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## **ROBOTICS IN HEALTHCARE:**

### **HF Issues in Surgery**

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Technology is ubiquitous in healthcare today. Without a doubt, automation and use of robotics will play an ever increasing role as medicine continues to evolve in technological sophistication. Increasingly, automation and use of robotics in the laboratory, such as for blood analysis and cell-sorting, is common-place; medical research depends on this technology for genomics, proteomics and drug discovery processes. State-of-the-art biotechnology enterprises use robots to feed and manage tissue cultures for growing human skin -- the source of tissue used for grafting extensive burn victims. Home healthcare and long-term disease management (e.g., diabetes, kidney dialysis, etc.) is beginning to utilize semi-intelligent and automatic drug delivery and monitoring devices. The field of medicine is in the very early stages of applying robotics to healthcare. Successful robotic application in healthcare depends on innovative technology and effective integration of this technology into the complex human-machine interactions in the healthcare environment. Nowhere is human factors consideration more critical for the success of technology application than the use of robotics in the clinical setting. In fact, the use of robotics is more prevalent in

surgery than in any other specialty of healthcare. This chapter reviews the key human factors issues in applying robotics to medicine, using minimally invasive surgery as a context for discussion. The discussion of human factors issues in surgery is divided into two levels: the human-robot level of interaction, and the team-robot level of interaction.

### **Overview of Robotics in Surgery**

The Robot Institute of America's definition of a robot is "a reprogrammable multi-functional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks" (Sheridan, 1992, pg. 3). Much excitement has been generated about the development of robotic systems in surgery, where technology seems to have the highest potential impact on patient care. For example, robotics promises to enhance surgical performance by replacing tedious and repetitive tasks, increasing dexterity, or automating surgical tasks that are difficult to perform (Garcia-Ruiz *et al*, 1998; Ben-Porat, Shoham, Meyer, 2000). Robotics can increase the precision and accuracy of the surgeon's fine motor performance by stabilizing tremor (Taylor *et al*, 1999), or by scaling down the motions made by a surgeon's hands. There is also the potential to enhance the surgeon's sense of touch through haptic interfaces (Rosen *et al*, 1999a).

Robotic systems for surgery have seen rapid development, but only tentative acceptance by the general public. Initially, the most common use of robots in MIS is for positioning the laparoscope using voice control (AESOP). The benefit of using a robot for this task is that it does not fatigue, does not shake, and can be controlled verbally by the primary surgeon. This greatly increases the efficiency of the visualization process, as the surgeon controls exactly what is being viewed, and brings the procedure closer to a cost-effective “solo-operation” where fewer surgeons are needed in the operating room (Omote *et al*, 1999). More sophisticated robotic systems have been developed that play a larger role in the surgical process.

Current robotics applications in surgery include positioning devices such as AESOP/Sydne (formerly Computer Motion, Inc., now Intuitive Surgical, Inc.); image-guided radiosurgical systems such as CyberKnife (Accuray, Inc.); and telesurgical manipulators for performing surgery, such as the RoboDoc (Integrated Surgical Systems), Acrobot (Acrobot Company Ltd.), NeuroMate (Integrated Surgical Systems), and Zeus and Da Vinci (Intuitive Surgical, Inc.) (see Figure 1). The clinical areas where robots are currently in use are general surgery, gynecological surgery neurosurgery, orthopedics, urology, maxillofacial surgery, ophthalmology, and cardiac surgery.

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Insert Figure 1 about here.

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Because these robotic systems are novel to most researchers working in the field of human factors and ergonomics, very little is known about their performance and efficacy from a human factors perspective. Few studies have been conducted to compare the performance of robotic surgery to ‘traditional’ minimally invasive surgery (Garcia-Ruiz *et al*, 1998; Melvin *et al*, 2002; Nio *et al*, 2002; Webster, 2004). Case studies and institutional reviews have been published on robot assisted laparoscopic surgery (Cao & Taylor, 2004; Mack 2001; Marescaux *et al*, 2001). The successful completion rates were similar to those of human laparoscopic surgery. However, the robot was almost never faster than its human counterpart (Garcia-Ruiz *et al*, 1998; Marescaux *et al*, 2001; Nio *et al*, 2002). Much public attention has also been directed at the failures of robotic surgery (Brink, 2002).

These studies barely scratch the surface of the application of robotics to surgery and highlight the institutional and psychological barriers to the entry of robotic technology into the operating room, and to healthcare in general. For robotics, or any new technology, for that matter, to be accepted, the instrumentation must fit into the environment without disrupting familiar routines at the level of individual tasks and functions, at the level of team coordination and functions, and at the level of institutional management. The successful coupling

of technology with individuals and teams is determined by the system constraints and requirements, which vary depending on the system environment.

### **HF at Individual-Robot Level**

The use of robotics in minimally invasive surgery (MIS) is a natural progression following the evolution and development of surgical technology. Indeed, it is a promising solution to the limitations and constraints of MIS technology, and requirements of surgical therapy. However, while some of the human factors issues associated with MIS technology at the individual level (such as physical and perceptual/cognitive ergonomics, and usability) can be addressed by robotics, new ones are also created, often at higher levels of interaction.

Compared to traditional open surgery, MIS procedures impose additional safety concerns and precision requirements, as well as greater physical and visual-motor constraints on the surgeon (Berguer, Forkey, Smith, 1999; Cao, 1996; Cao, MacKenzie, Payandeh, 1996; Cuschieri, 1995). These human factors issues are due to restricted access to the operative site within the respective body cavities, with respect to visual, tactile and motor skills. In other words, the very tools that allow surgical operations to be performed with minimal invasiveness represent both major physical and perceptual barriers to the surgeon. Physically, the surgeon's hands and arms are elevated throughout the surgical procedure, leading to increased muscular discomfort and fatigue (Berguer *et al*, 1999). Visually, information regarding the surgical site is altered. The lack of stereoscopic view and adequate depth cues results in longer performance times (Cao & MacKenzie,

1997; Crostwaithe *et al*, 1995; Tendick *et al*, 1993;), and more wasteful movements with the surgical instruments (Kim *et al*, 1987). In addition to a restricted view of the operative site, and loss of depth perception, other visual-motor constraints include displaced visual space; image magnification, coupled with a separation of hand space from workspace (operative site); and, frequently, a rotation of the display space relative to the operative site. Holden, Flach, and Donchin (1999) have shown that changing the camera position or the surgeon's position with respect to the task space disrupted performance, but when the position of the camera and surgeon changed together while retaining relative orientation, skill performance was maintained. These findings are consistent with the motor control/learning literature (Cunningham & Welch, 1994; Flach, Linter, Larish, 1990) which suggests that surgical skill depends on a consistent mapping between the virtual hands (displayed tool end-effectors) and the eyes, but not the particular visual or motor orientations. This has implications for the design of user interfaces for robotic systems.

In MIS, tactile sensation from the tissues and surgical tools is reduced, while manipulation of the endoscopic tool is usually restricted to 4 degrees of freedom. The control of the surgical tools is further complicated by the fact that the tools rest on a fulcrum at the entry port into the body cavity. Therefore, hand movement direction and tool end-effector directions are reversed. Furthermore, because the camera is controlled by an assistant, it often requires some adjustments guided verbally by the operating surgeon. This requires experience

also on the part of the assistant, who ideally should understand the intentions of the operating surgeon, and even anticipate them where possible.

The combination of the physical, precision, safety and visual-motor constraints makes MIS a very difficult task to learn and to master. This is evidenced by the large number of medical errors associated with this technology (Bateman, Kolp, Hoeger, 1996; Schafer, Lauper, Krahenbuhl, 2000; See, Cooper, Fisher, 1993; Shea *et al*, 1996; Puljiz *et al*, 2003; Targarona *et al*, 1997; Way *et al*, 2003). Some of these 'medical errors' have been directly related to poor design of technology and rapidly changing technology (Cook & Woods, 1996; Joice, Hanna and Cuschieri, 1998; Tendick *et al*, 2000; Way *et al*, 2003), as well as insufficient knowledge or training of surgeons (Joice *et al*, 1998; Katz, 1999; Ostrzenski & Ostrzenska, 1998; Watson, Baigrie, Jamieson, 1996; Wu *et al*, 2000;). Some of these injury-causing errors do not exist in open surgery (Cuschieri, 1995), while others are associated with the use, or misuse, of unfamiliar instruments, such as applying too much force with the graspers, or tearing the gallbladder.

In robot-assisted surgery, these same complications persist, although many can be mitigated by implementing 3D displays (Gulbins *et al*, 1999), 6 degree-of-freedom manipulators (Guthart & Salisbury, 2000), and a seated posture for the surgeon (Menozzi *et al*, 1994). However, the development of haptic interfaces for robotic surgery remains a difficult objective to achieve. The promise of robotic

surgery is still hindered by challenges in providing tactile and haptic feedback to the surgeon through the robotic interface (Carrozza *et al*, 1997), even though it has been shown that force feedback can increase speed and accuracy in teleoperation tasks (Massimo & Sheridan, 1994; Salcudean, Ku, & Bell, 1997). Thus far, most researchers have dealt primarily with using force feedback to augment the visual feedback (Kennedy *et al*, 2002; Ortmaier *et al*, 2001; Rosen *et al*, 1999b). These approaches attempt to translate forces, as measured by the force sensors in the instrument, through a servomechanism to the fingers of the surgeon. The force information alone is not representative of the rich information normally perceived by the haptic sense, which includes tactile, kinesthetics, proprioception, as well as texture, temperature and contour information, but it is better than no force information at all (Cao *et al*, 2003).

Unfortunately, these innovations are still not enough for robotics to be accepted by both surgeons and patients. The design of the current robotic systems is modeled after the design of the laparoscopic instruments. In addition to the same human factors issues associated with traditional MIS technology (i.e., physical constraints, visuomotor coordination issues, precision and safety requirements), the robots are bulky and difficult to use. Their bulky presence displaces other instrumentation and OR personnel in the room, resulting in rearrangement of the OR physical space (see Figure 2). In addition, the large size

of the robotic arms can sometimes result in external collisions of the arms, especially when working on a small patient (see Figure 2).

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Insert Figure 2 about here.

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An unexpected outcome of using a robot for laparoscopic surgery is the additional physical and cognitive demands placed on the surgeon. The robot changes the surgeon's tasks and responsibilities (Nio *et al*, 2004; Webster, 2004). Not only is the surgeon responsible for performing the surgery (i.e., cutting and suturing), but she is now also responsible for driving the robot. For the latter task, a high degree of coordination and integration of information from various sources and locations is required. Figure 3 shows the difference in the number of steps performed in a surgical task (i.e., changing a tool) between a conventional laparoscopic procedure and a robot-assisted laparoscopic procedure. For example, in laparoscopic surgery, when a surgeon needed to have a tool changed, the surgeon informed the nurse which tool was needed, pulled out the current one, handed it to the nurse in exchange for the new tool, took the new one, and inserted it into the patient (see Figure 3, top). Often, the nurse anticipated the need for a new tool and had it ready.

In robot-assisted surgery, this process was much more complicated (see Figure 3, bottom). First, the surgeon informed the nurse what tool was needed. Then, using the robotic handles to navigate the menu on the robotic console, the surgeon disabled the robotic arm by selecting an item on the pull-down menu. Because of OR setup (the system console blocked the surgeon's view of the patient and the nurse at the side of the operating table, and vice versa), the nurse could not see the menu screen which indicated that the arm had been disabled. The surgeon had to verbally communicate the state of the robot to the nurse who then removed the old tool. When the new tool was inserted, the surgeon could see the image of the tool end-effector on the monitor at the console, even before the tool can be secured externally. Sitting at the console, the surgeon could not see whether the tool had been secured at the patient site. The surgeon had to rely on the nurse for this information. After being informed that the tool had been secured, the surgeon navigated the menu to enable the arm, and then continued with the surgical procedure.

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Insert Figure 3 about here.

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Not only is the number of steps increased, the information required to accomplish the task is distributed and sometimes unavailable. This means that even an expert surgeon must first learn to drive the robot before she is able to do her job (i.e., perform surgery), and possibly learn new ways of performing the surgery due to the new tool. This has implications for the safety of the patient and the success of the surgical procedure.

### **HF at Team-Robot Level**

The introduction of robotics into the OR has improved the technical performance of surgical procedures, but it has also led to unexpected interactions within the surgical team and new forms of errors (Cook & Woods, 1994; Reason, 1990). Several studies have shown that when new technology is introduced into the operating room, the goals, tasks, and responsibilities of the surgeon and nurses change (Edmonson, Bohmer, Pisano, 2001; Nio *et al*, 2004; Webster, 2004). For example, prior to adopting a new, minimally invasive cardiac surgery system, the surgeon and nurses often communicated non-verbally; the nurse could tell by the surgeon's body language what was needed and when it was needed. Everyone in the OR also had visual access to the information source (the heart) so could anticipate the next steps (Edmonson *et al*, 2001). With the new MIS system, information was located in new places, many of the visual cues were removed, and the nurses became responsible for providing critical information to the

surgeon (Edmonson et al, 2001). Studies of OR team performance have revealed that preventable medical errors are related not to technical competence, but to interpersonal aspects of the OR team functioning (Helreich & Schaefer, 1994; Zinn, 1995), indicating a need for better communication to improve safety, efficiency and team morale.

A recent study conducted to examine the changes in performance and communication pattern within the OR team as a result of the introduction of a surgical robot, the LaproTek (see Figure 4), revealed large disparities in terms of the amount and type of information required by the surgeon in order to perform the surgical procedure (Cao & Taylor, 2004). The introduction of a robotic surgical system into the OR changes the flow of information, as well as the point of access to the information and how that information is shared (see Figure 5). Figure 5 shows that in laparoscopic surgery, the surgeon's informational needs are fulfilled through interaction with the patient, whereas in robot-assisted surgery, the information is distributed amongst the nurse and the robotic console. Adjustments in team communication were necessary to accommodate the novel technology, new procedures, and altered roles of the OR personnel. Being removed from the surgical site, the surgeon could not receive the full range of sensory information normally obtained through vision, audition, the vestibular apparatus, haptics, and the olfactory senses. Rather, most of the available information was received through the visual channel. Even that modality,

however, was based on video images of the remote surgical site, which provided a restricted field of view and limited depth information from a frequently poor vantage point. Moreover, the physical barrier imposed by the robotic technology also represented a perceptual barrier for the surgeon, increasing the uncertainty regarding the status of the remote system, and increasing information processing demands. If the surgeon and nurse could see each other's actions, as is the case with conventional laparoscopic surgery, they would better be able to coordinate their actions, thus reducing down time and potential confusion (Segal, 1995). Confusion about who should provide information and when that information should be provided forms the basis for most of the potential errors. Thus, it is clear that the addition of a robot places many additional information input and output requirements on the surgeon, increasing the overall communication load on the surgical team.

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Insert Figure 4 about here.

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Insert Figure 5 about here.

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The dynamic and complex socio-technical environment of an operating room where each participant has a task to perform and individual expertise relevant to a multitude of tasks underscores its complexity in team interaction. When new technology which affects work practice in the OR is introduced, adjustments must be made in order to accommodate the change with greater potential for miscommunication and inefficiency. Adjustments in team communication must be made to accommodate the novel technology, new procedures, or altered roles of the OR personnel in order to establish common ground (Clark, 1996, Clark & Schaefer, 1989, Wilkes-Gibbs & Clark, 1992). As roles change when technology is introduced, people are less familiar with their new roles (as seen with the introduction of a robot). When new technology is introduced, new forms of errors are also possible, as well as interruptions from the use of the technology itself (Coiera & Tombs, 1998; Moss & Xiao, 2004). Given the importance of communication efficiency and safety in surgery, and in particular, the potential of the errors when adapting to working with new technology, it is important to implement training for the team before working with patients.

The operating room environment is a cultural hierarchy with conventions that have evolved over the past century. The surgeon and the assistants must have direct access to the patient and must be able to view each other, the patient, and

the anesthesiologist during the procedure. Change in the operating room environment must be gradual, with new technology integrated relatively seamlessly into current routine processes.

The ultimate goal for the designer of robots is to make the robotic technology transparent to the user, just as the complex technology of a desktop computer is not apparent to the person typing a letter. The surgeons should not feel that they are using a robotic system; rather that they are holding an instrument as an extension of their hands to enhance their performance. The instrumentation must be easy to use. New technological advances that require a steep learning curve will be adopted only gradually if at all, as younger surgeons trained in their use during residency mature in their practices. On the other hand, robotic instrumentation that is transparent will be adopted much more quickly, even by seasoned surgeons who are expert in using the “old” technology. Therefore, the burden of adaptation must be on the technology and its designers, not on the surgeon.

### **HF Lessons for Implementing Robotics in Healthcare**

Thus far, the robots do not add much to the manual method of surgery, and they are very expensive. Furthermore, they require refitting of the OR, and a change in the OR culture. For robots to become sufficiently useful in the OR to be generally adopted, and accepted by both surgeons and patients, they must

overcome the problems related to safety, usability, and appropriateness and fit within the complex socio-technical environment of the OR. Robots must provide a quantum leap in benefit, not a marginal improvement. Until this occurs they will not be worth the cost and potential causes of error introduced by their use.

In the aerospace industry, robots have been developed that provide this quantum leap. With increasingly crowded skies in commercial aviation, the autopilot, which can respond to neighboring aircraft position and airport controllers, is in general use, leading to safer air travel. Current technology in aeronautics also allows aircraft to be landed in zero-visibility weather. This increases the utility of the aircraft and extends the pilot's abilities beyond that which he or she would be able to accomplish without technological aid.

The success of technology development and utilization in aviation is due in large part to a great deal of human factors research and the design of effective human-machine interfaces. In the case of robotic technology used in medicine, similar efforts are needed. The coupling between the medical team and the robot can greatly affect the usefulness of the enabling technology. Much can be learned from the work already done in the aviation industry and adapted to the complex medical domain.

The ideal interaction between robot and human in the healthcare environment is one in which there is an optimal "division of labor". That is, the robot is assigned to the task that it is good at, while the human is assigned to the task that she is good at. It is unlikely that the medical robot will ever be autonomous. Therefore, it is in the balance of robotic and human skills that the

benefit will be maximized. Prudence must be exercised in the design and adoption of robotics into the healthcare environment. Again, the analogy to automation in the aviation industry is useful. Automation in the cockpit has increased the safety of air travel and extended its use into circumstances in which the aircraft would be grounded without it. However, pilots of airliners are often resentful of the extent to which automation has taken over their work. While the pilot is still ultimately responsible for all decisions and activities related to flying, he or she no longer performs many of the routine tasks involved in flying. These are performed by an ever-increasingly sophisticated autopilot. This can lead to many problems typical in automated industries such as loss of control and increased unfamiliarity, resulting in inattention and degradation in performance (Sheridan, 1992). It is important that the analogous situation be avoided in the healthcare environment. The healthcare provider must never be in a situation where he or she abdicates control. Rather, robotics should enable the healthcare provider to enhance his or her skills, and if possible, extend them beyond human capabilities, and relieve him or her of physically strenuous and repetitive tasks.

As with any other technology, usable robotics for healthcare must address the system requirements and constraints at the physical level (i.e., what the robot contains), functional level (i.e., what the robot does) and operational level (i.e., how the robot is used). In addition, its interactions with the individual user and the team must be examined to prevent unintended outcomes. For sophisticated robotic systems, specialized training for the individuals and teams should be implemented. A good coupling between healthcare system and robotic

technology depends on the fit between the requirements of the system and the capabilities of the technology, without imposing additional demands on the system.

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Figure 4. Laprotek by endoVia Surgical.

Figure 5. Information need by the surgeon in order to complete the surgery, with (shaded area) and without the robot (unshaded area).

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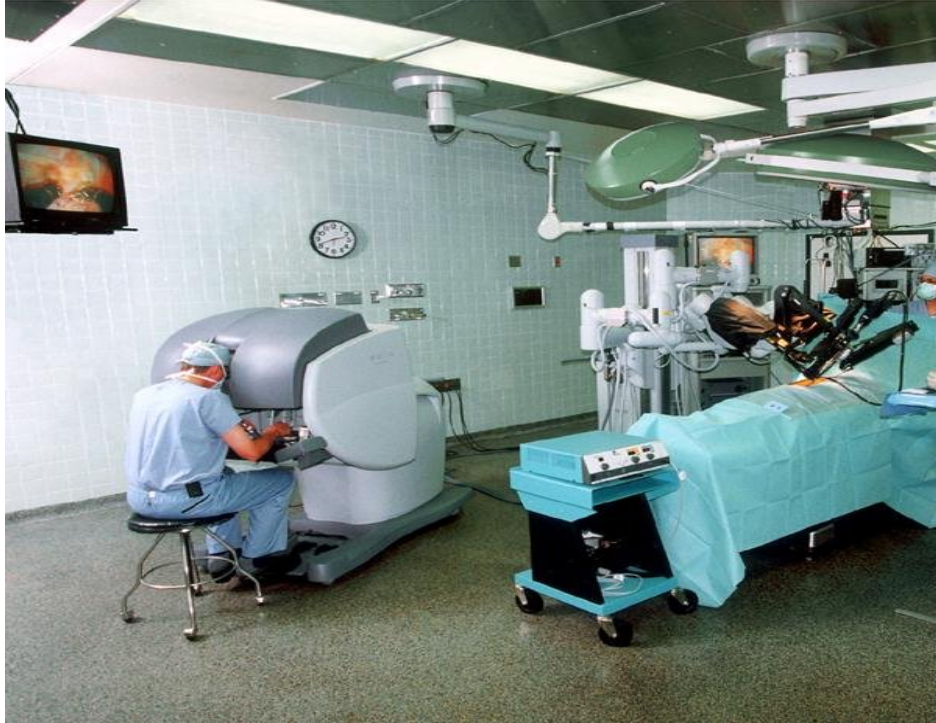


Figure 1. The da Vinci robotic system by Intuitive Surgical.



Figure 2. The da Vinci robotic system draped at bedside.

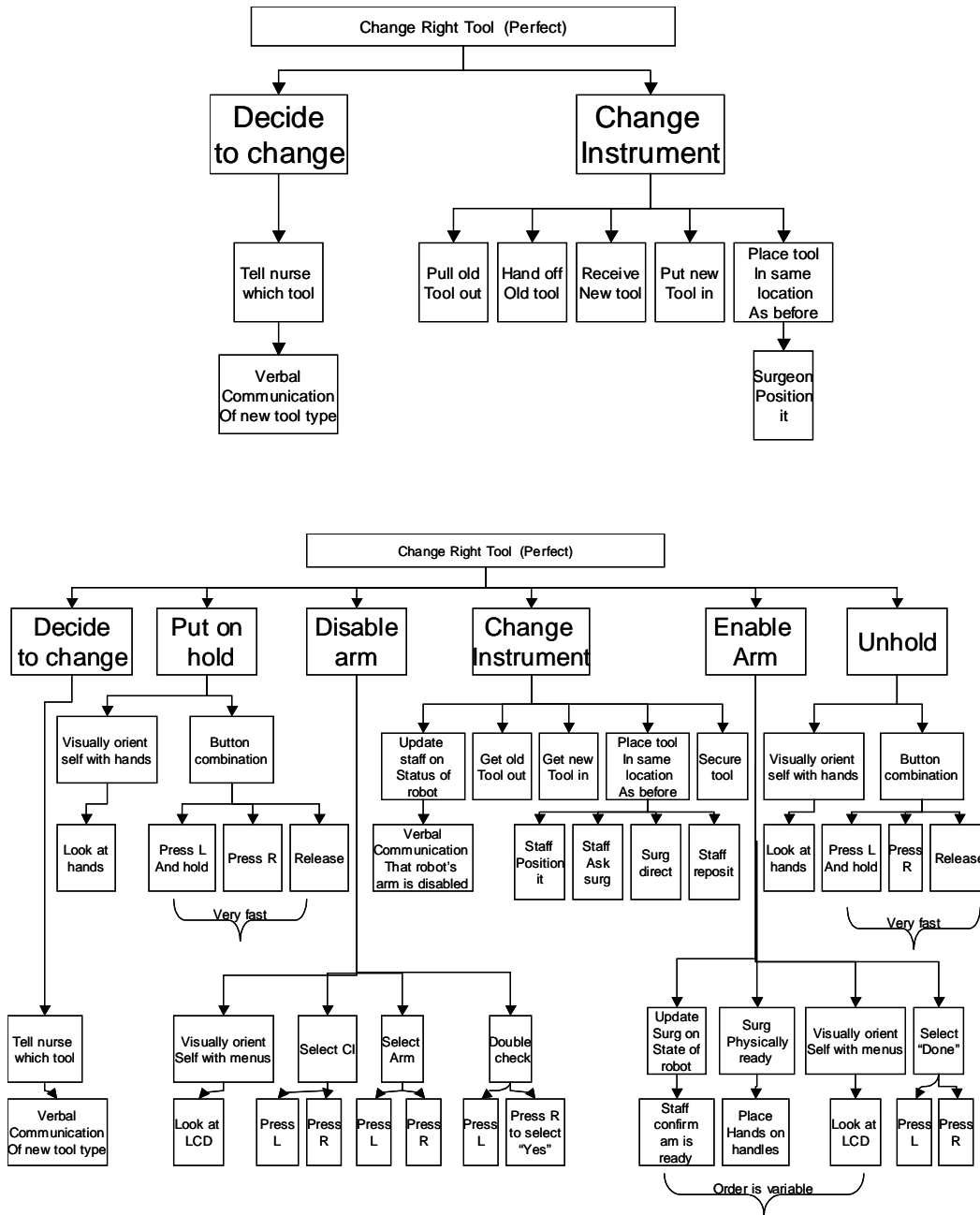


Figure 3. Comparison of a tool changing task in traditional laparoscopic surgery (top) with the same task in robot-assisted surgery (bottom).



Figure 4. Laprotek by endoVia Surgical.

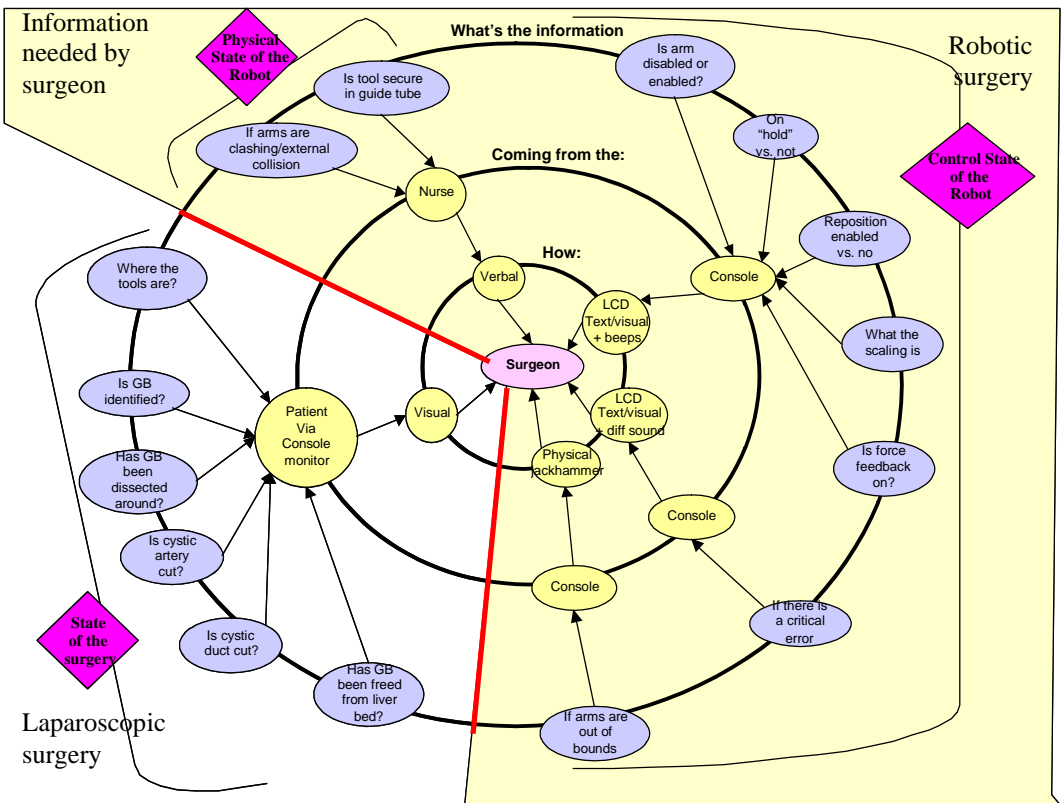


Figure 5. Information need by the surgeon in order to complete the surgery, with (shaded area) and without the robot (unshaded area).