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Microsurgical Techniques in Ophthalmology – Current Procedures and Future Directions

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1. Introduction

Given the small dimensions of the human eye, ocular surgery demands the ability to both visualize and precisely manipulate delicate tissue within a microscopic space. Microsurgical technological advancements have rapidly changed the way in which ophthalmic microsurgery is performed and have provided for greater surgical efficiency and improved functional outcomes.

A thorough understanding of normal ocular anatomy is critical to define pathologic anatomic conditions, to delineate surgical goals, and to develop and utilize surgical tools to optimize patient outcomes. The anatomy of the eye and orbit can be broadly categorized as extraocular structures (including the eyelids, lacrimal gland, canalicular system, conjunctiva, and extraocular muscles) and intraocular structures, located within the globe of the eye. Intraocular structures are further grouped based on their location in the anterior or posterior segments of the eye (figure 1). The anterior segment consists of (from anterior to posterior): the cornea, anterior chamber, iris, and crystalline lens. The crystalline lens is suspended in place by hundreds of zonular fibers, which extend from the ciliary body to a thin capsule surrounding the lens. Contraction of the ciliary body changes the tension of the zonular fibers on the lens, allowing the lens to change its shape and focusing power. The cornea and lens are of particular importance as a majority of ophthalmic surgical interventions are performed on these structures, such as corneal transplantation, refractive corneal surgery, and cataract extraction.

The posterior segment of the eye consists of the vitreous humor (a clear gelatinous substance composed primarily of water, type II collagen, and hyaluronic acid), the neurosensory retina, the retinal pigment epithelium (which promotes the function and viability of the neurosensory retina), and the choroid (a vascular layer interposed between the retinal pigment epithelium and the sclera). The neurosensory retina is a highly organized extension of the central nervous system composed of photoreceptors and multiple layers of interconnected neurons. These neurons ultimately synapse on ganglion cells, whose axons coalesce into the optic nerve. Posterior segment ophthalmic surgery generally involves

removal of the vitreous humor to: 1) relieve traction of the vitreous on the retina, 2) remove visually-significant opacities within the vitreous, or 3) to gain access to the retina or sub-retinal space for further surgical manipulation.

The origins of ophthalmic surgery date back as far as the sixth century B.C. when ancient Indian surgeons used curved needle-like instruments to dislodge a cataract, a technique termed "couching". Further contributions by Greek, Middle Eastern and European physicians provided detailed functional knowledge of the eye and intraocular structures.

Development of the surgical microscope further revolutionized ophthalmic microsurgery. Although initially little more that a binocular telescope worn by the surgeon, the modern ophthalmic microscope provides a well-lit binocular stereoscopic view with a high-level optical clarity (figure 2). Foot pedal controls allow the surgeon to adjust magnification (approximately 10-30x), illumination intensity, x-y axis movement and level of focus. Furthermore, both contact and non-contact lens based systems are now employed to provide a wide-angle stereoscopic view of the posterior segment. Indeed, the ophthalmic microscope has enabled precise visualization of both anterior and posterior segment structures making modern ophthalmic microsurgery possible. Two such ophthalmic surgeries, cataract extraction and pars plana vitrectomy, are described below in detail.

1.1 Cataract extraction

1.1.1 Technique overview

Over two million cataract extractions are performed yearly in the United States making it the most common ophthalmic surgery, and among the most frequently performed surgeries in any field. A "cataract" refers to a focal or diffuse opacification of the crystalline lens, a structure that is normally optically clear and measures approximately 10mm wide and 6mm deep. Opacities within the lens limit the normal focusing ability of the lens resulting in blurred vision. Although cataract formation is most commonly an age-related process, cataracts may form at any age due to a number of different etiologies including medications, systemic metabolic disease, and ocular trauma. Although many methods have been developed to remove cataracts, the most common technique employed in modern ophthalmic microsurgery is "phacoemulsification".

Standard phacoemulsification for cataract extraction typically begins with the creation of a 2.2 to 3 mm tunnel or wound in the peripheral cornea to gain access to the anterior chamber. The anterior chamber is stabilized during intraocular manipulation with an ophthalmic viscoelastic device (a clear, removable, gel-like substance composed primarily of water and hyaluronic acid). A circular opening is then created in the anterior face of the lens capsule, termed a "continuous curvilinear capsulorrhexis". With the lens contents now accessible, the tip of a handpiece connected to a phacoemulsification machine is placed within the anterior chamber. This handpiece performs three functions: 1) administration of ultrasonic energy to fracture the lens material into small pieces; 2) aspiration to remove the small lens particles; 3) irrigation of a saline-like solution to maintain the volume of the anterior chamber (Figure 3).

Once the lens material is successfully removed, a clear artificial lens is typically placed within the intact capsule of the lens. Although early intraocular lenses were composed of

rigid polymethylmethacrylate (PMMA) requiring enlargement of the corneal wound for intraocular placement, modern intraocular lenses are composed of silicone or acrylic, both of which are biologically inert and can be folded and placed into the eye through a small corneal incision.

2. Principles of phacoemulsification

The fluid dynamics of phacoemulsification require constant fluid irrigation into the anterior chamber to maintain normal depth while lens material is aspirated. Due to the small volume of the anterior chamber, fluid circulation during phacoemulsification is critical to ensure efficient removal of the cataract while preventing complications due to anterior chamber collapse. Indeed, if outflow, or aspiration through the handpiece is allowed to exceed inflow, or irrigation, even for a fraction of a second, anterior chamber instability may result in unintended damage to intraocular tissue.

The formula that governs fluid flow during phacoemulsification surgery is Poiseuille's law:

$$Q = \Delta P \, \pi \, r^4 \, / \, 8 \, \eta L,$$

where Q is flow rate, ΔP is the pressure gradient, r is the radius of instrument tip, η is fluid viscosity, and L is length of the tubing. Given that the viscosity of the fluid and length of the tube are constant, flow is essentially proportional to the change in pressure and radius of the tubing.

In the case of phacoemulsification surgery, ΔP is the pressure gradient between the infusion pressure and the vacuum driving aspiration. The source of fluid inflow is a bottle of balanced salt solution, the height of which can be adjusted relative to the patient's eye to control infusion pressure. Fluid outflow is dependent on the vacuum level generated by the machine. The surgeon can control both the infusion pressure and vacuum or aspiration.

3. Phacoemulsificaiton instruments

The primary tool of phacoemulsification is the handpiece (figure 4). The tip of this tool delivers ultrasonic energy to break up the lens, aspirate fluid and lens material, and provide inflow of fluid to the anterior chamber. The handpiece is connected to a machine that regulates the aspiration pressure, the infusion pressure, and the intensity of the ultrasonic energy delivered by the handpiece. The design of the handpiece tip varies with respect to the angle and size of the lumen. Steeper tip bevels (less angled) provide better cutting ability into dense lens nuclear material whereas flatter tip bevels provide a larger surface area for improved aspiration of large lens fragments.

Modern phacoemulsification machines also employ foot pedal controls with at least three positions that allow the surgeon to control the fluidics of phacoemulsification. The first position typically provides irrigation only, which cools the handpiece and keeps the anterior chamber formed. The second position, in addition to irrigating, engages the aspiration mode at a constant or variable rate, depending on the settings selected by the surgeon. In the third position, ultrasound energy is delivered in addition to irrigation and aspiration. Many other microsurgical instruments are also utilized in conjunction with the phacoemulsification probe to facilitate manipulation of the lens material and to improve the efficiency of cataract extraction.

Ultrasonic power for phacoemulsification is generated by applying a time-varying electric field across a piezoelectric crystal in the phacoemulsification handpiece. The oscillating crystal deforms in response to the electric field, resulting in the conversion of electrical to mechanical energy. Oscillation of the tip occurs at a preset frequency that varies from 27 kHz to 60 kHz. The amplitude of the movement, or stroke length, ranges from 50 μm to 100 μm and is modulated when the phacoemulsification power is changed. As the tip retracts, a vacuum is created resulting in the formation of "cavitation bubbles". When the bubbles implode, they release heat and shock waves that fracture the lens material. Phacoemulsification power can also be modulated by varying the duty cycle; the period of time when the phacoemulsification power is being delivered. Varying the duty cycle allows for efficient administration of phacoemulsification energy to promote fracturing of lens material while minimizing excess heat and energy that may damage the cornea or other intraocular structures.

4. Phacoemulsification systems

While there are a variety of phacoemulsification machine manufacturers and configurations, they all generate the required vacuum and aspiration based on one of two pump types: Venturi and peristaltic.

A peristaltic system (figure 5) utilizes a series of rollers to displace fluid, producing flow in a compressible tube that is wound tightly around a rotating wheel. As the wheel turns, a segment of fluid trapped between two rollers is moved, resulting in more fluid being drawn into the tubing. Therefore, the flow rate is directly proportional to the speed of the rotary mechanism. Significant vacuum is generated only when the tip is occluded. The surgeon sets a desired flow rate and vacuum limit. The flow rate determines how rapidly the vacuum builds up when the handpiece tip is occluded and flow is restricted.

The Venturi pump (figure 6) utilizes the Venturi effect to create vacuum. The Venturi effect refers to the creation of vacuum secondary to the flow of a fluid (typically nitrogen or air in a phacoemulsification machine) over an opening. Thus, a Venturi pump allows a given vacuum level to be generated immediately, without occlusion of the phacoemulsification tip as is required in the peristaltic system. As such, flow cannot be directly modulated and is dependent on the vacuum level generated. The Venturi system provides the surgeon with near instantaneous vacuum levels and potentially higher flow rates.

5. Femtosecond laser technology and the future of phacoemulsification

In the near future, a new application of an existing technology may alter the way in which cataract surgery is performed. The femtosecond laser is a device that emits coherent optical pulses with a wavelength of 800nm and duration on the order of 10^{-15} seconds. It has been used extensively in ophthalmology due to its ability to alter delicate tissue in a precise and predictable way. In addition to its precision, the femtosecond laser can cut tissue with practically no heat development. Clinical trials utilizing the femtosecond laser to perform the incisional steps of cataract surgery, including cornea wound creation, capsulorrhexis creation, and disassembly of the lens are currently ongoing. Future applications of this laser may allow many steps of phacoemulsification to be automated, thus minimizing risk and error while increasing surgical efficiency.

5.1 Vitreoretinal surgery

5.1.1 Basic techniques

Vitreoretinal surgery, in its modern form, is a minimally invasive technique similar to laparoscopic surgery whereby small entry ports or trocars are placed on the surface of the eye to gain surgical access to intraocular structures. A variety of instruments including surgical manipulators, illuminating probes, laser probes, and infusing and aspirating devices can be placed through the trocars for a variety of surgical procedures. The trocars are placed at a safe anatomic entry point, the pars plana, located within a narrow band around the eye 3 to 4 mm posterior to the corneoscleral junction. This space lies just posterior to the highly vascularized ciliary body but anterior to the retina. Placing trocars too far anteriorly or posteriorly can lead to significant complications and surgical failure.

The vitreous body, a clear gelatinous structure located between the crystalline lens and the retina, occupies approximately 80% of the volume of the human eye. It is mainly composed of water (99%), collagen fibrils (type II collagen), and hyaluronic acid. The vitreous gel is integral in the pathogenesis of many posterior segment diseases. For example, in diabetic retinopathy, bleeding into the vitreous cavity can severely reduce visual acuity since dense hemorrhages can become loculated within the vitreous body. In some instances where the hemorrhage does not dissipate on its own, vitrectomy is necessary to remove the vitreous and blood. The vitreous body is adherent to a number of structures in the posterior segment including tight adhesions over the optic disc, the macula, retinal blood vessels and the ora serrata (a band which straddles the anterior retina and the pars plana where the vitreous and retina are anatomically fused and cannot be surgically separated). Thus, vitreous removal must be performed in a precise and controlled fashion to minimize excessive traction of the retina, which may result in complications such as retinal tears and detachment. Although the vitreous plays an important role in ocular development *in utero*, removal of the vitreous in the adult eye has no deleterious effects on the health of the retina. Once vitrectomy is performed, the vitreous cavity is typically replaced by the surgeon with balanced salt solution, which is eventually replaced by the eye with aqueous humor. Therefore, the vitreous body does not reform once it is removed.

5.2 Principles of vitreoretinal surgery

Surgery within the posterior segment of the eye is bound by the same principles as anterior segment surgery: the volume of the eye must be maintained as material is removed. Adding complexity to vitreoretinal surgery is the difficulty in visualization of the posterior segment during intraocular surgical maneuvers. External illumination is generally inadequate to visualize the retina and, despite advances in modern lens systems, the surgeon's view of the retinal periphery can be limited while operating near the posterior pole.

The first pars plana vitrectomy was performed by Robert Machemer in 1970 using a 17-gauge (1.42 mm diameter) one-port system that combined an infusion cannula and vitreous cutter in one handpiece. Since that time, numerous innovations have improved the efficiency and outcomes of this procedure and led to the development of the modern 3-port 20-gauge pars plana vitrectomy. In this procedure, three 20-gauge sclerotomies are created within the pars plana. One sclerotomy is used to anchor a cannula that infuses balanced salt

solution into the posterior cavity while the vitrectomy is performed, thus maintaining intraocular pressure. The remaining ports are used for the vitrectomy probe and a light probe to remove the vitreous and illuminate intraocular structures respectively. Following removal of the vitreous, the sclerotomy can be used to introduce other instruments such as intraocular forceps and laser probes to further manipulate and treat the retina (figure 7).

Visualization during pars plana vitrectomy is performed using the operating microscope in conjunction with a contact lens (which can be held by the assistant or sewn onto the eye at the corneoscleral junction) or a non-contact lens viewing system. Direct contact visualization systems allow for greater field of view and enhanced three-dimensional perception. Non-contact lens viewing systems are easier to use and do not require an assistant or additional surgical maneuvers to anchor the lens to the ocular surface, but sacrifice some field of view and three-dimensional perception.

5.3 Vitrectomy instruments

The basic tools of pars plana vitrectomy are a vitreous cutter, illuminating device, laser probe, various tissue manipulators such as micro-forceps for delicate intraocular work, and an infusion cannula to maintain intraocular pressure. The workhorse of pars plana vitrectomy is the vitreous cutter, whose basic function is to remove the vitreous in a controlled fashion. Because the vitreous is a semi-solid structure with adhesions to the retina, simple aspiration of the vitreous results in excess traction on the retina. To minimize such traction, the vitrectomy probe is designed with both an aspiration port and a cutting mechanism to aspirate a small volume of vitreous into the handpiece and to cut and remove it. High cut speeds allow for incremental removal of small amounts of vitreous while minimizing tractional forces of the vitreous on the retina. Lower cut speeds result in removal of larger volumes of vitreous, thereby increasing the rate at which vitreous is removed. Most modern high-speed (600-5000 cuts per minute) vitrectomy probes are pneumatically driven with a side-cutting guillotine port near the tip of the instrument (figure 8).

Most vitrectomy machines are equipped with a built-in light source employing either yellow or white light from a halogen or metal-halide light source. The light probe, a fiberoptic cable encased in a plastic handpiece, is connected to the light source and can function as a separate instrument or, in some cases, can be combined with the infusion cannula to simultaneously illuminate and irrigate the posterior segment. A recent innovation has been the introduction of a xenon light source, which can provide bright illumination through a narrow probe. This has facilitated the performance of smaller gauge surgery and eliminated light wavelengths under 400 nm that can be phototoxic to the retina.

Many surgical instruments have been developed to facilitate surgical procedures on the macula. The macula is located at the center of the posterior pole of the retina and has the highest concentration of photoreceptors. It is responsible for fine central visual acuity needed for such tasks as reading, driving and other activities of daily living. Pars plana vitrectomy may be required to treat a variety of macular diseases including epiretinal membranes, macular holes, vitreo-macular traction, and hemorrhagic age-related macular degeneration. Instruments used to manipulate and treat the macula include a variety of micro-forceps (e.g. end-grasping and pick forceps), scissors, needles and cannulas.

The intraocular laser probe allows for minimally invasive and precise ablation of retinal tissues and is used in a wide variety of surgical procedures. Similar to the light probe, the "endolaser" probe is also a fiber-optic cable encased in a plastic handpiece. The intensity of the laser ablation is controlled by the surgeon by modulating the power and duration of the laser as well as by altering the distance of the probe tip to the retina. Intraocular laser is typically employed for two key purposes: 1) to treat retinal tears by creating a fibrous scar between the retina and the underlying choroid thus preventing fluid in the eye from collecting underneath the retina; and 2) to ablate non-perfused or ischemic retinal tissue (as in diabetic retinopathy and other occlusive retinal vascular diseases) to decrease the pathologic production of growth factors that result in retinal neovascularization, intraocular hemorrhage and retinal edema.

5.4 Vitrectomy systems

Vitrectomy machines, similar to phacoemulsification machines, are complex devices that drive the vitreous probe cutter, provide irrigation at an adjustable level to control intraocular pressure, aspirate and remove intraocular material, and provide a light source for intraocular illumination. Many of these functions are controlled via foot pedal by the surgeon, similar to the previously-described phacoemulsification machine.

Two major types of systems are used to drive the vitrectomy probe cutter: electric guillotine and pneumatic guillotine. The electric guillotine employs an electric drive motor with a sinusoidal transmission, translating the rotary motion of an electric motor shaft to the linear guillotine motion of the cutter tip. The profile of motion of the guillotine remains constant as the cut rate is altered. That is to say, the duty cycle, or ratio of time the cutter port is open or closed, remains constant regardless of the cut rate.

The second type of handpiece, which is pneumatically driven, uses pulses of air or gas to close the cutter tip. The pneumatically-driven guillotine is attached to a diaphragm. When a pulse of air is delivered, the diaphragm and guillotine extend, closing the cutter tip and completing a cut. The guillotine then retracts to its original position either through a spring mechanism or through a "dual drive" system where an additional pulse of air pushes the guillotine back, thus opening the cutter tip. In the spring mechanism, as the cut rate is increased, the duration of open time per cut decreases, while the closed time remains constant (decreasing the duty-cycle). The "dual drive" system allows for improved duty cycle compared with the spring mechanism, but the duty cycle still decreases at high cut rates.

6. Current directions

Recent advances in vitreous surgery have resulted in the development of smaller instruments: the 23- and 25-gauge transconjunctival suture-less vitrectomy systems (figure 9). A standard 20-gauge (0.9 mm diameter) vitrectomy requires removal of the conjunctiva and sutures to close the sclerotomies used to access the posterior segment. 23-gauge (0.6 mm diameter) and 25-gauge (0.5 mm diameter) entry wounds, when constructed properly, are small enough to self-seal and thus can be placed through the conjunctiva and sclera without the need for closing sutures. To allow for easy entry and exit of surgical instruments during vitrectomy and to align the entry holes in the conjunctiva and sclera, a 23- or 25-gauge trocar

is placed at the site of the desired sclerotomy. The trocar consists of two components: a polyimide cannula and a polymer hub. The polyimide cannula maintains the transconjunctival and transcleral tunnel through which surgical instruments are passed. The polyimide cannula material provides both strength and flexibility, allowing the cannula wall to be thin while avoiding collapse or buckling. The polymer hub is the part of the trocar visible on the surface of the eye and prevents the trocar from sliding into the vitreous cavity. The hub has a central hole that is continuous with the cannula, allowing for instruments to be inserted into the vitreous cavity.

Many surgeons believe the potential advantages of smaller gauge, suture-less techniques include shortened operative time and faster patient recovery. However, the reduction in port diameter results in reduced flow rates compared with 20-gauge cutters, and therefore, smaller-gauge surgery may require more time to remove the same amount of vitreous or may be inadequate to remove dense or highly organized vitreous. Other concerns with suture-less techniques include the increased risk of post-operative hypotony and infection if the sclerotomies are not constructed properly.

7. The future of ophthalmic surgery – Robot-assisted microsurgery?

With recent innovations in engineering and the demands for increasingly precise and efficient ophthalmic microsurgery, the next major advancement in ophthalmic surgery may be the integration of mechanization and robotics into ophthalmic microsurgical techniques. The potential benefits of robotic surgery in ocular surgery include increased precision, reduction of human error, task automation and the capacity for remote surgery.

Guerrouad and Vidal described one of the first ocular robotic systems in 1989. Named the "Stereotaxical Microtelemanipulator" (SMOS), it provided relatively good range of motion for basic surgical tasks but the technology was too premature at that time to raise tangible interest for further development. In the 1990s, Steve Charles and researchers at Northwestern University demonstrated the use of robotic platforms for ophthalmic surgery with precise position measurement and fine incremental motion but these prototypes were limited by the complexity of its software control and the need for increased robotic responsiveness to human controls.

Presently, the Food and Drug Administration has approved the *da Vinci* Surgical System (Intuitive Surgical, Sunnyvale, CA), which has become the most commonly employed robotic platform in human surgery (figure 10). Although it has been used in the fields of general surgery, urology, gynecology and cardiac surgery, its use in ophthalmic surgery is in its early phases. Preliminary studies have demonstrated good robot arm responsiveness to human controls for external and intraocular surgical tasks. However, the remote center of motion (pivot point) and limited range of motion of the robot arm make intraocular manoeuvrability difficult with excessive distortion of the globe of the eye. Furthermore, while the visualization system of the *da Vinci* system is adequate for extraocular and some anterior segment surgical procedures, posterior segment surgery is hampered by a limited field of view. Finally, the surgical instruments of the *da Vinci* instruments are not well-suited to ophthalmic microsurgery due to their bulkiness. Recent studies have better defined the range of motion required for robot-assisted ophthalmic surgery and further refinements to the robot surgery platform are underway to make this technology a tangible option in the near future.

Ocular robotic surgery poses a myriad of unique challenges and the application of this technology will undoubtedly require many stages of evolution. Further work will be required to continue to integrate traditional surgical techniques with new devices to bring the advantages of robotics to the field of ophthalmology.

8. Conclusion

Ophthalmic microsurgery has rapidly evolved in recent history as advances in medical device technology have led to the development of numerous minimally invasive procedures for the treatment of ocular diseases. The multi-disciplinary integration of technology and knowledge from the fields of biomaterials, optics, lasers, ultrasonics and pneumatics have helped to refine the surgical tools available to ophthalmic surgeons, increasing their efficiency and surgical outcomes. As life expectancy and the prevalence of various systemic diseases continue to rise, so too will the burden of ocular disease. Further advances to better address these demands will undoubtedly lead to novel surgical techniques and devices, expanding the role of ophthalmic surgery to undiscovered heights.

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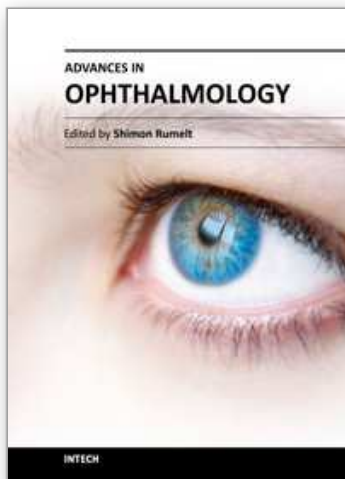
Advances in Ophthalmology

Edited by Dr Shimon Rumelt

This book focuses on the different aspects of ophthalmology - the medical science of diagnosis and treatment of eye disorders. Ophthalmology is divided into various clinical subspecialties, such as cornea, cataract, glaucoma, uveitis, retina, neuro-ophthalmology, pediatric ophthalmology, oncology, pathology, and oculoplastics. This book incorporates new developments as well as future perspectives in ophthalmology and is a balanced product between covering a wide range of diseases and expedited publication. It is intended to be the appetizer for other books to follow. Ophthalmologists, researchers, specialists, trainees, and general practitioners with an interest in ophthalmology will find this book interesting and useful.

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