ROBOTICS IN MICROSURGERY: USE OF A SURGICAL ROBOT TO PERFORM A FREE FLAP IN A PIG

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We present the concept that a surgical robot may be used to successfully perform a free flap. To study different microsurgical techniques, a porcine free flap model was developed in our laboratory. Dissection of the free flap model and isolation of the vessels were completed under traditional loupe magnification. The da Vinci® robot was then used to perform vessel adventitiectomy and microanastomoses. The model was observed for 4 h postoperatively, noting flap color, temperature, capillary refill, and Doppler signal. At the end of this period, the flap was noted to be viable; anastomoses were evaluated and found to be grossly and microscopically patent. Advantages conferred by the da Vinci® robot include elimination of tremor, scalable movements, fully articulating instruments with six degrees of spatial freedom, and a dynamic three-dimensional visualization system. Drawbacks include the cost and the absence of true microsurgical instruments. © 2005 Wiley-Liss, Inc. Microsurgery 25:566–569, 2005.

First-generation surgical robots consisted mainly of robotic arms designed to assist the primary surgeon by holding and positioning instruments such as a laparoscopic camera or retractor. Newer surgical robots have transcended the role of assistant to become the primary surgeon's hands through a computer interface.[1,2] One such robot, the da Vinci® Surgical System (Intuitive Surgical, Inc., Sunnyvale, CA) (Fig. 1), incorporates three-dimensional (3D) stereoscopic vision with 2 or 3 robotic slave arms equipped with instruments that have six degrees of freedom and wrist-like motions. It has the ability to filter tremor, gives the primary surgeon dynamic control over the camera, and offers the surgeon the option of scaling down motions to allow ultrafine manipulations, all of which benefit the operating surgeon. Many surgical specialties are applying this new technology. Cardiac surgeons have used the da Vinci® to perform successful closed-chest internal mammary artery harvesting, coronary artery bypass grafts, and mitral valve repair.[3–5] Urologists have used the robot to successfully perform radical prostatectomies and nephrectomies.[6,7] General surgeons have used it for minimally invasive cholecystectomy, Nissen fundoplication, gastric bypass, and adrenalectomy.[8,9]

The same attributes that make the da Vinci® robot suitable for minimally invasive surgery make it an attractive option for reconstructive microsurgery, a discipline that demands optimal visualization, minimization of tremor, technical skill, and precise surgical manipulations.[10,11] Using our porcine model, we demonstrate that the da Vinci® can be used to successfully perform a microsurgical free flap.

MATERIALS AND METHODS:

All methods and protocols were approved by the Johns Hopkins University Animal Care and Use Committee. None of the authors have any proprietary interest in the da Vinci® robot. Neither the Johns Hopkins University School of Medicine nor any of the authors received funding from Intuitive Surgical, Inc.

Anesthesia

Anesthetic procedures were initiated, maintained, and monitored by qualified veterinary staff. Prior to surgery, the pig was sedated using a Telazol (50-mg tiletamine and 50-mg zolazepam mixture) ketamine and xylazine mixture (TKX "cocktail:" into a vial of dry Telazol powder, 2.5 ml of ketamine were mixed with 2.5 ml of xylazine and administered i.m. at 1 ml/50 kg body weight). Once sedated, the pig was transported to the prep room, and an i.v. line was placed. Induction was achieved with i.v. pentobarbital (10 mg/lb). After intubation, a ventilator was used to deliver a mixture of isoflurane gas and oxygen to achieve general anesthesia throughout the entire procedure.

Robotic Setup

The da Vinci® robot was draped in a sterile fashion. Each slave arm was equipped with sterile Black Diamond microforceps (Intuitive Surgical, Inc.) (Fig. 2). Our da Vinci® robot has two slave arms only; some newer models are equipped with a third arm that may be equipped with other instruments, such as scissors. The

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Figure 1. Da Vinci® surgical system in preparation for practice session. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

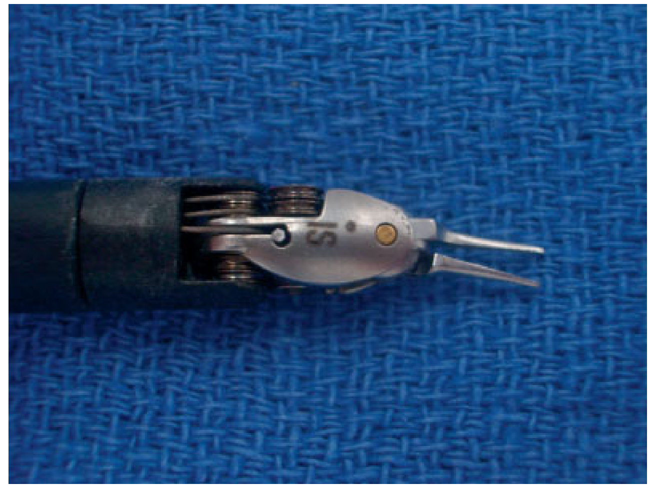

Figure 2. Black Diamond microforceps. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Figure 3. Primary surgeon comfortably seated at surgeon's console. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

slave arms were positioned over a previously dissected surgical site. The primary surgeon was seated at the surgeon's console (Fig. 3).

Surgical Procedure

Once anesthetized, the animal was placed in the dorsal recumbent position. Using electric shears, the hindleg was shaved at the level of the hock. The skin was prepped with iodine solution, and the animal was draped in sterile fashion. Doppler was used to trace the course of the femoral artery as it travels distally down the each hindleg to the level of the hock. One leg was chosen at random to be the ''control'' leg upon which a traditional microvascular anastomosis would be performed. The other leg was designated the ''treatment'' leg, upon which a robotically assisted microvascular anastomosis would be performed. The same operation was performed on each leg, differing only in the use of the da Vinci® robot to perform the microvascular adventiectomy and anastomoses in the designated treatment leg.

The harvest was performed without the robot. Using a no. 15 scalpel blade, a horizontal incision was then made at the level of the animal's hock. Under loupe magnification, the cranial tibial artery and recurrent tarsal vein were isolated and protected. All surrounding soft tissue (including skin, muscle, and all other vessels) was completely removed down to the bone 1 cm above and 1 cm below the site of the proposed anastomosis. The vessels were then clamped, cut, and repaired by the primary surgeon, using either the da Vinci®robot or traditional microscopic techniques. All vessels were repaired in end-to-end fashion using interrupted 8-0 nylon sutures. All sutures were cut by the first assistant, positioned at the operating table opposite the primary surgeon or surgical robot. Patency was confirmed visually, by Doppler signal and capillary refill, as well as

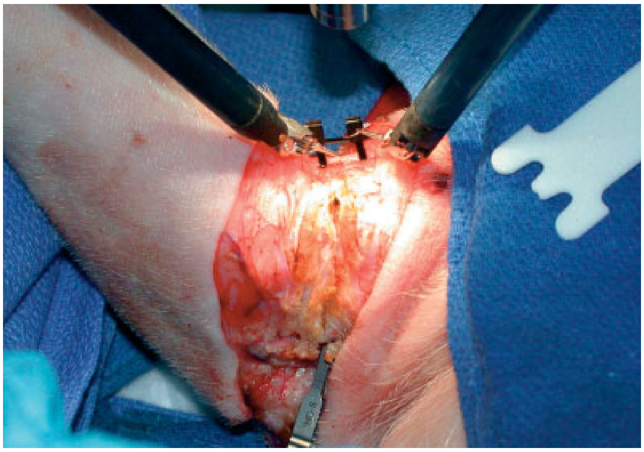

Figure 4. Da Vinci® robot in use during arterial anastomosis. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

by the warmth and color of the distal extremity. Dissection time and total warm ischemia time were recorded. Four hours after completion of the anastomoses, they were reevaluated for patency, using the same parameters described above. Flow to the lower extremity was confirmed by making a small incision in the distal forefoot and checking for active arterial bleeding. Venous outflow was confirmed visually and by the ''squeeze'' test (gently compressing the vein to empty it of blood distal to the anastomosis, and then releasing the squeeze and observing filling proximal to the anastomosis). After the 4-h evaluation, the animal was euthanized, and the anastomoses were harvested for microscopic evaluation.

RESULTS

Preparation and Operative Times

Preparation of the da Vinci® robot, including draping and positioning the arms, was performed in 27 min. The free-flap ''harvest'' was completed in 40 min. Microsurgical procedures performed with the da Vinci® robot (including adventiectomy, arterial anastomosis, and venous anastomosis) took a total of 44 min (Fig. 4).

Vessel Size and Patency

The average artery size was 1.5 mm, and the average vein size was 1.3 mm. Grossly, all anastomoses appeared patent (Figs. 5, 6). This was confirmed by audible Doppler signals distal and proximal to the arterial and venous anastomoses, respectively. The vessels were also noted to have brisk refilling after the ''squeeze'' test. For the duration of the postoperative period, the distal extremities were noted to be warm and pink, with capillary refill at approximately 2 s. At no time did the

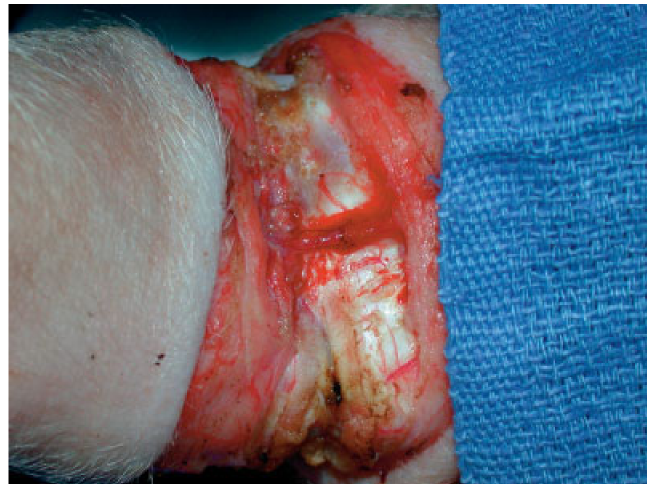

Figure 5. Completed arterial anastomosis performed with da Vinci® robot. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

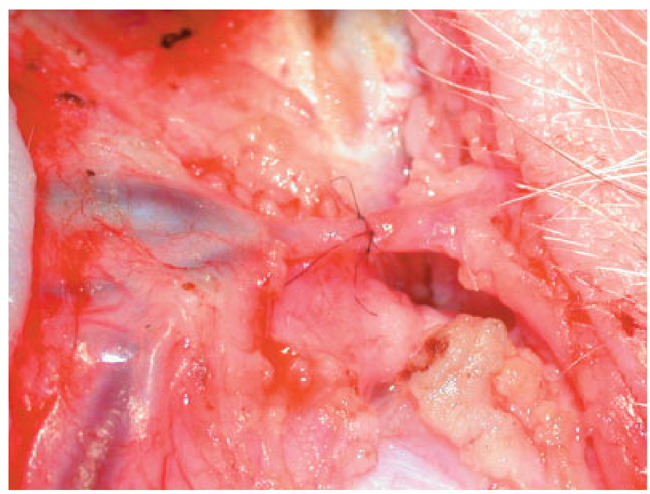

Figure 6. Completed venous anastomosis performed with da Vinci® robot. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

extremities appear threatened or ischemic. After 4 h, an incision in the distal forefoot of each leg revealed arterial bleeding, indicating distal flow. Microscopically, the sutures were noted to contain intima, media, and adventitia. There were no errant sutures.

DISCUSSION

Traditional microsurgical techniques utilize an operating microscope or loupe magnification and rigid, nonarticulating microinstruments. Though microsurgeons enjoy high free-flap success rates, the loss of a free flap carries with it an enormous emotional and financial burden. Most often, a compromised free flap is the direct result of a technical error.[12,13] Thus, any intervention that may reduce the frequency of technical errors during microsurgical procedures deserves further study.[14] The da Vinci® robot offers a 3D dynamic visualization system, fully articulating instruments with six degrees of freedom, scalable movements, and the ability to eliminate tremor.

We found the da Vinci® robot to be comfortable and intuitive. The primary surgeon, seated at the ‘‘surgeon’s console,’’ views the operative field through a 3D viewfinder. From this console, the primary surgeon can easily rotate the operative field of view and achieve up to 8 × zoom. Hand controls are used to work the robot’s ‘‘slave arms,’’ and are ergonomically designed to minimize fatigue.

For the purpose of our experiment, we equipped both ‘‘slave arms’’ with Black Diamond microforceps. These instruments, with their wrist-like motion, demonstrated flexibility and ease of use, handling the microvasculature without trauma. Though lack of haptic feedback may be discussed as a reason not to use this robot with delicate tissues, we experienced no difficulty performing vessel adventiectomy or repair with this limitation. In fact, traditional microsurgery does not rely on haptic feedback; before a microsurgeon can feel a needle tearing through a 1-mm vessel, he or she should see the vessel being stretched. We found this to be similar when using the robot.

The da Vinci® setup time was 27 min, which is comparable to that of a traditional operating microscope. Setup should be done before the case has begun, and is greatly facilitated by staff knowledgeable with the equipment. Our warm ischemia time of 44 min is comparable to anastamoses performed with traditional methods.

Obvious limitations of the da Vinci® include cost (approximately one million dollars per robot) and the absence of true microsurgical instruments. The effective cost for the individual reconstructive microsurgeon is significantly less, as it is already used in many other specialists, such as urologic, cardiac, and gastrointestinal surgeons. Though the Black Diamond microforceps can be used for vessels greater than 1 mm in diameter, they should be refined further. Other instruments that would be of benefit include a vessel dilator, microscissors, and micro-bipolar electrocautery. These instruments could be attached to the third arm, thus providing the primary surgeon with even more independence and control.

CONCLUSIONS

This porcine case report shows that the da Vinci® robot can be used to safely perform microanastomoses during free tissue transfer. Normal physiological tremor is eliminated, and movements are scalable. With its adjustable optics and articulating instruments, it may be of benefit during reconstructions involving difficult angles or limited spaces such as the axilla in breast reconstruction, or around external fixation devices in lower-extremity reconstruction. Further investigation and development of this technology are warranted.

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