Excerpta Medica

The American Journal of Surgery

The American Journal of Surgery 187 (2004) 309–315

Surgical education

# Multiservice laparoscopic surgical training using the daVinci surgical system

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Manuscript received October 28, 2002; revised manuscript March 3, 2003

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## Abstract

**Background:** The daVinci surgical system affords surgeons a magnified three-dimensional videoscopic view of the operative field and precise articulating laparoscopic instruments. The learning curve for this advanced surgical robotics system is poorly characterized.
**Methods:** Twenty-three surgeons representing seven surgical subspecialties participated in a surgical robotics training program consisting of standardized daVinci system training (phase 1) followed by self-guided learning in a porcine model (phase 2).
**Results:** The average number of recorded procedures performed per surgeon during phase 2 was 5.5. The mean daVinci system set-up time was 45 minutes and decreased by an average of 56.1% by the third successive set-up ($r = -0.702$, $P < 0.005$). Operative times decreased 39.0% by the third successive practice operation ($r = -0.860$, $P < 0.0005$).
**Conclusions:** New use of the daVinci robot is associated with a rapid learning curve and preclinical animal model training is effective in developing surgical robotics skills.

*Keywords:* Surgery; Education; Robotics; Laparoscopy; Learning curve; daVinci surgical system

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The advantages of minimally invasive surgery are well accepted. Shorter hospital stays, decreased postoperative pain, rapid return to preoperative activity, decreased postoperative ileus, and preserved immune function are among the benefits of the laparoscopic approach [1–7]. However, conventional videoendoscopic surgery does have shortcomings. The surgeon's two-dimensional view of a three-dimensional operative field and limited freedom of movement within the abdominal or thoracic cavity pose unique challenges for surgeons and unique dangers for patients [8]. The modified "chopstick" instruments of laparoscopy afford surgeons limited precision and poor ergonomics, and their use is associated with a significant learning curve [9–15].

Nevertheless, the introduction of the laparoscopic approach marks one of the great advances in surgery. Conventional laparoscopy is excellent for basic procedures that require minimal reconstruction. Virtually every general surgeon, young and old, has become adept at exploiting basic laparoscopic skills for simple organ removal, such as in laparoscopic cholecystectomy. Some surgeons have developed advanced laparoscopic skills including complex bimanual manipulation, suturing, and knot-tying, and are thus able to perform advanced reconstructive surgery using minimally invasive approaches. The amount of time and energy necessary to develop and maintain such advanced laparoscopic skills is not insignificant, and thus the majority of advanced laparoscopic cases are performed by a small number of surgeons [8].

The daVinci surgical system (Intuitive Surgical, Mountain View, California) allows all laparoscopists to perform

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0002-9610/04/$ – see front matter
doi:10.1016/j.amjsurg.2003.11.021

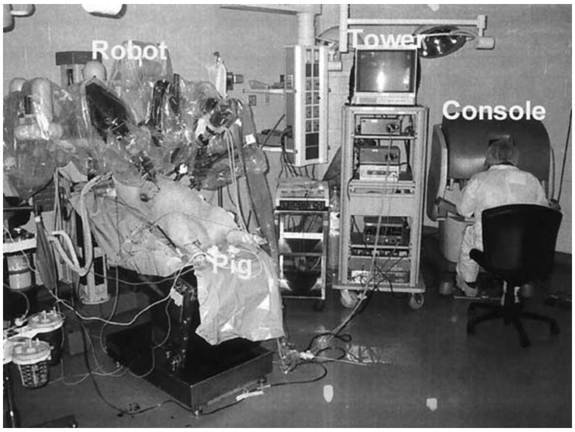

Fig. 1. The daVinci surgical system consists of three main components: the console, the laparoscopic tower, and the patient-side robot. Here a surgeon practices an upper abdominal procedure in a pig during the self-guided learning phase (phase 2) of the training protocol.

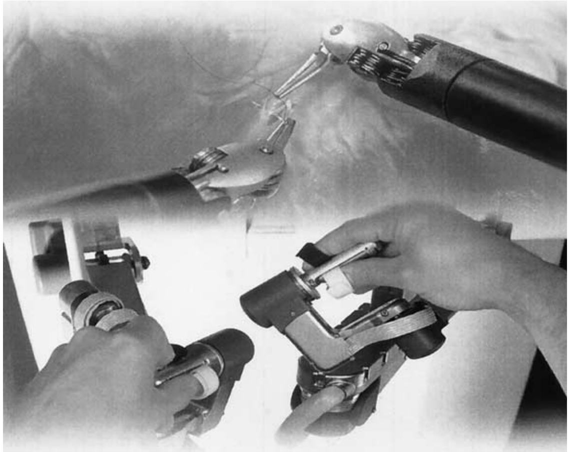

Fig. 2. The daVinci surgical system translates the natural movements of the surgeon's hands into precise laparoscopic instrument movements inside the patient.

advanced laparoscopic procedures with greater ease. Dual offset video cameras provide a three-dimensional view of the operative field with adjustable magnification. Robotic articulating laparoscopic instruments move with the same number of degrees of freedom as human hands in open surgery, and provide motion scaling and elimination of surgeon tremor allowing an unparalleled level of operative precision.

The daVinci surgical system consists of three main components: the console, the laparoscopic tower, and the patient-side robot (Fig. 1). The surgeon console provides the interface between the surgeon and the robot. The surgeon views the two video images converged in the viewfinder, controls the instruments with hand controls, and operates the camera and energy devices using foot pedals. The system's configuration allows the primary surgeon to be in direct control of three devices—two instruments and the camera—whereas in conventional laparoscopy, the surgeon can control a maximum of two devices. As depicted in Fig. 2, the system translates the natural movements of the surgeon's hands into precise laparoscopic instrument movements inside the patient. The tower houses a monitor that allows surgical assistants to view the operation, the light sources for the cameras, the harmonic scalpel generator, the insufflators, and the camera controls. The patient-side cart or "robot" has three mechanically driven robotic arms: the camera arm and two instrument arms.

The potential advantages of surgical robotic systems like daVinci include making advanced laparoscopic surgical procedures accessible to surgeons who do not have advanced videoendoscopic training and broadening the scope of surgical procedures that can be performed using the laparoscopic method. However, the learning curve associated with the introduction of a surgical robotic system into a surgeon's armamentarium is unknown. The hypothesis of our study was that systematic training on a new surgical robotic system in an animal model would result in measurable improvement in robotic surgical skills, and that surgeons would benefit from such preclinical training. We sought to characterize the learning curve associated with new use of the daVinci surgical system by surgeons from multiple surgical disciplines in a porcine model.

## Methods

### *Phase 1: daVinci system training*

Surgeons from Walter Reed Army Medical Center, Uniformed Services University of the Health Sciences, Malcolm Grow Medical Center, and The Johns Hopkins University School of Medicine interested in receiving surgical robotics training using the daVinci surgical system were recruited for this educational protocol. Twenty-three surgeons were enrolled in the study and completed the first phase of the training—daVinci system training. The daVinci system training is a Food and Drug Administration mandated 2-day course for all users of the robot taught by instructors from the makers of daVinci, Intuitive Surgical. Topics covered in this training include system basics, draping procedures, console instruction, patient-side instruction, patient positioning, and port placement. Participants engage in both inanimate practice and an animal laboratory where they discover the grip strength of each of the daVinci instruments and practice two-handed dissection and manipulation of tissues, ligation and transection of vessels, and intracorporeal suturing and knot-tying. The students are tested on system troubleshooting and emergency conversion (to open surgery) procedures in a hands-on practical examination, and must pass a 50-question multiple-choice written examination to complete the course.

Table 1
Surgical subspecialty training background of participating surgeons in each study phase: number of procedures performed by each subspecialty (percentage of total cases performed in parentheses)

| | Surgical subspecialty | | | | | | | Totals |
|---|---|---|---|---|---|---|---|---|
| Surgical subspecialty | General | Urology | CT | Gyn | ENT | Plastic | Neuro | 7 |
| Phase 1 surgeons | 4 | 3 | 5 | 5 | 2 | 2 | 2 | 23 |
| Phase 2 surgeons* | 3 | 3 | 4 | 4 | — | — | — | 14 |
| Number of procedures | 16 (37%) | 13 (30%) | 8 (19%) | 6 (14%) | — | — | — | 43 |

* Excludes surgeons who engaged in self-guided practice without recording data.
CT = cardiothoracic; Gyn = gynecology; ENT = otolaryngology; Neuro = neurosurgery.

### *Phase 2: self-guided learning*

The second phase of training was the unique portion of our training protocol—self-guided learning in a porcine model. In this phase of the training protocol, surgeons practiced procedures that they anticipated later performing in humans. Endpoints hypothesized to be associated with learning and effective skills development were evaluated to measure each surgeon's progress. Each surgeon prospectively recorded their daVinci system set-up and operative times, the number of instrument exchanges (ie, the number of times that an instrument arm was disengaged to replace the active instrument with a different instrument), the number of accessory ports used (in addition to the standard three daVinci ports), and the number and description of complications for each procedure performed. In Fig. 1, a surgeon is shown practicing an upper abdominal procedure in a pig during this portion of the protocol.

### *Animal care*

All procedures were part of a protocol reviewed and approved by both the Walter Reed Army Institute of Research (WRAIR) Institutional Animal Care and Use Committee and the Walter Reed Army Medical Center, Department of Clinical Investigations Institutional Review Board. Yorkshire pigs, 30 to 150 kg in size, were housed in cages where standard feed and water were available ad libitum. The pigs were fasted for 12 hours prior to procedures. The WRAIR veterinary team provided anesthesia according to accepted guidelines. Pneumoperitoneum for abdominal procedures was achieved by insufflating the peritoneal cavity with $CO_2$ at a pressure of 9 to 10 mm Hg. Postoperatively, animals were euthanized by lethal intravenous injection using a commercially available euthanasia solution (eg, Euthasol, 100 mg/kg) while still under general anesthesia.

### *Data analysis*

To enable comparison of operative times for different procedures and daVinci system set-up times for different-size set-up teams, data for these parameters were expressed as a percentage of a specific surgeon's or team's first attempt. The association between the number of attempts and set-up time, operative time, number of instrument exchanges, and number of accessory ports was analyzed using Pearson's correlation coefficient. The logarithmic transformation of both time variables (set-up and operative times) was used in the analysis. Differences were considered significant when $P \leq 0.05$, and all tests for significance were two-tailed. Analyses were performed using SPSS (SPSS Inc., Chicago, Illinois) and Excel (Microsoft Corp., Redmond, Washington) software.

## Results

### *Participating surgeon demographics*

The 23 surgeons who participated in phase 1 of the training protocol (daVinci system training) represented seven surgical subspecialties: cardiothoracic surgery, gynecology, general surgery, urology, otolaryngology, plastic surgery, and neurosurgery (Table 1). Of these surgeons, 17 subsequently participated in self-guided practice in a pig model (phase 2). Three of these 17 surgeons did not record any data, and therefore their participation was excluded from the final analysis. The average number of procedures performed by the 14 surgeons from whom data was collected was 5.5. A total of 43 practice operations were performed during phase 2 of the training (Table 1). Of these 43 procedures, 11 were performed by single surgeons, 30 by two-surgeon teams, and 2 by three-surgeon teams. The procedures performed included the following (number in parentheses): cholecystectomy (10), prostatectomy (8), internal mammary artery take-down (6), tubal anastomosis (6), Nissen fundoplication (3), bowel anastomosis (2), pericardial window (2), cystoureterostomy (2), adrenalectomy (1), cystotomy repair (1), nephrectomy (1), and pyeloplasty (1).

### *Learning curve parameters*

The daVinci system set-up time ranged from 120 minutes for a single-person set-up to 8 minutes for a three-member team on their fourth set-up. The mean system set-up time was 45 minutes and the median set-up time was 40 minutes. Consecutive set-up events for same-member

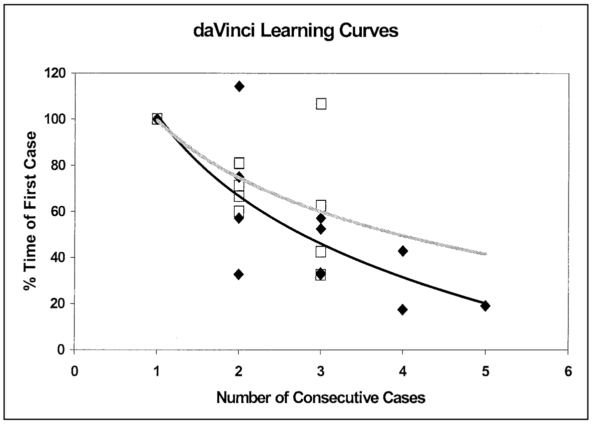

Fig. 3. Surgeons from several surgical subspecialties participated in a surgical robotics training program with standardized daVinci system training (phase 1) followed by self-guided learning in a porcine model (phase 2). Phase 2 times for consecutive team-specific set-ups (**diamonds**) and procedure- and surgeon-specific operations (**squares**) are expressed as percentages of the first times in their respective series. Logarithmic regression lines for set-up times (**black line**) and operative times (**gray line**) are shown. Both set-up and operative times decrease significantly ($r = -0.702$, $P < 0.005$; and $r = -0.860$, $P < 0.005$, respectively) after a limited number of attempts, indicating rapid learning among surgeons new to surgical robotics.

teams (ie, teams of surgeons, nurses, and technicians with the same members for each practice session) were analyzed to elucidate changes in set-up times over the course of training. Set-up times decreased by an average of 29.2% by the second and 56.1% by the third successive set-up for each same-member team's successive set-up ($r = -0.702$, $P < 0.005$). Operative times for consecutive surgeon- and procedure-specific practice cases were compared with evaluate changes in operative speed over the course of training. Operative times decreased by an average of 26.6% by the second and 39.0% by the third successive practice operation ($r = -0.860$, $P < 0.0005$). Set-up and operative times expressed as the average percent of surgeons' first set-up and first operative times plotted over the number of consecutive cases are shown in Fig. 3. Logarithmic regression lines for these data demonstrate downward sloping curves for both parameters indicating correlation between experience and speed. The set-up and operative time outliers at the top of Fig. 3 correspond, respectively, to instances in which a team's second set-up occurred a month after their first set-up (while their first set-up occurred much closer to their initial training), and in which a surgeon reported encountering a "gallbladder with atypical anatomy" during his third robotic cholecystectomy.

The number of instrument exchanges (ie, the number of times that a robotic arm was disengaged for removal and replacement of a robotic instrument) was recorded for each practice procedure. The number of instrument exchanges per case ranged from 0 to 16 with a mean of 4.5 and median of 4. There was no correlation between the number of instrument exchanges per procedure and the amount of daVinci-specific surgeon experience or the operative time of consecutive cases. Accessory laparoscopic ports (beyond the daVinci's standard three) were often necessary to allow a patient-side surgeon to assist the primary surgeon controlling the robot. The number of accessory ports used for each procedure ranged from 0 to 3 with a mean of 1.2 and a median of 1. There was no correlation between the number of accessory ports necessary to perform each procedure and the amount of daVinci-specific surgeon experience or the operative time of consecutive cases. Linear regression analysis of instrument exchange and accessory port data revealed nearly flat slopes indicating little to no change in these parameters over successive cases.

Complications were prospectively divided into five categories, and participating surgeons were asked to record the number of each type of complication and to annotate each complication. The five complication categories consisted of (1) computer (problems attributable to the robot's system software); (2) robotic (problems attributable to the robot's hardware); (3) operative (problems attributable to the surgeon); (4) anesthetic (problems attributable to anesthesia); and (5) material (problems attributable to lack of supplies). Table 2 shows the number of complications reported in each category for each of the two halves of the training period. In each category of complication (except computer complications, of which there was only one), the number of complications was fewer during the second half of cases than during the first half of cases.

During the 43 cases performed, there were a total of 10 operative complications. One unintended cystotomy, one inadvertent ureteral ligation, and one inferior vena caval injury were repaired laparoscopically using the robot, and one episode of broad ligament bleeding was controlled with the daVinci's hook electrocautery. One case was delayed when the pig was not properly positioned prior to connect-

Table 2
Number of complications reported in each category for each of the two halves of the training period

| Complications | Computer | Robotic | Operative | Anesthetic | Material | Total |
|---|---|---|---|---|---|---|
| Entire training period | 1 | 6 | 10 | 6 | 5 | 28 |
| First half of training | 0 | 4 | 7 | 4 | 3 | 18 |
| Second half of training | 1 | 2 | 3 | 2 | 2 | 10 |

Computer = problems attributable to the robot's system software; robotic = problems attributable to the robot's hardware; operative = problems attributable to the surgeon; anesthetic = problems attributable to anesthesia; material = problems attributable to lack of supplies.

Table 3
Robotic-unique complications

| Complication | Number of occurrences | Solution | Resultant Time Delay |
|---|---|---|---|
| System failure | 1 | Replace motherboard | 6 hours |
| "Frozen arm" | 4 | Reposition arm or master | 0–5 minutes |
| Malfunctioning grasper | 1 | Exchange instrument | 1 minute |
| Robotic arm failure | 1 | Replace arm | 24 hours |

ing the robot to the laparoscopic trochars. In one case, a needle was broken during bimanual robotic manipulation of the needle. In two other cases, solid organ bleeding ensued after excessive force application to patient-side organ retractors. Finally, two cardiac injuries occurred as a result of traumatic thoracic trochar insertion in small pigs (approximately 20 kg each).

A total of seven complications considered unique to the robotic aspect of the surgery being performed occurred during the study (Table 3). Computer system failure on one occasion prevented the start-up of the robot at the beginning of a training day. This failure required replacement of the system's motherboard, which was accomplished by the Intuitive Surgical engineer within six hours. When a surgeon attempts to move a robotic arm past its limit, the arm will sometimes "freeze up" temporarily until the arm or the control master is brought back into the normal range. Four such events were reported and each was resolved in less than five minutes. During one case, a training instrument that had been used for more than the manufacturer's recommended number of 10 uses began to malfunction (the grasping mechanism became "sticky"). This instrument was exchanged for a new instrument in less than one minute. On one occasion early in the training protocol, one of the robotic arms was damaged during set-up necessitating replacement of that arm, which was accomplished by the Intuitive Surgical engineer within 24 hours.

The costs associated with both phases of our training protocol totaled $10,355. This included $6,480 in animal procurement costs, $932 in animal housing costs, and $2,943 in supplies. This total does not include the indirect costs of the protocol borne by the Walter Reed Army Institute of Research for veterinary and operating room support. The total also does not include the cost of the daVinci system itself.

## Comments

While characterization of the learning curve associated with standard laparoscopic instrumentation has been well described [9–15], descriptions of the learning curve associated with use of an advanced surgical robotics system are relatively few in the surgical literature. Prasad et al [16] compared learning using the Zeus robot (Computer Motion) to learning using standard laparoscopic instruments. While this study used standardized manual skills drills performed in inanimate models and thus lacks direct applicability to the clinical setting, it did demonstrate an early phase of greater learning with robotic systems. Other researchers have reported initially steep learning curves for specialty- and procedure-specific use of surgical robots [17–19]—a finding that certainly warrants further investigation.

Our study sought to characterize the learning curve associated with new use of an advanced surgical robotics system among surgeons from multiple surgical disciplines in a more clinically relevant setting. Given the complexity of this system and its need for significant preoperative preparation, we felt it important to measure the time taken for surgical teams to prepare the robot for surgery. In all but one instance, same-member healthcare teams progressively improved their set-up times—on average, by almost 30% each time they prepared the system. While the average set-up time in our study was 45 minutes—clearly a significant amount of time to add to "in-room" time in the clinical arena—experienced teams were routinely setting up the system in 20 minutes or less near the end of our training period.

While set-up times are important from an operating room cost perspective, patients are more directly affected by their surgeons' operative times. To analyze global changes in surgeon operative times (rather than operative times for specific procedures), surgeon- and procedure-specific operative times were normalized to each surgeon's first operative time for that specific procedure. Surgeons clearly benefited from participation in our study as their operative times decreased substantially (more than 20% each time they practiced) throughout the training period, and the absolute operative times achieved by many of the surgeons near the end of the training protocol were excellent. For example, the average operative times for the last three cholecystectomies and the last three prostatectomies performed during the training period were 37 minutes and 100 minutes, respectively.

Because learning curves for manual skills development generally follow logarithmic kinetics [20], we chose to analyze both set-up and operative times using logarithmic regression analysis. The correlation between the log of the times for these parameters over successive cases was noteworthy with correlation coefficients (absolute value) greater than 0.7 for both parameters (0.860 for set-up time and 0.702 for operative time). Furthermore, the reduction in both set-up and operative times for consecutive cases was highly significant ($P < 0.005$ for set-up time and $P < 0.0005$ for operative time). Together these results indicate that learning in our protocol as indicated by reduced set-up and operative time was both predictable and significant.

We had hypothesized that as surgeons became more experienced using a robotic surgical system they would learn to save time and maximize economy of movement by minimizing the number of instrument exchanges used for each case. However, our data revealed poor correlation between the number of robotic instrument exchanges and operative time. Furthermore, increased daVinci-specific surgeon experience did not reduce the number of instrument exchanges. We attribute these findings to the fact that in each surgeon's early experience with the robot, instrument exchanges are considered significant events—that is, they are viewed as time-consuming hassles. However, as surgeons grow familiar with the relatively simple instrument exchange procedure, the process becomes less intimidating. An experienced patient-side assistant can exchange a robotic instrument almost as quickly as conventional laparoscopic instruments can be exchanged from conventional ports. Thus any reduction in instrument exchange rate that might have occurred as a result of learning may have been masked by decreasing mental resistance to instrument exchange on the part of the surgeon. An alternative explanation is that because the successful completion of every surgical procedure requires that an inherent number of steps be performed—each requiring a minimum number of instrument exchanges—surgeons may have used their standard steps in performing their robotic procedures thus predetermining the number of instrument exchanges that would be required. The number of accessory laparoscopic ports used by surgeons remained relatively constant, and, therefore, did not correlate with surgeon experience, or operative time.

In an effort to obtain a detailed picture of problems encountered during training, surgeons were encouraged to be liberal in their inclusion of "complications." For example, surgeons were encouraged to report instances of bleeding even when the bleeding was quickly controlled, and surgeons were asked to report even minor "glitches" encountered when using the robot (eg, a malfunctioning instrument that was easily exchanged). Therefore, our absolute complication rate is much higher than would be the case if standard clinical criteria had been used. We included an anesthetic complication category to distinguish surgeon- and robot-related problems from anesthesia misadventures, and a material complication category primarily as a means of identifying supplies that were in short supply in the animal laboratory.

While the absolute number of complications recorded in our protocol has little clinical relevance, a number of important observations can be made from the detailed complication data. Of the 43 cases attempted during our training protocol, only two had to be abandoned because of robotic equipment failure. Given the complexity of the daVinci system, this seems to be an excellent reliability rate. If robotic equipment fails in the clinical arena, procedures can always be completed using standard laparoscopic or open methods. Of the 10 operative complications, four are worthy of discussion because they outline robot-specific issues of which surgeons need to be aware to achieve safe and successful clinical use of the system. In one case, a surgeon was delayed when he had to disconnect the robot from the laparoscopic trochars in order to place the patient in Trendelenberg position. This case emphasizes the need to perform patient positioning prior to the engagement of the relatively cumbersome daVinci robot. In a second case, a surgeon broke a needle as he attempted bimanual manipulation of the needle. In two other cases, solid organ bleeding (liver in one case, spleen in another case) ensued after excessive force application to the patient-side organ retractor from the inadvertent bumping of the proximal portion of a robotic instrument (out of the surgeon's view) against the retractor. While the broken needle in our study was simply removed and replaced, and while retractor-related solid organ injury would be expected to be less likely in the clinical arena where patient-side assistants hold and monitor retractors (because of manpower limitations in the laboratory, we generally fixed retractors to the table), these latter three complications underscore one of the most significant limitations of current surgical robotic systems—a lack of haptic feedback for robotic arms possessing great strength. While researchers from Intuitive Surgical and a great many others are pursuing ways to provide surgeons with effective haptic feedback, for now, safe use of the daVinci system necessitates that the surgical team pay careful attention to this issue.

The direct costs associated with our training protocol totaled $10,355. By delaying clinical use of the robotic system purchased by our department for the purpose of engaging in in-house animal model training, we were able to significantly reduce the $63,250 cost associated with daVinci system training for 23 surgeons at designated Intuitive Surgical Training Centers ($5,500 for two surgeons). Our model of "on-site" training resulted in a cost savings of approximately $52,895 for our medical center and provided improved training opportunities for our surgeons (ie, the entire second phase of our training protocol). While the cost savings would not be as great for hospitals without dedicated animal operating room and veterinary support services, we nevertheless recommend similar training protocols for institutions implementing clinical surgical robotics programs. Subsequent to the completion of our training protocol, we have introduced our department's daVinci system into clinical practice at Walter Reed. While it is still very early in our institution's experience with the system, our surgeons have greatly appreciated the opportunities they had to practice with the robot prior to clinical use. Our systematic training program seems to have afforded our department a smooth transition into the world of surgical robotics.

Because the cost of complex surgical robotic systems like daVinci is high (approximately $1,000,000), our hospital was eager to have the robot used in the clinical arena as early as possible. Thus our study was somewhat limited regarding the duration of the second phase of the protocol: our study did not observe surgeons or surgical teams long enough to determine at what point operative and set-up times plateau. However, our study does suggests that hospitals implementing clinical surgical robotics programs that institute preclinical surgical robotics training programs similar to ours can expect to enjoy a 40% reduction in preclinical operative time and a 50% reduction in preclinical set-up time by allowing their surgeons and surgical teams to practice only three times.

In conclusion, new use of an advanced surgical robotic system is associated with a rapid learning curve among experienced surgeons from multiple surgical disciplines. Surgeons can quickly learn the skills necessary to take advantage of the daVinci robot's benefits. Preclinical animal model training is effective in developing such skills and allows surgeons the opportunity to refine their surgical robotic technique prior to human application. As the field of robotic surgery continues to grow, graduate medical education and continuing medical education programs that address the surgical robotic learning needs of residents and practicing surgeons need to be developed.

## Acknowledgments

The specific daVinci system used in this study was purchased outright by Walter Reed Army Medical Center (WRAMC), and the study was funded entirely by the WRAMC Department of Surgery with veterinary support from the Walter Reed Army Institute of Research. The authors of this study have no conflicting financial or other interests in Intuitive Surgical, the makers of the daVinci robot.

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