Overview of General Advantages, Limitations, and Strategies

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For centuries surgical technique remained relatively unchanged despite an improved understanding of medicine. Only 30 years ago, the general surgeon's work spanned the abdomen, chest, neck, and soft tissues, but in the late 1980s, minimally invasive surgery (MIS) segmented general surgery into sub-specializations and challenged the general surgeon to learn new skill sets to take advantage of the innovative tech tools. More recently, the explosion of robotic technology is poised to repeat further segmentation and challenges the surgeon to adopt an even more advanced skill set to keep pace with more advanced technology that overcomes obstacles as rapidly as they are encountered [1]. This is especially so for single incision or no incision procedures. Robotic technology now enjoys a presence in cardiology, electrophysiology, neurology, gynecology, urology, bariatric, pediatrics, orthopedics, and radiosurgery. This introduction reviews general advantages and limitations related to technical and clinical aspects, strategies of robotics, and the future of robotics.

Technical Advantages of Robotics

In general, the development of robotic surgery with Intuitive Surgical's da Vinci platform has successfully built on the advantages of laparoscopic surgery and overcome its fundamental limitations allowing completion of complex and advanced surgical procedures with increased precision in a minimally invasive approach [2–4]. Technical advantages of robotics are plenteous and embrace mechanical improvements, surgery via telecommunication systems, and safe simulation systems that allow skill training prior to actual human procedures.

Improved mechanical advantages include enhanced stabilized three-dimensional stereoscopic vision of the operative field, boost visual sharpness, and depth perception beyond the standard laparoscopic monitor. Additionally, the ability to digitally zoom without sacrificing clarity provides greater confidence in preciseness of surgical dissection and reconstruction. The increased maneuverability of articulating wrist instruments created additional degrees of freedom from five movements to seven, improving the surgeons' dexterity and allowing greater precision in the

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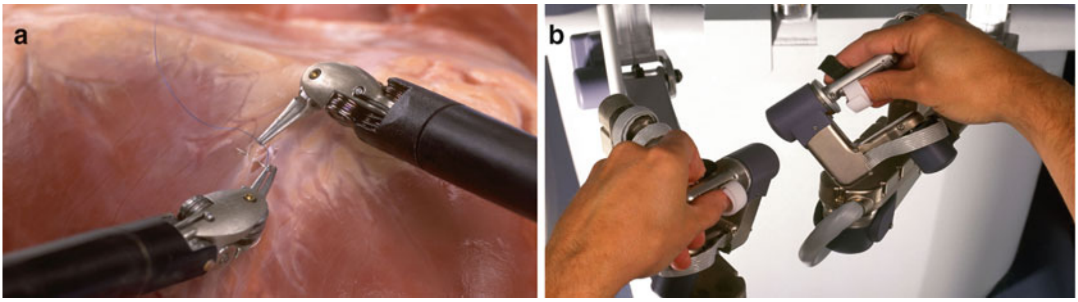

Fig. 3.1 Freedom of (**a**) movement and (**b**) instrumentation

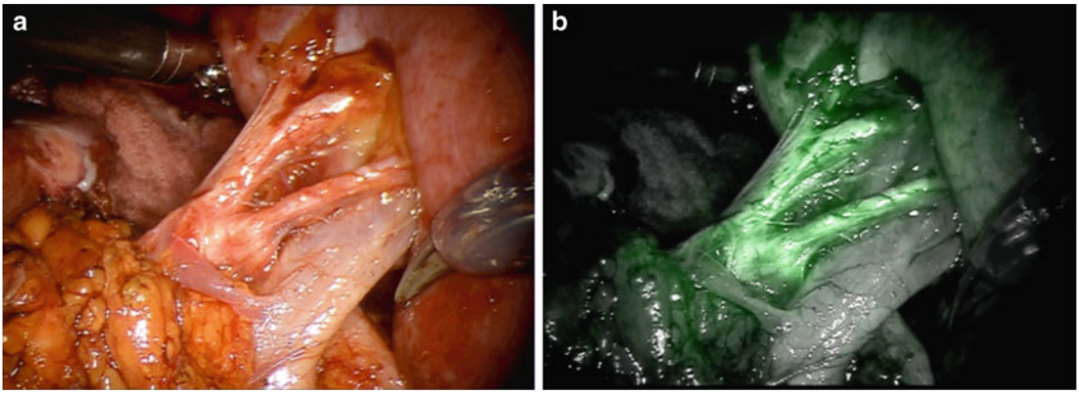

Fig. 3.2 (**a**) White light and (**b**) fluorescent imaging

surgical field, which more closely mimics open surgery (Fig. 3.1a, b). Coupled with this technology, hand stabilization eliminates surgeon tremor and allows for refinement of scaled movements.

This gives the surgeon the capability of adjusting the degree of precision of his or her motions from bold to very fine. One of the newest additions to the platform is a new integrated fluorescence imaging capability that provides real-time, image-guided identification of key anatomical landmarks using near-infrared technology (Fig. 3.2a, b). This allows the surgeon to visualize the end perfusion of the tissue of interest.

Linking the robot to a telecommunication device creates two new revolutionary applications. The SOCRATES system achieves a "telepresence" surgery with "telerobotic" and "telementoring" capability [5, 6]. In a telerobotic procedure, the surgeon, operating from a console miles away from the slave robot, guides the procedure via fiber-optic cable. In 2001, the first major transatlantic surgery via telerobotic presence was a cholecystectomy performed by robot in Strasbourg, France, by surgeons in New York, NY [7, 8]. Since then, many telerobotic operations have been performed allowing surgeons to operate where their skills are needed without being in the direct presence of the patient. Proponents of telerobotic surgery tout the beneficial delivery of surgical care in medically underserved areas [9, 10]. However, the cost of a surgical robot (>$1 million) is beyond the financial ability of many medically underserved areas, but when finances are not limiting, robotic surgery presents the potential for delivering surgical care to patients who have no direct access to a surgeon [11, 12]. In telementoring, two surgeons located a distance away "share" the view of the surgical field and control the robotic system, communicating via microphones. This system has advantages for teaching surgical skills to fellows, junior surgeons, and advanced medical students all around the world by expert colleagues [13–15].

A robotic simulation system provides a medium for anyone to acquire or refine their surgical skills, thus reducing the learning curve and surgical error [5]. Utilizing the 3D, virtual reality of the simulator, visual simulations, and soft tissue models recreate the textures of human tissues through forced feedback haptics [15, 16]. Image-guided simulations of the anatomy of the actual patient allow for practice of planned reconstructions prior to the actual procedure [17–19]. Since all surgical movements in both simulation sessions and actual surgery are automatically captured as objective precise data measurements by the robotic system, they can be utilized as a means for establishing surgical proficiency criteria, measuring quality improvement in surgical skill; provide hospitals quality measures on surgeons; and as best practice for educational instruction. In due course, simulation training may be integrated into surgical course work and licensing of surgeons to provide an objective means for assessment of surgical effectiveness.

Clinical Advantages

Clinical advantages for robotic surgery touch the patient, the surgical institution, and the healthcare insurer. Due to greater precision, smaller incisions, lack of fatigue during extended operative procedures, reduction of blood loss, less pain, quicker healing time, and a reduction of complications, benefits such as reduced duration of hospital stays, transfusions, and use of pain medications are common. Patients undergoing robotic procedures typically return to normal activity faster and experience very low mortality and morbidity events [1]. The advantage of multiple robotic arms that do not become fatigued, hold instruments steady, and provide constant strength in holding selected tissue opens greater surgical opportunity to the morbidly obese patient or patient with difficult anatomy (usually due to scaring or altered anatomy from prior abdominal surgeries) and allows multiple teams of surgeons to seamlessly and effortlessly transition during extended procedures, making wider range of procedures more realistic.

Technical and clinical advantages of robotics have been well documented, and safety has been substantially established with many series of cases reporting favorable outcomes [20–23]. Robotic technology is expected to play an increasingly important role in the future of surgery.

Limitations in Robotics: Technical and Clinical

Technical limitations form the drawback for the majority of resistance to robotic surgery. Near the top of the list is the decreased tactile feedback sense. It remains that the robot is still a self-powered, computer-controlled device not intended to act independently from human surgeons or to replace them [1, 3, 11]. Although true "feel" of tissues has yet to be realized, there are some crude haptics that occur if the instruments bump or hit each other (usually due to poor trocar placement or planning), transmitting a tactile sensation back to the surgeon's console finger apparatus. Otherwise, the surgeon must maintain visual contact through the monitor to guide the instrumentation and ensure appropriate and safe manipulation is preserved. It has been our experience that with time working with the robot, it may become possible for visual cues to become so strong a faux tactile sensation can be realized.

The size of the available robotic instruments becomes a real limitation in certain surgical specialties. For example, the trocar and instrument size in relation to the pediatric patient may prevent its advantage in this population. In otorhinolaryngology and head and neck surgery, this small area of accessibility also limits the use of robotics.

More minor technical limitations include the bulkyness of the robot, extended time to set it up in position for activity, and difficulty traversing wide fields. While bulkyness may be a valid issue in a small operating space, the time to set up can through practice be reduced to less than 5 min. Traversing multiple quadrants has been addressed through alternate positioning of the robot at the head of the patient and a specific five or six trocar placement system that avoids patient repositioning (cite book1).

Clinical Limitations

Although rapidly overcoming technical limitations, robotic surgical technology has yet to achieve its full potential due to substantial clinical limitations. Undoubtedly, the greatest clinical limitation is the cost of the robot system. Two studies comparing robotic procedures with conventional operations showed that although the absolute cost for robotic operations was higher, the major part of the increased cost was attributed to the initial cost of purchasing the robot [24, 25]. Coming in at over $2 million, $500–$1,500/case in disposable costs, maintenance cost upward to $100,000/year, and robotic instruments limited to a fixed number of uses (unrelated to instrument wear), the cumulative cost is prohibitive to most healthcare organizations. Even in the USA, surgical robots are chiefly limited in availability to hospital systems and large academic centers. Factors such as more wide spread acceptance, decreased operative times, complications, and hospital stay will contribute to the cost-effectiveness. Conversely, further technical advances may at first drive prices even higher. Although there is research and development currently underway to develop indefinitely reusable instruments, until then the robot remains a major capital expense to the bottom line. It has been estimated that the sum of these costs each year is approximately 10 % of the capital acquisition cost [24, 25]. The cost factor also becomes prohibitive to the spread of telerobotic technology to underserved areas that need it most. Studies to determine the cost over time vs. reduction of morbidities and mortalities and associated collateral costs are needed to better evaluate the long-term cost/benefit ratio. Ultimately, it is felt that competition and marketing of various robotic systems such as the Amadeus from Titan Medical, Inc. (Canada), the ARAKNES robot from SSSA BioRobotics Institute and Surgical Robotics S.p.a.'s Surgenius (both from Italy), the DLR system (Germany), and Mazor Robotics Ltd's SpineAssist (Israel) may drive costs down.

Another major limitation is that performance of robotic procedures requires specialized training. A chief complaint is the steep learning curve to become proficient in the needed technical skills. While a hybrid laparoscopic and robotic approach has been suggested, nothing can substitute time logged on the simulator or the actual robot [1]. However, the majority of hospitals, fellowships, and residency programs in the USA do not provide formal training in robotic surgery skills. This glaring deficit of development in surgical technology needs to be addressed as robotics is likely to reshape the way we practice surgery.

A review of residency programs in the USA shows an inadequate emphasis on training in robotic surgery [11]. A 2002 survey reported 23 % of surgical program directors have plans to incorporate robotics into their programs [26]. Sadly, the same survey group also reported that although 57 % of surgical residents indicated a high interest in robotic surgery, 80 % did not have a robotic training program at their institution [27]. Currently, individual hospitals bear the burden of ensuring competency to perform robotic procedures. There is a glaring need for standardized credentials to be developed and required to obtain robotic surgical privileges.

In conjunction with training, documentation and publishing of clinical randomized controlled trials comparing robotic-assisted procedures with laparoscopic or open techniques are needed to inform data-driven decisions for the surgeon, hospital administrator, and medical education institutions in regard to cost, training, and clinical effectiveness of robotics.

Robotic surgery, while still in a relatively early stage, is on a continuous journey that will have substantial implications for the future of surgery. This emerging technology allows surgeons to perform operations that were not so long ago, impossible, tedious, visually and physically challenging, replete with complications, and not amenable to minimal access techniques. The future of robotics is yet to be fully written but is already holding great promise.

Future of Robotics

The future of robotics is poised to include earth, under the sea, and space—the great frontier. In 2005, studies were already underway by the National Aeronautics and Space Administration

(NASA) for robotic application in emergency surgery on astronauts in a submarine to simulate conditions in space [28]. The project is called NEEMO 7. Additionally, testing telerobotic capabilities, the Pentagon also invested $12 million in a project using a “trauma pod” surgical robot. The system tests the ability to evacuate wounded soldiers under enemy fire and then operate on them [11, 29]. To address the size limitations of instruments and versatility, the University of Nebraska Medical Center has led a multicampus effort to provide collaborative research on mini-robotics among surgeons, engineers, and computer scientists [30].

Although surgical robotics is growing, the market is yet to be fully matured. Concerns regarding costs, standardization for evaluating surgeon skill level, robotic education to the medical student, and other challenges remain; however, as more industry investments are made and more competition develops for robotic systems, robotics will become the primary mechanism for surgical interaction with the patient. The digital platform will allow for infinite opportunities to produce learning avenues, a higher quality surgeon, and make surgery safer, better, faster, and ultimately cheaper.

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