Innovations in ophthalmology have expanded greatly in recent years, and we believe that the next major advancement in ophthalmology will be the integration of robotic surgery. Robotic systems have been utilized in the surgical environment for more than 15 years. Since then, robotic surgical systems have proliferated in several disciplines such as urologic surgery, gynecologic surgery, and cardiovascular surgery. Multiple robotic surgical systems have been developed over the years, and the current standard is the da Vinci Surgical System (Intuitive Surgical, Sunnyvale, CA).

ROBOTIC SURGICAL SYSTEM

The da Vinci Surgical System consists of two primary components, a control console that allows the surgeon to manipulate the robotic arms remotely, and the robotic apparatus with three arms (or four arms in a recent addition) that holds a dual-channel endoscope. An ocular viewfinder on the console provides a stereoscopic view of the operative field from the endoscope. The surgeon manipulates the controls using fingers, wrists, hands, and arms, while a computer processor filters, scales, and relays the movements to the robotic arms and instruments. There is no measurable delay between the movement of the surgeon’s controls and the mirrored movement of the robot apparatus. The processor eliminates tremors and minor movements. The architecture of the instruments and the da Vinci system allows the surgeon to insert, extract, roll, pitch, yaw, and grip with the robotic tools. The robotic arms are capable of tilt in two planes, achieved with two “elbow” joints. The robotic arms can be equipped with a variety of instrumentation to allow for specialized surgical procedures. Robotic surgery addresses some of the limitations of traditional surgery, allowing the completion of advanced procedures. Advantages of robotic surgery include increased precision, improved range of motion, elimination of tremor, ability to maneuver in small anatomic spaces, and surgeon safety.

Figure 1. The surgeon sits comfortably at the surgical console, having a 3-D view of the surgical field and easy access to the control handles.

Figure 2. The da Vinci robotic system has three arms. One central arm holds the endoscope, and two side arms (green and yellow stripes) hold surgical instruments.
Recently, the feasibility and applicability of robotic ocular surgery were analyzed through a series of pioneering studies.\textsuperscript{17-19} First-time demonstrations of external ocular surgery (corneal and scleral wounds), anterior segment surgery (foreign body removal and capsulorrhexis), and posterior segment surgery (25-gauge vitrectomy) while utilizing the da Vinci surgical robot have been performed at the Center for Advanced Surgical and Interventional Technology at the University of California, Los Angeles. All the experiments were performed on harvested porcine eyes secured with pins on a Styrofoam mannequin head in the anatomic position. The head was placed on a surgical table positioned directly under the robotic apparatus. The initial step was to manually inflate the eye with balanced salt solution to reach good intraocular pressure.

Visualization of the eye was achieved with the 3-D endoscope placed above the globe in the midline, thus mimicking the axis of standard ocular surgery using an operating microscope. The robotic arms were placed on either side of the globe at approximately 45° angles, resembling the approach used by an operating surgeon. The surgical console was located approximately 15 feet from the surgical table and robotic arms. Viewing the operative field via a 3-D image and placing the hands on the master controls below the display, the surgeon was seated comfortably. All procedures were performed by an experienced retinal surgeon with no prior practice in robotic surgery.

SURGICAL PROCEDURE

Robotic external ocular surgery was performed with robotic arms each equipped with sterile Black Diamond microforceps (Intuitive Surgical). Several 10-0 nylon filament sutures were placed to close each corneal and scleral wound. To evaluate the feasibility of anterior-segment robotic surgery, the tip of a 3-mm keratome held by the robotic forceps was used to create a clear corneal incision by manipulation of the robotic arms. Healon GV (Advanced Medical Optics, Santa Ana, CA) was introduced into the anterior chamber, and a 5.0x2.5x 0.2-mm copper strip (Rogers Corporation, Chandler, AZ) was placed over the lens by a human assistant. The intraocular forceps linked to the robotic arm were used to grasp and remove the metallic foreign body from the anterior chamber. Healon GV was injected by the assistant to deepen the chamber, and a cystotome held by the robotic forceps was used to fashion a 360° capsulorrhexis via movement of the robotic arms.

Twenty-five–gauge robotic vitrectomy was performed after adaptation of the commercially available intraocular instruments for use with the robotic forceps. To allow gripping with the robotic tools, small metal plates were fixed to the handles of a 25-gauge vitreous cutter and endoilluminator (Alcon Surgical, Fort Worth, TX). The instruments were held by a magnetic stand to facilitate easy grasping and storage (Figure 5). Intraocular forceps were fitted with a custom bracket to facilitate operation with the robotic arm and wrist (Figure 6).
Using the robotic forceps, a 25-gauge infusion trocar (Alcon Surgical) was placed approximately 3 mm posterior to the limbus in the inferotemporal quadrant. An infusion cannula was placed in the trocar with the robotic forceps and turned on by an assistant (Figure 7). Two additional trocars were placed in a similar fashion approximately 3 mm back from the limbus in the superotemporal and nasal quadrants. A disposable wide-view vitrectomy contact lens (Dutch Ophthalmic USA, Kingston, NH) was placed on the cornea with viscoelastic. The vitreous cutter and endoilluminator were grasped from the magnetic stand with the robotic forceps and placed through the 25-gauge ports using the robotic arms (Figure 8). Under high-magnification view, a core vitrectomy was performed. At the end of the vitrectomy, the instruments were placed on the magnetic stand and the trocars removed from the eye with the robotic forceps. All the vitrectomy procedures were performed with the Accurus 800CS (Alcon Surgical) fitted with a xenon light source.

**POST-SURGICAL OBSERVATIONS**

Several observations were noted at the conclusion of this study. First, visualization was a challenging aspect that will require refinement. While the resolution of the dual-channel endoscope’s camera was of high quality and provided excellent depth perception for the external and anterior segment steps of the ocular surgery, it did not yield the detail of an optical microscope routinely used in intraocular surgery. Also, the camera realignment was frequent and time-consuming. For instance, each time an ocular instrument was fetched from the magnetic stand, the endoscope had to be tilted and zoomed out to facilitate adequate view. Lack of an optical inversion system prevented the use of standard wide-angle vitrectomy lenses.

Currently, the microforceps are tailored toward placement of 7-0 sutures in cardiac surgery. Further miniaturization of the forceps would facilitate more delicate maneuvers and enhance grasping of smaller objects.

Control and manipulation of the ocular surgical instruments was performed with relative ease by moving the tip of the robotic forceps. For example, insertion of the instruments into the globe and minute adjustments during the vitrectomy were relatively easy tasks. Application of the trocars and insertion of the vitreous cutter and endoilluminator through the 25-gauge ports were smooth and swift. Anterior capsular manipulations, however, were less accurate, and a round curvilinear capsulorrhexis was not achieved. The surgeon’s wrist movements translated almost intuitively to instrument manipulation with no notable difficulties, despite lack of prior experience with the robot.

We observed that arm movements were not as intuitive as wrist movements. Capable of two-plane tilt without joint rotation, the robotic arms do not mirror the exact movements of human arms. Indeed, this robot was...
been demonstrated,20,21 and in the future this may bring robotically assisted surgery has also motions or complete automation of surgical procedures. imaging with robotic systems may enable guidance of microsurgical manipulations can be safer with less iatrogenic drug delivery, may become more feasible as robotic accuracy such as retinal vessel cannulation and intravascular procedures that demand perfect stability and high degrees which only the robotic system renders possible, or which in ophthalmic surgery lie in performing interventions which do not match the abilities of the human eye.

CONCLUSION

As this study demonstrated, the da Vinci robotic system provided the needed dexterity for delicate intracocular manipulations. The da Vinci Surgical System in its current design, however, presents two limitations for intracocular surgery. First, having a stable point of rotation above the robotic wrist renders intraocular maneuvers less controllable. Second, the endoscope-acquired images are inferior to those obtained with an ophthalmic microscope, as its dynamic range, optical resolution, and color presentation do not match the abilities of the human eye.

It is reasonable to assume that opportunities for robotics in ophthalmic surgery lie in performing interventions which only the robotic system renders possible, or which noticeably simplify the current approach. Surgical procedures that demand perfect stability and high degrees of accuracy such as retinal vessel cannulation and intravascular drug delivery, may become more feasible as robotic microsurgical manipulations can be safer with less iatrogenic complications. In addition, integration of advanced imaging with robotic systems may enable guidance of motions or complete automation of surgical procedures. Remote trans-Atlantic robotically assisted surgery has also been demonstrated,20,21 and in the future this may bring emergency eye care to sites such as the battlefield or environments with limited accessibility.

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