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The ZEUS robotic system: experimental and clinical applications

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In the last decade, virtually all open surgical procedures have been shown to be feasible with a minimally invasive approach, and there is a growing body of evidence that laparoscopic surgery is preferable to the open approach, due to a wide array of benefits including shorter hospital stay, less pain, better cosmetic results, and faster return to normal activities.

Laparoscopic procedures, however, pose technical challenges to the surgeon who is a novice to this approach and specific training and skills are needed to achieve all the possible benefits of laparoscopic surgery. Indeed, surgeons are hampered by the lack of tridimensional view and of haptic sense, as well as by the limitations imposed by remote operating. Unlike in open surgery, where the surgeon has a great degree of flexibility in positioning his elbow, wrists, and fingers, and can control his actions by direct visual and tactile feedback, 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 limits the movement of instruments to only four degree 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 that the surgeons need to learn. Moreover, the need for a human assistant to hold and move the camera adds further disadvantages; fatigue, tremors, orientation errors, and unstable camera may compromise the smoothness of the operation.

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The limitations of laparoscopic surgery mostly depend, as we have just said, on the physical separation between the surgeon and tissues and organs; however, this feature is the truly revolutionary aspect of laparoscopy, because this physical gap gives access to robotic and computer interfaces. The computer allows digitization of the surgical movements and images. Once digitized, this information can be modified to filter and exclude nonfinalized movements (ie, physiologic tremor of the surgeon) [1], potentially resulting in greater dexterity and precision for performance of difficult tasks [2]. 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.

There are several robotic systems currently available for general surgery and surgical subspecialties. This article reviews the experimental and clinical use of the ZEUS robotic system and discusses its possible role in the operating room of the future.

The ZEUS robotic system: history

The first applications of robotics in surgery were actually camera-holding and guidance systems. In 1994, the Food and Drug Administration (FDA) approved the use of AESOP (Automated Endoscopic System for Optimal Positioning) from the American company Computer Motion (Goleta, California). This robotic arm was designed to offer direct control over the laparoscope by means of a foot pedal and later on by voice control. The advantage of AESOP lies in the ability to have a steady view of the operative field, eliminating the possibility that an assistant's inexperience and fatigue could affect the smoothness of performance, especially during long-lasting cases [3,4].

To overcome the issue of dexterity in complex procedures, the concept of a master-slave telemanipulation system was developed in the early 1990s; one of the most important driving forces behind this concept was the goal of developing telesurgery to operate on patients from remote places such as battlefields or outer space. Initially, Computer Motion developed the telemanipulator system ZEUS specifically for cardiac operations, mainly to facilitate internal mammary artery harvesting and coronary artery bypass grafting. Later on, ZEUS was also used for laparoscopic procedures in animal models to verify the feasibility and applicability of robotic systems in different surgical areas, including general surgery, gynecology, urology, and pediatric surgery. In recent years, the ZEUS system has also been used clinically in several surgical specialties, and clinical series have attested its utility in gynecology and urology. In October 2001, the FDA granted limited clinical approval for abdominal operations in the United States.

The ZEUS system

The ZEUS system consists of two physically separated subsystems named "surgeon-side" and "patient-side" (Fig. 1). The surgeon's subsystem has a console that takes the surgeon's input; the patient's subsystem includes two robotic arms that translate the input into actual instrument manipulation and an additional robotic arm to control the endoscopic camera and that can be controlled by voice command. A variety of surgical instruments can be connected to the robotic arms, so that the surgeon can activate graspers, scissors, hook, and so on by simply manipulating the handles at the remote console. The three arms are independently attached to the operating room table and are controlled by a computer located within the surgeon's console. The surgeon sits in a comfortable chair in front of the video monitor and the computer interface can eliminate the surgeon's resting tremor and be set to downscale the surgeon's hand movement over a range of 2:1 to 10:1. The most recent version of ZEUS uses more ergonomic handles and a Storz three-dimensional (3D) imaging system (Karl Storz Endoscopy, Tuttlingen, Germany). The 3D imaging system is based on two separate right and left video cameras that visualize the operative field, a computer that merges and accelerates the broadcasted frames from the two videocameras, and a video monitor with an active

Fig. 1. The ZEUS subsystems: the surgeon's robotic console; robotic arms on the patient's side.

matrix covering its surface. The surgeon wears glasses that have a clockwise polarizing filter as the right lens and a counterclockwise polarizing filter as the left lens, and that allow the left eye to see only images coming from the left camera while the right eye sees images from the right camera. This system causes a 3D image to be projected from the video monitor.

Experimental use of ZEUS

Inanimate models have been used to investigate the feasibility and potential advantages of using the ZEUS robotic system for basic maneuvers and intracorporeal suturing. Garcia-Ruiz and coworkers [1] compared the manual performance of laparoscopic tasks and suturing to robotically assisted performance by twenty surgeons without previous experience of robotic surgery. These authors reported accurate reproduction of surgeon movements and efficient filtering of resting tremor by the robotic system. Moreover, although using robotic assistance resulted in longer operative times for suturing tasks using sutures size 2-0 and 4-0 ($P < 0.001$), they found no time differences for suture sizes 6-0 and 7-0, emphasizing the possibility that greater potential for using robotic assistance might be found in procedures requiring fine suturing tasks. Other studies documented the feasibility of performing coronary artery bypass surgery with ZEUS in plastic models [5], live animal models, and cadavers [6,7].

Lomanto and coworkers used ZEUS to perform cholecystectomies in seven pigs [8], with an operative time of 46 minutes (range 30–62), and interestingly found that practice resulted in dramatic reduction of setup time (from 30 to 14 minutes). Zhu et al [9] reported also the feasibility of robotic assistance for colecystojejunostomy (Roux-en-Y anastomoses) in the porcine model. Compared with standard laparoscopic approach, the authors found that robotic assistance resulted in longer operative time, but no leakages were found in any animal undergoing robotic-assisted anastomosis.

Hollands and coworkers [10] reported faster performance of porcine entero-enterostomies with ZEUS compared with standard laparoscopic techniques.

The same group also compared the repair of a choledochotomy in pigs using standard laparoscopic techniques with the same procedure performed using ZEUS [11]. In this experiment, the ZEUS repair required longer operative time, but resulted in significantly fewer complications, suggesting that suturing on the biliary tract with ZEUS may offer advantages over traditional laparoscopic techniques.

Our group has recently verified the feasibility of performing robotic-assisted carotid artery repair (unpublished data) in pigs, using a fully endoscopic approach and CO2 insufflation to dissect the common carotid artery. The interest of the model of endoscopic carotid surgery lies in the fact that porcine carotid artery has an average diameter of about 3 mm, and that using size 7-0 sutures for carotid repair represents a technical challenge requiring stability and very fine maneuvers in a confined space [12]. The model may be used to create extreme conditions where the advantages of using robotic systems may be better tested. A comparative study between robotic carotid repair and standard endoscopic carotid surgery is under trial at the time of this writing. At our institution, Dr. Joel Leroy has also conducted a study to investigate the feasibility of robotic assistance for hepatecomy in pigs. The study was performed on 15 pigs, and robotic assistance was found particularly suitable for dissection and ligature of the elements of the hepatic pedicle.

Margossian et al demonstrated that ZEUS-assisted suturing for uterine horn anastomoses resulted in a high degree of patency 4 weeks after surgery [13], emphasizing the potential role of robotic assistance for microsurgical suturing.

Gill et al have used ZEUS in experimental studies for pieloplasty, nephrectomy, and adrenalectomy in the porcine model [14]. The authors reported longer operative time for robotic pyeloplasty compared with laparoscopic pyeloplasty, but ZEUS assistance resulted in five watertight anastomoses out of six performed, compared with three out of four in the conventional laparoscopic group.

Other groups have specifically evaluated the impact of using ZEUS for instructing medical students, surgical residents, and surgeons in advanced laparoscopic techniques [1,14,15]. In summary, these studies showed that, whereas robotic assistance conferred little or no advantage on performance of simple tasks, suturing or other more complex tasks were accomplished with greater speed and precision when performed with ZEUS, regardless of the prior level of training of each surgeon. These data suggest that robotic assistance might facilitate the learning and performance of complex laparoscopic operations. A team at the University of California, Los Angeles has recently reported higher accuracy scores in knot-tying tasks with ZEUS compared with conventional laparoscopy among a group of junior residents [16].

Clinical use of ZEUS

Cardiac surgery

Most of the clinical series reported so far in the literature about patients operated on using the ZEUS system are related to this area. Operations include mainly mammary artery harvest, coronary artery bypass, and mitral valve surgery. Boyd and coworkers [17] have reported a series of 104 patients undergoing endoscopic harvesting of internal thoracic arteries (ITA) with use of both the AESOP system and ZEUS robotic telesurgical system. Average ITA harvest time was 61.3 ± 20.9 minutes, and there were only three distal ITA injuries; all the remaining vessels were patent after harvesting and demonstrated no angiographic evidence of injury.

In 1999, Reichenspurner et al reported the first successful clinical use of ZEUS for coronary artery bypass [18]. Two patients were operated on with the ZEUS system. Both the endoscopic harvesting of the left internal mammary artery and the anastomosis of the bypass graft with the left anterior descending coronary artery were performed endoscopically with the ZEUS system. More recently, the same group reported a series of 41 patients with single and multivessel disease operated on using the ZEUS system [19]. The average time for endoscopic anastomosis was 41 minutes on the arrested and 36.5 minutes on the beating heart, with an overall duration of surgery between 4.0 and 8.0 hours. The total patency rate of all graft anastomoses was 97%. Prasad et al [20] reported the first prospective clinical trial of robotically assisted endoscopic coronary bypass surgery in the United States. Nineteen patients underwent coronary artery bypass grafting of the left internal thoracic artery to the left anterior descending artery, with favorable short-term outcomes and no adverse events.

Several other groups have reported smaller series of successful internal mammary arteries harvesting and anastomosis with the left anterior descending coronary artery.

Luison and Boyd [21] have also reported a pericardiectomy accomplished with a 3-D imaging system and Grossi et al [22] have used ZEUS for mitral valve surgery.

The team of Dr. Laborde in Paris, France reported robotic assistance for closure of a patent ductus arteriosus [23]. Among 56 children undergoing this surgical procedure, 28 patients underwent conventional videothoracoscopic technique and 28 underwent a robotically assisted approach with the ZEUS system. The robotically assisted approach required a longer operative time but was otherwise comparable with the videothoracoscopic technique in terms of complications and postoperative hospital stay.

Abdominal surgery

It was not until October 2001 that the FDA granted ZEUS limited clinical approval for abdominal operations in the United States. Therefore, clinical applications of ZEUS in general surgery have been almost all anecdotal so far. Our group at the European Institute of Telesurgery (EITS) in Strasbourg, France, has reported a clinical trial using ZEUS in abdominal surgery [24]. From September 1999, robotic-assisted laparoscopic cholecystectomy was performed on 25 patients as part of a nonrandomized, prospective study. The aim of this study was not to verify the advantages of using robotic assistance for cholecystectomy, but rather to identify whether using robotic systems in abdominal surgery could result in potential harm to patients and to test the acceptability of this system into a current operating room (OR) by surgeons and OR personnel in general. Twenty-four of the 25 laparoscopic cholecystectomies were successfully completed with robotic assistance; one procedure was converted to conventional laparoscopic cholecystectomy. Setup and takedown of the robotic arms took a median of 18 minutes. The median operative time for dissection and the overall operative time were 25 and 108 minutes, respectively, and there were no intraoperative complications. Operative times and patient recovery were similar to those of conventional laparoscopy performed routinely at our institution. This was the first step of a larger program, which, based on the robotic systems' ability to convert the surgical act into digitized data, aims to develop remote surgery and implementation of pre- or intraoperative imaging studies into surgical strategy to achieve better preoperative planning, and possibly automation of surgical operations.

At the 2003 SAGES Meeting, Dr. P. White from the Albert Einstein College of Medicine in New York City presented the data of a multicenter prospective randomized study performed in the United States comparing ZEUS-assisted Nissen fundoplication with the conventional laparoscopic approach [25]. One hundred patients were randomized in two groups of equal number of patients. In the ZEUS arm, surgical and procedure time were longer than in conventional laparoscopy; however, complications, blood loss, and functional outcomes were similar between groups. In the same meeting, the same team reported another randomized trial in which 50 patients were randomized to ZEUS-assisted laparoscopic cholecystecomy while 50 patients underwent the conventional laparoscopic procedure [26]. The findings of this study were quite similar to those of the Nissen trial. Indeed, patients undergoing ZEUS-assisted laparoscopic cholecystectomy experienced longer operative time, but blood loss, hospital stay, and adverse events were comparable between the two treatment groups.

These reports demonstrate that robotic assistance using the ZEUS system is as safe and effective as standard laparoscopic procedures, but also emphasize that, at least at the present time, longer operative times and no significant clinical benefits can be expected from the use of robotic assistance in general abdominal surgery.

Gynecology

After describing the first case of ZEUS assistance for tubal reanastomosis in 1999 [27], Falcone et al reported a series of 10 patients with previous tubal ligations undergoing laparoscopic tubal ligation reversal using the ZEUS system [28]. Tubal suturing was performed with a two-layered application of 8-0 polygalactin sutures. The procedure was completed successfully in all 10 patients without conversion to open surgery and with no complications. The mean time required to complete the anastomosis of both tubes was 159 ± 33.8 minutes. A postoperative hysterosalpingogram 6 weeks after surgery showed patency in 17 of the 19 tubes anastomosed (89%), demonstrating adequate patency rates.

Urology

Guillonneau et [29] al have performed robotic-assisted, laparoscopic pelvic lymph-node dissection in 10 consecutive patients with T3 M0 prostatic carcinoma, and have compared operative, postoperative, and pathological parameters with the results of their last 10 patients undergoing conventional, laparoscopic pelvic lymph-node dissection for similar indications by the same operator. The authors reported no specific intraoperative or postoperative complications in the robotic group. Mean operating time for the robotic group was 125 ± 57 minutes (range 75–215), significantly longer compared with that of their conventional laparoscopic experience ($P < 0.01$). The histological results concerning the number of lymph nodes removed were similar in both groups.

Remote surgery

The most important limitation for the performance of robotic assisted procedures across long distances was considered to be the reliability (or quality of service) of the telecommunication lines and the issue of latency (the delay time from when the hand motion is initiated by the surgeon until the remote manipulator actually moves and the image is shown on the surgeon's monitor). Due to the latency factor, it was believed that the feasible distance for remote surgery was no more than a few hundreds miles over terrestrial telecommunications [30]. Since 1994, surgeons and computer scientists at EITS and telecommunication and robotic engineers from Computer Motion have joined in a common effort aimed at verifying the feasibility of surgery over long distances. This project was articulated in several steps that ended on September 7, 2001 with the performance of the first transcontinental robot-assisted laparoscopic cholecystecomy on a human between New York (surgeons) and Strasbourg (patient) [31,32].

The ZEUS system was used in all the steps of this project. The first series of our experiments estimated the maximum time delay compatible with safe performance of surgical manipulations at about 300 msec. Subsequently, we measured a mean time delay of 155 msec over transoceanic distances when using dedicated ATM fibers [31]. This extremely short delay allowed the safe performance of a remote laparoscopic cholecistectomy in six pigs and has provided the basis for the clinical application, which was carried on successfully without specific difficulties or complications due to the use of the teletransmission of the surgical procedure [32].

The use of remote surgery in a routine fashion will depend upon a balance between real benefits and limitations. The latter include medico-legal issues and a lack of legislation regulating the practice of surgery across different countries, and the need for a specialized workforce and networks of appropriate telecommunication lines between hospitals. Costs are also another relative drawback at the moment. In spite of these limitations, however, potential benefits of remote surgery are multiple. Many abdominal operations can indeed be performed laparoscopically now, but complex procedures are still in the hands of a limited number of experts. Remote robotic assistance may perhaps provide useful help to inexperienced surgeons in the early phase of the learning curve. Furthermore, patients will be able to receive the type of treatment best suited to their condition, ideally in any part of the world. Challenging emergency operations in small rural hospitals could be performed by a young surgeon on call under the guidance of a distant expert from a major center. Availability of expert surgeons might also very well help in remote areas where military or scientific missions are being performed, or on remote islands.

Current limitations and future perspectives

One of the major technical criticisms of robotic systems is that they are associated with a lack of tactile feedback from the operating instruments, which is only in part compensated for by the 3D visual feedback. This may be a temporary drawback, as technology evolves rapidly and significant research efforts are focusing on the issue of providing tactile feedback to robotic systems. Recently, a group of scientists in Spain has developed a robotic finger with a sense of touch. This is made of a special polymer called polypyrrole, which expands in response to electric current and conducts differently in response to changes in pressure. This robotic finger can feel the weight of what it is pushing and adjust the energy it uses accordingly [33]. This report is promising and suggests that in the foreseeable future, technologic advancements may overcome, at least in part, the lack of tactile sensation characteristic of current robotic systems.

There is a variable amount of time during robotic procedures that is spent to set up the equipment, and this has an impact on the overall operative time. Although the setup time may be acceptable for complex surgeries, it is still too long for simpler operations and for a daily practice. Also, the robotic system can interfere with other OR equipment, such as radiograph and anesthetic facilities, in the available OR space. This limitation may be reduced by integrating robotic systems into the design of the operating room and operating tables.

So far, clinical and experimental studies have demonstrated the feasibility and safety of robotic assistance. Experiences in different centers, both clinically and experimentally, show that the use of the ZEUS system does not result in specific complications and achieves outcomes similar to those of standard laparoscopic procedures. It is a common findings, however, that the use of ZEUS increases operative time of procedures. Furthermore, all clinical studies performed so far failed to provide any evidence of specific patient benefits in general surgical procedures.

Although the lack of verifiable clinical benefits may be frustrating, the demonstration of the feasibility and safety of using ZEUS assistance for several surgical procedures should be seen as an encouraging starting point.

In fact, as Dr. Satava pointed out, "robotic systems are not a mechanical system but indeed an information system," where computer interfaces are placed between the surgeon and the patient. From this perspective, the future development of computer technologies and their applications might result in significant enhancement of performance of surgical robots. Current technology, indeed, already allows 3D reconstruction of anatomical and pathological structures. Translation of medical information contained in images into a set of 3D models would allow development of an actual interaction of virtual instruments with the virtual organs. Simulating a surgical procedure in a virtual environment would allow surgeons to perform it several times and rehearse it until the best possible performance is delivered. In theory, the digital data of the selected best-performed procedure could be stored and transferred to a robotic system to be automatically reproduced on the actual patient, with obvious advantages.

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