SCIENTIFIC PAPER

Performance Measurements in Endolaparoscopic Infrarenal Aortic Graft Implantation using Computer-enhanced Instrumentation: a Laboratory Model for Training

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ABSTRACT

Background: Performance measurements in an endolaparoscopic aortic animal laboratory model have been reported since Dion's work (1995). The purpose of this paper is to report performance measurements using computer-enhanced surgical instrumentation in a porcine model.

Methods: From February 2000 to December 2002, training in robotic instrumentation consisted of implantation of infrarenal aortic grafts in 3 groups of 5 animals each. The time frame to complete all 15 procedures reflects 2 major difficulties: the need to schedule procedures based on the surgeon's time off from his solo practice and the availability of laboratory sites to complete the procedures. A full endolaparoscopic technique was used to perform 2 end-to-end anastomoses through an intraperitoneal approach. A different method of computer-enhanced instrumentation was used for each group of animals as follows: (1) AESOP robotic arm and HERMES integrated voice control instrumentation, (2) AESOP-HERMES-ZEUS robotic systems, (3) da Vinci robotic system. The aortic clamp time, total operative time, and blood loss were recorded for each procedure. Secondary endpoints included spinal cord ischemia, graft thrombosis, and bleeding.

Results: All animals tolerated the procedure. All grafts were patent and suture anastomoses intact. Two instances of bleeding, both of which were controlled laparoscopically, occurred. Aortic clamping time was significantly improved in Group 3 compared with that in Group 2 ($P=0.008$).

Conclusion: The results of the first group reflect previous experience with the AESOP-HERMES instrumentation. However, the times of the ZEUS group and da Vinci group reflect initial exposure to the technology. The remote position of the surgeon at the console did not appear to affect the performance as shown in the last group. The da Vinci group provides an advantage compared with the ZEUS group. Both systems showed adaptability and versatility in controlling adverse bleeding encounters.

Key Words: Aortic surgery, Animal model, Computer-enhanced, Endolaparoscopic, Robotics, Training, Telemanipulation.

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INTRODUCTION

Since 1993, the pioneering work of Dion[1–5] in minimally invasive abdominal aortic surgery has stimulated the creation of different laboratory models to investigate new approaches for aortic repair. After successful completion of a fully endolaparoscopic aortic graft in the porcine model using voice activated computerized instrumentation, the next logical step appeared to be investigation of the role of telemanipulation by the current available robotic technology. The use of this remote telesurgery for endolaparoscopic abdominal aortic surgical reconstruction in the laboratory has not been previously reported even though the first human robot-assisted laparoscopic aortic reconstruction was accomplished in 2002.[6]

A logical question is "Why robotics in vascular surgery?" Simply or complexly, it is an evolutionary step in the development of computer-enhanced surgical instrumentation, which is applied both as science and as an art form toward anatomical vascular target organs, specifically the abdominal aorta. In 1995, Intuitive Surgical, from Mountain View, California, purchased the patent and finalized the project known today as the da Vinci Surgical System. In 1998, rapid application in laboratory models and in pioneering clinical trials followed both in the USA and Europe; in 1999, it expanded to cardiac surgery. Another leading robotic company, Computer Motion, from Santa Barbara, California, also emerged with similar computerized instrumentation, known as AESOP and HERMES voice integrated systems. Since 1995, these systems have gained acceptance among different surgical specialties for procedures needing the support of robotic arm and ancillary equipment. AESOP, HERMES, and ZEUS were used in the first transatlantic surgery, a laparoscopic cholecystectomy on September 7, 2001. In this instance, the surgeons were in New York and the patient was in Strasbourg, France.[7] The benefits of modern robotic systems are particularly applicable to complex technical reconstructions, such as cardiac, vascular, gastrointestinal, and urological surgical procedures.

Our objective was to compare the feasibility of 3 distinct computer-enhanced robotic systems for placement of an infrarenal interposition graft in the porcine model using 2 end-to-end anastomoses via a transperitoneal approach. In group 1, the AESOP Robotic Arm/HERMES integrated voice control instrumentation (Computer Motion, Goleta, CA) was used **(Figure 1)**. The AESOP/HERMES/ZEUS robotic systems (Computer Motion, Goleta, CA) **(Figure 2)** were used for group 2; and the da Vinci robotic system (Intuitive Surgical, Inc Sunnyvale, CA) was used in group 3 used **(Figure 3)**. The end points of the study were a comparison of aortic clamp times, bleeding, and total operative times. In addition, the study evaluated the performance of the surgical team in terms of adaptation to the different forms of computerized surgical instrumentation.

Figure 1. Positioning of pig and surgical team for endolaparoscopic repair. Animal in right lateral decubitus position in Trendelenburg. Left to right: video console with HERMES control system, surgical assistant, AESOP robotic arm, and surgeon wearing voice activation headset.

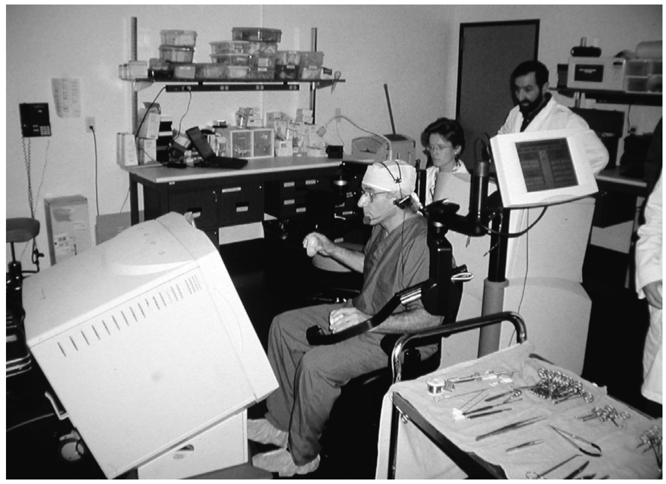

Figure 2. Surgeon seated at ZEUS console and using voice and hand controls.

Figure 3. Surgeon immersed in da Vinci console for 3D visual effectiveness. Hand controls are visible.

METHODS

Due to restrictions on the surgeon's time away from a private practice and availability of laboratory facilities needed to complete this project, the study was conducted between February 2000 and December 2002. The surgeon, being in private solo practice, scheduled the procedures around vacation and time off, so as not to interfere with patient care. Due to the complexity of the procedures and availability of the ZEUS and the da Vinci, laboratory facilities were limited in the geographic area of the practice. Arrangements were made with the identified laboratories based on their availability. Each group consisting of 5 porcine animals underwent procedures at different laboratory sites following each group's respective protocol for care and use. Group 1 was operated on at the Douglass Laboratory of St. Vincent Mercy Medical Center, Toledo, Ohio; the animals were recovered from anesthesia and kept alive for 24 hours. Group 2 was treated at Computer Motion Laboratory for Training, Goleta, California; the animals were kept under anesthesia and observation for 3 hours. The third group was operated on at Intuitive Surgical Laboratories for Training, Mountain View, California, Ohio State University, Columbus, Ohio and Cincinnati, Ohio. These animals were also kept under anesthesia and observation for 3 hours. Since the first set of procedures was done locally, the animals could be kept alive and the surgeon could monitor postoperative care. Animals in groups 2 and 3 were not kept alive due to cost and location; this minimized the surgeon's time away from practice. Because the primary endpoints were related to the surgical procedure itself, the data related to times (aortic clamp time, total operative time), blood loss, and control of bleeding could be compared. We were unable to monitor spinal cord ischemia/return to function in Groups 2 and 3. Fifteen female porcine animals with an average body weight of 56.13kg (SDV±9.05) were fasted overnight, premedicated for surgery with atropine (0.04 mg/kg, IM), and sedated with tiletamine and zolazepam (Telazol Lederle Parenteral, Inc., Carolina, Puerto Rico) at 6 mg/kg IM. Anesthesia was induced with 3% halothane in oxygen delivered by facemask. Groups 1 and 3 were orotracheally intubated, while Group 2 underwent tracheostomy. (A tracheostomy was performed solely on the anesthesiologist's requirements at that facility). Anesthesia was maintained with 1% to 3% halothane in oxygen with mechanical ventilation (Hallowell model 2000, Hallowell EMC, Pittsfield, MA, USA) to maintain end-tidal carbon dioxide between 35 mm Hg and 55 mm Hg.

Venous and arterial catheters were placed percutaneously for drug and fluid administration and blood pressure monitoring. ECG leads were placed. Serial samples of hematocrit and arterial blood gases were taken from the auricular arterial catheter. Blood gas samples were analyzed immediately on a calibrated blood gas analyzer (Ciba-Corning model 248, Global Medical Instrumentation, Albertville, MN, USA). Pulse oximetry (SpaceLabs model 90651A, Spacelabs Medical, Issaquah, WA, USA) was performed continuously during the procedures. Lactated Ringer's solution (Abbott Laboratories, Abbott Park, IL USA) was administered intravenously at approximately 10 mL/kg/hr throughout anesthesia.

The animals were placed in a full right lateral decubitus position (left side up) in the Trendelenburg position. Preliminary measurements were made for positioning of the working ports, which were similar in each of the 3 groups. The abdomen and groin were prepared with iodine-providone solution, and sterile drapes were applied.

The proximal aortic clamping was always executed using the Chitwood Trans Aortic Cross Clamp (Scanlon Medical Inc, St. Paul, MN) inserted in the left costoparavertebral angle. The direction of the clamp toward the infrarenal aorta was made as horizontal as technically possible. Distal clamping control was achieved using a #5 arterial Fogarty embolectomy catheter (Edwards Lifesciences, LLC, Irvine, CA, USA) introduced via the femoral approach **(Figure 4)**. This approach was performed via a cut down and percutaneously in 2/3 of the animals and 1/3 of the animals, respectively. Additional endolaparoscopic instru-

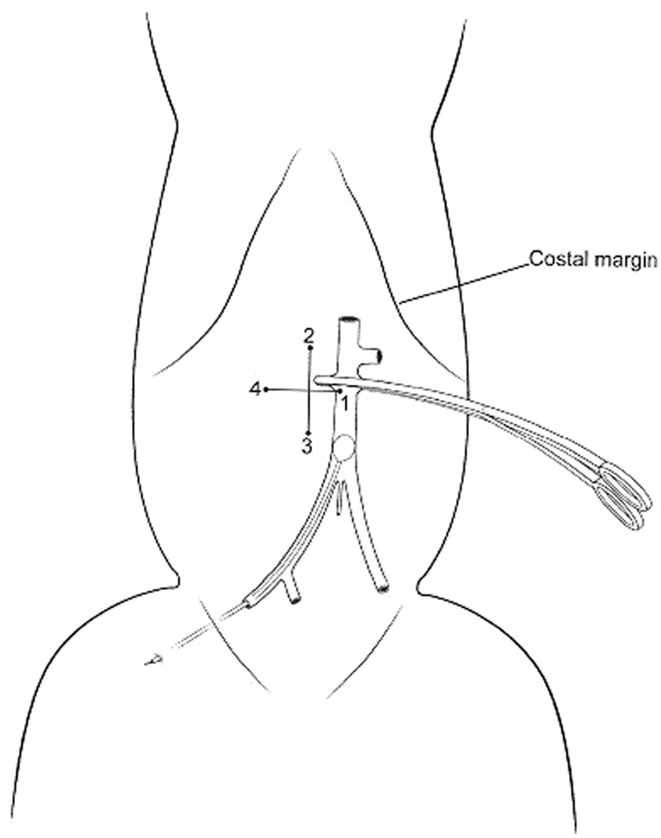

Figure 4. Port placement and clamp placement for porcine endolaparoscopic aortic repair: 1. Endoscope port (10 mm); 2. Left-hand port (5 mm); 3. Right-hand port (5 mm); 4. Assistant port (10 mm). Proximal control of aorta with Chitwood clamp. Distal control with Fogarty balloon catheter via right femoral percutaneous approach.

mentation included the UltraCision Harmonic scalpel and Ethicon Endoscissors (Ethicon Endo-Surgery, Cincinnati, OH, USA); two 512-mm Ethicon Endopath trocars for the 0° and 30° 10-mm endoscopes (Stryker Endoscopy, Mountain View, CA, USA) and the Nezhat-Schroeder suction irrigation system (Davol, Inc., Cranston, RI, USA); Ethicon Ligaclip clip applier (Ethicon Endo-Surgery), two 5-mm needle holders and two 5-mm graspers (Ethicon Endo-Surgery). CO_2 pneumoperitoneum was created via a 511H Ethicon Endopath nonbladed Optiview trocar or a Veress needle introduced through a small midline incision. Two techniques were used to gain experience with each; it was felt that the different methods for creating the pneumoperitoneum would not add a confounding variable to the procedure.

The ZEUS and da Vinci systems required the use of the following instrumentation designed to work with each surgical system: Debakey needle holder, electrocautery, scissors, and tissue forceps. The surgical team consisted of the endolaparoscopic surgeon, a standby technician, and a circulator. The surgeon had previously trained extensively in the dry laboratory simulating the aortic anastomosis accumulating the following hours in the different robotic systems: endolaparoscopic training (Ethicon instrumentation), 250 hours; ZEUS, 9 hours; and da Vinci Surgical System, 22 hours. Laboratory training hours were determined by the availability of the systems. The hours on the ZEUS were completed in a concentrated time frame, while the da Vinci hours were intermittent. The experience working with AESOP/HERMES and AESOP/HERMES/ZEUS undoubtedly contributed to the surgeon's success with the da Vinci training. However, the increased number of hours on the da Vinci system emphasizes the effect of dry laboratory training on the overall results. The endoscopic training protocol utilized is divided into the following 3 phases: Phase 1- endoscopic suturing, cutting, endo- and exoknot tying; Phase II - endoscopic suture anastomosis of 8-, 10-, and 12-mm grafts in vitro to develop technical precision; and Phase III - increasing both quality and speed of anastomoses until they can be completed within 20 minutes to 30 minutes.

The transperitoneal approach was deliberately selected, per our Stanford protocol (Protocol 6127–1), as potentially the most difficult procedure for maximum training benefit. To compare surgical performance outcomes and time parameters, no variations of this approach were allowed throughout the study. Trocars and ports were positioned as previously indicated **(Figure 4)**. The first objective intraoperatively was to control bowel loops, which were moved to the right side of the abdomen for maximum exposure of the posterior peritoneal space. The posterior peritoneum was opened by Harmonic scalpel in group 1, and by right robotic hand electrocautery micro-instrumentation in groups 2 and 3.

Approximately 5cm of the infrarenal aorta was exposed with a combination of blunt and sharp instrumentation, including the UltraCision Harmonic scalpel and Endoscissors in group 1 and the left-hand tissue micro-robotic forceps and right-hand electrocautery in groups 2 and 3. The lumbar branches encountered were visualized and controlled with Ligaclip endoscopic clip applier or micro-robotic Endoclips placed by the console surgeon. Systemic heparinization (3mg/kg IV) was administered. The surgeon executed proximal aortic clamping in group 1. In groups 2 and 3, the clamp was placed via a coordinated simultaneous maneuver with the actual clamping performed by the stand-by robotic technician, directed and visually controlled by the console surgeon. After the proximal aortic clamp was observed to be horizontally placed and secured, a #5 Fogarty balloon catheter was advanced retrograde through a #6 Pinnacle Introducer (Meditech, Boston Scientific, Corporation, Watertown, MA, USA) already placed in the right femoral artery. The advancement was made by the standby technician and visually guided by the console surgeon who was in control of the endoscope. When the catheter reached the clamp, gradual inflation was initiated. The catheter was pulled back approximately 3cm or 4cm to ensure the intraluminal aortic space was deprived of blood. If the vessel remained empty, the aortic lumen was ready for final cutting. If the aortic lumen remained full, collateral aortic branches may have been inadvertently missed and reassessment of the aortic branches was completed.

Vertical transection of the aortic wall was performed with a 5-mm or 8-mm Endoscissors in the right-hand port **(Figure 5)**. A posterior aortic wall bridge of 2mm or 3mm was purposely left for stabilization during the proximal anastomosis. An 8-mm or 10-mm diameter polytetrafluoroethylene graft (IMPRA Inc., Tempe, Arizona, USA) was implanted by continuous end-to-end suture anastomosis with 3–0 prolene with TF or BB needle (Ethicon, Sommerville, NJ, USA) using 5-mm endoscopic needle holders in group 1. Debakey needle holders were used in groups 2 and 3 (ZEUS and da Vinci, respectively). Two 15-cm lengths of prolene were used for each anastomosis. This particular length provided optimal ergonomics to secure the intracorporeal endoknots, especially using the Debakey needle holder in the ZEUS and da Vinci groups. Using the face of a clock as a reference, the proximal anastomosis was always initiated at hour 6 of the posterior aortic wall and the distal anastomosis was started at hour

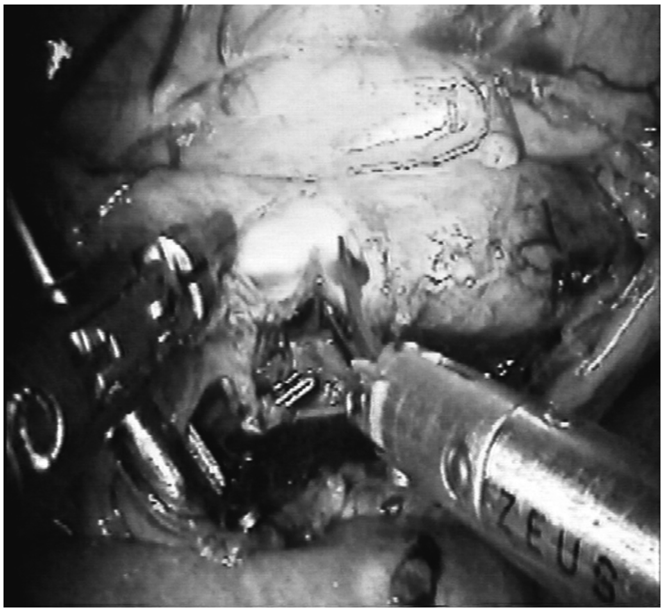

Figure 5. Vertical transection of the aortic wall was performed with a 5-mm Endoscissors in the right-hand port by using ZEUS. Proximal Clamp = Chitwood clamp. Distal endoluminal control = Fogarty catheter.

9. The more difficult portion of the anastomoses (the far wall in the proximal anastomosis and the posterior wall in the distal anastomosis) was always constructed first, therefore making it easier to finish the anastomosis by completing the near wall of the proximal anastomosis and anterior wall of the distal anastomosis **(Figure 6)**. There were 3 instances when a few interrupted sutures of 4–0 or 5–0 prolene were needed to reinforce potential or real areas susceptible to bleeding. The distal aortic balloon

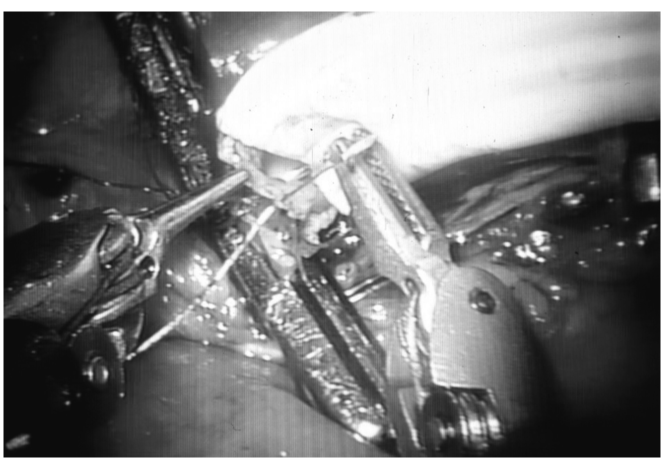

Figure 6. Proximal aortic anastomosis of anterior wall using 3–0 Prolene on TF needle.

was then gradually deflated followed by a gradual declamping process proximally to restore circulation to the lower legs. The aortic clamp was kept in situ near the aorta, if needed again. After the aortic repair was observed for 15 minutes, the posterior peritoneum was closed with an endostapling device. In group 1, in which the animals were kept alive for 24 hours, the ports were sutured with 2–0 Vicryl sutures (Ethicon Inc, Cincinnati, OH, USA). In groups 2 and 3, ports were not sutured.

All animals were sacrificed at the scheduled time followed by autopsy. During postmortem examination, 2 cm of proximal and distal aortic tissue including the 2 anastomoses and implanted graft was excised for final inspection. The suture lines were inspected with micro lenses, 3.5 magnification.

RESULTS

Full endolaparoscopic infrarenal aortic graft implantations, each involving 2 suture anastomoses, were successfully completed in the 15 animals. The *t* test, a parametric procedure for testing differences between groups, was used for data analysis. Mean times for aortic clamping, total operative time, and blood loss among groups were evaluated based on a significance level of 0.01. Mean aortic clamping times in groups 1, 2, and 3 were, respectively, 55.8 minutes (±3.3), 73.8 minutes (±11.5) and 51.6 minutes (±7.06) **(Table 1)**. Aortic clamping time was significantly improved in Group 3 compared with that in Group 2 (P=0.0086). There was significance between groups 1 and 2 (P=0.022). There was no statistical significance between groups 1 and 3. No differences were found in other parameters.

The ergonomic port base (distance between the right-hand and left-hand ports) was 12.0 cm, 16.0 cm, and 15.98 cm in Groups 1, 2, and 3, respectively. In group 1, a scope with a 30-degree angle was used; a 0- or 30-degree scope, or both, was used in groups 2 and 3. Mean data for the procedural steps including femoral access time, robotic engagement, aortic dissection, and anastomosis times for each group are delineated in **Table 2**.

Although no intraoperative bleeding was encountered during the aortic dissection in group 1, an incidental partial injury of the left renal artery occurred in group 2, and a lumbar branch occurred in group 3, which caused blood loss of more than 100mL. Both incidents were managed by a careful coordinated effort between the console surgeon and robotic standby assistant. The small tear of the renal artery was repaired with 4–0 Prolene suture in a figure 8; the aortic branch was controlled by an endoclip. Two animals required

Table 1.
Porcine Computer Enhanced Infrarenal Aortic Resection Model*

Device	Weight of Pig (kg)	Aortic Clamp Time (min)*	Total Operative Time (min)*	Blood Loss (mL)*
AESOP-HERMES (n = 5)	56.2	55.8 ± 3.3	167.4 ± 4.2	68 ± 66
ZEUS (n = 5)	57.4	73.8 ± 11.5	183.6 ± 22.5	154 ± 137.8
da Vinci (n = 5)	54.8	51.6 ± 7.06	155.8 ± 15.5	86.0 ± 91.8

*Mean ± standard deviations.

Table 2.
Procedure Times*

Device	AESOP-HERMES	ZEUS	Da Vinci
Ergonomic Ports	12.0 cm base	16.0 cm	15.98 cm base
Scope	30 degree	0 degree; 30 degree	0 degree × 4; 30 degree × 1
Femoral Access	11.2	12.4	10.5 m (2)
Percutaneous			3 animals
Port placement	29.4	24.8	14.6
Robotic Arm Engagement	3.4	6.8	4.2
Aortic Dissection	37.0	39.0	22.8
Proximal Anastomosis	28.2	29.0	21.4
Distal Anastomosis	25.8	30.0	20.6
Total Aortic Clamp Time	55.8	73.8	51.6

*Mean minutes.

an extra suture at the anastomotic site. All animals were kept alive according to the pre-established protocol guidelines. Postoperatively, the 5 animals in group 1 were observed to be ambulatory within 7.5 hours to 11.25 hours (mean, 10.35). At postmortem examination, all grafts were found to be patent and suture anastomoses intact.

DISCUSSION

Procedure

W. Wisselink, M. Cuesta, C. Gracia, and J. Rawerda[6] first performed a robotic- assisted aortic procedure in humans in February 2002 in Amsterdam, Holland. The procedure performed in 2 patients consisted of a full laparoscopic end-to-side aorto-bifemoral graft by using the ZEUS Robotic System (Computer Motion for atherosclerotic occlusive disease). The team preceded this unique technical effort with a laboratory-training program.[8]

Our present report was in part executed at the same time as this European-American effort at the end of 2001. Both laboratory models represent the first visionary attempts to bring modern computerized enhanced surgical instrumentation to the complex field of minimally invasive aortic surgery. Constant evolutionary changes in the laboratory aortic model by these 2 groups have occurred to improve team performance when using this modern technology in the challenging and complex human model.[8,9]

Similarities and differences can be identified in theses two. Both teams used a female porcine model, same right lateral decubitus positioning, and a pneumoperitoneum to create working space. While Ruurda performed a retroperitoneal approach to the infrarenal aorta by using a digital-guided balloon inflated under visual endoscope to enhance the space, we used a more direct intraperitoneal approach to the aorta **(Table 3)**. The clamping of the aorta differed in that Ruurda used detachable endoscopic clamps proximal and distally. In our study, a Chitwood endo-clamp was deployed proximally, and an intraluminal Fogarty balloon was used for distal control. Both methods appeared to be very effective **(Table 4)**.

Ruurda used PTFE as the interposition graft in the infrarenal aorta. This graft used PTFE suture on 2 needles with pretied knots already incorporated in the graft. Our approach was the creation of intracorporeal knot tying to initiate the anastomosis to maximize training as well as the handling of the suture material. In contrast, we used 3–0 prolene with a TF or BB needle, which has different suture memory and consequently different endoscopic behavioral characteristics. Another difference between the 2 studies was the position of the ports. We always approached the aorta from the right side, and the European protocol approach was from the left side, from the paralumbar musculature. This approach presents a narrower space to the trocars for the robotic arms because of the presence of the rib cage and hip bone. We believe the abdominal wall gives more freedom to place the trocars for the robotic arms. We found 14 cm to 17 cm between arm ports to be ergonomically correct.

The primary difference between our study and the Ruurda study is that the experience was divided into 2 groups of regular laparoscopic vs. da Vinci technology, comparing 3 surgeons, 2 with no robotic experience and 1 experienced robotic surgeon; we used only 1 surgeon with gradual "learned" experience in robotic techniques, but using different computer enhanced surgical systems in different laboratories.

Our group also compared the 2 robotic systems side by side (ZEUS vs. da Vinci) having set the baseline using the group done with laparoscopic instrumentation and AESOP/HERMES voice activated systems, as a control. The ZEUS system uses 2-dimensional instrumentation and requires the surgeon to become experienced with voice-activated commands and tone modulations for efficient control of the endoscope during the procedures. The open console design exposes the surgeon to environmental distractions, thus potentially decreasing concentration on the surgical field. The da Vinci Surgical System provides a 3-dimensional view. The surgeon is immersed in the console to increase concentration. The da Vinci also, via the Endowrist, provides increased freedom of movement of the instruments, thereby increasing surgical control and precision.

When making parallel comparison of the outcome timing measurements between the 2 laboratory experiences, certain interesting findings were observed. The 3 European surgeons averaged only 6.6 individual procedures per surgeon. In our study, a single surgeon performed 15 procedures, 5 in each group comparing not only the control vs. robot groups, but also comparing the 2 robotic systems available (ZEUS vs. da Vinci). This report shows the single surgeon was very competitive from the very initial interface with the da Vinci system. Total operative times and clamping aortic times were very similar and actually quicker than that in the control group. This was despite the fact that group 1 (AESOP/HERMES) was the

Table 3.
Comparison of Endolaparoscopic Aortic Procedures With da Vinci Surgical System in Porcine Models

	Wisselink et al	Martinez
No. Surgeons	3 surgeons	1 surgeon
Time Frame	Nov 2002-Feb 2003	Feb 2000-Dec 2002
No. Animals	20	15
No. Cases Per Surgeon	3.5	15
Weight	80–110 kg	45–80 kg
Position	Rt. Lateral Decubitus	Rt. Lateral Decubitus
Port placement	Left	Right
Approach	Retroperitoneal	Intraperitoneal

Table 4.
Comparison of Endolaparoscopic Aortic Procedures With da Vinci Surgical System in Porcine Models

	Wisselink et al.		Martinez	
	R*	C*	R*	C*
Aortic Dissection Time (min)	38	32	22.8	37
Aortic Clamp Time (min)	63	106	51.6	55.8
Proximal Anastomosis Time (min)	22	40	21.4	26.2
Distal Anastomosis Time (min)	22	41	20.6	68
Total Operative Time (min)	164	205	155.8	167.4
Estimated Blood Loss	55 mL	280 mL	86 mL	68 mL
Time frame	Nov 2002-Feb 2003		Feb 2000-Dec 2002	
Clamps for Aortic Control	Proximal = Detachable; Distal = Detachable		Proximal = Chitwood clamp; Distal = Fogarty balloon	

*R=da Vinci Robotic system; C=Control (Routine endolaparoscopic for Dr Wisselink et al and AESOP/HERMES for Dr Martinez).

second experience for the surgeon, compared with our Stanford Laboratory Model.[8] This observation indicates the benefit of the visual 3-dimensional power of the da Vinci system and endowrist movements at disposal for this complex aortic anastomosis. **Table 2** shows that the dissection of the aorta proximal and distal anastomotic split times are also an indication of how much faster the surgeon was with the da Vinci compared with conventional laparoscopic instrumentation in the AESOP/HERMES group. It is also very clear that our single surgeon was consistently quicker with the da Vinci compared with the ZEUS robotic performances. This observation needs an additional commentary, in that the surgeon, in the initial working phase with each system, had more dry-laboratory training with da Vinci (22 hours) than with ZEUS (9 hours). This was primarily due to the availability of the equipment and access to laboratory time. In the experience with the ZEUS robotic system, the same laboratory facility was used for all 5 procedures; however, this was not the case with the da Vinci exposure. These procedures were performed at 3 laboratories and with different personnel assisting the surgeon. Also, important to consider is the fact that logistically the experience with ZEUS was carried out within 6 months, and the 5 da Vinci cases were diluted over a 34-month period, as previously explained. We believe that despite these logistical differences the da Vinci system outperformed the ZEUS system for the same aortic laparoscopic reconstruction. When we compare the split times of the surgeons using the different instrumentations in the European laboratory model with our report, it is quite evident that in our control group we were consistently quicker, not in the aortic dissection, but in the proximal and distal anastomosis, therefore, in the aortic cross clamping and total operative time. This could be attributable to the use of voice-activated system (AESOP/HERMES) to facilitate the performance of the anastomosis. Also, as we compared the 2 studies, the da Vinci experience shows very similar times and a safer performance of the aortic anastomosis. The single surgeon in our study was consistently quicker, although not by a significant margin, in the split times of aortic exposure, and the proximal and distal anastomoses performance, and therefore, had quicker aortic clamping times **(Table 4)**. Perhaps this is related to more time dedicated to dry-laboratory practice and a somewhat higher caseload.

The total operative time in our report is also shorter probably due to the extra time required for the retroperitoneal space-making maneuvers, as the transperitoneal in our hands seems to be quicker. This is related in part to the animal preparation preoperatively, and aggressive full lateral decubitus positioning of the animal. As we demonstrated in our previous report, bleeding, thrombosis, and spinal cord ischemia are the most important end points to evaluate for this type of surgical reconstruction.[9]

Spinal Cord Ischemia

We could not fully evaluate spinal cord function in groups 2 and 3; therefore, no definitive conclusions can be made. All the animals in group 1 (24-hour survivors) were all fully ambulatory and recovered normal function. If we postulate that 90 minutes of total aortic cross clamping is a safe margin to predict the risk of spinal cord ischemia in the porcine model, then no animals in the da Vinci group were at risk. However, in the ZEUS group, despite the fact that all aortic clamp times were under 90 minutes, we had one animal (clamp time, 87 minutes) that was potentially at moderate to high risk for spinal cord ischemia.

Thrombosis

All animals demonstrated palpable femoral pulses, and autopsy evaluations showed all anastomoses intact, suture lines impermeable, and no signs of local thrombosis. This indicates the good quality of anastomoses obtained in the control group and the 2 robotic groups.

Bleeding

The most feared complication of both supporters and nonsupporters of endolaparoscopic surgery is bleeding. In our Stanford model, we reported 25% (6/24) rate of bleeding complications, not from clamping-related events, but related to dissection of tissue (aortic lumbar branches and vena cava). Defining bleeding as more than 100 mL for the entire procedure, 2 of these bleeding incidents had to be converted to minilaparotomy to control the bleeding site. The other 4 incidents were controlled endolaparoscopically, one animal required transfusion, and all survived the surgical procedure.[9] In this study, although we did not see any bleeding in group 1, we had 2 bleeding events in the robotic groups, both related to poor visual control of the left renal artery (ZEUS) and the left lumbar branch (da Vinci). Control of each event was successfully managed by a well-coordinated effort between the console surgeon and the robotic assistant. There were no conversions or indications for transfusion. Ruurda et al[8] report 2/20 failures to control hemorrhage, after declamping the aorta, leading to termination of the experiment in 2 cases in the control nonrobotic group. Also, during aortic tissue examination at autopsy, two of the control animals showed poorly tied knots, resulting in anastomotic dehiscence. However, there were no anastomotic failures in the da Vinci group. These 2 studies show the benefit of anastomotic architectural construction by the robotic instrumentation, and potential for minimizing hemorrhagic complications.

Training

In our previous study, we emphasized the importance of training.[9] Aortic clamp time and total operative time represent a benchmark for performance of the entire surgical team. Particularly important is the ability of the surgeon and assistant to interface during the different technically demanding tasks required to complete a good quality suture anastomosis. Team cohesiveness is necessary not only to perform all the required surgical steps, but also to allow the team to recover quickly in situations of adversity that may occur intraoperatively, especially during aortic clamping time. The different drills performed during dry-laboratory training are critically important for the surgeon in training. We demonstrated the need for practice before any robotic-assisted aortic reconstruction. In the ZEUS group, to perform an operation without dry-training laboratory practice represented a prolonged aortic clamp time of 119 minutes. On the other hand, in the same group, as well as the da Vinci group, preoperative practice of at least 40 minutes, represented aortic clamp time less than 90 minutes. The Wisselink group also demonstrated the importance of training in the laboratory in the stage immediately before the final assault of the human aortic anastomosis.[6]

Kolvenbach[10] has also demonstrated the importance of intensive training/practice to minimize aortic clamp time. Human aortic clamp times of less than 120 minutes and total operative times of less than 240 minutes are expected to minimize postoperative complications.[10]

CONCLUSIONS

As predicted, not only the surgeon, but also the entire surgical team is confronted by a tremendous challenge in terms of training and adaptation to this modern technology. Total operative times, and particularly, the aortic clamp times are very sensitive performance measures for the entire surgical team. The results in the AESOP/HERMES group were good, reflecting in our opinion the experience gained with 24 similar procedures previously performed using voice-activated computerized instrumentation. However, the times of the ZEUS and da Vinci groups reflect an initial exposure to the robotic remote telemanipulation. The position of the surgeon at the console did not appear to affect the performance, as shown, particularly in the da Vinci group. The da Vinci Surgical System appears to provide an advantage in performance when compared with the ZEUS, likely related to surgeon immersion at the console and 3-dimensional capability of the system.

The da Vinci Surgical System specifically provides freedom of movement via the Endowrist, which consequently, allows the surgeon specific hand movements required in such technical procedures. The system also provides unique visual control by a 3-dimensional view camera, which acts like the human brain and eyes. These 2 critically important elements enable the surgeon to do more precise and delicate craftsmanship under highly technically demanding conditions and in smaller surgical working spaces.

Using the AESOP-HERMES group as a control, this study comparing the ZEUS and da Vinci systems for performing aortic reconstruction in the laboratory was initiated in 2000 and completed in December 2002. We tested the 2 robotic systems side by side by performing a full endolaparoscopic aortic graft in the porcine model. We demonstrated that the da Vinci System provided an edge over the ZEUS System. This study appeared to be the first comparison study in aortic robotic surgery. Clearly, both robotic systems showed adaptability and versatility in controlling adverse bleeding encounters. We believe this study supports the mandatory need of adequate training methods, and credentialing for future clinical applications of robotic technology.

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