Robotic Retinal Surgery

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40.1 Introduction

The first introduction of the word "robot" to the world had its roots not in the fields of medicine or industry, but rather in literature. Karel Capek was a Czech playwright whose 1920 play, *Rossum's Universal Robots*, used the word "robot" for the first time [1]. Capek derived the term from the Czech *robota*, meaning "forced labor," and used it to describe fictional humanoid creatures enslaved to perform mundane tasks for their human masters. In medicine, the term robot can be used to describe any machine with mechanisms capable of augmenting or replacing the capabilities of the surgeon. The most well-known example of a surgical robot is the da Vinci surgical system (Intuitive Surgical, Sunnyvale, USA), which has performed over six million surgeries worldwide since its introduction in 1999 [2]. Widespread adoption of robotic-assisted surgery in ophthalmology has been limited to date, though several machine prototypes show great promise in expanding the physical limitations of the vitreoretinal surgeon. This chapter reviews the advantages, surgical approaches, indications, limitations, and future developments of robotic-assisted surgery in the field of vitreoretinal surgery.

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40.2 Advantages

The vitreoretinal surgeon works on the scale of microns, often at the limits of human visuospatial resolution, proprioception, and physiologic tremor. Surgeries require delicate maneuvers within a confined space that are highly dexterous with a low margin for error due to the required forces often being beyond the levels of human perception. Physiologic hand tremor has an amplitude of approximately 100 µm and can be a limiting factor with the risk of inadvertent tissue damage, particularly for the beginning or inexperienced surgeon [3]. Visualization of microstructures during surgery due to limited spatial resolution and depth perception can also present a challenge.

Robotic-assisted surgery has the potential to cancel hand tremor to provide stabilization of intraocular instruments and to automate certain steps or procedures. This in turn may limit surgeon fatigue and variability. The enhanced stability and dexterity provided by a robotic system could allow for the successful performance of certain high-risk surgical procedures, such as retinal vein cannulation, or subretinal injections. The ability of certain robotic systems to physically separate the operator and the machine also allows for the possibility of telesurgery. Ultimately, the technical potential of robotic-assisted surgery could lead to new frontiers in vitreoretinal surgery in terms of patient safety and efficacy.

40.3 Surgical Approaches

The ideal design of a robotic system should be intuitive, lightweight, and maneuverable; protect surgical entry points from instrument damage; be easily assembled by nontechnical staff; include a visualization system that matches or exceeds current surgical microscopes; and incorporate fail-safe mechanisms to prevent inadvertent injury in the event of sudden patient movements [4–6]. Three main types of surgical robots currently exist, which differ based on the complexity of the robot and the nature of human-machine interaction.

- **Conventional:** The surgeon uses a surgical microscope and microsurgical instruments to perform intraocular tasks with direct visual and proprioceptive feedback.
- **Robot-assisted tool:** The surgeon uses an optical microscope and handheld miniature robotic tool to perform intraocular tasks with visual feedback. The microsurgical tool has the ability to cancel tremor and lock depth, among other features.
- **Cooperative robotic system:** The surgeon controls the surgical tool in conjunction with the robotic system while a microscope and/or optical coherence tomography (OCT) machine provides visual feedback. The robotic system is capable of augmenting or correcting the movements of the surgeon.
- **Remote operator:** The surgeon remotely operates a joystick to direct the movements of a robot holding microsurgical tools while a surgical microscope or display provides visual feedback. This is also known as a "master-slave"-type system that was popularized by the da Vinci surgical system. Remote operator systems are the most technically complex form of surgical robots and have the potential to perform semiautomated or automated procedures with the assistance of a smart sensory feedback system.

The following subsections briefly review some published examples in the ophthalmic literature of robotic prototypes that fall under each category.

40.3.1 Robot-Assisted Tool

A robot-assisted tool, also known as a "smart" surgical tool, is an enhanced handheld instrument that is operated by the surgeon. The instrument has internal processes that allow it to augment and expand the capabilities of the surgeon. Published reports of experimental laboratory prototypes include both modified standard microsurgical tools and stand-alone devices. For example, Cutler et al. developed a 25-gauge force-sensing microforceps connected to an auditory feedback system that alerted the operator when a force exceeding 9 mN was applied during a simulated ophthalmic peeling procedure [7]. Balicki et al. attached an optical fiber to a 25-gauge microsurgical pick connected to a Fourier-domain common-path OCT that was capable of enforcing safety constraints to prevent unintentional contact with the retinal surface, scanning a surface while maintaining a constant distance, and placing the pick over a scan-identified subsurface target and penetrating the surface to reach the target [8]. Other published reports have reported similar enhancements to existing surgical tools to provide the surgeon with additional feedback [9].

In contrast to these modified existing microsurgical tools, the Micron (Fig. 40.1) is an active handheld stand-alone micromanipulator developed by Carnegie Mellon University and Johns Hopkins University capable of reducing hand tremor, detecting membrane puncture, and automatically holding a position in space [10]. When the Micron was evaluated in retinal vein cannulation of ex vivo porcine eyes, it had a 63% success rate compared to 29% using traditional tools. Importantly, the Micron is also capable of holding traditional intraocular tools. It can be further modified to include a force-pick on its tip to detect applied forces, OCT integration, a monocular camera system, or an intraocular "snake" instrument extension providing additional degrees of freedom [11–19].

Fig. 40.1 The Micron: a handheld robotic micromanipulator developed by Johns Hopkins University and Carnegie Mellon University (photo from Yang S, MacLachlan RA, Riviere CN. Manipulator design and operation of a six-degree-of-freedom handheld tremor-canceling microsurgical instrument. IEEE/ASME Trans Mechatron. 2014;20:761–72)
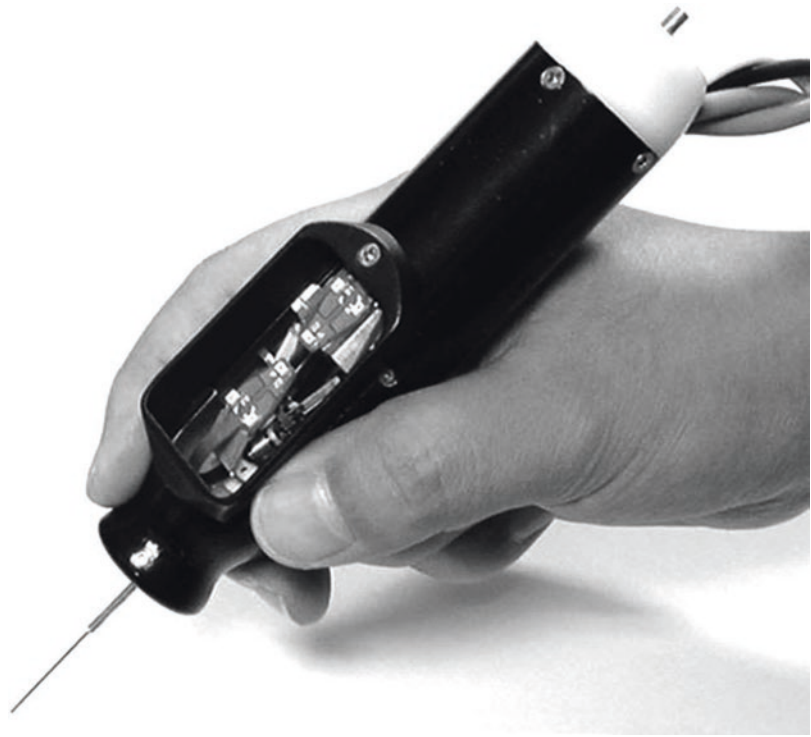
40.3.2 Cooperative Robotic System

The cooperative robotic system is configured so that the machine works simultaneously with the surgeon as co-manipulators. Instead of a remote joystick, the surgeon directly handles the arms of the robot while the robot concurrently works to smooth, cancel, or correct any operator maneuvers. The Johns Hopkins Steady-Hand Eye Robot is a surgeon-initiated robotic system with five degrees of freedom (three along the translational *x*-, *y*-, and *z*-axes and two along the rotational tilt and roll axes) [20]. The robot arm can hold either conventional or smart instruments that the surgeon then manipulates; as the surgeon directs the instrument, the robot arm increases the safety and efficiency of each movement. This device has been used in retinal vein cannulation and retinal membrane peeling in model eyes. It can also be further modified like the Micron for enhanced safety and efficiency [12, 21–23]. A similar device by the Katholieke Universiteit Leuven (KU Leuven) in Belgium was used to successfully perform retinal vein cannulation in a clinical trial of four patients with a retinal vein occlusion (Fig. 40.2) [24, 25]. Details and outcomes of the clinical trial have not yet been published.

40.3.3 Remote Operator

Remote operator systems separate the controls from the effector machine in a form of telemanipulation. The surgeon operates the controls at a workstation, often with some type of joystick, and those movements are translated by a computer processor to the machine, which then manipulates the instruments. Notable current examples include the da Vinci surgical system, PRECEYES Surgical System (Preceyes BV, Eindhoven, the Netherlands), and the Intraocular Robotic Interventional Surgical System (IRISS).

40.3.3.1 da Vinci Surgical System

The da Vinci surgical system (Fig. 40.3) was approved by the Food and Drug Administration in 2000 and is the most well-known and widely

Fig. 40.2
Co-manipulator robot
developed by KU
Leuven in Belgium
(photo from Gijbels A,
Smits J, Schoevaerdts L,
Willekens K, Vander
Poorten EB, Stalmans P,
et al. In-human
robot-assisted retinal
vein cannulation, a
world first. Ann Biomed
Eng. 2018;46:1676–85)

Fig. 40.3 da Vinci Xi surgical system being used in simulated strabismus surgery (photo from Bourcier T, Chammas J, Gaucher D, et al. Robot-assisted simulated strabismus surgery. Transl Vis Sci Technol. 2019;8(3):26)

used robotic system of this type, with applications in general surgery, cardiology, urology, and gynecology among others [26]. The device consists of a separate control console and a robotic apparatus with three or four arms that hold a dual-channel endoscope and various detachable surgical tools. The endoscope relays visual input to a binocular viewfinder on the remote workstation, allowing stereoscopic viewing. Four models have been produced since its initial introduction to the market: S, Si, HD, and Xi.

Using model eyes, the da Vinci has been previously tested in the laboratory setting to evaluate its suitability for external, anterior segment, and posterior segment ocular surgery [27–34]. Extraocular surgery, such as full-thickness corneal, scleral, muscle, and amniotic membrane suturing, was found to be feasible with the da Vinci system in experimental models [27, 29–31, 34]. In particular, researchers found the wrist movements needed to manipulate instruments to be intuitive and the range of motion adequate for extraocular surgery. Recently, Bourcier et al. were able to successfully perform amniotic membrane transplantation in three human patients and pterygium surgery in one human patient using the da Vinci surgical system without intraoperative complications or conversion to conventional surgery [30, 33].

However, Bourla et al. found anterior and posterior segment surgery to be notably more difficult with the da Vinci system [28]. In their experiments, anterior segment surgery consisted of anterior chamber intraocular foreign-body removal and capsulorhexis while posterior segment surgery consisted of 25-gauge pars plana vitrectomy. There was limited maneuverability of the robotic arms intraocularly and the high center of motion of the da Vinci system (9 cm away from the eye surface) caused external stress on the surgical wounds. Visualization of intraocular structures was also difficult with the da Vinci endoscope, which could not produce the retroillumination critical to anterior segment surgery and did not have the same resolution quality as the ocular microscope. To address the high center

of motion problem with the da Vinci instrument handling, future experiments used a microrobotic Stewart platform-based parallel manipulator attached to the robotic arms [35, 36]. The combined device of the da Vinci system and Stewart platform was called the hexapod surgical system (HSS). Using automated software, the HSS was able to place the remote center of motion on the ocular surface with excellent resultant dexterity and stability; however, translational and rotational maneuvers inside the eye were limited to a 30- to 40-degree cone. More recently, Bourcier et al. attempted anterior segment cataract surgery on Kitaro model eyes with the newest da Vinci Xi model, which improved upon the previous Si model used in earlier ophthalmic investigations with a 3-D high-definition viewing system [32]. However, the limitations related to a high center of motion persisted. A second surgical assistant was also needed for manual injection of intraocular solutions and operating time was found to be increased compared to conventional surgery.

40.3.3.2   PRECEYES Surgical System

In addition to the da Vinci surgical system, the PRECEYES Surgical System (Fig. 40.4) is the only commercially available robotic surgical system and the only system specifically designed for ophthalmic surgery. The device received the CE mark from the European Union in 2019 [37]. It consists of an input joystick controlled by the surgeon and a robotic apparatus with two mechanical arms firmly secured to the temporal side of the operating table. Appropriate alignment of the robot arms and the surgical entry site is provided by an electrically driven headrest. Visual feedback is provided by a conventional operating microscope or other visualization techniques.

In the initial experimental phases, the prototype was first used to cannulate retinal veins in live, anesthetized pigs with an induced retinal vein occlusion. De Smet et al. found that the PRECEYES provided consistent cannulation of the vein for up to 20 min and that intraluminal injection of ocriplasmin proximal to the site of

Fig. 40.4 PRECEYES
Surgical System: a
telerobotic surgical
system developed by
PRECEYES BV in the
Netherlands. This is the
only commercially
available ophthalmic
robotic surgical system
(photo from de Smet
MD, Stassen JM,
Meenink TC, Janssens
T, Vanheukelom V, Naus
GJ, et al. Release of
experimental retinal vein
occlusions by direct
intraluminal injection of
ocriplasmin. Br J
Ophthalmol.
2016;100:1742–6)

occlusion caused clot dissolution within a few minutes [38, 39]. The size of the veins cannulated was 80 μm in diameter or more and the distal tip of the glass pipette used for cannulation was 30 μm in diameter. Using virtual surgical simulation or video monitoring, the PRECEYES Surgical System has also been compared to conventional manual surgery. Robotic-assisted surgery was found to increase procedure time, but decrease intraocular instrument movement and surgeon-inflicted tissue damage, particularly in the novice surgeon [40–42].

In 2018, the PRECEYES Surgical System was used for the first time in human patients for retinal membrane peeling and subretinal recombinant tissue plasminogen activator (tPA) injection [43]. Twelve patients were randomized to either robotic membrane peeling or manual robotic peeling with the investigators reporting equally successful surgical outcomes in both groups. No statistical difference was noted in the amount of retinal microtrauma between the two groups, though the robotic system did require a longer operating time. In evaluating subretinal injection of tPA, six patients were randomized to either manual or robotic-assisted surgery. Subretinal tPA injection was successful in all patients.

40.3.3.3 Intraocular Robotic Interventional Surgical System (IRISS)

The intraocular robotic interventional surgical system (IRISS) is a similar remote operator system designed by the Jules Stein Eye Institute and the University of California, Los Angeles, Department of Mechanical and Aerospace Engineering for ophthalmic surgery [44, 45]. The device has two controlling joysticks and two arms that hold surgical instruments with alignment of the surgical incision to the remote center of motion by low-powered lasers. It has successfully performed capsulorhexis, viscoelastic injection, hydrodissection, lens cortex removal, core vitrectomy, PVD induction, and retinal vein microcannulation in porcine eyes.

40.4 Indications

The future indications for robotic-assisted surgery are varied. Given the enhanced mechanical maneuverability and precision, delicate procedures requiring exceptionally fine movements could be consistently and safely performed such as targeted intravascular drug delivery, retinal

vessel cannulation, and subretinal injection for gene therapy [28]. The safety of existing surgical procedures could also be improved given the ability of the robotic system to potentially dampen or eliminate tremor, provide safety feedback to prevent iatrogenic retinal damage, and allow enhanced visualization and targeting of various retinal microstructures. The robot could also act as a skilled surgical assistant in certain scenarios. In areas with limited access to ophthalmic care, and specifically vitreoretinal care, remote telesurgery could be a tool to address existing healthcare gaps and disparities. Finally, robotic-assisted systems could also improve surgical training and education by providing additional sensory feedback to the beginner surgeon.

40.5   Limitations

The transition of a novel technology from bench to bedside often depends on the ability of the new technology to provide improvements over the previous or current standard of care in either safety, efficiency, cost, or outcomes. Current limitations in the widespread adoption of robotic-assisted surgical systems in ophthalmology include the lack of large-scale clinical trials, minimally significant improvement over conventional surgery, and increased cost.

At present, the PRECEYES Surgical System is the only commercially available robotic device specifically designed for ophthalmic surgery. It has been clinically trialed in nine human subjects and is only clinically approved for use in the European Union. The da Vinci surgical system has also been trialed in a handful of human subjects. While these initial reported results offer promise for the use of robotic surgical devices, they provide little insight into the safety, efficacy, and efficiency of robotic-assisted surgery in a large diverse cohort of patients.

In both clinical trials and experimental investigations of robotic-assisted surgery, the robotic-assisted device was found to provide enhanced instrument stabilization and precision at the cost of greatly increased operating time. In simulated assessments of surgeon performance, the robotic-assisted device was found to improve surgeon instrument handling, especially in the novice surgeon, with decreased retinal microtrauma as a result. However, whether these experimental findings of reduced microtrauma can translate to the surgical setting in a meaningful way remains to be seen. In evaluating the PRECEYES Surgical System against conventional surgery in retinal membrane peeling, robotic surgery caused a statistically equivalent number of retinal microtrauma events with equivalent clinical outcomes at a significantly longer operating time [43].

The high clinical costs associated with implementation of a robotic surgical device such as the PRECEYES Surgical System are due to both direct costs related to equipment and indirect costs such as operating room time and case turnover. While costs may be lower with machines of lesser complexity such as robot-assisted tools and co-manipulator devices, their range of function is also more limited, potentially curtailing their usage and cost-effectiveness. Current success rates of vitreoretinal surgery are also very high, and the increased expense of robotic-assisted surgery may be prohibitive when weighed against potentially minimal improved clinical outcomes, especially in an increasingly cost-conscious healthcare landscape [46].

Given these limitations, the adoption of robotic-assisted surgery in the near future will likely remain restricted to technically difficult procedures with poor conventional outcomes such as retinal vein cannulation. However, these factors may change in the future as the abilities of these robotic devices continue to rapidly develop and expand.

40.6   Future Developments

The future of robotic-assisted retinal surgery is likely to include progressively greater levels of automation, potentially governed by artificial intelligence (AI) [4–6]. By coupling the surgical robot with a visual guidance system, an autonomous robotic system with the surgeon acting only in a supervisory role is possible. Using visual input from a surgical microscope or intraoperative

OCT machine, the robot could be programmed to navigate the retinal microenvironment and perform surgical steps or complete the procedure independently. This development could further be augmented and accelerated by coupling robots to AI, where deep learning methods could develop algorithms to predict, detect, and respond to various surgical situations in surgery. As with many other applications of AI, this would likely require the data input of thousands of surgeries in order to develop the algorithms necessary to correctly and reproducibly address the multifaceted decisions required in surgery.

40.7 Summary

Robotic-assisted vitreoretinal surgery is one of the next great horizons in ophthalmology and, indeed, all of surgery. The technical requirements of the vitreoretinal surgeon are becoming greater and more varied as novel interventions such as subretinal injections in gene therapy develop into reality. Future advances will likely include larger scale clinical trials, improved clinical outcomes, decreased operating times, and AI integration to achieve some degree of automation. Ultimately, robotic-assisted surgery has the potential to expand the physical capabilities of the surgeon to a superhuman level and provide even greater outcomes and safety for patients.

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