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# The da Vinci telerobotic surgical system: the virtual operative field and telepresence surgery

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The concept of telerobotic surgery was first developed with grants from the United States Department of Defense. The United States Army hoped to develop a mechanism by which combat surgeons could operate from a remote secure location on wounded soldiers on the battlefield [1]. The focus of this project was to attempt to minimize combat deaths with rapid surgical treatment of salvageable wounds. On the battlefield, 90% of all combat deaths occur before the soldier reaches a medical facility; few soldiers die after reaching military hospitals [2,3]. Hemorrhage from peripheral extremity major vessels accounts for most salvageable mortal wounds. The Army hoped to develop a new mechanism to surgically treat these life-threatening hemorrhages immediately on the battlefield [4].

The early work for the Army on telemanipulation was performed by SRI International, a research and defense contractor located in Palo Alto, California. In the early days of the SRI work, Phil Green and his colleagues were successful in building a device that demonstrated, in prototype form, the basic ability to perform remote surgical telemanipulation. The system was designed for large-incision, open surgical technique. Two large video cameras were placed above an operating room table to project the image of a patient from the battlefield back to the remote computer console at which the surgeon sits. This console (termed the "master") displayed the video image of the patient, and was designed to electronically accept and transfer the motions of the surgeon's hands, back to a two-armed telerobot (the

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"slave") at the surgical site. In this way, the surgeon was able to use a master/slave system to carry out surgical tasks at great distance from the patient [5].

The purpose of this early prototype system was to demonstrate feasibility of telemanipulation in open technique, and had little to do with minimally invasive surgery. One of the authors (FM), however, hypothesized that the true value of the SRI prototype was not as a demonstration of remote surgery, but instead represented the first step in a possible technical solution to the fundamental limitations of conventional laparoscopic technique. These limitations include lack of articulation of the instruments, inadequate precision, and nonintuitive motion due to the length of laparoscopic tools and the fulcrum effect created by the body wall. It was proposed that these fundamental technical shortcomings could be eliminated by electronically controlling and articulating the tip of an instrument, thus improving range of motion and dexterity.

Thus Intuitive Surgical was formed with the belief that telemanipulation, if converted into a format compatible with minimally invasive technique, could offer benefits to the surgeon superior to those of conventional endoscopic methods. In 1995, Intuitive licensed the rights to patents from SRI, International Business Machines, and the Massachusetts Institute of Technology and began work to build a telerobotic system whose specification included three basic components:

1. A master/slave, software-driven system that provided intuitive control of a suite of seven-degree-of-freedom laparoscopic instruments
2. A stereoscopic vision system displayed in an immersive format
3. A system architecture composed of redundant sensors to provided maximum safety in operation

One of the first decisions to be made in the development of the da Vinci system was to decide on a location, in virtual space, where the surgeon would "grab" the instrument. Because an electronic interface provides the freedom to choose the virtual location of the surgeon's hand, experiments were conducted to determine the optimal position. The concept of tip-to-tip control was evolved over a number of months of prototype development. A determination was made that to provide maximum control and dexterity, the surgeon's fingers at the master console should be connected, in a virtual manner, to the jaws of the instrument themselves. The preference for tip control, combined with the belief that it was critically important to provide seven-degree-of-freedom articulation at the instrument tip, demanded that software algorithms be developed to make tip movement intuitive. These transformations insure that when manipulating an articulated tool at the level of the instrument jaws via software, the surgeon's orientation is never lost, and the movements are true to the surgeon's intentions.

In March of 1997, Intuitive tested its first prototype in humans. This system demonstrated the benefits of articulating instruments, but also underscored the inadequacy of the currently available, off-the-shelf stereo endoscopes. Thus for the better part of 1998, Intuitive focused on the development of a binocular endoscope, which could achieve the stereo separation and resolution necessary for complex abdominal surgery and microvascular procedures in the chest.

In 1999, Intuitive completed development of the system architecture for da Vinci. This system combined cart-mounted robotic arms able to drive a variety of articulating instruments, and a master console that displayed a three-dimensional (3D) view gathered by a novel binocular endoscope. In addition, the da Vinci was equipped with an elaborate safety system designed to check its servomotors and verify the position of the teleoperated tool tip every 750 microseconds, thereby eliminating the possibility of erroneous movement.

The company completed a 200-patient randomized clinical trial, which demonstrated both the safety and efficacy of the device in the procedures of cholecystectomy and Nissen fundoplication. The completion of this trial, together with a formal review of the submitted data, led to Food and Drug Administration (FDA) approval of the da Vinci robot in July of 2000. In the remainder of this brief introductory article we provide a detailed description of the da Vinci telerobotic surgical system. We describe each of its components and explain how the surgeon controls each of the telerobotic functions. Finally, we suggest what directions future evolution of telerobotics and telepresence surgery may take.

## da Vinci telerobotic surgery system

The da Vinci robotic surgical system consists of three main components. The surgeon sits at a surgeon's computer console. A cart encases the video and lighting equipment. A robotic tower supports the three or four robotic arms.

### *Surgeon's computer console*

The surgeon controls da Vinci at the computer console. This computer console is positioned remotely away from the patient. In its current configuration, a cable attaches the computer console to the video cart and robotic tower. The FDA requires that American surgeons perform telerobotic operations within the same operating room as the patient. The surgeon sits on a stool before the console.

### *Surgeon-robot interface*

The computer console serves as the interface between the surgeon and surgical robot (Fig. 1). The da Vinci is a master/slave type of robot. The surgeon is the master and controls all actions of the slave robot. The surgeon views the operation through binoculars housed in the hood of the

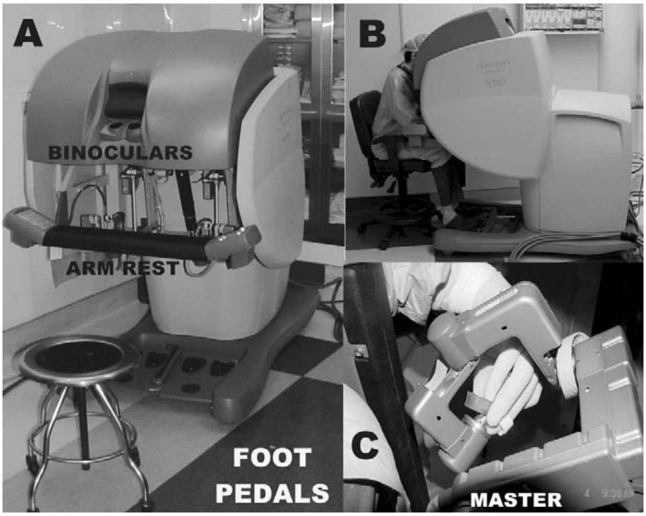


Fig. 1. The surgeon's master computer console for control of the da Vinci telerobotic surgical system. (*A*) The surgeon sits at the surgeon's console. He views the operation through the 3D binoculars and places his arms on the arm rest. (*B*) The hood of the console raises or lowers to a comfortable viewing height for the surgeon. (*C*) The individual left and right masters translate the motions of the surgeon's hand into motions of the telerobotic surgical instruments.

console (see Fig. 1A). An infrared beam deactivates the robotic tower whenever the surgeon removes his eyes from the binoculars. The surgeon's arms are supported by a padded armrest (see Fig. 1A). The surgeon's hands are inserted into freely moving "masters" (see Fig. 1C). The masters convert the 3D motions of the surgeon's hands into electrical signals. The computer translates these electrical signals into computer commands that direct the robotic instruments to perform identical 3D movements.

*Console controls*

Several mechanisms permit the surgeon to adjust specific functions of the video system and robotic arms. The armrest contains a panel of buttons. The surgeon raises or lowers the binoculars to a comfortable viewing height with one set of buttons. Another set changes the virtual operative field from two-dimensional to 3D imaging. Another toggles between imaging with 0° or 30° telescopes. The surgeon can also control motion scaling between movements of the masters and the translated motions of the robotic surgical instruments. The surgeon can select 1 to 1, 3 to 1, or 5 to 1 motion scaling. When the 5 to 1 scaling is selected, 5 in motions of the surgeon's hand are reduced to 1 in motions of the robotic instruments. The computer also filters out regular oscillations of the surgeon's hand motions, such as a resting tremor. In the new four-arm da Vinci, a set of buttons determines which two robotic arms the two masters control.

*Haptic feedback*

Webster's Unabridged Dictionary of the English Language defines haptics as "the branch of psychology that investigates cutaneous sense data" [6]. The da Vinci masters provide some tensile feedback to the surgeon. When tying a suture, for example, the masters indicate through resistance of movement the tension applied to the suture material by the two robotic arms. The resistance of the piano wires and pulleys in the robotic arms under some circumstances, however, will obscure this haptic feedback. In particular, bending the most distal articulation of the surgical instruments, their "wrists," eliminates the tensile feedback. Additional haptic sensors that provide tactile feedback are available but have not been incorporated into the da Vinci system. The surgeon indirectly gains tactile and tensile information through visual clues.

*Foot controls*

The surgeon controls other aspects of da Vinci's functions with five foot pedals (see Fig. 1A). The far right pedal activates electrocautery. The middle right pedal turns on ultrasonic instruments. The middle peddle adjusts the focal point of the video cameras. The middle left pedal acts as a clutch for the masters; stepping on this pedal allows the surgeon to disengage the masters from control of the robotic surgical instruments so that the masters can be repositioned in a more comfortable alignment. The far left pedal toggles the masters between control of the three or four robotic arms.

*Video cart*

The mobile video cart supports the components of the video imaging system. This includes the two video camera control boxes and the two light sources for the cameras. Controls on these components adjust brightness, contrast, and gain of the two video images. The synchronizer keeps the video frames of the two video cameras in phase. Other laparoscopy tools, such as insufflators, are often housed on the video cart. A video monitor rests on top of the cart for viewing of the operation by operating room personnel.

*Robotic tower*

The da Vinci robotic tower supports either three or four robotic arms. The original system offered three arms and a newer system now permits the surgeon to perform the operation with four robotic arms.

*Three-arm da Vinci*

The original robotic tower supports the three robotic arms (Fig. 2A). The central arm holds the video telescope. During the operation, the robotic tower is wheeled into the side of the operating room table (Fig. 3A). Piano

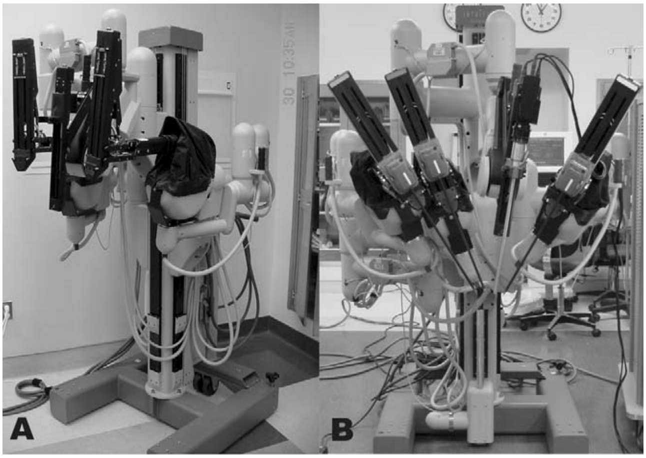


Fig. 2. The two generations of da Vinci robotic towers. (*A*) The original robotic tower supports three robotic arms: the middle one holds the video telescope and the lateral ones surgical instruments. In this picture, the robotic arms are empty. (*B*) The second generation of da Vinci robotic towers supports four arms. This picture shows the four robotic arms loaded with a video telescope and three surgical instruments.

wires running around pulleys inside of the robotic arms activate the movements of the surgical instruments. Surgical instruments are attached to the remaining robotic arms with a robotic-arm instrument adapter (Fig. 4). The adapter serves as the sterile interface between the robotic arm and sterile surgical instrument. The robotic arms are attached to reusable metal trocars through which the robotic instruments enter the patient's chest or abdomen (Fig. 3B). The two masters can activate separately the left and right robotic arms or control together the video telescope. A foot pedal toggles control between the two surgical instrument outer arms or the central camera arm. The masters allow the surgeon to move the camera in and out or up and down, and to axially rotate it.

*Fourth robotic arm*

In December 2002, the FDA approved a new generation of da Vinci telerobots for clinical use in the United States. A fourth arm is attached to the robotic tower (Fig. 2B). The fourth arm is identical to the two original outer arms. The surgeon toggles with a foot pedal between control of any two of the three surgical-instrument robotic arms. The arm not currently under control by one of the masters remains fixed in position. If the current instrument is a grasper, it remains locked in position with its jaw open or shut as last positioned by the master. If the instrument was used to grasp and to retract a loop of bowel, it continues to do so when the surgeon switches control to the other two instruments. Typically, the fourth arm acts as a static retractor that is periodically repositioned (Fig. 5).


Fig. 3. (*A*) The four-arm da Vinci attached to a patient, sterilely draped and ready for use. (*B*) The robotic arms attach to reusable 8-mm laparoscopy trocars. The black shaft of the surgical instrument is inserted through the green valve of the trocar.

## Stereoscopic video telescopes

The central robotic arm holds the stereoscopic video telescope. The telescope is 12 mm in diameter (Fig. 6). Thirty-degree and 0° telescopes are available. Telescopes for cardiac surgery offer greater magnification of the image than the abdominal telescopes. The 12-mm cylinder contains two separate 5-mm telescopes. A separate three-chip video camera is attached to each 5-mm telescope. Two sets of fiber-optic cables carry light down the 12-mm cylinder to illuminate the operative field. The video signal from each 5-mm telescope remains separate from the other. The video signal from each is projected on separate high-resolution cathode ray tube screens within the

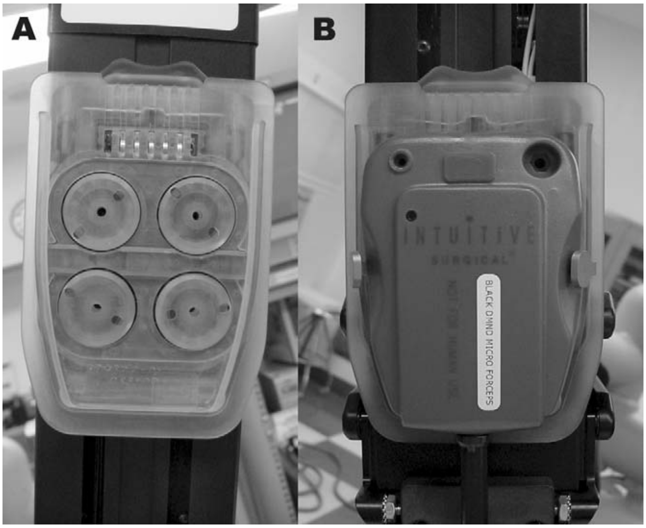


Fig. 4. Sterile instrument arm adapters are required to secure the semidisposable surgical instruments to the robotic arm. (*A*) The sterile instruments dock into this sterile shield. The four wheels move gears within the housing of the surgical instruments to control the wrist motions and the opening and closing of the instruments. (*B*) The head of the surgical instrument docks into the instrument arm adapter. Each instrument can be reused in 10 different operations.

computer console. Mirrors reflect these images to the binoculars for viewing by the surgeon. The synchronizer in the video cart keeps the separate video frames from each camera in phase so as to avoid motion sickness in the viewer. The 12-mm telescope enters the thorax or abdomen through a standard 12-mm disposable laparoscopic trocar (Ethicon Endosurgery Inc., Cincinnati, Ohio).

In the near future, da Vinci systems will provide telescopes with three video cameras. The two 5-mm telescopes that provide stereoscopic imaging remain

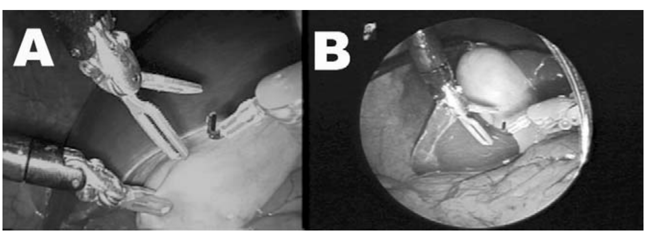


Fig. 5. The four-arm da Vinci performing a cholecystectomy. (*A*) The atraumatic Cadiere grasper on the left is grasping the gallbladder in anticipation of pushing it up to the diaphragm for exposure. The surgeon will use the second Cadiere grasper for counter-traction and the electrocautery hook to perform the dissection. (*B*) This wide-angle view from a new prototype telescope shows the far left Cadiere grasper pushing the gallbladder up toward the diaphragm and the other two instruments ready to initiate dissection.

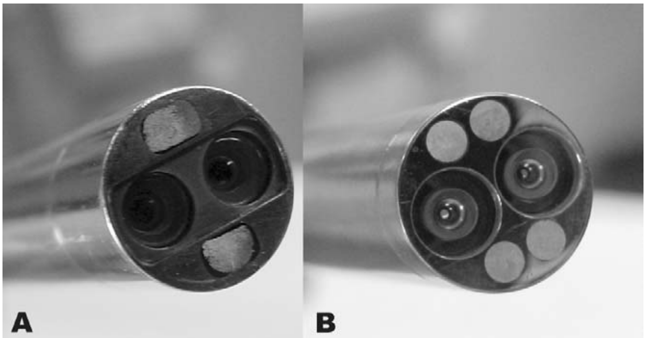


Fig. 6. The two different stereoscopic video telescopes that are used with da Vinci. (*A*) The wider view of this telescope is used for abdominal operations.(*B*) The greater magnification of this second telescope facilitates surgical procedures with a small field of view, such as suturing a coronary artery bypass anastomosis. The magnified view of this telescope requires the additional light delivered by the four fiber-optic bundles.

the same in these telescopes. An additional wide-angle lens and with super video chip offer a panoramic view of the operative field. The surgeon toggles between the close-up, three-dimensional view and the wide-angle, two-dimensional view with one of the foot pedals. The wide-angle view is helpful for checking the position of the static retracting fourth robotic arm and for maintaining anatomical orientation during complex abdominal operations.

## Robotic surgical instruments

The da Vinci robotic surgical instruments attach by a sterile interface to the robotic arms. Each instrument can be used in 10 separate operations. The computer keeps track of the number of times the specific individual instrument has been used and deactivates it after 10 operations. The instruments can be removed and reattached an unlimited number of times during each individual operation. The robotic arms bend at an elbow during motions of the surgical instruments. Each instrument also articulates at a wrist. In general, the instruments move with seven degrees of freedom. These include:

1. in and out.
2. elbow up and down
3. elbow left and right
4. wrist up and down
5. wrist left and right
6. open and shut
7. axial rotation

Motion of some instruments is limited. The ultrasonic scissors lack wrist motions because ultrasound waves cannot be bent around corners. A wide range of instruments is available. These include electrocautery hooks, scissors, and graspers.

## Integrated operating rooms

The da Vinci surgical robotic system is best used in an electronically integrated operating room. The computer console provides a VHS video jack for directing one of the video channels to a central router. This facilitates display of the video image on monitors supported by ceiling booms within the operating room. Similarly, the cable that joins the computer console to the video cart and robotic tower can be built into the wall with connection sockets placed at various locations around the operating room. This expedites turnover times for different operations that require the robotic tower to be moved to different orientations with respect to the patient and operating room table.

## Telepresence surgery

da Vinci was engineered from its inception to perform telepresence surgery. In this type of surgery, the surgeon is physically and visually separated from the patient. Their only contact is the video image. To facilitate telepresence surgery, the computer console purposely isolates the surgeon from his environment. The console hood serves as blinders that obstruct the surgeon's periphery vision. As the surgeon inserts his head into the viewing area and gazes into the binoculars, he descends into the virtual 3D operative field. The video image transports the surgeon to the remote operative field. The surgeon perceives the abdominal or thoracic walls as surrounding him. He is inside the patient. This 3D perception of the abdomen or thorax helps to maintain the surgeon's orientation within these complex operative arenas. This perception is particularly important if the surgeon is performing surgery on a patient in another room or 100 miles away on a battlefield. Nonetheless, even when operating from within the same operating room, as currently mandated by the FDA, the surgeon still achieves this perception of teletransportation to the operative field.

Telepresence surgery is most likely to achieve initial clinical use in the military. The da Vinci robotic surgery system, as indicated above, evolved from this original concept.

Telepresence surgery, however, may also offer technological solutions to other surgical manpower problems. Telepresence surgery may offer a means of improving clinical outcomes in the United States for infrequently performed difficult operations. One can envision a future in which an expert surgeon performs operations such as Heller myotomy, radical prostatectomy, or laparoscopic colectomy for an entire region from a central location such as the state university. Telepresence surgery might also serve as a tool to address the shortage of trained surgeons in third world countries and remote geographic locations. Mobile vehicles caring the telerobotic surgical arms could migrate across underserved remote areas. Surgeons at universities or government-run sites could perform telepresence surgery on these remote patients in a safe yet time-efficient manner.

The ethics and legality of telepresence surgery remains ill defined. Indeed, some of the ethical and legal paradoxes raised by telepresence surgery have already been pointed out. Remote telepresence surgery certainly interferes with traditional clinician-patient relationships [7]. The impact of state and international borders on medical licensing remains ill defined [8]. It will prove necessary to balance the advantages of delivering sophisticated surgical care to remote areas against the importance of direct surgeon-to-patient contact.

## Future evolution of da Vinci

The enthusiastic adoption and use of the da Vinci system in over 150 medical centers suggests that telerobotic control of laparoscopic instruments does provide significant clinical value. The ultimate utility of robots in surgery can and will extend far beyond current capabilities, however. In the near future, the da Vinci system will add such features as smaller and more diverse tools with smoother movement and expanded range of motion. The numbers of surgical arms will increase, and their size will shrink. Also, the addition of a second master computer console to existing systems will allow for multiple arms to be controlled and exchanged between the surgeon and the assistant. The addition of software simulation programs will allow the surgeon in training to perform a procedure on the da Vinci console many times before the instruments actually touch the patient. As the volume of telesurgical procedures rise, costs associated with use of the technology will shrink, and the inevitable progression of electronic processing speed will help simplify design and add capability.

Longer term, many of the most powerful attributes of robotics can be incorporated into the practice of telesurgery. The ability for robotic systems to compute and act on positional information in three dimensions makes them the perfect counterpart to future imaging modalities. The use of detailed image guidance capable of locating and characterizing pathology will most certainly become a partner to surgical robotics. Image overlay technology, which can register imaging data to the surgeon's real-time view, will help guide and perfect surgical tasks. As computational power and artificial intelligence progresses, preprogramming of automated movement may encompass much of what is required in future surgical intervention.

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