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Robotic surgery: potentials, barriers, and limitations

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Roboterchirurgie: Möglichkeiten, Barrieren und Hindernisse

Zusammenfassung. *Grundlagen:* Laparoskopische Chirurgie stellt die Voraussetzungen für die Einführung von Computer- und Robotertechnologien in der Chirurgie dar. Roboter und Computertechnologie können die Geschicklichkeit verbessern, Bewegungsabläufe und Videosignale digitalisieren und Informationen komprimieren und über weite Entfernungen übertragen.

Methodik: Literaturübersicht über experimentelle und klinische Anwendungen der Roboter-assistierten Chirurgie.

Ergebnisse: Viele klinische Serien haben Machbarkeit und Sicherheit Roboter-assistierter Chirurgie aufgezeigt. Trotzdem fehlt die Evidenz für einen klinischen Benefit. Viele Bereiche der Roboterchirurgie werden noch nicht ausreichend ausgeschöpft, wie zum Beispiel die ferngesteuerte Operationstechnik und die Integration von Robotern und virtuellen Technologien.

Schlussfolgerungen: Viele Eingriffe in der Allgemeinchirurgie können heute sicher Roboter-assistiert durchgeführt werden. Zukünftige Entwicklungen, welche Roboter und ferngesteuerte Chirurgie sowie virtuelle Realität verbinden, werden die medizinische Versorgung verbessern und leichter machen.

Schlüsselwörter: Roboter, virtuelle Realität, chirurgische Ausbildung, Zeus-Operationsroboter, da-Vinci-Operationsroboter.

Summary. *Background:* The advent of laparoscopic surgery has created the room for the introduction of computer and robotic technologies in surgery. Robotic and computer technologies can be used to enhance dexterity, digitize gestures and video signals, and compress information that can be transmitted over a distance.

Methods: We reviewed current literature about clinical and experimental applications of robotics-assisted surgery. In this article we give an overview of the most important advances and issues deriving from the application of robotic technologies in surgery.

Results: Many clinical series have documented the feasibility and safety of robot-assisted surgery for virtually any kind of operation in general surgery. However, evidence of significant clinical benefits is still lacking. Important aspects of robotic technology, such as remote surgery and integration of robotic and virtual-reality technologies have not been fully exploited.

Conclusions: Robotics-assisted surgery is feasible and safe for many operations in general surgery. Further technical development, particularly in the field of remote surgery and virtual-reality technology applied to robotics, will likely boost application of robotic surgery and possibly improve both patients' care and surgical education.

Key words: robotics, virtual reality, surgical education, Zeuss surgical system, da Vinci surgical system.

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Introduction

The advent of laparoscopy paved the way for the introduction of robotics into surgical operations. In laparoscopic surgery the procedure is performed under the guidance of images displayed on a video monitor using specific instruments through the abdominal wall and with fixed entry points. This creates limitations of the movement of instruments to only four degrees of freedom and amplifies the physiologic tremor of the surgeon's hand. Basic surgical maneuvers in open surgery such as suturing become highly difficult tasks in laparoscopy and require specific technical skills. To overcome the issue of dexterity in complex procedures, the concept of a "master–slave" telemanipulation system was developed in the early 1990s, however, a major goal of this project was to develop telesurgery to operate on patients from remote places such as battlefields or outer space. Current robotic machines should be defined as a computer interface between the surgeon and the patient, which is often referred to as "computer-assisted surgery". Typically, robotic systems are based on the two physically separated subsystems. The surgeon's subsystem has a console that takes the surgeon's input, while the robot subsystem (located at the patient's side) translates the input into actual instrument manipulation and endoscopic camera's control. Importantly, robotic telemanipulation systems have computer interfaces that allow digitalization of the surgical movements and images. Once digitized, this information can be modified to filter and exclude nonfinalized movements (i.e., physiologic tremor of the surgeon) [1] potentially resulting in greater dexterity and precision for performance of difficult tasks [2–4]. Furthermore, through telecommunication lines, digitized information can be transmitted to remote locations, potentially enabling surgeons not only to deliver surgical care in remote or underserved areas but also to enhance surgical education.

Clinical applications of robotic surgery

Since the mid-nineties, robotic assistance has been used for virtually any type of abdominal operations. Our group performed laparoscopic robotic cholecystectomy in 25 patients with no robot-related morbidity and with operative time and patient recovery similar to those of conventional laparoscopy [5]. Cadiere et al. [6] have reported a series of 146 patients undergoing robot-assisted laparoscopic surgeries, including antireflux procedures, gastroplasties, cholecystectomies, inguinal hernias, hysterectomies, and prostatectomies.

Robot-assisted Nissen fundoplication is the only procedure in general surgery for which a randomized controlled clinical trial currently exists [7]. Results of this trial showed that robot-assisted and laparoscopic conventional Nissen can be performed with similar blood loss, length of stay, and perioperative morbidity. The only significant difference was the main operative time. Standard laparoscopic cases had a main operative time of 52 minutes compared with 76 minutes in the robot-assisted group ($P < 0.01$).

Another prospective nonrandomized study was performed by Melvin's group [8] and compared 20 consecutive robot-assisted Nissen fundoplications to 20 consecutive standard laparoscopic Nissen fundoplications. The clinical outcomes were similar in both groups, and as in the previous study, the robot-assisted procedures took longer operative time (average of 45 minutes longer). More than 250 reported robot-assisted Nissen fundoplication procedures in the literature in multiple small case series, almost all have similar clinical outcomes.

The robotic systems may show a real benefit when used in advanced esophageal surgery. The improved visualization afforded by the robot's magnified three-dimensional view and the enhanced range of motion should be very helpful, particularly in totally laparoscopic transhiatal approach, where the dissection high up in the mediastinum will be much facilitated under vision and using the multiarticulated robotic wrist. Experience with the robot-assisted esophagectomy however is limited, although both total transhiatal esophagectomy and thoracoscopic resection of esophageal leiomyoma have been reported using the da Vinci system [9].

In performing a robot-assisted hand-sewn gastrojejunostomy for completion of the laparoscopic Roux-en-Y gastric bypass procedure, the hope would be to decrease the risks of leak and/or stricture reported with conventional laparoscopic approach using circular stapler. In theory, the microprecision of the articulating instruments and 3-dimensional view may facilitate completion of the hand-sewn anastomosis, especially when the working space beneath the liver is decreased as in superobese patients with enlarged left lobe of the liver. The first robot-assisted gastric bypass was done in September 2000 by Horgan et al. [10]. Published data reveal more than 100 cases of robot-assisted Roux-en-Y gastric bypasses by 7 surgeons in the United States in 2003 [11]. In this series of combined experience, results seem promising because the leak and anastomotic stricture rates approached 0%. One stricture that required dilatation was reported. Four additional complications were related to robotics. However, some difficulties in port placement and robotic arm movement were reported in this series.

Robot-assisted colorectal procedures have been reported, including right and left hemicolectomies, anterior resection, abdominoperineal resection, rectopexy, and total colectomy with postoperative results similar to those of standard laparoscopic series.

D'Annibale et al. [12] compared the outcome of 53 colorectal procedures performed by means of the da Vinci system with the results obtained in 53 colorectal procedures performed by conventional laparoscopic techniques during the same time interval.

In 22 patients of the robotic group, the pathology was cancer, 4 with stage 0, 2 with stage I, 11 with stage II, and 5 with stage III. This study showed that robotic and laparoscopic techniques can achieve the same operative and postoperative results but the authors suggested that the dexterity and flexibility of the da Vinci system may be useful in certain stages of the surgical procedure (splenic flexure takedown, dissection of the inferior mesenteric artery with identification of the nervous plexus, and dissection of a narrow pelvis). There is indeed a potential advantage in using robotic technology for rectal surgery as the enhanced dexterity afforded by these machines may facilitate nerve-sparing total mesorectal excision in a deep narrow pelvis. However, this theoretical advantage needs to be demonstrated by clinical trials for justification of the cost of adoption of this technique in colorectal surgery.

Giulianotti et al. [13] reported 21 patients who had robot-assisted laparoscopic gastric surgery; 18 patients with gastric carcinoma underwent D2 subtotal ($n = 8$ cases) or D2 total ($n = 10$ cases) gastrectomy, 2 patients with unresponsive benign gastric ulcers received partial gastrectomies, and 1 underwent a wedge resection of the gastric fundus for a carcinoid tumor. Morbidity was 9.1% for robot-assisted subtotal gastrectomy and 30% for robot-assisted total gastrectomy. The operative time for robot-assisted procedures was almost twice that for open gastrectomies.

The same team [13] reported 13 robot-assisted laparoscopic pancreatic procedures for benign and malignant pathology, including both pancreaticoduodenectomy and distal pancreatectomy with morbidity and mortality comparing favorably with their own open experience.

Robotic assistance has been also used for laparoscopic adrenalectomy [14], nephrectomy [6], and radical prostatectomy [15, 16]. The latter indication is today considered as the best application of robotic technology in surgery.

Endoscopic cardiac surgery, including coronary artery bypass and mitral valve repair [17, 18] is a further important field of application of robotic surgery and will probably benefit in the future by the possibility to operate on a beating heart through motion compensation, which would allow the surgeon to manage any moving structure with the same precision as if it was perfectly still [19].

The analysis of clinical applications of robot-assisted surgery suggests that at least so far, the application of robotic technology has not translated into clear benefits and improved outcomes in general surgery. One of the major drawbacks is the fact that robotic operations generally take longer than standard laparoscopic operations. This is because of several technical reasons. One is that when using robotic systems the surgeon is hampered by the complete lack of tactile feedback from the operating instruments. There is also a variable amount of time that is spent to set up the equipment and this has an impact on the overall operative time. Moreover, the robotic system can interfere with other OR equipment, X-ray and anaesthetic facilities in the available OR space.

However, on the other hand, experiences in different centers, both clinically and experimentally, are suggesting that the use of robotic systems does not result in specific complications and achieves outcomes at least similar to those of standard laparoscopic procedures. This is an important finding. In fact, the demonstration of the feasibility and safety of using robot assistance for several surgical procedures should be seen as an encouraging starting point. Many limitations indeed should be seen only as temporary drawbacks that newer technologic developments will likely soon overcome.

Remote surgery

Robotic technologies can also be used to perform remote surgery, intended as the performance of a surgical operation from a long distance. There had been general conviction that application of remote surgery would be limited to telementoring rather than to remote manipulation due to the issue of time delay. For the transmission of information, indeed, video images and surgical manipulations must be compressed with algorithms that require significant time and processing power. The time lag is defined as the delay for an instruction to be locally encoded, propagated over a transmission line to a remote machine, decoded, and executed. Due to the latency factor, the feasible distance for remote surgery was supposed to be no more than a few hundred miles over terrestrial telecommunications [19], while satellite systems which have a latency of nearly 1.5 s are considered unsuitable for performing long surgery. Since 1994 at the European Institute of Telesurgery we have set up a program aimed to verify the feasibility of surgery over long distances. Using asynchronous-transfer-mode telecommunications, our group was able to decrease the time lag across transoceanic distances to less than 160 ms [20]. This allowed the performance of laparoscopic cholecystectomy on six pigs during July 2001 and on September 7, 2001, the first long-distance remote operation on a human being, between New York (surgeons) and Strasbourg (patient) [21] using the Zeus surgical system (Computer Motion Inc, Santa Barbara, Calif., U.S.A.).

Anvari and colleagues [22] reported a series of remote surgeries between a teaching hospital (St. Joseph's Hospital in Hamilton, Canada) and a community hospital (North Bay General Hospital) more than 400 km away. Since February 28, 2003, the date on which the service commenced, until March 2005, a total of 21 telerobotic laparoscopic surgeries have been undertaken, including 13 fundoplications, 3 sigmoid resections, 2 right hemicolectomies, 1 anterior resection, and 2 inguinal hernia repairs. The telesurgical robotic system used was the Zeus TS microjoint system. The telecommunication link was provided by a commercially available IP/VPN (Internet protocol virtual private network) with quality of service which linked the 2 hospitals at a bandwidth of 15 Mbps. With a commercial fiber-optic network already in existence between the rural and teaching hospitals in Canada, the latency experienced by the telerobotic surgeon was 135–140 ms. The ability to use such a network means that this service can be expanded with lower costs.

Remote surgery has both limits and advantages. Limitations include the availability of high-speed telecommunication lines, costs, ethical and legal issues, clinician–patient relationship, and shortages of surgeons with proper dedicated training. These issues are however balanced by a number of potential advantages not only for health care delivery capabilities but also for surgeons' training and teaching as well. Remote surgery might also determine a better standardization of surgical care throughout a country and throughout the world and improve surgical outcomes by reducing the detrimental effects of the early phase of the learning curve. Infrequently performed or technically demanding operations, new minimally invasive techniques, emergency operations in small rural hospitals to be performed by young surgeons on call, patients located on islands or military areas are just some examples in which an active intervention from a remote expert is suitable. Remote surgery means that all degrees of intervention, from the complete performance of an operation to simple assistance and exposure of structures, are possible. This might reduce errors that are caused by lack of experience or related to the early phase of the learning curve of surgeons for new procedures.

Potentials and future perspectives of robotic surgery

Technological developments may actually revolutionize the same concept of robotic surgery as it is intended and performed today. Indeed, if we consider that robotic systems are truly information systems, where computer interfaces are placed between the surgeon and the patient, it appears clear that we have not at all exploited all the potentials of robotic machines. It is very reasonable to expect that future developments of dedicated software and systems will result in significant enhancement of the performance of surgical robots as well as in an expansion of their clinical applications.

For instance, an enhancement of robotic technology for surgical application may be achieved by implementing virtual and augmented reality in robotic systems. Today, three-dimensional reconstruction of anatomical and pathological structures is mainly used for diagnostic purposes. Virtual colonoscopy, gastroscopy, and virtual reconstruction of liver tumors are being performed in specialized centers. At the European Institute of Telesurgery, we use virtual reality for reconstruction of adrenal glands and tumors, as well as for imaging of biliary tract and liver pathology [23]. The interest in using these virtual-reality tools is that anatomy can be seen from different points of view while transparency and intraluminal navigation add to the comprehension of the anatomy as well as perhaps enhance our ability to detect tumoral invasion.

However, virtual reality is not restricted to diagnostic interest. Three-dimensional reconstructions indeed could also be applied to simulate a surgical procedure in a virtual environment. In such a type of setting, a surgical operation can be performed several times and rehearsed till the best possible performance is delivered.

Preoperative planning of robotic arms with the virtual images of a real patient can help to determine the best robot setup in the OR and to predict possible conflicts between robotic arms, thus possibly reducing the operative time.

Furthermore, in our institute, computer scientists have developed a system that is able to filter out movements of a mobile structure and synchronize a robotic arm with it in order to maintain a constant distance between the tip of a tool and a target area. This system could be used to filter out physiologic respiratory excursions of the diaphragm or the beating of the heart. This system holds great potential for performance of complex tasks such as suturing with fine sutures on a beating heart and possibly for future automation of surgical procedures. Although this might appear an unrealistic expectation, by simulation of a surgical procedure on a real patient's anatomic reconstruction, one can rehearse a procedure or a task (i.e., needle puncture of a hepatic lesion for radiofrequency ablation) several times till a certain standard of performance is achieved. Then, digital data of the selected best performed procedure can be stored and transferred to a robotic system and automatically reproduced on the actual patient, with obvious advantages.

By coupling remote expert assistance with virtual-reality technology and surgical simulation, we might achieve a reduction in medical errors related to the early phase of the learning curve. This would translate into reduced health costs, indeed overcoming the current drawback of costs of robotic systems.

With further development of robotic technology we can expect newer systems made available by the industry, with features and capabilities not yet provided by the ones we have at present. It is obvious that cardiac surgery, urology, gynaecology, and general surgery have different needs and problems and therefore require different technical solutions. In the near future, we might have robotic systems dedicated to surgical subspecialties which may perhaps better achieve the goal of improving performances and outcomes.

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