally invasive and robotic surgical procedures is a vital patient safety and professional standard. All institutions have formal privileging processes in place, which include, but are not limited to, completion of a training course or fellowship that is accredited, successful completion of a number of cases that are proctored, and objective assessment of the surgeon's ability to perform the procedure safely and effectively. Case-volume requirements are often used as a metric for evaluating a surgeon's level of experience. This is particularly relevant for high-complexity robotic procedures where increased number of procedures enhances proficiency which directly correlates with improved patient outcomes [63,64].

While initial training is important, maintaining competence over time is equally important, as technology, equipment and techniques can change. To maintain competence, surgeons may have to participate in continuing education courses to refresh their knowledge of current practices, undergo further simulation training, participate in surgical skills workshops and have their performance reviewed on an annual basis. More and more institutions are beginning to use structured assessment tools such as video peer review of surgical procedures using video footage, motion analysis or scoring systems to evaluate and ensure reliability and objectivity. This move towards competency assessment using more evidence and data-based methods, highlights the on-going commitment to a culture of lifelong learning and quality improvement in surgical practice [65].

Challenges in Training Adoption

Despite advances in surgical education, integrating robotic systems into routine training presents practical challenges beyond resource limitations. A key issue is the impact of the learning curve on operative performance and patient safety [48,54,57].

During early training, procedures are often associated with longer operative times, increased workload, and greater resource use, which may elevate the risk of perioperative complications. This creates a tension between the need for hands-on training and the obligation to maintain optimal patient outcomes [48].

To address this, structured, competency-based training pathways incorporating simulation before live surgery are recommended. Dual-console systems allow real-time supervision, while proctorship and mentorship help facilitate skill acquisition while minimizing risk [30,62].

Careful case selection is also critical. Training should begin with low-complexity cases, with progression guided by defined competency thresholds and institutional policies to support safe implementation [60,63,64].

Emerging approaches such as telementoring and remote proctoring may expand access to expertise, particularly in resource-limited settings, but require robust infrastructure and governance. Overall, balancing training with patient safety demands a systems-level approach integrating curriculum design, oversight, and continuous evaluation [30].

Future Directions in Minimally Invasive and Robotic Surgery

Artificial Intelligence and Automation

Artificial intelligence (AI) is here to revolutionize the future of minimally invasive and robotic surgery. Real-time AI-assisted systems using intraoperative data can instantly recognize and identify anatomical landmarks and vulnerabilities as well as locate sensitive tissue, giving the surgeon a faster decision-making tool. Also, sophisticated image recognition technology improves the surgeon's understanding of the visual field during surgery, enhancing precision and safety and helping to prevent tissue damage [66,67,68].

The use of augmented reality (AR) guidance systems in which digital annotations or preoperative images are superimposed over the real-time operative scene is a developing theme. There is a prospect for integrating the virtual planning component with the real time surgical activity and the future scope of predictive analytics is vast as well. It is anticipated that advanced AI systems will be able to learn a vast array of patient factors, including comorbidities, anatomy, and risk of various procedures and make accurate predictions of likelihood of postoperative complications and other surgical outcomes. Surgeons will not be replaced but empowered by enhanced safety, accuracy, consistency, and decision support. AI technology will serve to enhance and reaffirm the role of the surgeon [69].

Autonomous and Semi-Autonomous Surgery

In today's healthcare landscape, the quest for a fully or even partially autonomous surgical robot is arguably one of the most ambitious and ongoing challenges in robotics engineering. Currently, a variety of semi-autonomous functionalities, such as autonomous suturing, automated tissue approximation, or camera movements are under development and evaluation. But the holy grail of fully autonomous surgery — a robot that can operate a patient without human intervention— is still a subject of research and has been limited to very basic, simple and highly repetitive tasks, and is far from being ready for clinical adoption [37].

The rapid pace of progress in all these areas raises fundamental ethical, legal and practice questions. Who is liable if an autonomous system is involved in an adverse event? How do we achieve informed consent from patients when the decision making is done by a machine? It will be a challenging task for the regulatory bodies to come up with appropriate, clear and evidence based guidelines to ensure safety and performance of these systems before they become part of the mainstream practice. In the short term, most developments will be focused on the use of assistive and semi-autonomous technologies that will augment and relieve human clinician workload while preserving clinical judgment and decision making [59,60,61] .

Next-Generation Technologies

New robotic platforms are addressing long-standing challenges such as size, cost, portability and versatility. Miniature and flexible robots promise better dexterity in tight spaces, ease of handling in the operating room and greater versatility. Single-port technology, which involves multiple articulated instruments introduced through a single small incision, offers the promise of less tissue trauma, less patient recovery time, and aesthetically pleasing scarring [70,71].

In the last decade, natural orifice transluminal endoscopic surgery (NOTES) has evolved towards a truly incisionless surgery model, which in the future could indeed exclude the use of any incisions for specific procedures. On the other hand, telesurgery and remote robotic surgery will allow, thanks to the new possibilities offered by low-latency communication networks and technologies such as haptic feedback, for the extension of surgical expertise to distant locations, thereby increasing access and equity of care, especially in rural and underserved areas. In summary, there is an unrelenting trend toward less invasive, more precise and more accessible surgery [70,71].

Personalized and Precision Surgery

Minimally invasive and robotic surgery is closely aligned with the trend towards personalized and precision medicine. Using patient specific planning based on a detailed analysis of the patient's anatomy from preoperative imaging and 3D computer simulation along with an assessment of their risk profile for surgery can enable a procedure to be delivered in a highly individualized fashion to the particular anatomy and condition of each patient. Incorporating genomic information with high resolution imaging can enable more precise margin definition, better lymph node assessment and improved organ preservation with no compromise to oncologic efficacy [66,69].

Individualized surgical procedures allow for a more precise treatment, less tissue damage and better long term outcomes. The new era in surgery focuses on matching the individual's own biology and needs to achieve the most minimally invasive yet optimal care possible for patients.

Limitations

This review has several limitations that should be acknowledged. First, the study was conducted as a narrative review rather than a formal systematic review or meta-analysis. This approach allows for a broader and more flexible synthesis of a rapidly evolving, multidisciplinary field, encompassing technological, clinical, educational, and ethical dimensions. However, it limits reproducibility and increases susceptibility to selection bias, as study inclusion is not based on a strictly predefined protocol.

Second, there is potential for publication and reporting bias, as studies with favorable outcomes are more likely to be published. This may lead to an over-representation of the benefits of robotic-assisted surgery and underreporting of neutral or negative findings, thereby influencing overall interpretation.

Third, the rapid pace of technological advancement in minimally invasive and robotic surgery presents an important limitation. Surgical platforms and associated technologies, including artificial intelligence, are continuously evolving, meaning some evidence may become outdated within a short timeframe, particularly regarding costs and technical capabilities.

Finally, heterogeneity across studies in terms of procedures, surgeon expertise, institutional volume, and healthcare systems limits the generalizability of findings. Outcomes are often context-dependent, and caution is needed when extrapolating results across different settings.

Despite these limitations, this review provides a balanced overview of current developments while highlighting key areas for future research and policy consideration.

Conclusion

Minimally invasive surgery continues to be a key component of modern surgical practice by facilitating improved precision, faster recovery and reducing morbidity in comparison to the traditional open approach. This method of surgery has evolved from traditional laparoscopic techniques to the utilization of robotic-assisted systems that enable the surgeon to have greater flexibility, enhanced visual capabilities, and improved overall performance in order to manage a wide array of complex surgical cases safely and efficiently.

Despite rapid innovation in minimally invasive surgery, several challenges remain including cost, accessibility, and ethical considerations particularly in resource-limited settings. Future directions for minimally invasive surgery will integrate emerging technologies, including artificial intelligence and personalized surgical planning, to overcome current barriers to widespread adoption. Further innovation, policy-making, and global collaboration are needed to make effective and equitable delivery of minimally invasive surgery a reality.

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