Article

Robot-Assisted Pterygium Surgery: Feasibility Study in a Nonliving Porcine Model

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Purpose: This study aims to investigate the feasibility of pterygium surgery using the DaVinci Si HD robotic surgical system, and to describe a porcine model for pterygium surgery and evaluate its usefulness.

Methods: The pterygium models were constructed using enucleated pig eyes and cold cuts. Robotically-assisted pterygium surgeries in nonliving biological pterygium models were performed using the DaVinci Si HD robotic surgical system. Twelve models were prepared, and 12 pterygium excision and conjunctival autografts were performed.

Results: The DaVinci system provided the necessary dexterity to perform delicate ocular surface surgery and robotic tools were safe for the tissues. The mean duration of the surgical procedures was 36 minutes. There were no intraoperative complications and no unexpected events.

Conclusions: Robotic-assisted pterygium surgery is technically feasible for porcine eyes using the DaVinci Si HD robotic surgical system. The pterygium model that we describe could be of interest for surgical training.

Translational Relevance: Little research has been done in robotic microsurgery. Animal experimentation will allow the advantages of robotic-assisted microsurgery to be identified, while underlining the improvements and innovations necessary for clinical use.

Introduction

The introduction of surgical robots in the operating room has revolutionized a number of specialties, such as urology, digestive surgery, gynecology, plastic reconstructive surgery, throat surgery, neurosurgery, thoracic surgery, vascular surgery, hand surgery, and peripheral nerve surgery.^{1–3} Robots are used currently in many situations and the list of appropriate indications is growing rapidly. The number of procedures performed every year with the DaVinci robotic surgical system (Intuitive Surgical, Inc., Sunnyvale, CA), the only surgical robot currently available on the market, also is increasing rapidly as its technology has improved and has become more financially accessible. If we look at the research being done, the number of studies listed in the PubMed

database using the keywords “robot” and “surgery” has increased exponentially over the last 20 years. However, the number of ophthalmology-related studies on the topic over the same period has remained surprisingly low since the first publication in 1995.⁴ Ocular surgery already is minimally invasive microsurgery yielding excellent results. Nonetheless, there are many potential advantages of the use of robotics in eye surgery, including increased precision and maneuverability (degree of freedom), scalability of motion, tremor filtration, better ergonomics, ability to simultaneously manipulate three surgical instruments and cameras, improved patient access to surgeons, and surgical training.^{5–7} As a result, robotics may improve patient care and could well become clinically relevant for ocular surgery in the future.

A pterygium is a wing-shaped, fleshy, fibrovascu-

lar overgrowth arising from subconjunctival connective tissue extending across the limbus over the cornea. The prevalence of pterygia is related directly to geographical proximity to the equator (the nearer to the equator, the greater the prevalence); sex (men), high level of outdoor ultraviolet radiation exposure, absence of solar protection (sunglasses), and sandy environments are risk factors that also have an influence on the prevalence of pterygia.^{8,9} Surgical treatment is required when pterygium growth decreases visual acuity, ocular motility is restricted, recurrent inflammation is unresponsive to topical corticosteroids, or there is a significant cosmetic blemish. Various surgical techniques have been investigated in the past, but the gold standard currently is excision coupled with a conjunctival or limbal-conjunctival autograft transplantation due to the low rate of recurrence.¹⁰ Since this technique has been considered by experienced surgeons to be easy and not associated with severe intraoperative complications, in opposition to intraocular anterior or posterior segment surgeries, residents often are allowed to perform the procedure. Two different studies have shown, however, that the surgeon's degree of experience increases success rates and reduces complications, including recurrence rates in pterygium surgery.^{11,12} In other words, pterygium surgery, as for all surgical techniques, requires a significant amount of practice; hence, reinforcing the need to train surgical residents. Since there currently is no surgical simulator program and no training model for pterygium surgery, there is a real interest in developing a nonliving biological model.

The aim of this study was to investigate the feasibility of robotically-assisted pterygium surgery using the DaVinci Si HD robotic surgical system, and to describe a porcine model for pterygium surgery and evaluate its usefulness.

Material and Methods

The Robot

As previously described, the DaVinci Si HD robotic surgical system consists of three components: a mobile instrument cart with four articulated arms, an imaging cart, and a console used by the surgeon to control the robotic arms.¹³ The mobile cart contains the articulated robotic arms, three of which carry surgical instruments, and a fourth that manipulates the digital high definition (1080 i) 12-mm stereoscopic camera, which allows the surgeon to visualize the

Figure 1. The DaVinci Si HD remote console. The surgeon's console is equipped with an optical viewing system, two telemanipulation handles, and five pedals. The optical viewing system, called the stereo viewer, provides a 3-dimensional view of the operating field. The two handles allow remote manipulation of the articulated robotic arms.

surgical field. The camera provides 3-dimensional vision with progressive magnification up to 15 times. Each of the arms has multiple joints that allow for 3-dimensional movement of the surgical instruments and optics. The surgeon's console is equipped with an optical viewing system, two telemanipulation handles, and five pedals. The optical viewing system, called the stereo viewer, offers a 3-dimensional view of the operating field, and displays text messages and icons that reflect the status of the system in real time. The two telemanipulation handles allow for the remote manipulation of the four articulated robotic arms (Fig. 1). The robot also allows the surgeon to scale down surgical movements and improve accuracy by a factor of 1.5:1 ("quick" position), 2:1 ("normal" position), or 3:1 ("fine" position).

Figure 2. Kit for the pterygium surgery model. A freshly enucleated pig eye, mortadella, duck meat, beef, 1 euro cent coin, 30-gauge needle, 2-mL syringe, disposable scalpel blade, millimetric ruler, gentian violet surgical marking pen, bottle of BSS, and glue are necessary to prepare the pterygium model.

Pterygium Model

We used freshly enucleated pig eyes (local slaughterhouse), mortadella, duck meat, and beef as well as a 1 euro cent coin, a 30-gauge needle, a 2 mL syringe (Becton Dickinson, Fraga, Spain), a disposable 15 scalpel blade (Swann-Morton, Sheffield, England), a millimetric straight edge, a gentian violet surgical marking pen (Aspen Surgical, Caledonia, MI), balanced salt solution (BSS; Alcon, Fort Worth, TX), and glue (UHU GmbH, Bühl, Germany; Fig. 2). In our model, the round mortadella slice represented Tenon's capsule, the piece of duck meat the pterygium tissue, and the slice of beef the conjunctiva.

Pterygium surgeries on pterygium models were performed using the DaVinci Si HD robotic surgical system from January to May 2014. For each procedure, the duration and successful completion of the surgery with or without complications or unexpected events were assessed. The procedures were documented with photographs and videos.

The pterygium model was prepared in several steps. First, the pig eye was refilled by intravitreal injection of BSS to obtain an intraocular pressure of approximately 20 mm Hg. The round slice of mortadella was centrally trephined using the 1 euro

cent coin and the scalpel. The trephined mortadella then was glued to the pig eye (drying time 30 seconds). A piece of duck meat 8 mm long and 6 mm wide was cut with the scalpel. This small piece was glued onto the pig's cornea, limbus, and adjacent underlying mortadella (drying time 30 seconds). The slice of beef then was trephined with the coin and scalpel, and glued onto the mortadella and duck construction (drying time 30 seconds). The final result is illustrated in Figure 3. Preparation time was 5 minutes. A total of 12 pterygium models was prepared.

The surgical procedures were performed by an ophthalmic surgeon with prior experience in robotic microsurgery certified by the Robotic Assisted Microsurgical and Endoscopic Society (RAMSES). Surgical movements were scaled to 3:1. At the beginning of the procedure, the pterygium model was positioned under the robot's arms as if it were a nasal pterygium on a right eye. The temporal edge of the duck piece was grasped with Black Diamond Microforceps (left arm; Intuitive Surgical, Inc.) and dissected toward the limbus using a Snap-fit scalpel (right arm; Intuitive Surgical, Inc.; Fig. 4). Horizontal incisions above and below the duck piece and the overlying beef slice were made with Potts scissors

Figure 3. Final result of the pterygium model construction before surgery. The freshly enucleated pig eye is in the center. The round mortadella slice represents the Tenon's capsule, the small piece of duck meat (8×6 mm) the pterygium tissue, and the large square piece of beef the conjunctiva.

Figure 4. Dissection of the pterygium (step 1). The temporal edge of the pterygium (duck piece) is dissected toward the limbus using a Black Diamond Microforceps (*left arm*) and a Snap-fit scalpel (*right arm*). The arms are positioned at a 45° angle to the surgical field. The camera is located *above* the model and oriented vertically.

Figure 5. Excision of the pterygium (step 2). The pterygium tissue (duck piece) and conjunctiva (beef piece) are removed using Black Diamond Microforceps (*left arm*) and Potts scissors (*right arm*).

(*right arm*). A vertical incision (parallel to the limbus) on the duck piece and beef slice was made on the nasal edge of the duck piece (Fig. 5). The two layers then were reflected centrally and removed. The glue that remained on the cornea was scarified using the Snap-fit scalpel. To prepare the graft, an 8×6 mm piece of beef meat located at 12 o'clock and marked with the surgical pen was held with fine tissue forceps. It was separated from the mortadella and then cut with Potts scissors (Fig. 6). This piece of beef was shifted to the area of excision, filling the defect above the mortadella. It was sutured to the edges of the

Figure 6. Preparation of the conjunctival graft (step 3). An 8×6 mm piece of beef located at 12 o'clock (the future graft) is grasped with fine tissue forceps and cut with Potts scissors.

Figure 7. Suture of the conjunctival graft (step 4). The graft is shifted to the excision area and sutured to the edges of the same area with 8 interrupted 8/0 polyglactine sutures.

nasal defect with 8 interrupted 8/0 polyglactine sutures (Johnson & Johnson, New Brunswick, NJ). Each suture had 3 loops (Fig. 7). At the end of the procedure, the piece of beef covered the mortadella surface, leaving approximately 1 mm of bare sclera adjacent to the limbus (Fig. 8).

Results

An experienced surgeon (TB) performed 12 robotically-assisted pterygium procedures using a Snap-fit scalpel, Potts scissors, Black Diamond microforceps, and fine tissue forceps instead of conventional ophthalmological instruments (crescent blade, Vannas scissors, Bonn microforceps, and Troutmann microforceps, respectively). Even if they are not fully dedicated to ophthalmic microsurgery, robotic microsurgical tools were safe for the tissues used in this model of ocular surface surgery. Feasibility is confirmed. The mean operative time was 36 minutes (range, 29–42 minutes). The mean durations for pterygium excision, graft preparation, and eight sutures placement were 9, 7, and 20 minutes, respectively. The DaVinci Si HD robotic surgical system provided the necessary dexterity to perform delicate ocular surface manipulations allowing for all required surgical maneuvers (dissection, excision, graft preparation, graft suture) to be performed. There were no intraoperative complications and no conflict between the arms of the robot for all 12 procedures.

Figure 8. Final result. The excision area is completely covered by the graft. The sutures are very precisely placed. The Tenon's capsule located at 12 o'clock is left bare.

Discussion

The reasons for the difference between the significant expansion in robotic surgery for abdominal, endoscopic, and macrosurgical procedures in general over the last 20 years and the much more modest expansion in robotically-assisted procedures in microsurgical specialties, such as ophthalmology, are of interest to us. The DaVinci Si HD robotic surgical system already has been used in experimental conditions to suture corneal lacerations (porcine eyes),¹⁴ perform penetrating keratoplasties (porcine and cadaver eyes),¹⁵ and remove foreign bodies, lens capsules, and vitreous (porcine eyes).¹⁶ However, procedures were longer when compared to conventional manual surgeries. Investigators reported a lack of precision resulting from poor visualization of the operative field and the absence of microsurgical instruments. These elements were considered to be hurdles to further clinical investigations.¹⁵ Given the reservations expressed, notably concerning poor visualization, we decided to continue surgical research using the new DaVinci robot to perform ophthalmic surgery on porcine eyes. The DaVinci Si HD Surgical System has been available since 2009, and has a 12-mm camera that provides greater magnification and

better resolution than the previous HD model. Facing another hurdle, the absence of specific microsurgical instruments, we decided to perform pterygium surgery, ocular surface surgery that combines dissection, excision, and suturing because the currently available DaVinci instruments still are not suitable for intraocular surgery.

Concerning the length of procedures, as previously reported by Mines et al.,¹⁷ Tsirbas et al.,¹⁴ and Bourges et al.,¹⁵ who were pioneers in corneal robotic surgery, the procedures in our study still last longer than manual procedures. This is due to the relative lack of the surgeon's experience in robotic surgery compared to conventional manual ophthalmologic microsurgery (2 vs. 20 years).

When operating, the surgeon noted that the remote center of motion of the DaVinci robotic surgical system (namely the pivot point) is too proximal when compared to conventional manual surgery in which the surgeon directly handles the instruments with his/her fingertips. On the other hand, the suppression of physiological tremor improves the quality of surgical movements. The robot also allows the surgeon to change the orientation of the instruments in the operative field during surgery. This possibility was very helpful during the phase of graft preparation. It also could be a real advantage when a right-handed surgeon performs surgery on a pterygium located on the left eye or in patients with prominent noses or superciliary arches.

The absence of thread or needle breakage during the suture phase confirms that the absence of tactile feedback force was compensated by the visual control provided while tying knots.¹⁸

Finally, when evaluating the value of the remote console and camera, we found that the magnification of the operating field and the quality of the 3D image are good in the Si HD version of the robot and close to those that one can find in modern surgical microscopes. The millimetric precision provided is acceptable for ocular surface surgeries, such as pterygium surgery, but this precision must be increased to the micron level for intraocular anterior or posterior segment surgeries. This may account for the fact that many experimental prototypes of robots totally dedicated to eye surgery have been developed recently.^{19–23} These prototypes have been used in animal models to perform anterior and posterior segment surgeries. This is a promising area of research, specifically for vitreoretinal surgery.

Of secondary but significant interest to us is the usefulness of the pterygium model for resident robotic

surgical training. We developed a nonliving biological pterygium model using porcine eyes and cold cuts to simulate this type of procedure. It is inexpensive, easily available, similar to biological tissues, and without ethical issues. The model presented could help ophthalmology residents learn pterygium surgery and can be used either in conventional or robotic microsurgery. Because conventional microsurgery practice is much cheaper than robotic training, the pterygium model could first be included in basic ophthalmological surgical training before being used in robotically-assisted simulations. As previous experience in microsurgery has been shown to significantly improve surgeon's performance in robotic surgical training,²⁴ robotically-assisted procedures could be performed once such experience has been acquired. Further investigations are required to test robotic microsurgery as a new approach to resident training.

We hope that further research will lead to several improvements in robotically-assisted microsurgery, such as the development of specific microsurgical instruments, distalization of the arm's pivot point, automation of repetitive movements, and imaging and laser delivery systems. In addition, the use of robotics and the development of telesurgery for pterygium surgery might be a good option in areas that lack ophthalmological infrastructures or surgeons.

Should these improvements and innovations be implemented in surgical platforms, the use of robotics in a clinical setting certainly will become a clear and intuitive choice.

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