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Robotic Surgery: Review on Minimally Invasive Techniques

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Abstract

Robotic surgery represents a significant advancement in minimally invasive techniques, offering enhanced precision, flexibility, and control compared to traditional methods. This review explores the evolution, benefits, and current applications of robotic surgery in various medical fields. Utilizing robotic systems such as the da Vinci Surgical System, surgeons can perform complex procedures through small incisions, resulting in reduced trauma, minimized blood loss, and faster recovery times for patients. Robotic surgery is particularly beneficial in fields like urology, gynecology, and cardiothoracic surgery, where precision is paramount. High-definition 3D visualization and articulated instruments allow surgeons to perform intricate movements with enhanced dexterity and accuracy. Additionally, the integration of advanced imaging technologies and real-time data analytics further improves surgical outcomes. Despite its advantages, robotic surgery presents challenges, including high costs, steep learning curves, and the need for specialized training. This review also addresses the ongoing development of more affordable and user-friendly robotic systems, as well as the potential for integrating artificial intelligence and machine learning to enhance surgical planning and execution. This abstract underscores the transformative impact of robotic surgery on minimally invasive techniques, highlighting its potential to improve patient outcomes, reduce surgical risks, and expand the capabilities of modern surgery.

Keywords: 3D Visualization; Advanced Imaging; da Vinci Surgical System; Minimally Invasive; Precision; Robotic Surgery; Surgical Outcomes

Abbreviations: AI: Artificial Intelligence, MIRA: Minimally Invasive Robotic Association, SAGES: Society of American Gastrointestinal and Endoscopic Surgeons, VR: Virtual Reality

1. Introduction

Robotic surgery, also known as robot-assisted surgery, has emerged as a revolutionary advancement in the field of minimally invasive techniques. This cutting-edge technology allows surgeons to perform complex procedures with exceptional precision, flexibility, and control, offering numerous benefits over traditional open surgery. During robotic surgery, surgeons operate through small incisions using highly advanced robotic systems that provide a magnified, high-definition 3D view of the surgical site [1, 2, 3]. These state-of-the-art robotic platforms, such as the renowned da Vinci Surgical System, are designed to enhance surgical dexterity and facilitate intricate maneuvers. As a result, patients undergoing robotic surgery often experience fewer complications, reduced pain and blood loss, shorter hospital stays, quicker recovery times, and smaller scars compared to conventional open procedures. While robotic surgery carries its own set of potential risks, including a small risk of infection, it continues to be explored through clinical trials for various applications

across multiple medical specialties (Fig. 1) [4, 5, 6, 7].

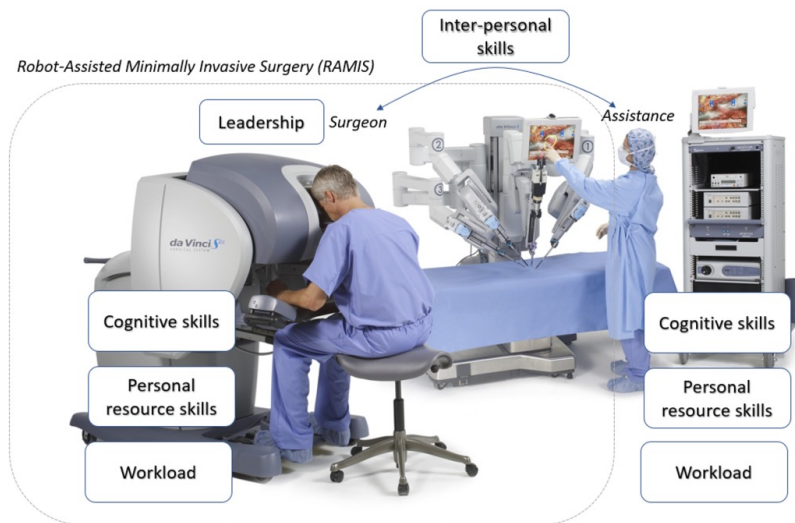


Figure 1. The da Vinci Surgical System.

1.1 Evolution of Surgical Robotics

The concept of robotic surgery can be traced back over 50 years, with early developments emerging in the late 1980s. The first fully functional multipurpose surgical robot was developed through a partnership between the Department of Defense and innovative startups/research agencies. Initially, these early surgical robots were specialty-focused, with the original intent being for long-distance trauma surgery in battlefield settings [8, 9]. Some key milestones in the evolution of surgical robotics include:

- 1986-1987: SRI International and DARPA developed the 'Green Telepresence Surgery System' prototype.
- 1990s: Computer Motion developed the AESOP and ZEUS robotic systems.
- 1995: Intuitive Surgical was founded and began developing the da Vinci Surgical System.
- 1999: The da Vinci Surgical System was introduced, offering 7 degrees of freedom.
- 2000: The da Vinci Surgical System received FDA approval for use in the US.

Table 1. Year and Milestones

YEAR	Milestone
1985	First use of a robot (PUMA 200) in surgery for needle placement in a CT-guided brain biopsy.
1994	The AESOP system, combining a telemanipulator with a foot pedal for stabilizing the camera view, was approved by the FDA.
1990s	The ZEUS system, with separate hubs for the surgeon and patient sides, allowing the surgeon to control the patient-side robotic arms, was developed.

From the above Table 1, the ZEUS system, with separate hubs for the surgeon and patient sides, allowing the surgeon to control the patient-side robotic arms, was developed. The term 'robot' itself was conceived in the early 20th century, derived from the Czech word 'robota' meaning 'labor'. While robotic technology has been applied to surgical procedures for over 35 years, significant growth in the field has occurred in the last two decades. Intuitive Surgical, founded in 1995, continues to create and refine robotic surgical systems, with the da Vinci DXi being the 4th generation, incorporating over 20 years of learnings to enhance surgical performance [10, 11, 12].

1.2 The da Vinci Surgical System

The da Vinci Surgical System, developed by Intuitive Surgical, a pioneer in robotic-assisted surgical technology, has revolutionized the field of minimally invasive techniques. This state-of-the-art system provides surgeons with enhanced vision, precision, and control compared to traditional open or minimally invasive surgery.

The system comprises three main components:

1. **Surgeon Console:** This is where the surgeon sits and controls the tiny, highly maneuverable instruments that are inserted into the patient through small incisions.
2. **Patient Cart:** This component holds the robotic arms that perform the surgical procedure based on the surgeon's movements at the console.
3. **Vision Cart:** This component houses the high-definition 3D endoscopic camera, which provides the surgeon with a magnified, detailed view of the surgical site.

One of the key advantages of the da Vinci system is its ability to translate the surgeon's hand movements at the console in real-time, allowing the instruments to move with a greater range of motion than the human hand. This feature, combined with the system's advanced optics and ergonomic design, enables surgeons to perform complex procedures with exceptional dexterity and control [13] as in the Table 2.

Table 2. Feature and Benefits

Feature	Benefit
Enhanced Vision	Magnified, high-definition 3D view of the surgical site
Ergonomic Design	Comfortable positioning for the surgeon, reducing fatigue
Minimally Invasive	Smaller incisions, reduced pain, and quicker recovery for patients

Intuitive Surgical provides comprehensive education, training, and support for surgeons, operating room staff, and hospital care teams to ensure safe and effective use of the da Vinci Surgical System. As of 2022:

- Over 60,000 surgeons worldwide have been trained on da Vinci systems.
- More than 10 million procedures have been performed using the technology.
- Over 1,700 da Vinci Systems have been installed in hospitals worldwide.
- Over 775,000 patients worldwide have undergone a da Vinci procedure.

The latest model, the da Vinci Xi System, features an overhead instrument arm design for easier anatomical access and improved endoscope architecture with better visual definition and clarity. It is widely used for urologic, gynecologic, colorectal, and other surgical procedures (Fig. 2) [14, 15].

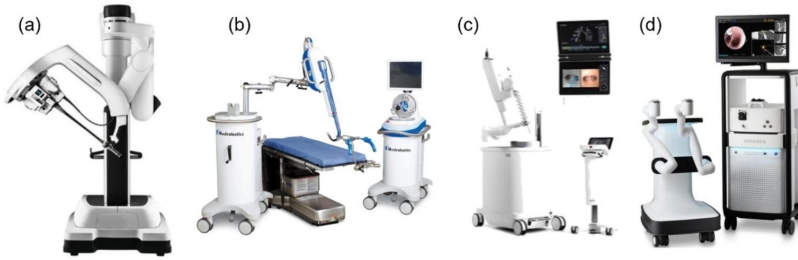


Figure 2. Surgical robot for single-port surgery and flexible robot for endoluminal surgery.

1.3 Robotic Surgery Setup and Workflow

The setup and workflow for robotic surgery (RS) involve several key components and personnel. The basic system consists of three main parts:

1. **Vision Cart:** This houses the high-definition 3D endoscopic camera, providing the surgeon with a magnified, detailed view of the surgical site.
2. **Patient Cart:** This component holds the robotic arms that perform the surgical procedure based on the surgeon's movements at the console.
3. **Surgeon's Console:** This is where the trained robotic surgeon sits and controls the tiny, highly maneuverable instruments inserted into the patient through small incisions.

The minimum personnel required includes the robotic surgeon, anesthesia team, surgical assistant(s), trainees/residents, circulating nurse, and operating room (OR) technicians. Various laparoscopic and robotic instruments are needed, such as Veress needles, ports, scopes, and Endowrist instruments.

Proper setup is crucial for successful robotic surgery:

- The operating room must be configured to accommodate the robotic system, with the patient positioned appropriately for the procedure.
- Port placement is critical for optimal triangulation and exposure during the procedure.
- Docking is facilitated by a laser targeting system, where the user points the endoscope at the surgical site, presses a button, and the system configures itself into the optimal position.
- The new endoscope requires no draping, calibration, or white balance - just plug it in and go.

Once set up, the robotic system provides surgeons with 3D imaging and precision-guided wrist movements, allowing them to combine the benefits of endoscopic and open surgery. However, limitations include cost, safety concerns, lack of tactile feedback, and potential for mechanical failures. Proper training and a dedicated, experienced surgical team are essential for successful robotic surgery [16].

2. Advantages of Robotic Surgery

Robotic surgery offers numerous advantages over traditional open and laparoscopic procedures, making it an attractive option for both patients and surgeons. One of the primary benefits is the reduced trauma and faster recovery times for patients. As robotic surgery involves smaller incisions, patients experience less pain, reduced risk of infection, minimal scarring, and shorter hospital stays [17]. Additionally, the minimally invasive nature of robotic surgery leads to lower blood loss and a decreased need for blood transfusions (Fig. 3) [18].

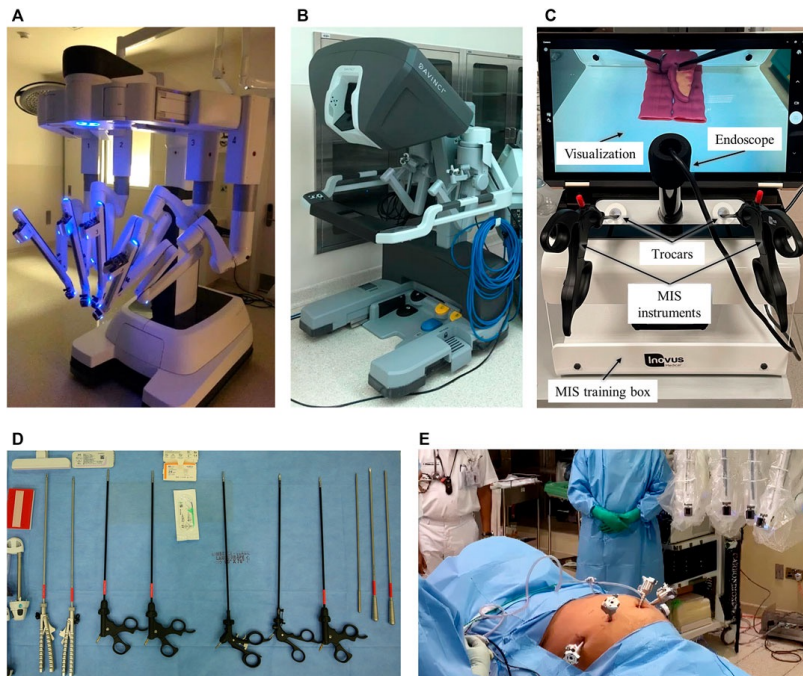


Figure 3. Minimally Invasive Surgery Systems.

From a surgical perspective, the robotic system provides superior visualization and enhanced dexterity. The sophisticated camera used in robotic surgery offers magnified, high-definition 3D views of the surgical area, improving visualization and precision [19]. Furthermore, as in the Table 3, the robotic arms have a greater range of motion and can make more exact movements than a human hand, allowing for complex and delicate dissection or reconstruction [20].

Table 3. Advantages of the key features

Advantage	Description
Reduced Pain and Discomfort	Smaller incisions lead to less pain and discomfort for patients
Faster Recovery	Minimally invasive approach allows for quicker return to normal activities
Minimal Scarring	Smaller incisions result in minimal scarring for patients
Enhanced Visualization	High-definition 3D camera provides magnified views of the surgical site
Improved Precision	Robotic arms offer greater dexterity and precision than human hands
Ergonomic Comfort	The robotic system provides an ergonomic working environment for surgeons

The advantages of robotic surgery extend beyond the operating room. Patients may benefit from reduced complications, shorter hospital stays, and faster recovery times [9]. The minimally invasive approach and enhanced precision offered by robotic systems aim to create the safest and least invasive option for surgery, with the belief that minimally invasive techniques should be the standard of care [21].

2.1 Applications in Various Specialties

The da Vinci Surgical System has been widely adopted across various medical specialties, enabling minimally invasive procedures for a range of conditions. Some key applications include:

- **Urology:** Robotic techniques are the preferred method for radical prostatectomy, with over 60% of minimally invasive prostatectomies performed using robotic assistance. Robotic surgery is also used for procedures like nephrectomy and pyeloplasty.
- **Gynecology:** Over 60% of minimally invasive hysterectomies for endometrial cancer are performed robotically. Robotic surgery is also utilized for myomectomy, sacrocolpopexy, and other gynecologic procedures.
- **General Surgery:** Robotic options exist for procedures like cholecystectomy, hernia repair, and colorectal surgery, although they are less frequently utilized compared to other specialties.
- **Cardiothoracic Surgery:** Robotic techniques have been employed for mitral valve repair or replacement, coronary artery bypass grafting, and congenital heart procedures.
- **Pediatric Surgery:** Robotic surgery has been used for various pediatric procedures, including pyeloplasty, nephrectomy, and thoracic procedures.

Table 4. Common Robotic Procedures

Specialty	Common Robotic Procedures
Urology	Radical prostatectomy, nephrectomy, pyeloplasty
Gynecology	Hysterectomy, myomectomy, sacrocolpopexy
General Surgery	Cholecystectomy, hernia repair, colorectal surgery
Cardiothoracic Surgery	Mitral valve repair/replacement, coronary artery bypass grafting
Pediatric Surgery	Pyeloplasty, nephrectomy, thoracic procedures

While initially concentrated in urology and gynecology, the applications of robotic surgery continue to expand, with institutions like UC Davis Health offering minimally invasive and robotic-assisted procedures across various specialties, including cardiothoracic, gastrointestinal, head and neck, gynecologic oncology, spine, brain, and urology [22] as in the Table 4.

3. Overcoming Challenges

While robotic surgery offers numerous advantages, there are several challenges and limitations that need to be addressed:

- **High Initial Costs:** One of the primary barriers to wider adoption of robotic surgery is the high initial cost of the systems, which can range up to \$4 million. Additionally, there are ongoing maintenance and operational costs associated with these advanced systems.
- **Steep Learning Curve:** Surgeons must undergo extensive training to become proficient in robotic surgical techniques. The learning curve can be steep, potentially leading to longer operative times and increased risk during the initial phase.
- **Technical Failures:** Like any complex technological system, robotic surgical systems are susceptible to technical failures or malfunctions. These can range from minor issues to more significant problems that may require aborting the procedure.
- **Safety Concerns:** While robotic surgery aims to improve patient outcomes, there are inherent

safety concerns associated with the use of advanced technology in a surgical setting. Potential risks include instrument collisions, electrical arcing, and system errors.

Table 5. Crucial challenges

Challenge	Description
High Initial Costs	Robotic systems can cost up to \$4 million, limiting widespread adoption.
Steep Learning Curve	Surgeons must undergo extensive training to become proficient.
Technical Failures	Systems are susceptible to malfunctions or errors.
Safety Concerns	Potential risks include instrument collisions and system errors.

To overcome these challenges, hospitals and healthcare organizations must carefully evaluate the costs and benefits of implementing robotic surgery programs as in the Table 5. While the initial investment may be substantial, the potential for improved patient outcomes, reduced recovery times, and long-term cost savings may offset the high upfront costs. Additionally, robust training programs, strict adherence to safety protocols, and regular maintenance and updates of the robotic systems are essential to mitigate risks and ensure the safe and effective use of this technology [23].

4. Training and Certification

Proper training is crucial for surgeons to perform robotic surgery safely and effectively. A structured training curriculum incorporating evidence-based techniques and benchmarks for progress is recommended. The training process typically involves two main components:

1. Patient-Side Training

- Developing skills in patient positioning, port placement, and basic laparoscopic techniques.
- Mastering the ergonomics and setup of the robotic system.

2. Console Training

- Online modules and virtual reality (VR) simulators for initial skill development.
- Dry lab practice on inanimate models.
- Wet lab training using animal or cadaveric models.
- Supervised practice in the operating room under the guidance of experienced robotic surgeons.

Table 6. Training components and their description

Training Component	Description
Patient-Side	Patient positioning, port placement, laparoscopic techniques.
Console	Online modules, VR simulators, dry/wet lab practice, supervised OR cases.

In addition to technical skills, training programs also emphasize the development of non-technical skills, such as teamwork, communication, situational awareness, and decision-making as in the Table 6. These skills are crucial for effective collaboration within the surgical team and ensuring patient safety.

Structured curricula implemented at high-volume centers with qualified trainers have shown improved outcomes and reduced learning curves for novice robotic surgeons. For example, in Brazil,

the training curriculum consists of a basic/pre-clinical stage and an advanced/clinical stage, with requirements such as online training, simulator practice, and supervised procedures.

While there is currently no standardized credentialing process for robotic surgeons, efforts are being made to create a standardized curriculum with competency-based assessments. Organizations like the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) and the Minimally Invasive Robotic Association (MIRA) have published guidelines for the educational requirements and certification of robotic surgery [24].

5. Future Developments

The field of robotic surgery continues to evolve rapidly, with exciting advancements on the horizon. Recent technological developments include:

- **Haptic Feedback:** Researchers are working on incorporating haptic feedback systems into robotic surgical platforms. This technology would allow surgeons to experience tactile sensations, enhancing their ability to differentiate tissue types and apply appropriate force during procedures.
- **Multi-Jointed Robotic Arms:** Next-generation robotic arms with increased dexterity and a greater number of joints are being developed. These advanced arms will enable more complex and intricate maneuvers, expanding the range of procedures that can be performed robotically.
- **Single-Port Platforms:** While current robotic systems require multiple incisions for instrument access, emerging single-port platforms aim to minimize invasiveness further. These systems would enable surgeons to perform procedures through a single, small incision, potentially reducing patient trauma and recovery times.

Emerging frontiers in robotic surgery include:

1. **Miniaturization:** Researchers are exploring the development of miniaturized robotic systems, which could enable access to confined spaces within the body and potentially revolutionize areas like neurosurgery and microsurgery.
2. **AI and Machine Learning Integration:** The integration of artificial intelligence (AI) and machine learning algorithms into robotic surgical systems holds immense potential. These technologies could assist surgeons with tasks such as surgical planning, real-time guidance, and even autonomous execution of specific procedural steps.
3. **Telesurgery and Remote Surgery:** Advancements in telecommunication and robotic technologies are paving the way for telesurgery, where surgeons can remotely operate on patients located in different geographical locations. This could improve access to specialized surgical care in remote or underserved areas.
4. **Nanorobots:** The development of nanorobots, microscopic robots capable of navigating within the human body, could revolutionize minimally invasive procedures. These tiny robots could potentially diagnose and treat diseases at the cellular level, opening up new frontiers in precision medicine.
5. **Haptic Feedback:** As mentioned earlier, incorporating haptic feedback into robotic surgical systems is a significant area of research. This technology could enhance surgeons' ability to perceive tactile sensations, improving precision and safety during procedures.
6. **Personalized Surgery:** The integration of patient-specific data, such as medical imaging and genomic information, into robotic surgical systems could enable personalized surgical planning and execution tailored to each individual's unique anatomy and condition.

Table 7. Emerging Frontiers and their description

Emerging Frontier	Description
Miniaturization	Development of miniaturized robotic systems for confined spaces.
AI and Machine Learning	Integration of AI algorithms for surgical planning and guidance.
Telesurgery and Remote Surgery	Enabling surgeons to operate on patients remotely
Nanorobots	Microscopic robots for cellular-level diagnosis and treatment
Haptic Feedback	Providing tactile sensations to enhance surgical precision
Personalized Surgery	Tailoring surgical planning and execution to individual patient data

As these cutting-edge technologies continue to advance, they hold the potential to further enhance the precision, safety, and accessibility of robotic surgical procedures, ultimately improving patient outcomes and pushing the boundaries of what is possible in minimally invasive techniques as explained in the Table 7.

6. Conclusion

The field of robotic surgery has made remarkable strides in minimally invasive techniques, offering numerous advantages over traditional open procedures. From enhanced visualization and precision to reduced patient trauma and faster recovery times, robotic systems like the da Vinci Surgical System have revolutionized the way complex surgeries are performed across various medical specialties. However, challenges such as high costs, technical failures, and a steep learning curve must be addressed to ensure safe and effective implementation of this technology. As the field continues to evolve, exciting developments like haptic feedback, AI integration, and miniaturization hold the promise of further advancing robotic surgical capabilities. With ongoing research and innovation, robotic surgery is poised to reshape the landscape of minimally invasive techniques, offering improved patient outcomes, personalized surgical approaches, and the potential to expand access to specialized care, ultimately ushering in a new era of precision medicine.

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