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Developing Robotic Procedures: New Technology and Applications for Medicine

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In open surgery, the motility of the wrists and hands inside the abdomen allows all kinds of movements in all kinds of directions. In laparoscopy, however, the fact that one must work through a fixed opening with straight instruments means that the number of degrees of freedom is limited. The remaining degrees of freedom concern in and out, top to bottom, rotation, and oscillatory movements. Procedures are performed under visual guidance from a two-dimensional screen that is relatively immobile and cannot always be placed in the working axis (1–3) throughout the procedure. These conditions result in awkward operating positions and impaired dexterity (4–6).

A computer-guided mechanical interface, commonly referred to as a "robot," allows for the following: restoration of lost degrees of freedom thanks to an intraabdominal articulation of the surgical tools; three-dimensional visualization of the operative field at all times in the same direction as the working direction; modulation of motion amplitude by stabilizing or downscaling; and remote control surgery (telesurgery). Because of these improvements, surgical tasks can be performed with greater accuracy and in a perfect ergonomic position (7).

To place a computer interface between a surgeon and a patient should allow enhancement of the surgeon's skills and possibly revolutionize surgery in the same way as it did in aviation (Fig. 1).

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DEVELOPMENT OF ROBOTIC PROCEDURES

The first laparoscopic robotic procedure on human beings was performed in March 1997 by our team in Belgium (8). The MONA system (Intuitive Surgical, Mountain View, CA) was used (Fig. 2). Following this experience, we worked at improving the various components of the system: the surgical cart containing the robot arms, the computer, and the working console. The most significant innovation was changing the shape of the clinical laparoscopic tools to handles resembling joysticks. In May 1998, our team performed the first two Nissen fundoplications by robot technology at Broussais Hospital in Paris (9) (Fig. 3). In 1999 in Mexico, we performed a randomized trial comparing the robotic approach with the laparoscopic approach for cholecystectomy and Nissen fundoplication (10). Data were recorded for the U.S. Food and Drug Administration.

After these experiences, the MONA system was improved. This resulted in the present da Vinci system. During this evolution, we succeeded in progressively cutting down on the need for the continuous presence of an engineer. We benefited from constant improvement in ergonomics and electronic performance at the console. The bulk of the robot was significantly reduced, and the tools were improved according to the needs of each procedure.

The U.S. Food and Drug Administration approved the da Vinci system for abdominal surgery in July 2000. Several teams have since adopted this system and are rapidly gaining experience with this novel surgery (11–14). Another manufacturer, Computer Motion (Goleta, CA), presently offers the Zeus system, which has

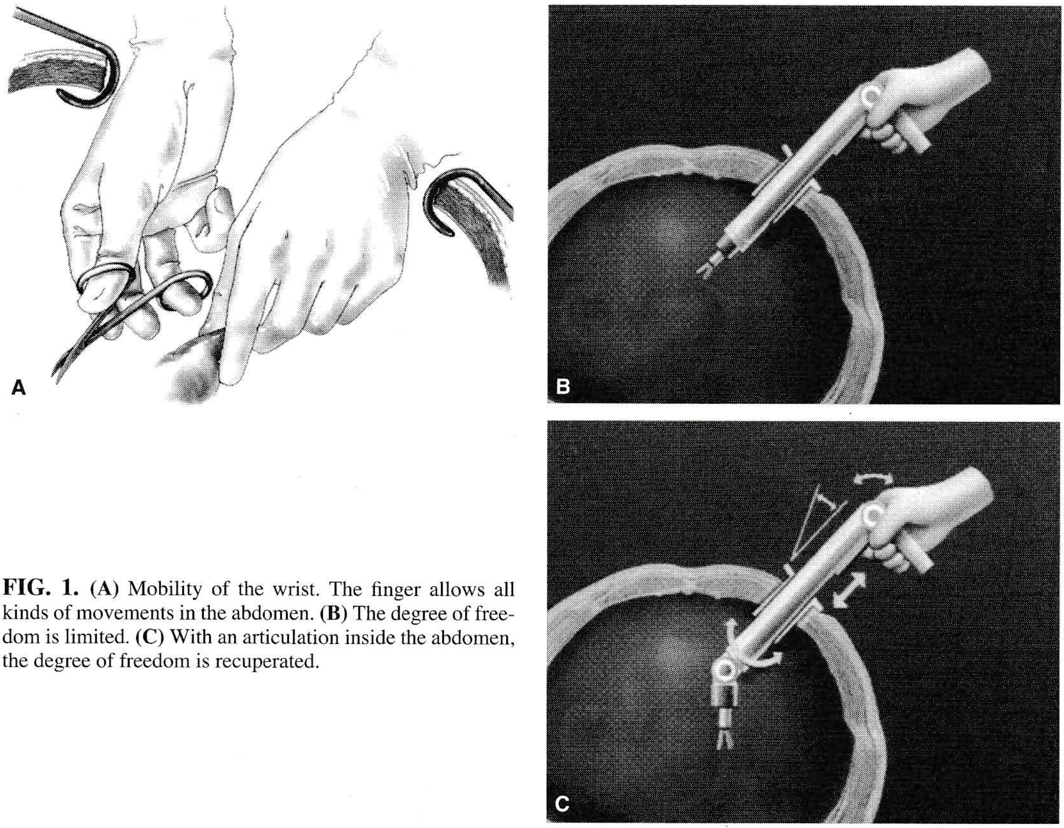


FIG. 1. **(A)** Mobility of the wrist. The finger allows all kinds of movements in the abdomen. **(B)** The degree of freedom is limited. **(C)** With an articulation inside the abdomen, the degree of freedom is recuperated.

been approved by the U.S. Food and Drug Administration for abdominal surgery as well (15).

The da Vinci system consists of two primary components: the surgeon's viewing and control console and a moveable cart with three articulated robot arms. The surgeon is seated in front of the console, where he/she manipulates handles that are similar to joysticks. This is the master part of the robotic system. The imaging system, which displays the operative field through binoculars, offers a high-resolution, truly three-dimensional image. Manipulation of the handles transmits the electronic signals to the computer, which transfers the exact same motions to the robotic arms. The computer interface has the capacity to control and modify the movements of the instrument tips by downscaling deflections at the handles by a factor between 5:1 and 2:1. It can eliminate physiologic tremor and can adjust grip strength applied to the tools. The computer-generated electrical impulses are transmitted by a cable (10 m long) and command the three articulated robot arms. Disposable laparoscopic articulated instruments are attached to the distal part of two of these arms and introduced inside the abdomen through trocars mounted on the arms. The third arm carries an endoscope with dual optical channels, one for each of the surgeon's eyes. In every procedure, the optimal placement of the slave arm trolley

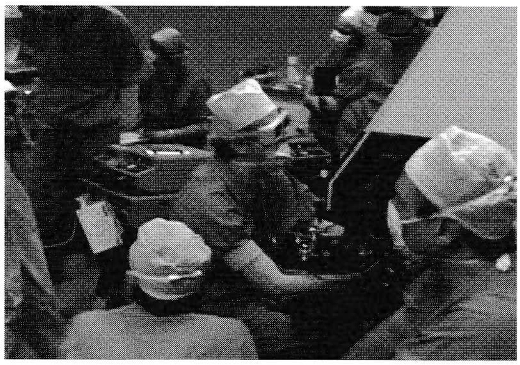
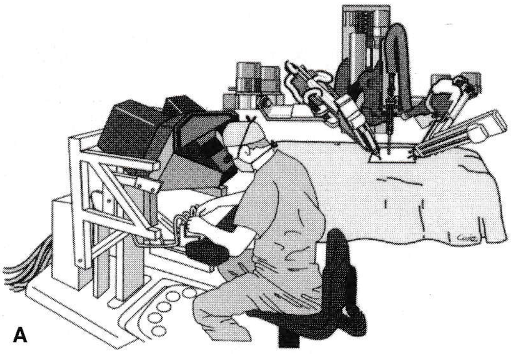


FIG. 2. First clinical prototype in 1997: a three-dimensional picture is obtained with specific glasses. The handles resemble the usual surgical tools.



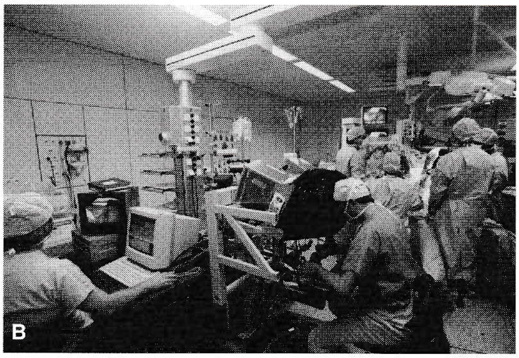


FIG. 3. (**A**) The MONA robot in 1998: binocular direct vision without glasses. (**B**) An engineer must be present at all times.

must be determined to accommodate the operating table and especially to avoid crowding by the slave arms during the operation (Fig. 4).

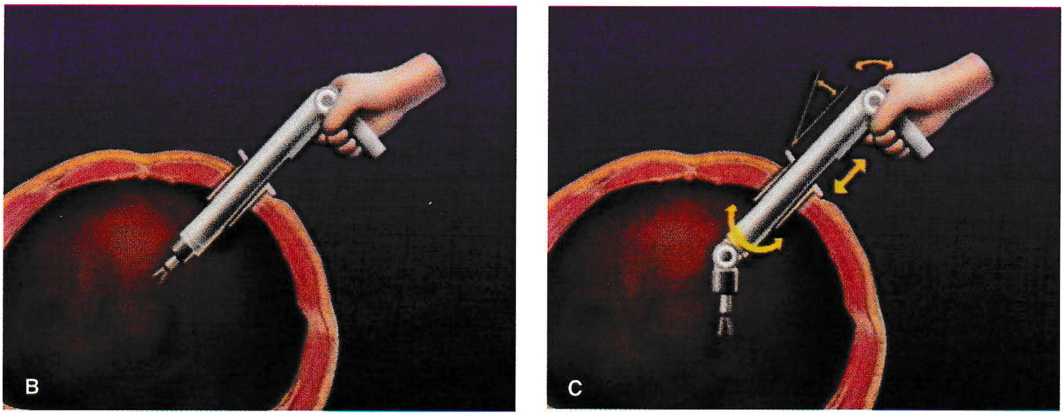
CLINICAL LAPAROSCOPIC EXPERIENCE UP TO 2002

Each procedure has its own characteristics. It appeared worthwhile to analyze some of the most common ones with reference to robotics. From 1997 to 2002, the following laparoscopic interventions have been performed with robot technology: antireflux surgery, appendectomy, cholecystectomy, deferent duct reanastomosis, endometriosis eradication, gastroplasty, hysterectomy, inguinal hernia, intrarectal procedure, lumbar sympathectomy, neosalpingostomy, gastrectomy, esophagectomy, pyeloplasty, prostatectomy, tubal reanastomosis, and varicocele ligation.

FIG. 4. The da Vinci system: the computer is integrated in the console.

The operative time for the Nissen procedure compares favorably with that for the laparoscopic procedure. We experienced substantial advantage from the articulated tools while dissecting behind and around the esophagus. Hence, it might be possible to consider for the future less extended dissection at the level of the peritoneal attachments of the stomach's cardia. This might render the procedure easier and more like the conventional open operation. Another step of the operation where the tools' articulations proved beneficial was the dissection of the short gastric vessels. Suturing the wrap appeared more straightforward, as it is easier to follow the curve of the needle while driving the suture through the tissues. We experienced a net improvement in tying the knots thanks to the articulated tools. The evaluation of the knots' tension is however more difficult, because there is no tactile feedback. The theoretical advantage brought by the downscaling ability did not add a substantial benefit in the fundoplication as compared with the laparoscopic technique. However, we did experience a significant drawback of the robot system in its present embodiment. As the three-dimensional optical system is characterized by a very narrow field of vision, we continuously had to interrupt the dissection for repositioning of optics. These frequent interruptions, as well as the absence of a general view of the operative field, might be responsible of the bleeding we encountered while dissecting the greater curvature with the robotic system. This bleeding necessitated conversion to a conventional laparoscopic approach.

In cholecystectomy, we had to change the conventional position of the trocars to accommodate



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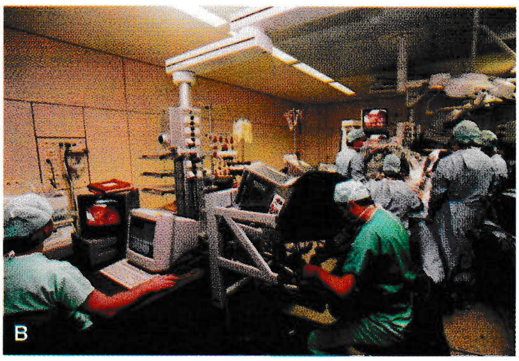

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the robot arms. We experienced significant benefit from the articulated coagulating hook in dissecting the anterior and posterior peritoneal sheet at the level of Calot triangle. We had similar benefit in dissecting the cystic duct and artery. The cystic duct could easily be ligated rather than clipped, just like in open surgery. The operative time depended merely on the degree of inflammation we encountered. However, we do believe that the robot did help us in the cases of acute cholecystitis, and the operative time tended to lessen as we gained experience.

In fallopian tube reanastomosis, the gold standard is still the open microsurgical approach because the conventional laparoscopic approach does not allow adequate microsuturing. With the computer enhancement and downscaling, suturing becomes more straightforward and more precise. The surgeon can rest his hands, and since all tremor is eliminated by the computer interface, suturing is extremely accurate, which results in excellent clinical results. In the robotic technique, however, operative time for the anastomosis is comparable with the gold standard, while hospital stay seems to be reduced.

In obesity surgery, it is difficult to manipulate the instruments as the thickness of the patient's body wall impairs the mobility of trocars and ancillary tools. The root-driven articulated instruments deal well with this condition. The problems of ergonomics encountered with massively obese patients are obviously solved by placing the surgeon at a working console at a distance. However, in the case of local hemorrhage, the surgeon cannot intervene and must rely on the skills of the assistant for control. This new situation can be extremely frustrating for the surgeon.

The new system has also been used for retroperitoneal procedures (retroperitoneal lumbar sympathectomy and preperitoneal inguinal hernioplasty). These procedures demonstrated the possibility of benefit from computer enhancement in very confined working spaces. Relatively complicated tasks like dissecting the minuscule rami communicantes in the close neighborhood of the large abdominal vessels were successfully achieved without problems.

In transanal intrarectal procedures, the surgical tools are very tangential with the lesion. With the da Vinci system, the three-dimensional image, together with the fully mobile articulations, brings every millimeter of this small cavity within reach and at a 90° angle of approach. The robot arms accurately repeat fingertip motions. The drawback of this approach is the relative bulk of the instruments and the optical system that needs to be introduced transanally.

In esophagectomy, the wide operative field is a continuous problem for the management of the surgical cart. However, the dissection of the intrathoracic part of the esophagus by the thoracoscopic approach causes less trauma in the intercostal space because of reduced motions of the trocars thanks to the improved freedom of motion of the intracavitary articulated tools.

In general, for the laparoscopic procedures mentioned, we did not encounter specific system-related morbidity. Operating time and hospital stay were within acceptable limits. The system appeared most beneficial in intraabdominal microsurgery and for manipulations in a very small space. Optimized ergonomics and increased mobility of the instrument tips proved advantageous in a few selected steps of abdominal surgical procedures.

The procedures in which the system is the most efficient are tubal reanastomosis, intrarectal procedures, and, considering our clinical experience, intrathoracic dissection of the esophagus (16–18). The current challenges of robotics include an operating field with the currently available scope that is smaller than conventional laparoscopic optics. There is no tactile feedback. The setup and tool change require extensive team training. Team cohesion is of the utmost importance as surgeon–assistant interaction is essential, especially in the case of hemorrhage or other perioperative mishaps. The cost issue must be revaluated once more widespread use of robotic systems has been achieved.

INDISPENSABLE INNOVATIONS WITHIN 5 YEARS

Two systems are commercially available, the da Vinci system and the Zeus system. Since we do not have experience with the Zeus system, our discussion will be related solely to the use of the da Vinci system.

The input system (i.e., the imaging system as well as all the afferences to the surgeon) and the output system (including the final surgical actions) are now mediated by a new technology commonly called robotics. This is a genuine revolution, but in 2003 we are still just at the dawn of a new era. There are arguments that indicate that this invention might trigger a commotion within the surgical community comparable with the introduction of the model T in the automobile sector. We now have to improve the system to make our "model T" look like a car of today. The improvements concern the technology itself, the codification of the surgical procedures, and the social organization around this new technology.

Regarding the afferences, the ideal optical system must of course provide a three-dimensional image. At present, to restitute the three-dimensional image, the optical system needs to be placed at too close a distance from the operative field, which leads to frequent changes in the angle of view. A system must be designed to restitute a wider view, the ultimate aim being a three-dimensional high-definition television picture that combines adequate three-dimensional perception with visual acuity. In addition, the fact that the actual visual input to the surgeon takes place from a remote point (video screen) technically permits integration of additional information. Indeed, the power of computerized graphics can be used to display digitalized pictures that can be overlaid, superimposed, or mixed with the actual "real time pictures" from the operative field on the video screen. Three-dimensional pictures can be obtained by magnetic resonance imaging or by computed tomography, which can be superimposed and thus compared with the actual three-dimensional operative view. The following improvements can be anticipated: reduction of the size of the trocars from 8 mm to 5 mm; reduction of the bulk of the robot, which so far takes a large place in the operating theater; return of tactile sensation; and addition of an articulation inside the abdomen to resolve the problem of crowding at the robot arms. This is a specific problem in abdominal surgery where more amplitude of movements is needed to cover an intraperitoneal field. One can imagine a tool looking like a Swiss knife at the tip of an instrument that would avoid continuous tool changes and would offer more autonomy for the surgeon. This will enable him/her to control suction and to tackle surgical bleeding. Once the problem of "arm crowding" is solved, one can consider an additional articulating arm controlled by the surgeon at the console.

The standardized codification of the procedures must be reinvented. Trocar placement must take into account the volume of the articulating arm and the presence of an articulation inside the abdomen.

This new technology implies a new social organization. There is now a need for a new individual dedicated exclusively to the well functioning of the robot during the procedure. We chose to call this person a clinical technician. This person needs a clinical as well as a technical background. His/her competence is the determinant factor in operative time and safety of the procedure. The surgeon must accept the consequences of performing the procedure at a distance from the patient and must rely more on technology.

We must resolve all these challenges for robotics to be more beneficial in a greater range of laparoscopic procedures and to be introduced in our everyday general surgical practice.

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