Robotic-Assisted Microsurgery for an Elective Microsurgical Practice

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Abstract

Keywords

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- Vein Viewer
- flexible fiberoptic CO₂ laser
- water-jet dissection

Robotic-assisted microsurgery can be utilized for either intracorporeal or extracorporeal surgical procedures. Three-dimensional high-definition magnification, a stable ergonomic platform, elimination of physiologic tremor, and motion scaling make the robotic platform attractive for microsurgeons for complex procedures. Additionally, robotic assistance enables the microsurgeon to take microsurgery to challenging intracorporeal locations in a minimally invasive manner. Recent adjunctive technological developments offer the robotic platform enhanced optical magnification, improved intraoperative imaging, and more precise ablation techniques for microsurgical procedures. The authors present the current state-of-the art tools available in the robotic-assisted microsurgical platform.

The advent of the operative microscope allowed surgeons to perform ultrafine surgical procedures in reconstructive plastic surgery and neurosurgery. In open surgery, the use of minimally invasive techniques such as laparoscopy and robotic-assisted laparoscopy has also evolved. The advantages of the robotic surgical system in laparoscopy have clearly led to its gaining momentum for these types of procedures. As the robotic platform has become more widespread, microsurgeons have also explored its potential use in microsurgery.

Given that the robotic platform (the da Vinci system, Intuitive Surgical, Sunnyvale, CA) was initially designed for cardiac and laparoscopic applications, its use in microsurgery requires the use of some new adjunctive tools to optimize its performance for microsurgery. The original instrumentation was created for cardiac reconstructive procedures that do enter the realm of microsurgery and thus perhaps the platform is finally coming full circle with its renewed application

in other reconstructive microsurgical fields such as plastic surgery, hand surgery, and urology (vasectomy reversal, varicocele, and targeted denervation of the spermatic cord for chronic orchialgia).

In this article, we present the currently available robotic surgical system, its microsurgical applications, and novel adjunctive microsurgical tools. We also discuss the robustness of the use of robotic-assisted microsurgery in an elective microsurgical urology practice and potentially other fields.

The da Vinci Robotic Platform and Robotic Microsurgical Instrumentation

Today, the da Vinci robotic surgical system is the only commercially available robotic surgical system approved by the Food and Drug Administration (FDA). The first da Vinci system was launched in 1999 and as of November 2013, more

than 2,500 robotic systems are being used all over the world. Since 1999, two updated versions have been released. The latest system (Si system) has one camera arm and three instrument arms and provides a three-dimension (3D) high-definition view in the surgeon console. The da Vinci surgical system includes three components: a surgeon console, patient cart (the robotic arms), and an imaging tower. The system has also more than 40 different types of fully articulating robotic EndoWrist instruments. Black Diamond microforceps, microbipolar forceps, Potts scissors, and the curved monopolar scissors are the most commonly used EndoWrist instruments in robotic microsurgical practice. These instruments are placed onto the robotic instrument arms and controlled by the surgeon while he or she is sitting at the surgeon console. The da Vinci robotic system provides surgeons with digital magnification (10–15 $\times$), high-definition (HD) 3D visualization, elimination of physiologic tremor, and motion scaling.

The instruments are passed through 8-mm trocars even if used extracorporeally (provides stability). The robotic instruments are advanced 2 to 3 inches beyond the tip of the trocar to optimize the range of motion. The Black Diamond microforceps can be used for micro dissection, retraction, and as a needle driver for suturing with sutures as small as 11–0. The bipolar microforceps can also assist with fine cauterization in addition to micro dissection and retraction, and can also be used as a needle driver for suturing (larger sutures down to 6–0). Both the Black Diamond microforceps and the bipolar microforceps can hold adjunctive microsurgical tools (discussed below).

The Si robotic platform also uses imaging software called TilePro (Intuitive Surgical) in the surgeon console. This software allows the addition of two more simultaneous image inputs into the surgeon console. Thus, the robotic microsurgeon is able to see three real-time video images (one from the 3D HD robot camera and two other imaging sources) simultaneously. This essentially creates a fighter jet-like cockpit experience for the surgeon. Reducing the need for the surgeon to get up from the console and stop operating may enhance surgical efficiency.

Robotic Microsurgical Applications

In 2000, Degueldre et al demonstrated the early feasibility of performing a microsurgical laparoscopic anastomosis with robotic assistance in a fallopian tubal reversal.¹ This group noted that the magnified 3D view and articulated instruments provided greater ease in tying of knots and offered a fast learning curve. This was one of the earliest demonstrations of using the robotic platform to perform microsurgery in a minimally invasive manner in a location difficult to access with a microscope (inner pelvis).

Another example of the robotic platform providing microsurgeons with unique access is for intra-abdominal microsurgical vasovasostomy in patients who have had iatrogenic vas deferens occlusion from a previous hernia repair. Performing this vasal reconstruction with the operative microscope in an open fashion is extremely challenging due to the

difficulty in dissecting the vas away from the mesh in the inguinal area and then trying to obtain the distal end of the vas above the mesh in an open manner. Laparoscopic techniques could be used to mobilize the distal vas from the inside out into the groin. However, because the anastomosis is still performed with the microscope on the outside, this is very difficult due to the need to pull adequate vas from the inside out to create a tension-free anastomosis. Our group has now demonstrated the ease of utilizing a purely intra-abdominal robotic laparoscopic microsurgical approach where the proximal vas is dissected free below the mesh through small incisions and then tunneled directly into the pelvis to allow the microsurgeon to perform the anastomosis inside the pelvis in a tension-free manner without much distal vas dissection.² This offers the patient tremendous advantages in terms of obviating the need for large groin incisions or extensive groin dissection.

Today, robotic assistance is employed for various microsurgical procedures in numerous surgical disciplines including plastic surgery; ear, nose, and throat surgery; hand surgery; orthopedics; and urology. Several studies have shown the feasibility, safety, and effectiveness of robotic microsurgical nerve repair, vascular anastomosis, transoral procedures, brachial plexus repair, skin or muscle-flap transfers, vasectomy reversal, microsurgical denervation of the spermatic cord, and varicocelectomy.^{3–8} This is still a field that is evolving.

Enhanced Optical Magnification for Robotic Microsurgical Procedures

Microsurgical procedures occasionally require magnification in the 20 to 25 $\times$ range to clearly view ultrafine anatomical structures. However, one of the caveats of the da Vinci robotic 3D HD camera is its limited 10 to 15 $\times$ digital magnification. The digital camera of the robotic platform may reveal pixilation at the maximum magnification levels decreasing image resolution at this high magnification. Therefore, our group has incorporated a novel nitrogen powered arm (as a fifth robotic arm) with an optical magnification video lens system (Point-Setter arm and the VITOM lens; Karl Storz, Tuttlingen, Germany) into the robotic platform for extracorporeal robotic microsurgical procedures (—Fig. 1). The VITOM is an optical lens-based, HD exoscopic video system utilized for spinal surgery and pediatric surgery.^{9–11} This system offers 16 to 25 $\times$ optical magnification. The TilePro imaging software in the surgeon console allows the microsurgeon to simultaneously view the image from the VITOM system right below the main 3D robot camera view. —Fig. 2 illustrates a sample case of a robotic microsurgical vasoepididymostomy with a cockpit view of three simultaneous real-time images in the surgeon console: the main 3D HD robot camera view in the top middle, the VITOM optical magnification view in the lower right, and the view from the laboratory phase-contrast microscope assessing fluid from the epididymis for sperm in the lower left.

The five-arm enhanced robotic platform provides the microsurgeon with improved visual acuity at higher

Fig. 1 VITOM lens-camera & Point-Setter Nitrogen powered arm system (Karl Storz Inc., Tuttlingen, Germany) for enhanced optical magnification. (A) Positioning of the VITOM lens-camera system during a robotic-assisted microsurgical vasectomy reversal. (B) The VITOM lens-camera is positioned by adjusting the Point-Setter nitrogen powered arm.

magnification. The VITOM system also provides improved efficiency in terms of being able to visualize complex reconstructive maneuvers from two different angles at different focal lengths. Thus, the need to have to zoom in and zoom out is obviated by having two cameras at differing focal lengths using this five-arm robotic approach. Incorporating the laboratory microscope into the surgeon view also improves efficiency in terms of allowing the surgeon to continue operating while assessing fluid from the field simultaneously.

Advances in Intraoperative Imaging during Robotic Microsurgery

Despite the advantages of the da Vinci robotic system, the lack of tactile feedback is one drawback. Tactile feedback is helpful for surgeons in identifying specific anatomical structures

such as arteries, veins, and tumor masses. The lack of tactile feedback can cause inadvertent tissue or vessel laceration and suture breaks during knot tying in robotic-assisted procedures.¹² Therefore, a demand has been created for adjunctive tools to help compensate for this lack in tactile feedback. Such tools include Firefly fluorescence imaging (Intuitive Surgical Inc., Sunnyvale, CA), micro-Doppler sensing and ultrasound imaging, and Vein Viewer technology (Christie Digital Systems, Cypress, CA). These tools provide additional visual and sensory guidance during robotic microsurgical procedures.

Firefly Fluorescence Imaging

Firefly fluorescence imaging technology was integrated into the da Vinci Si robotic system to allow surgeons to assess vascular perfusion differences in tissues. This imaging system requires intravenous injection of indocyanine green dye and a

Fig. 2 Surgeon's view in the surgeon console during a robotic-assisted microsurgical vasoepididymostomy (for vasectomy reversal) showing three views: (A) Main view from the three-dimensional high-definition robot camera in the middle top (10–15 $\times$ magnification). (B) Magnification view (40 $\times$) on the lower left-hand side from the optical phase-contrast microscope in the laboratory assessing the epididymal fluid for sperm. (C) View on the lower right-hand side from the VITOM optical magnification lens-camera (Karl Storz Inc., Tuttlingen, Germany; 16–25 $\times$ magnification).

Fig. 3 The Firefly (Intuitive Surgical Inc., Sunnyvale, CA) imaging mode is being used to identify the renal arteries during an intra-abdominal renal case.

near-infrared camera. The indocyanine green dye rapidly binds to plasma proteins; it is predominantly accumulated in the vascular system. Infrared wavelength light is absorbed by the dye and is reflected at a longer wavelength. This reflected longer wavelength light is then detected by a robotic near-infrared camera.¹³

This near-infrared technology offers real-time, image-guided detection of anatomical structures by visualizing their vascularity (► **Fig. 3**). Tumor masses, neurovascular bundles, hepatobiliary anatomy, a healthy intestinal anastomosis, and sentinel lymph nodes are easier to identify with this imaging technology.^{14–17}

Intraoperative Micro-Doppler Sensing and Ultrasound Imaging

Recently, a flexible open or laparoscopic drop-in Doppler sensing probe has been introduced (Vascular Technology Inc., Nashua, NH) for robotic procedures. The system includes a Doppler transceiver with sterile, disposable probes that generate ultrasound waves and sense reflected echo from blood flow (► **Fig. 4**). This system provides an auditory pulse signal to identify blood flow allowing real-time Doppler monitoring of surrounding vasculature and tissue.¹⁸ There are two different types of probes: an 8 MHz probe to detect larger vessels (4–5 mm or larger), and a 20 MHz probe to detect smaller vessels (1–2 mm or smaller) for microsurgical procedures.

Another novel micro full-depth-ultrasound probe has been developed by Hitachi (Hitachi-Aloka, Wallingford, CT). This probe provides a full depth (up to 6 cm) ultrasound image with Doppler flow imaging as well. The image from the ultrasound device can be directly transmitted to the surgeon console through the TilePro software (► **Fig. 5**).

Due to the ergonomics of the robotic platform, both the micro-Doppler probe and the microultrasound probe can be easily maneuvered using the robotic instruments in a wide

range of angles. The use of the fourth instrument arm to hold these probes also helps to obviate the need for a skilled microsurgical assistant. The surgeon could essentially perform real-time sensing or imaging with one arm, while operating with the two other arms.

Vein Viewer

A new biomedical device, the Vein Viewer was developed to facilitate difficult vein access especially in the pediatric population. The system emits near infrared light that is directed on the patient's skin. Near infrared light is inherently absorbed by hemoglobin in superficial veins. The reflected light is then captured and processed by the device. The system then projects a green image back onto the patient's skin with dark areas identifying the veins.¹⁹ The effectiveness of this system was shown by a randomized control trial in neonates.²⁰ Recently, the benefits of this system were also described when preoperatively planning venous flaps in plastic surgery.²¹

In urology, we have utilized this system to detect varicose veins during robotic-assisted microsurgical varicocelectomy procedures (► **Fig. 6**). This is helpful in cases where there may be extensive scarring or difficulty in dissecting planes. This tool provides added confirmation about whether a vessel is an artery or vein.

Advances in Ablation Tools for Robotic Microsurgical Procedures

In addition to reconstructive technique, microsurgical procedures also require precise ligation and dissection of delicate tissues. The most common tools utilized for ligation are instruments equipped with monopolar and/or bipolar electrocautery. However, these energy sources may have some dispersion in surrounding tissues that may be noticeable in microsurgical applications. We now present two novel tools

Fig. 4 The audible micro-Doppler sensing probe is being used to detect the testicular artery in the spermatic cord (Vascular Technology Inc., Nashua, NH).

that provide a more precise ability to ligate or dissect tissues with minimal thermal spread: a flexible fiber optic CO₂ laser probe and a high-pressure water-jet hydrodissection probe.

Flexible Fiber Optic CO₂ Laser Probe

Carbon dioxide laser energy is a novel energy source that has been utilized since the 1960s. However its use via a flexible

laser fiber was only introduced in 2009.²² Previous animal and human studies have shown that the CO₂ laser creates a more predictable tissue ablation with minimal collateral spread.^{22,23} The CO₂ laser has a long wavelength of 10.6 μ m. This leads to a high absorption within both the target tissue and water. This high absorbance results in the rapid conversion of light energy to heat energy within a small

Fig. 5 The micro-Doppler ultrasound probe is detecting varicose veins in the spermatic cord (Hitachi-Aloka, Wallingford, CT).

Fig. 6 Dilated varicose veins are seen under regular light (A) and then under near-infrared Vein Viewer light (B) the veins are dark (Christie Digital Systems, Cypress, CA).

volume of tissue, thus preventing thermal damage to peripheral tissues.²² The energy is quickly dissipated in water, thereby allowing for very precise ablation of tissues along natural planes that have been irrigated with saline.

We recently performed a study comparing monopolar electrocautery (ERBE Inc., Atlanta, GA) versus the CO₂ laser ablation (OmniGuide, Cambridge, MA) on a fresh human cadaver spermatic cord model to assess the degree of peripheral thermal injury or damage to surrounding tissues.²⁴ We found a significantly decreased amount of peripheral thermal damage with CO₂ energy compared with standard monopolar electrocautery. The Black Diamond microforceps was able to handle the flexible fiberoptic laser probe without any difficulty. The dissection lip at the tip of the CO₂ laser holder provided a blunt edge that could be used to separate tissue planes while ligating the tissue with the laser (→Fig. 7).

The flexibility of the CO₂ laser probe and precise tissue ablation with minimal peripheral thermal injury make this an attractive tool for delicate robotic microsurgical procedures.

High-Pressure Water-Jet Dissection

High-pressure water-jet dissection is applied using a fine high-pressure stream of saline through the Erbejet2 hydro-dissector probe (ERBE Inc., Atlanta, GA). This technique has been used for dissection of tumors from normal parenchyma, or nerve fibers from adjacent tissues.^{25,26}

The pressure of water jet can be adjusted depending on the type of dissection that is being performed and the density of the tissues being dissected. Our group has demonstrated the use of this technology to ablate small nerve fibers on the vas deferens while preserving surrounding blood vessels in an animal model.²⁷ We have also described the use of this technique during robotic microsurgical targeted denervation

Fig. 7 The flexible fiberoptic CO₂ laser probe is being used for dissection and ligation of the cremasteric muscle fibers during targeted microsurgical denervation of the spermatic cord (OmniGuide, Cambridge, MA).

Fig. 8 High-pressure water-jet hydrodissection is used to ablate residual nerve fibers around the vas deferens while preserving the vasa vasorum (ERBE Inc., Atlanta, GA).

of the spermatic cord to ablate residual nerve fibers around the vas deferens (► Fig. 8).⁸

The Future of Robotic Microsurgery

Despite the advantages of robotic assistance in microsurgery, there are some limitations. Cost and the lack of tactile feedback are two main factors. The lack of tactile feedback may be overcome by the novel adjunctive tools mentioned above. As new and competing robotic platforms are devel-

oped, it is likely that the cost of these systems will fall, making this technology more accessible. Currently, we have been able to reduce the total out-of-pocket costs to patients for our robotic microsurgical procedures by increasing surgical throughput. We have gone from performing approximately one to two pure microsurgical cases a day to performing approximately three to four robotic-assisted microsurgical cases a day in a similar amount of time. This improvement is surgical efficiency, less reliance on a skilled microsurgical assistant, and higher case volumes have helped to make the

Fig. 9 Utilization of the confocal laser endomicroscope probe (Cellvizio, Mauna Kea Technologies, Paris, France) to visualize the cremasteric muscle fibers and to try to detect any nerve fibers within the muscle during targeted microsurgical denervation of the spermatic cord.

cost of our robotic micro cases similar to our pure micro cases. We currently charge \$6,900 for our robotic vasectomy reversal (total all inclusive charge to the patient), which is less than what most centers in our region charge for a pure microsurgical vasectomy reversal. This is simply an illustration that the costs can be comparable in a high-volume setting even with our currently priced robotic systems. We have now performed over 1,000 robotic-assisted microsurgical procedures and continue to explore new applications for this platform in urologic microsurgery.

As technology evolves, our imaging tools are likely to improve. The robotic system provides the perfect platform for the integration of such imaging. New robotic platforms are likely to emerge as well. The following three sections cover these new areas.

Confocal Laser Endomicroscopy

Confocal laser endomicroscopy (Cellvizio, Mauna Kea Technologies, Paris, France) is a new optical imaging method mainly adopted by gastroenterologists and pulmonologists.^{28,29} This technology enables real-time in vivo histological evaluation of tissues on a cellular level. It provides real-time intraoperative cellular-level magnified images with up to 1 to 5 μm resolution. A concurrent laser beam provides optical imaging with or without fluorescein. **Fig. 9** shows the manipulation of the probe with robotic microinstruments during a targeted denervation of the spermatic cord procedure. The TilePro software allows the microsurgeon to view the confocal laser endomicroscopy image simultaneously during surgery (**Fig. 9**). In this case, the probe was being utilized to visualize the cremasteric muscle fibers and to try to detect any nerve fibers within the muscle.

Multiphoton Microscopy

Multiphoton microscopy is another imaging modality that generates images by measuring nonlinear interactions between a laser photon beam and varying tissues.³⁰ This technology provides even sharper images than confocal microscopy by enabling visualization of subcellular structures.³¹ This imaging modality tends to identify nerve fibers in tissues without any type of contrast-enhancing or labeling markers. Ramasamy et al³² and Laudano et al³³ have reported the use of this imaging modality for microsurgical denervation of the spermatic cord in animal models. It not only provides an imaging modality, but by increasing the laser energy, can also be used as a precise cellular-level ablation tool as well.

Novel Robotic Platforms

There are several new robotic surgical platforms that are currently being developed. SPORT (Single Port Orifice Robotic Technology; Titan Medical Inc., Toronto, Ontario, Canada), is one such novel robotic platform.³⁴ This robot allows the surgeon to perform single-port surgery using a compact low-profile system. This device may have microsurgical applications given its compact dimensions and microtool arms. The same company has another prototype called Amadeus (a multiport robotic surgical system), which features tactile

feedback. The addition of tactile feedback may provide benefits when dealing with microsurgery.

Another system with tactile feedback is the Sofie (Surgeons Operating Force-Feedback Interface Eindhoven) from the Eindhoven University of Technology in the Netherlands. The Department of Defense in collaboration with the University of Washington has also been developing the Raven surgical robotic system. The main aim of Raven is to perform telesurgery for military purposes.³⁵ However, this system may also have microsurgical applications.

Conclusion

The introduction of the operative microscope in the 1970s revolutionized the field of microsurgery. Today, robotic-assisted microsurgery may be on the verge of creating a new era in microsurgery.

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