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CME ARTICLE

ROBOTIC LAPAROSCOPIC SURGERY: A COMPARISON OF THE *da VINCI* AND ZEUS SYSTEMS

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ABSTRACT

Objectives. To evaluate two currently available robotic surgical systems in performing various urologic laparoscopic procedures in an acute porcine model.

Methods. Robotic laparoscopic surgery was performed in 14 swine. Data were compared between the *da Vinci* Robotic System and the Zeus Robotic System.

Results. During laparoscopic nephrectomy, the *da Vinci* System (n = 6) had a significantly shorter total operating room time (51.3 versus 71.6 minutes; $P = 0.02$) and actual surgical time (42.1 versus 61.4 minutes; $P = 0.03$) compared with the Zeus System (n = 5). However, the blood loss and adequacy of surgical dissection were comparable between the two groups. For laparoscopic adrenalectomy, the *da Vinci* System (n = 5) had a shorter actual surgical time (12.2 versus 26.0 minutes; $P = 0.006$) than did the Zeus System (n = 5). For laparoscopic pyeloplasty, the *da Vinci* System had a shorter total operating room time (61.4 versus 83.4 minutes; $P = 0.10$) and anastomotic time (44.7 versus 66.4 minutes; $P = 0.11$). During pyeloplasty anastomosis, the total number of suture bites per ureter was 13.0 for the *da Vinci* System (n = 6) and 10.8 for the Zeus System (n = 6). The complications included an adrenal parenchymal tear each during a *da Vinci* System-based left adrenalectomy and a Zeus System-based right adrenalectomy. An inferior vena caval tear during a Zeus System-based right adrenalectomy occurred in 1 case, which was suture-repaired telerobotically.

Conclusions. Robotic laparoscopic procedures can be performed effectively using either the *da Vinci* or Zeus System. In this limited study, the learning curve and operative times were shorter and the intraoperative technical movements appeared inherently more intuitive with the *da Vinci* System. Additional clinical experience is necessary. UROLOGY **58:** 893–898, 2001. © 2001, Elsevier Science Inc.

Laparoscopy has changed the way we perceive and practice surgery. Although patients benefit considerably from the minimal invasion, laparoscopic surgeons are challenged with somewhat constrained technical abilities. As increasingly complex laparoscopic procedures are undertaken, optimization of laparoscopic efficacy takes on added importance and urgency.

Recent advances in robotic and computer technology may elevate laparoscopic surgery to yet another level by enhancing human performance using master-slave manipulators. Currently, two surgical telemanipulators are capable of performing remote telerobotic surgery: the *da Vinci* Robotic Surgical System (Intuitive Surgical, Mountain View, Calif) and the Zeus Robotic Surgical System (Computer Motion, Goleta, Calif).[1,2] We have previously reported our initial experience with remote robotic laparoscopic urologic procedures in a porcine model.[3,4] In the current study, we prospectively compared the latest version of the two robotic systems with a view to evaluating the operative feasibility and technical efficacy. For comparison, data from the initial version of the Zeus System were also evaluated retrospectively. To our knowledge, this is the first reported study comparing these two robotic systems in laparoscopic surgery.

MATERIAL AND METHODS

Fourteen female farm pigs, each weighing 30 to 40 kg, were used. The *da Vinci* Surgical System was used to perform six nephrectomies, five adrenalectomies, and six pyeloplasties.

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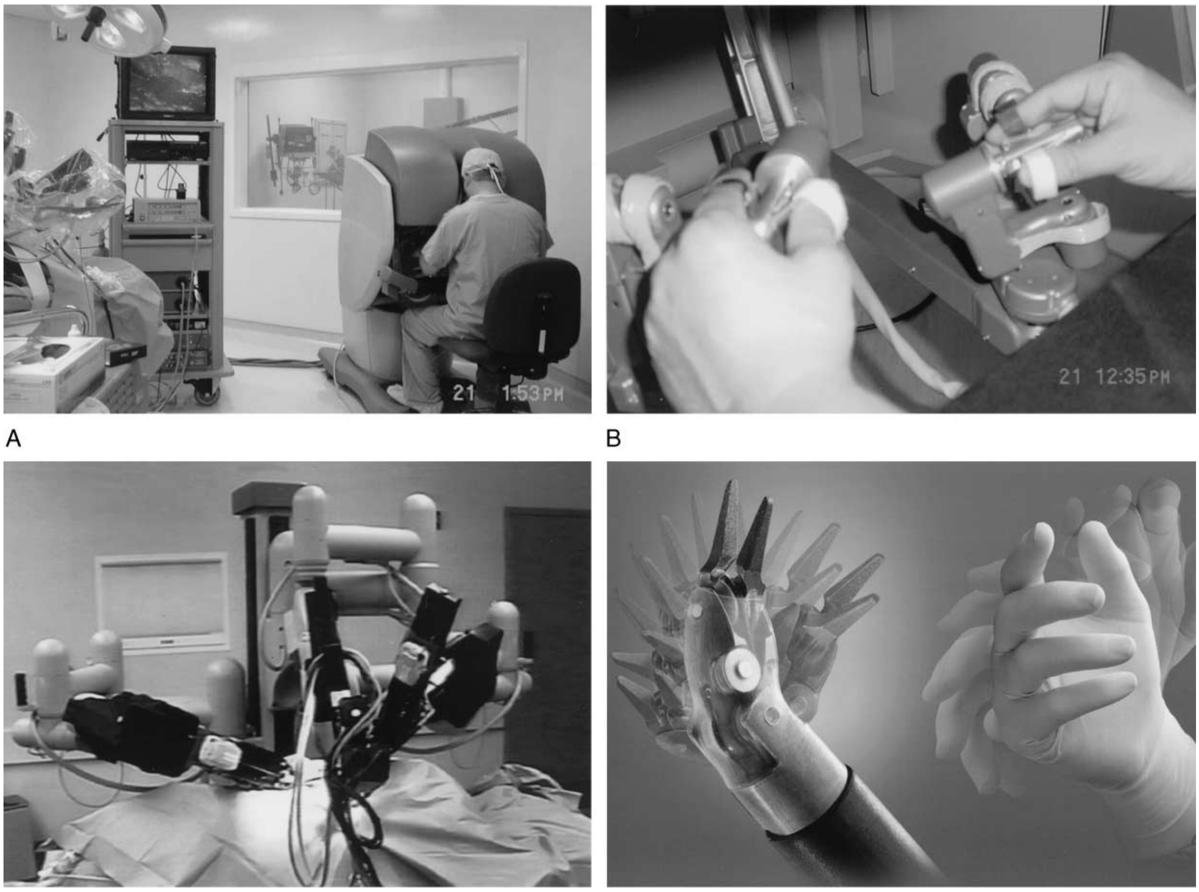

FIGURE 1. da Vinci *Surgical System. (A) Remote surgeon seated at the surgical console. At the console, the visual illusion that the tips of the instruments are in direct continuity with the master handles is created. (B) While observing the operative field, the surgeon performs operative maneuvers by manipulating hand-controlled manipulators linked electronically to motor-driven arms. (C) Surgical cart with three telemanipulator arms: a camera arm (center) controls the 12-mm stereoscopic laparoscope, and two instrument arms (lateral) manipulate a variety of 8-mm surgical instruments. (D)* EndoWrist *Instruments (tiny computer-enhanced mechanical wrists) technology allows a full 7° range of motion at the instrument tips. The range of motion of* EndoWrist *Instruments appears comparable to the human wrist. Figure 1D, © 1998 Intuitive Surgical, Inc., is used with permission.*

The latest version of the Zeus Robotic Surgical System (Z2P) was used to perform five nephrectomies, five adrenalectomies, and six pyeloplasties. As a historic control, the data on five nephrectomies, four adrenalectomies, and six pyeloplasties from the initial version of the Zeus System were also retrospectively compared.

The *da Vinci* System consists of three components (Fig. 1): a surgeon console with an integrated three-dimensional display stereo viewer, a robotic manipulator with three cart-mounted arms (one arm for the camera, two arms for the 8-mm instruments), and a vision cart. Visualization is obtained by two three-chip cameras mounted within one integrated, three-dimensional 12-mm stereo endoscope with two separate optical channels. The laparoscope is controlled by moving the master robotic handles. The operative images are transmitted to a high-resolution binocular display at the surgeon console.

Unique laparoscopic instrument tips, called "*EndoWrist* Instruments," provide articulated motion with a full 7 degrees of freedom inside the abdominal cavity. Tip articulations mimic the up/down ("pitch") and the side-to-side ("yaw") flexibility of the human wrist. Instrument tips are aligned with the instrument controllers electronically to provide optimal hand-eye orientation and natural operative capability.

The latest version of the Zeus System (Z2P) has three major components (Fig. 2): surgeon console, computer controller, and three interactive robotic arms. While seated at the surgeon console, the remote surgeon manipulates the robotic handles attached to the console. The movements are precisely filtered, scaled, and relayed to the computer controller, which transmits these movements across an electromechanical interface to the robotic arms and instruments. The 10-mm three-dimensional laparoscope is controlled by a voice-activated automated endoscopic surgical optimal positioning (AESOP) arm, and two robotic arms control the 5-mm laparoscopic instruments used to perform the procedure. At the time of this study, the laparoscopic instruments did not have an articulating tip. The initial version of the Zeus System did not have three-dimensional laparoscopic vision.

System electronics permit motion scaling in both robotic systems. An assistant remained on site at the animal operating table only to exchange various robotic instruments, including the needle driver, graspers, electrosurgical J-hook, tissue dis-

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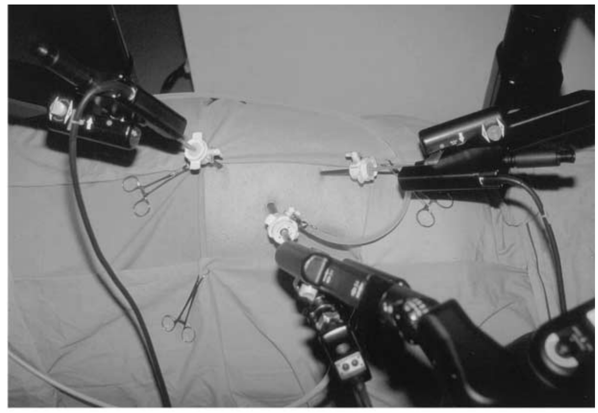

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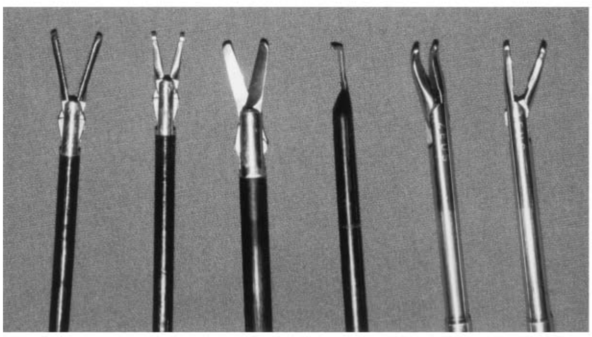

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FIGURE 2. *Zeus Surgical System. (A) Remote surgeon seated at the surgeon console. The laparoscope is controlled by a voice-activated AESOP arm. Laparoscopic instruments are remotely manipulated by the two robotic handles. (B) Three robotic arms are secured to the operating table: one arm holds a 10-mm laparoscope, and the other two arms manipulate a variety of 5-mm laparoscopic instruments. (C) Choice of laparoscopic instruments includes, from right to left, needle driver, needle holder, hook electrocautery, sharp scissors, right-angle endoscopic dissectors, and endoscopic graspers.*

sector, and scissors, at the voice command of the remote surgeon and to troubleshoot the robotic arms.

For robotic laparoscopic nephrectomy, the renal artery and vein were mobilized individually. A previously inserted 2-0 silk tie was used to triple ligate the renal artery and double ligate the renal vein. The ureter was divided and the kidney mobilized circumferentially. For robotic laparoscopic adrenalectomy, adrenal mobilization, including control of the main adrenal vein, was achieved by electrocautery. For robotic pyeloplasty, the upper ureter was mobilized and obliquely transected in close proximity to the renal hilum. Unstented anastomotic suturing was performed robotically using two running 5-0 Biosyn sutures. The entire pyeloplasty procedure was performed telerobotically from the remote workstation in both the *da Vinci* System group and the Zeus System group.

The animals were killed immediately postoperatively. The intraoperative parameters included the total operative time (“initial skin incision to last skin stitch”), actual surgical time, robotic setup time, blood loss, number of ligature ties placed on the renal artery and vein, complications, surgeon fatigue, and technical performance and incidents of the robot. The actual surgical time was defined as the time elapsed from the initial laparoscopic manipulation of the intra-abdominal tissues until completion of the adrenalectomy, nephrectomy, or pyeloplasty.

Statistical analyses were performed using Student’s *t* test for all comparisons between the types of surgery, except for the comparison of the complications, for which Fisher’s exact test was used. Statistical significance was assessed with two-tailed tests and $P < 0.05$.

RESULTS

All procedures were technically successful using a three-port laparoscopic approach. Data on the two principal groups (ie, the *da Vinci* System group and the latest version Zeus System group [Z2P]) were prospectively compared.

ROBOTIC NEPHRECTOMY

For the robotic nephrectomy, the *da Vinci* System group (n = 6) had a significantly shorter total operating room time (51.3 ± 4.0 minutes versus 71.6 ±12.8 minutes; $P = 0.02$) compared with the Z2P Zeus group (n = 5). Even when the robotic setup time was excluded, the *da Vinci* System nephrectomy required significantly shorter actual surgical time (42.1 ± 3.6 minutes versus 61.4 ± 13.0 minutes; $P = 0.03$). However, the blood loss and adequacy of surgical dissection appeared comparable between the two groups (Table I). No intraoperative complications were observed, and no significant malfunction of the robotic device was noted.

ROBOTIC ADRENALECTOMY

For the robotic adrenalectomy, the *da Vinci* System group had a significantly shorter actual surgical time (12.2 ± 3.3 minutes versus 26.0 ± 7.6 minutes; $P = 0.006$). During a left adrenalectomy from the *da Vinci* System group, an adrenal parenchymal tear occurred, resulting in a 50-mL blood loss and requiring hemostatic pressure with a 4 × 4 gauze to control oozing. An adrenal parenchymal

TABLE I. *Intraoperative data on* da Vinci *System vs. Zeus System robotic laparoscopic nephrectomy, adrenalectomy, and pyeloplasty*

Variable	*da Vinci* System	Initial Zeus System (1999 data)	Latest Zeus System [Z2P] (2001 data)	*P* Value (*da Vinci* System vs. Zeus 1999)	*P* Value (*da Vinci* System vs. Z2001 [Z2P])	*P* Value (Zeus 1999 vs. Zeus 2001 [Z2P])
Laparoscopic nephrectomy						
Procedures (n)	6	5	5			
Ports (n)	3	3	3			
Mean total operative time (min)	51.3 ± 4.0	85.2 ± 6.4	71.6 ± 12.8	<0.001	0.02	0.07
Mean actual surgical time (min)	42.1 ± 3.6	73.4 ± 6.9	61.4 ± 13.0	<0.001	0.03	0.11
Mean blood loss (mL)	<10	<10	<5	1.00	1.00	1.00
Complications (n)	0	0	0	1.00	1.00	1.00
Laparoscopic adrenalectomy						
Procedures (n)	5	4	5			
Ports (n)	3	3	3			
Mean total operative time (min)	21.0 ± 3.3	51.0 ± 3.3	33.2 ± 7.4	<0.001	0.01	0.003
Mean actual surgical time (min)	12.2 ± 3.3	38.5 ± 3.4	26.0 ± 7.6	<0.001	0.006	0.02
Mean blood loss (mL)	10.0 ± 11.2	28.8 ± 47.5	19.0 ± 20.4	0.49	0.71	0.69
Complications (n)	1 (20)	1 (25)	2 (40)	1.00	0.54	1.00
Laparoscopic pyeloplasty						
Procedures (n)	6	6	6			
Ports (n)	3	3–4	3			
Mean total operative time (min)	61.4 ± 3.2	115.2 ± 18.6	83.4 ± 23.3	0.01	0.10	0.06
Mean anastomosis time (min)	44.7 ± 3.3	75.7 ± 10.2	66.4 ± 23.8	0.01	0.11	0.57
Suture bites/ureter (n)	13.0 ± 0.8	13.0 ± 3.22	10.8 ± 1.1	1.00	0.005	0.30
Mean blood loss (mL)	<5	<5	<5	1.00	1.00	1.00
Complications (n)	0	0	0	1.00	1.00	1.00

Data presented as the mean ± standard deviation, unless otherwise noted.
Numbers in parentheses are percents.

tear also occurred during a Z2P Zeus left adrenalectomy because of inadequate exposure of the intraoperative field. During a Z2P Zeus right adrenalectomy, a small vena caval tear occurred by the monopolar right angle hook because of a sudden jerking movement of the anesthetized animal, resulting in a 40-mL blood loss. The vena caval injury was remotely repaired telerobotically with intracorporeal suturing using 5-0 polypropylene suture that was inserted into the abdominal cavity by the on-site assistant.

ROBOTIC PYELOPLASTY

For robotic pyeloplasty, the *da Vinci* System group had a slightly shorter total surgical time (61.4 ± 3.2 minutes versus 83.4 ± 23.3 minutes; $P = 0.10$) and anastomosis time (44.7 ± 3.3 minutes versus 66.4 ± 23.8 minutes; $P = 0.11$). The mean number of suture bites per ureter was greater in the *da Vinci* System group than in the Z2P Zeus group (13.0 ± 0.8 versus 10.8 ± 1.1; $P = 0.005$). Using intravenous injection of indigo carmine, the anastomoses were confirmed to be immediately watertight in five of six *da Vinci* System and five of six Z2P Zeus pyeloplasties. No intraoperative complications occurred.

Retrospectively comparing the latest version of the Z2P Zeus System and the initial 1999 version of the Zeus System, the mean actual surgical time for performing robotic nephrectomy, adrenalectomy, and pyeloplasty was 12, 12.5, and 9.3 minutes faster, respectively, with the Z2P version of the Zeus System. This represents an improvement of the Z2P Zeus System by 16%, 32%, and 12%, respectively, compared with the 1999 version of the Zeus System.

TECHNICAL PROBLEMS

Overall, both systems functioned well, without significant intraoperative errors. The technical problems with *da Vinci* System included transient loss of control of a monopolar hook electrode on three occasions, with each lasting less than 15 seconds. In the Z2P Zeus System, transient loss of grasping force occurred on four occasions, with each episode lasting less than 15 seconds. These transient system errors did not result in intraoperative surgical complication on any occasion. Surgeon fatigue and tremor appeared quite comparable between the two systems. However, it was quite apparent that the *da Vinci* System had a shorter learning curve and allowed considerably more intuitive execution of surgical maneuvers compared with the Zeus System.

COMMENT

The transition from a large single open incision to a few small keyhole incisions to gain access to the abdominal cavity has revolutionized our approach to surgery. In open surgery, the surgeon performs under three-dimensional visualization with technical maneuvers performed efficiently, ergonomically, and with excellent tactile feedback. However, in conventional laparoscopy, the operator is faced with certain constraints such as the lack of three-dimensional visualization, limited tactile feedback, restriction in the degrees of freedom of movements because of nonarticulating laparoscopic instruments and a fixed point of insertion, mirroring of hand movements, potential inaccuracy during delicate reconstruction because of natural hand tremor, awkward hand-eye coordination, and inferior ergonomics.[5–8]

Some of these impediments may be corrected by using the principle of a master-slave manipulator, in which the handle of the instrument and its tip are physically disconnected. All movements from the instrument handles ("master unit") are transformed into electronic signals filtered and scaled and transmitted in real time to the "slave unit," a motorized robotic instrument positioner controlling the instrument tips.[9–11]

The two current commercially available telemanipulator systems were evaluated in this study. The *da Vinci* System uses a kinematic (or joint movement) structure, allowing the surgeon to use open surgical movements and techniques while maintaining the benefits of access through keyhole incisions. The instruments are capable of delivering a total of 7 degrees of freedom (including grip): the surgical manipulator delivers 3 degrees of freedom (yaw, pitch, and insertion), and an additional 3 degrees of freedom are delivered by the *EndoWrist* Instruments. This cable-driven mechanical *EndoWrist* Instruments articulates the instrument tips in any direction, delivering the dexterity of the surgeon's hand and wrist to the operative site. In our study, *EndoWrist* Instruments allowed for an impressively complete range of motion of the instrument tips, readily facilitating tissue dissection and optimal needle positioning, comparable to open surgery. In other words, the system is intuitively designed to incorporate open surgical maneuvers into laparoscopic techniques. The *da Vinci* System incorporates a natural stereoscopic vision which provides the eyes of the user with a viewpoint derived from a two-channel endoscope. Each channel is sampled with its own three-chip NTSC video camera and then displayed on its own cathode ray tube (CRT) display. Unlike conventional laparoscopy or the Zeus System, in which the surgeon can see the rest of the operating room in addition to the endoscopic view on the television monitor, in the *da Vinci* System, the surgeon gets the impression of being completely immersed in the endoscopic operative field without any external bearings or visual cues whatsoever. This makes for intuitive hand-eye coordination and superb depth perception during tissue handling and suturing.

The Z2P Zeus System offers somewhat different features in terms of visualization and instrumentation. The Zeus System used in this study provided three-dimensional visualization and instruments with nonarticulating tips. The surgeon's hand movements resemble laparoscopic, not open, movements. This system allows 5 degrees of freedom within the abdominal cavity: horizontal, vertical, in and out, rotational, and grasping. The Z2P Zeus System incorporates improved voice-recognition technology and stereovision using passive eyewear. In this passive eye system, the two small shutter-glasses are replaced by one large shutter-glass that is fixed to the television screen. The shutter-glass polarizes the two pictures on the screen into a right-polarized picture for the right eye and a left-polarized picture for the left eye.

Although Zeus System-based procedures required a longer operative time, both systems provided high visual magnification, movement scaling, and tremor filtering, which allowed for precise tissue dissection. However, interference between the robotic arms or between the arms and the body of the animal occurred during dissection on a few occasions in both systems. Future miniaturization of the architecture of the arms should solve this problem.

Certain limitations in the current robotic systems and its end-effectors were evident. The lack of tactile feedback was a major drawback in both systems. Current haptic sensing technology allows for detection of approximately 0.6 N of force, which is equivalent to a 4-mm deflection of soft tissue.[12] This degree of sensitivity may be insufficient for performing robotic microvascular procedures clinically. As such, novel software programs need to be developed to incorporate force (haptic) feedback seamlessly with the three-dimensional visual feedback.

A critical question is how the different robotic surgical systems will perform in clinical cases.

Another drawback is the cost of these systems, currently ranging from $750,000 to $1 million.

Presently, latency is the biggest hurdle in delivering telepresence surgery, with a time delay of greater than 700 ms making telesurgical manipulation impractical.[13,14] Instantaneous transmission using very high bandwidth communication channels will be integral to successful telesurgery.

CONCLUSIONS

Urologic laparoscopic procedures can be performed effectively using either the *da Vinci* Robotic System or the Zeus Robotic Surgical System. In this limited study, the learning curve and operative time were shorter and the intraoperative technical movements appeared more inherently intuitive with the *da Vinci* System. Although suitable for select clinical applications at present, further advances in device technology are needed to provide viable force feedback and a greater selection of appropriate instrument tips.

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