Introduction

The introduction of minimally invasive surgery techniques during the 1980s by a French surgeon is considered one of the most disruptive surgical innovations, to the point that it has been defined “The second French revolution.” Minimally invasive surgery follows the fundamental principles of traditional open surgery with the considerable advantage of reduced tissue trauma because the operating field is obtained through limited skin incisions, and organ manipulation is carried out using microinstruments. Minimally invasive surgery can be seen as an initial movement towards a surgeon-patient distancing process. However, minimally invasive surgery poses some difficulties: a reduced depth perception because the standard flat monitors offer a 2D vision; the hand-eye disjunction that produces a loss of the visual haptic drive; a reduced and focused field of view; and a reduced tactile sensation. Computer sciences and robotics have produced, at the end of the 20th century, the technology to facilitate minimally invasive surgery. The commercially available surgical platform, the DaVinci® system (Surgical Intuitive, Inc., Sunnyvale, CA) is equipped with a binocular camera that provides a stereoscopic, 10-fold magnified and high-resolution view. It also offers a haptic interface that allows the surgeon to operate while comfortably seated. The surgeon controls the effectors with natural movements of his hands that are precisely replicated through the Endowrist® technology with a downscaled, tremorless motion (Figure 1). Robotics has pushed to the extreme the possibilities of the surgeon-patient distancing process by laying the groundwork for the “telesurgery.”

Robotic assistance confers undeniably increased dexterity to the minimally invasive surgeon. Whether this improvement translates into significant benefits to the patient...
is still a matter of debate. However, the robotic telemanipulator remains a very appealing cutting-edge technology that plays a substantial marketing role and can increase patients’ recruitment. Disadvantages such as higher costs and longer set-up times as compared to open and laparoscopic surgery may be reduced by an increased experience with robotics and by the upcoming rupture of the monopoly of Surgical Intuitive with new generations of surgical all-in-one robotic platforms that are appearing in the market.

**Robotic assistance in gastrointestinal surgery**

While for simpler digestive surgical procedures such as cholecystectomy, laparoscopic hernia repair, gastric banding or sleeve gastrectomy, the place of robotic assistance seems today very limited, with unfavorable cost/benefit ratio for patients, some very demanding laparoscopic techniques might greatly benefit from robotic assistance with possibly increased widespread penetration. As an example, laparoscopic pancreatoduodenectomy that has been performed since the 1990s had a very timid uptake. Giulianotti et al. first reported a series of 60 robot-assisted laparoscopic pancreatoduodenectomies. The authors could conclude that the robotic approach was safe with a complication rate comparable to that of open surgery and with the advantages of a minimally invasive approach. Similarly, robotic assistance could be beneficial in liver surgery offering microsurgical dissection and control of the elements of the hepatic pedicle, especially in cases in which a biliary reconstruction, difficult in standard laparoscopy, should be needed. The largest series on robotic liver resections has been reported by Giulianotti et al., including 27 major (≥3 liver segments) and 43 minor liver resections. We recently performed a series of robotic liver resections under augmented reality guidance. The real-time guidance based on a patient-specific 3D anatomical model obtained by a software reconstruction of preoperative imaging combined with the enhanced skills offered by the robotic manipulator allowed a straightforward segmental liver resection with precise vascular control of the portal branches and precise identification of resection margins.

For esophageal oncologic surgery, robotic assistance may improve the dissection in the thoracic cavity thanks to the greater dexterity, the three-dimensional magnified view, and the ability to achieve a stable exposure. However, no randomized trials have been performed and current evidence insufficient to support the wide use of robotic technology in this field. Similarly, many investigators believe that robotics can facilitate accurate lymph node dissections in minimally invasive gastrectomy for cancer. However, although safe and feasible, real benefits of robotic gastrectomy remain elusive.

Laparoscopic RYGBP is a particularly challenging procedure with a steep learning curve. Robotics has the potential to decrease the minimum number required to achieve proficiency as reported by some authors. In addition, the enhanced suturing ability may be used to perform stapler-free, “manual” gastrointestinal anastomoses within a convenient operative time frame. Colorectal surgery is another field of gastrointestinal surgery in which robotics could ensure continuity towards a wider implementation of the minimally invasive approach. It has now been ~10 years since the first robotic colorectal resections, and some evidence of potential benefits are being reported, especially in rectal resections with a significantly lower conversion rate to open surgery. Despite the fact that these data come from non-randomized studies, these cumulative experiences encourage further trials in rectal robotic-assisted surgery. The 3D stereoscopic magnified view may be a valuable adjunct for a nerve-sparing total mesorectal excision and functional outcomes could be the optimal endpoint to further assess robotic dexterity in the pelvis.

**Telesurgery**

The idea to apply robotic technologies to surgery dates back to the 1970s when a military project of the National Aeronautics and Space Administration (NASA) aimed to provide surgical care to astronauts with remotely controlled robots and to replace the surgeon’s physical presence in situations of mass casualties in hostile environments such as war or natural catastrophes. The first generation of surgical robots that entered the OR was designed to perform image-guided precision tasks, but was limited by basic computer interfaces. The evolution of surgical robots has led to a current generation of real-time telesmanipulators. In these units, the “master” control console, from which the surgeon operates, is physically separated from the “slave” unit, composed of the robotic arms performing surgery on the patient. Data transmission speed is the main challenge in remotely controlled operations, particularly when dealing with large distances or in the presence of insufficient retransmission infrastructures. Network latency affects the surgical performance with a longer task completion time of a factor of 1.5 and 2 in the presence of delays of 250 msec and 500 msec, respectively, when compared to no time delay. Latency in data transmission limited telesmanipulation to a few hundred kilometers. In September 2001, the first transatlantic surgical procedure (Operation Lindbergh) was performed by our team over the distance between New York (United States) and Strasbourg (France). Lindbergh opera-
ion is considered the milestone of global telesurgery.4,5 The surgeon was controlling the master unit in New York, while the patient in Strasbourg was operated by the Zeus® telesurgical system developed by Stanford Research International. This technical exploit was made possible thanks to the efforts of France Telecom providing high-speed fiber-optic connection with an average delay of 155 msec with advanced asynchronous transfer mode. The ultimate application for robotic telesurgery is probably the one that was initially conceived by the NASA: to provide surgical care to astronauts during long-lasting, extreme-distance space explorative missions in which self-sufficiency of the space crew to face surgical emergencies is mandatory. The challenges that must be overcome to make this possible are still manifold: the ability to perform surgery in reduced gravity conditions, portable and light equipment and, most importantly, the possibility of cosmic distance data transmission. The feasibility of zero-gravity surgery has been demonstrated with a cyst removal on a human subject onboard the European Space Agency (ESA) Airbus A-300 Zero-G Aircraft. Weightlessness phases were achieved performing parabolic flights. In addition, intensive research in miniaturization of surgical telesurgical systems is underway and a number of prototypes have been built with the aim to extend the possibilities for telesurgery, offering more versatile platforms. An example is the M7, which is a light and portable robotic device developed by Stanford Research International, equipped with 2 arms with 7 degrees of freedom (DOF), and which integrates haptic feedback. The software of the M7 is suitable for teleoperations and, in September 2007 it was successfully tested in the NASA first Zero-Gravity robotic experience during parabolic flights.6 Real-time interaction between the ground and the spacecraft is inversely related to distance. Internet-based communication speed is sufficient to practice telesurgery on planet Earth, with delays of ~400 msec. With satellite-based transmissions (signals propagating at light speed = 300,000 Km/sec), ~1 second delay would be experienced for an Earth-Moon distance, which can still be sufficient for basic remotely controlled procedures. Increasing the distance, as an example, for an average orbiting distance between the Earth and Mars (72 million Km), the delay would be ~6 minutes, which means that both remotely controlling real-time procedures and telementoring would not be possible. The limitation for effective telementoring is probably below a 60 second delay. Beyond this range, a trained surgeon should be onboard and able to perform “solo.”

Preoperative simulation using virtual reality patient models and real-time guidance systems based on Augmented Reality could provide support to resolve the issue of semi-real-time monitoring of the surgical act. Virtual reality medical software programs may elaborate a 3D virtual model of the patient from Digital Imaging and Communication in Medicine (DICOM) format images. This 3D virtual model enables navigation through the human body and performing a virtual exploration, highlighting anatomical details that might be underestimated on a customary image.6,7 Virtual exploration can be used during the preoperative phase to plan and simulate the surgical procedure. During the intraoperative phase, the 3D virtual reality model may be superimposed onto real-time patient images providing augmented reality. This fusion of live images and synthetic computer-generated patient-specific images may provide the surgeon at extremely remote distance a powerful navigation tool, highlighting target structures and anatomical variations. In this interactive operating room configuration providing computer-assisted navigation, ground-spacecraft communication lag time would become less significant (Figure 2).

Telesurgery is fascinating but not yet mature and is pervaded by significant challenges including data transfer speed, lightweight surgical robotic platforms, and cost-effectiveness. Potential benefits of telesurgery are becoming evident with the development of telementoring programs. The specific applications of space missions and military projects could well be the impulse for further developments.

References


