EXPERT REVIEWS

Advances in cataract surgery

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Recent advances in cataract surgery have increased the safety and efficacy of this common procedure. Cataract surgery has evolved from 'couching' with sub-optimal results to phacoemulsification with excellent results. Introduction of the femtosecond laser into cataract surgery may further the safety and predictability of this procedure. In addition, innovations in intraocular lens material have enabled the surgery to be done through a small incision with quicker recovery and more predictable refractive outcome. New intraocular lens design technologies have helped patients minimize their need for glasses at most distances. Further, invention of ophthalmic viscosurgical devices reduced the risk of endothelial decompensation and corneal edema. These innovations have transformed the goal of cataract surgery from purely visual rehabilitation to a refractive procedure as well.

Keywords: cataract surgery • femtosecond laser • intraocular lens • ophthalmic viscosurgical devices

Cataract is a leading cause of blindness worldwide and cataract surgery is one of the most frequently performed operations in the world. Cataracts affect more than 20 million Americans older than 40 years. By 2020, more than 30 million Americans will have visually significant cataract and 9.5 million are expected to have pseudophakia or aphakia [1]. Advancements in phacoemulsification and intraocular lens (IOL) technology have ushered in a new era of cataract surgery. Innovations in IOL design and phacoemulsification instrumentation have potentiated improved surgical outcomes, reduced perioperative morbidity and increased likelihood of spectacle independence. As a result, surgeons are attaining unprecedented safety, efficiency and precision. The breakthrough of new technology is paralleled by patients' heightened expectations from cataract surgery. In this new era, many patients arrive to their appointment well-researched and prepared with anticipation of exceptional postoperative visual acuity, both near and distance, without correction [2].

History

The first record of cataract being surgically treated is from 600 B.C. by Susruta of India [3]. Cataracts were surgically addressed by couching. Basically the surgeon would insert a long instrument posterior to the limbus and push the lens into the vitreous cavity, thus clearing the visual axis of the dense lens. Complication rate was high at that time, but it would change the patient's life by giving him some ambulatory vision and self-dependence. Couching is still performed by some traditional 'healers' in some parts of Africa, the Middle East and few other parts of the world. 33.3% of patients who undergo traditional couching end up with no light perception vision [4]. It is likely that outcomes of couching would have been worse in ancient times when there was no recourse to modern antibiotics for endophthalmitis or treatments for glaucoma. The concept of cataract extraction rather than pushing the lens inside the eye was introduced by Ammar Ibn Ali in *Choice of Eye Diseases* written in Egypt in the 10th century. Ibn Ali invented the hollow needle and oral suction device, for the purpose of cataract extraction:

"Then I constructed the hollow needle, but I did not operate with it on anybody at all, before I came to Tiberias. There came a man for an operation who told me: Do as you like with me, only I cannot lie on my back. Then I operated on him with the hollow needle and extracted the cataract; and he saw immediately and did not need to lie, but slept as he liked. Only I bandaged his eye for seven days. With this needle nobody preceded me. I have done many operations with it in Egypt [5]."

As one would expect, this technique would not work on dense cataract and couching remained the widely performed surgery to treat cataract for many decades [3].

In 1747, a French ophthalmologist, Jacques Daviel, was the first to perform

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extracapsular cataract extraction through a large corneal incision. Then, he would incise the anterior capsule and express the nucleus. Because of the incomplete removal of the cortex, chronic inflammation with glaucoma and secondary capsular opacification would lead to unsatisfactory outcome. Thus, the procedure was not widely accepted at that time and surgeons tried to remove the lens as a whole with the capsular bag. In 1753, Samuel Sharp was among the first to successfully perform intracapsular cataract extraction (ICCE) through limbal incision using pressure from his thumb.

Lens expression technique was improved over many years by using different approaches. In 1957, Joaquin Barraquer used α-chymotrypsin to dissolve the zonules to facilitate lens removal. However, glaucoma and clogging the trabecular meshwork with zonule fibers remnant was one of the many complications of the technique. Cryoprobe was first introduced in 1961 by Tadeusz Krwawicz to remove the lens by forming iceball and lessen the risk of capsular rupture. ICCE was a very successful operation compared to couching and early ECCE. However, the rate of potentially blinding complications was 5% apart from aphakia related habitation problems [6].

The gradual introduction of operating microscopes during the 1970s offered better intraocular visibility and ability to safely place multiple corneal sutures. In addition, it had the advantages of leaving the posterior capsule intact which reduced the risk of potentially blinding complications (e.g., vitreous loss or retinal detachment). It also allowed posterior chamber lens implantation.

Phacoemulsification was introduced in 1967 by Dr. Charles Kelman. Since then, there has been significant improvement in fluidics, energy delivery, efficiency and most important, safety of this procedure. Currently, phacoemulsification is the standard of care for cataract extraction in the western world. The major advantage of phacoemulsification is that it reduced the morbidity from cataract surgery by reducing the incision size with subsequent faster recovery and decreased risk of complications including endophthalmitis.

A major advance in cataract surgery was the invention of an intraocular lens that can be implanted to replace the extracted cataractous lens. Casaamata is believed to be the first surgeon to implant an intraocular lens (IOL) in 1795 [7]. The idea of IOL implantation was revived by Harold Ridley. Ridley inserted an artificial lens in the form of polymethyl-methacrylate (PMMA) in 1949 [7,8]. However, the idea of PMMA IOL did not gain popularity due to miscalculation of the postoperative refraction. The cause of this miscalculation was later discovered to be due to the difference in the refractive index of PMMA material in air vs in fluid inside the eye. Another drawback of the PMMA lenses is that they were rigid and could not be folded which necessitated large corneal incisions to insert such lenses. Subsequent IOLs made of acrylic and silicone, were flexible and could be folded and inserted through a significantly smaller incision.

Ophthalmic viscosurgical devices

Healon (sodium hyaluronate 1%, Abbott Medical Optics Inc. Santa Ana, CA, USA) was the first ophthalmic viscosurgical device (OVD) to be introduced in 1979. Since then, a number of OVDs have been manufactured with varying composition and rheologic behavior. OVDs have variety of uses in ophthalmic surgery which could be summarized in space creation, tissue stabilization and corneal endothelial cell protection [9]. OVDs used to be classified as either dispersive or cohesive.

Dispersive OVDs (e.g., Viscoat, Alcon. Fort Worth, TX, USA) are low in viscosity and molecular mass, have short molecular chain length and require longer aspiration time for complete removal. Typically, dispersives remain in the eye during phacoemulsification to protect the endothelium from turbulent flow.

Cohesive OVDs (e.g., Healon, Abbott Medical Optics Inc.) are typically more viscous; have a higher molecular mass, possess longer chains, result in excellent space maintenance and are easy to remove. Thus, cohesives are used to expand the capsular bag for intraocular lens insertion at the end of cataract surgery.

The introduction of Healon5 (sodium hyaluronate 2.3%) in 1998 heralded a new class of OVDs termed viscoadaptive [10]. Viscoadaptives (e.g., Healon5 and DisCoVisc, Alcon.) behave similar to superviscous cohesives under low shear stress. With change in fluid dynamics, the viscoadaptives fracture freeing pieces to float around in the balanced salt solution. This biphasic nature has resulted in viscoadaptives being referred to as pseudodispersive in ophthalmic surgery because they are well retained in the anterior segment similar to dispersive OVDs [11].

OVDs have led to dramatic improvement in the safety of cataract surgery and minimized damage to the ocular structures that used to occur previously as a result of cataract surgery. Indeed, OVDs are of the most important advances in cataract surgery.

Intraoperative floppy iris syndrome

Intraoperative floppy iris syndrome (IFIS) typically occurs in patients receiving α-1 blocker. Features of IFIS include poor pupil dilation; progressive intraoperative pupillary miosis, iris prolapse and floppy iris. To decrease the risk of complications, few peri- and intraoperative interventions have been successfully attempted. Pre-operatively, using atropine drops for few days is recommended [12]. Intraoperatively, short and posterior corneal wound construction should be avoided. Intracameral preservative free epinephrine may be utilized and adding preservative free epinephrine to a 500 ml BSS irrigation bottle is recommended (off-label). There should be a low threshold for using pupillary dilation devices. Because of the ability to place an iris retractor subincisionally, we prefer iris retractors to pupil expansion rings in IFIS cases with poor pupil dilation. Manual

pupillary dilation and stretching should be avoided, so is overfilling and overly pressurizing the chamber with OVD. Some OVD should be removed by pressing on the wound before performing hydrodissection. Low fluidic parameters should be utilized, and suturing the main corneal incision to avoid iris prolapse in case of leaky wound. Arshinoff described modified soft-shell and ultimate soft-shell technique (SST-USST) for IFIS [13] which relies solely upon OVDs for iris stabilization by using Viscoat (Alcon.) and Healon5 (Abbott Medical Optics Inc.) to add a semi-rigid OVD roof to stabilize the iris and cause some viscomydriasis. Chang *et al.,* reported that the use of preoperative atropine followed by intraoperative Healon5, iris retractors and pupil expansion rings resulted in excellent surgical outcome [14].

Viscoat may be useful in compartmentalization especially in cases of localized weakness of the zonules (e.g., trauma). The reverse soft shell technique (packing Viscoat in a region of broken zonules followed by placing cohesive OVD over it to prevent vitreous from prolapsing) can be used in case of posterior capsule rapture to cover and stabilize the tear. Viscoat can also partition residual lenticular material from the prolapsed vitreous. In July 2012, Healon EndoCoat was approved by the US FDA as a dispersive OVD.

Capsular staining

The advent of capsular staining has improved the safety of cataract surgery by allowing enhanced visualization. Indications for capsular staining include cases with a poor red reflex as in mature or white cataracts, opalescent cortical material, dense posterior subcapsular opacification, vitreous hemorrhage, or corneal opacity. In addition, staining is also useful for pediatric cataract extraction and for surgeons learning new intraoperative techniques requiring good visualization of the anterior capsule. Numerous intraocular dyes have been reported in the literature including indocyanine green (ICG), fluorescein, crystal violet, gentian violet and brilliant blue G (BBG) [15]. However, only trypan blue is FDA approved as an adjunct to cataract surgery [16].

Intraocular lenses

In recent years, significant technological advances have improved our understanding of the aberrations of the normal human eye as well as the human eye that has been altered by refractive surgery. New corneal imaging techniques such as Scheimpflug imaging, placido-disk videokeratography and anterior segment optical coherence tomography have enhanced our understanding of the shape and functionality of the human cornea. These instruments have shown that the normal cornea is flatter in the central 2 mm, with steepening from 2-4 mm, and, then, flattening again beyond 4 mm. This correlates well with the fact that the spherical aberration value is not a constant throughout the cornea, but rather varies as one moves radially from the center of the cornea [101]. Further, in the young human eye, the positive spherical aberration introduced by the cornea is partially corrected by the negative spherical aberration introduced by the crystalline lens [17]. However changes that occur in the lens with age cause the positive spherical aberration of the lens to increase [18]. Thus, the aberration compensation is gradually lost, leading to an increase in total ocular aberrations. This, in turn, leads to a corresponding loss in optical and visual quality, reduction of scotopic contrast sensitivity and increase in optical side effects such as glare and haloes [19,20].

This new understanding of ocular optics and aberrations has led to the development of new aspheric IOLs to neutralize the positive corneal spherical aberration and improve visual quality [21]. This may be due to the improvement in contrast sensitivity and improved retinal image [22,23]. However, caution must be exercised in using aspheric IOLs in patients at risk of decentration (e.g., pseudoexfoliation and trauma) as this may induce further higher order aberrations [24]. Aspheric IOL should also be avoided in eyes that had hyperopic LASIK treatment as this might increase the negative spherical aberration of the eye.

Intraocular lenses for presbyopia correction

Presbyopia remains one of the most challenging optical problems in cataract and refractive surgery. Different approaches to treat presbyopia have been studied in recent years. These include scleral remodeling (scleral expansion and sclerotomy techniques) [25]; corneal procedures (presbyLASIK [26], corneal inlays [27] and conductive keratoplasty [28]); and monovision techniques [28]. Each of these techniques has limitations, advantages and disadvantages. There has been increasing interest in correcting presbyopia at the time of cataract surgery by using presbyopia-correcting IOLs. The two major presbyopia-correcting IOL designs are the accommodating and the multifocal IOLs.

The first presbyopia-correcting IOL to be FDA-approved was the Array (Advanced Medical Optics, Santa Ana, CA, USA and USA) in 1997. The Array is a refractive multifocal lens with five progressive concentric zones on its anterior surface. Zones one, three and five are distance-dominant, whereas zones two and four are near-dominant. In some of the first studies, 72% of the eyes implanted with the Array could see both 20/40 for distance and J3 for near compared with 48% with a monofocal lens [29].

In 2005, the FDA approved two new multifocal designs, the refractive Rezoom IOL (Advanced Medical Optics, Inc.) and the diffractive Acrysof Restor IOL® (Alcon Laboratories, Inc.). The Rezoom represents new engineering of the Array platform, including a hydrophobic acrylic material and a shift of the zonal progression. Aspheric transitions between the zones offer intermediate vision. The near-dominant zones provide +3.50 D of add power at the IOL's plane for near vision, yielding approximately +2.57 D of add power in the spectacle plane. The Rezoom has been shown to provide spectacle independence in 93.4, 92.6 and 81.4% for distance, intermediate and near vision, respectively [102]. The major drawbacks of the Rezoom are its moderate dependence on spectacles for near tasks and the increased incidence of photic phenomena compared to other multifocal lenses [30].

The AcrySof® ReSTOR® IOL employs a central 3.6 mm diffractive zone. This area comprises 12 concentric steps of gradually decreasing (1.3-0.2 microns) heights, the farther from the center. These steps allocate energy based on lighting conditions and activity to create a range of vision. The ReSTOR has been shown to yield high rates of spectacle freedom with uncorrected distance visual acuity of 20/30 or better in 93.8% eyes and an uncorrected near visual acuity of 20/30 or better in 75.0% of eyes [31,32]. Glare and halos have been reported as the main complication of this type of lens. Moderate glare was reported by 21.3% of the patients compared to 7.1% for a monofocal IOL.

In 2007, the FDA approved the aspheric version of the ReSTOR (AcrySof IQ ReSTOR), which has a negative asphericity, while maintaining its apodization, diffractive and refractive components. The AcrySof IQ ReSTOR IOL + 3.0 D (SN6AD1) incorporates a +3.0 diopter correction at the lenticular plane (~+2.5 D at the spectacle plane). It also has nine concentric steps (three less steps than the original IOL) farther apart to improve intermediate vision over the AcrySof IQ ReSTOR IOL +4.0 D (SN6AD3), with similar near and distance visual acuity. Halos and glare are still common complaints of patients implanted with these lenses. Patients implanted with the SN6AD1 noticed more glare and patients implanted with SN6AD3 noticed more halos [33,34]. The ReSTOR Toric is the newest addition to this lens design. It provides a single platform to correct astigmatism and improve near and intermediate vision. This lens is currently available in Europe and Canada, but is not yet available in the United States.

In 2009, another diffractive IOL was approved, the Tecnis multifocal (Advanced Medical Optics, Inc. Santa Ana, California). The newer version is a single-piece acrylic (ZMB00) and has a full diffractive posterior surface that makes it pupil independent. It has an aspheric anterior surface with +4 D near add (+3.0 D at the spectacle plane). A retrospective study on the earlier version of this IOL found an uncorrected distance visual acuity of 20/30 in 85% of eyes and an uncorrected near visual acuity of J1 in 93.7% of 2500 eyes, 3 years postoperatively [35]. Glare and halos were reported as severe by 6.1 and 2.12% of patients, respectively.

Multifocal lenses have the persistent drawback of the potential for patients to see glare or halos for few weeks or months following surgery. Indeed, it has been shown that multifocal lenses have greater incidence of glare and halos than monofocal IOLs [36]. However, it has been shown that glare and halos symptoms decrease as most people learn to disregard them with time [37]. Another drawback of multifocal IOLs is the potential for decreased contrast sensitivity especially in dim lights. However, contrast sensitivity with multifocal IOLs improves over time and may approximate the levels found with spherical monofocal lenses by 6 months postoperatively [38]. Patient selection for multifocal IOL is critical. Patients with high expectations, or those with significant astigmatism, ocular surface disease (e.g., epithelial basement membrane disease and severe dry eye), zonular weakness (e.g., pseudoexfoliation) or patients with retinal diseases (e.g., macular degeneration and epiretinal membrane) may not be good candidates.

Accommodating lenses

The Crystalens (Bausch & Lomb, Aliso Viejo, CA, USA) is the only FDA approved 'accommodating' lens to correct presbyopia in patients with cataracts. The Crystalens has undergone several modifications since the original model (AT-45). It has silicone optic and two flexible, hinged plate haptics. The latest models (HD and AO) have a central 1.5 mm blended bispheric optical zone to enhance near vision [39]. The Crystalens has been shown to have better uncorrected near visual acuity than a monofocal lens [39]. Although it was thought that the Crystalens mode of action is through accommodation, several studies have failed to demonstrate a significant accommodative shift. Indeed, the Crystalens have been shown to have poorer uncorrected near visual acuity than the multifocal lenses. Thus, many Crystalens surgeons may aim for -0.50 D to -0.75 D of myopia in the nondominant eye to induce 'mini-monovision' in their patients [40-42]. Another drawback of the Crystalens has been issues with tilting and decentration of the lens caused by capsular contraction and fibrosis [43]. On the other hand, there are less complains of glare and halos from Crystalens than from the multifocal lenses. Thus, Crystalens is a good option for patients who are willing to accept some compromise in near vision but have a low threshold for glare and halos that may be present with multifocal lenses [44].

One of the new accommodating lenses currently undergoing FDA trials is the Synchrony accommodating IOL (Abbot Medical Optics, Abbott Park, IL, USA). The Synchrony IOL consists of a foldable, single piece, dual-optic system. A spring haptic joins the high plus anterior optic to a minus powered posterior optic [45]. During attempted distance vision, the two optics are close together. Near vision is achieved by attempted accommodation with subsequent decrease in capsular bag and zonular tension. This in turn moves the front optic forward and changes the focal point to intermediate or near vision. In a small prospective study, the Synchrony lens was shown to have equivalent uncorrected-distance and uncorrected- near visual acuity to the ReSTOR lens while providing better uncorrected-intermediate visual acuity and less halos and glare [46].

Another promising technology is the three-piece Light Adjustable Lens (Calhoun Vision Inc., Pasadena, CA, USA) made of a photosensitive silicone material. Within two weeks post-operatively, the residual refractive error could be corrected by shining an ultraviolet light on the IOL through a dilated pupil to change the shape of the lens. The Light Adjustable Lens corrects spherocylindrical errors as well as presbyopia by creating a small near zone add according to the pupil diameter [47-49].

Implantable miniature telescope

In July 2010, the FDA approved the Implantable miniature telescope TM (IMT, VisionCare Ophthalmic Technologies Inc., Saratoga, CA, USA). The implantable miniature telescope (IMT) is a system which magnifies objects to improve vision

in patients with end-stage age-related macular degeneration (AMD). It is indicated for monocular implantation in patients with stable, but severe to profound vision impairment (best corrected distance visual acuity 20/160-20/800) caused by bilateral central scotomas associated with end-stage age-related macular degeneration, a visually significant cataract and who achieve at least a 5-letter improvement on the visual acuity chart using a trial external telescope. Two models are available: one with 2.2-times magnification and the other with 2.7-times magnification. The device's glass cylinder housing the micro-optics is 4.4 mm long and 3.6 mm in diameter. The rigid haptic loops are 13.5 mm in diameter. The device is placed in the capsular bag while the anterior aspect protrudes through the pupil by 0.1-0.5 mm. The prosthesis projects an enlarged image of the patient's central visual field onto the retina; thus reducing the size of the scotoma relative to the objects in the central field of vision. The implanted eye sees 20-24 wide field of view due to the enlarged image projection.

The IMT has shown promise with 59.5% of 173 IMT-implanted eyes gaining three lines or more of BCVA compared to 10.3% of 174 fellow control eyes ($p < 0.0001$) after 2 years of follow-up. Meanwhile, 0.6% of 173 telescope-implanted eyes lost three lines or more compared to 7.5% of 174 fellow control eyes ($p = 0.0013$). Two cases of corneal edema in IMT-implanted eyes required grafts between 9 and 12 months [50]. There were no cases of corneal decompensation between 1 and 2 years after surgery. The mean endothelial cell density stabilized after the first year through the second year [51].

Zonules-supporting devices

The anterior approach of removing a cataract with significant zonular weakness used to be ICCE until endocapsular devices were introduced in 1991 [52,53]. The capsular tension ring (CTR) is made of polymethyl-methacrylate (PMMA) material and has an oval-shaped cross section with eyelets at both free ends. The diameter of CTR is larger than that of the capsular bag and comes in different sizes. The CTR expands the capsular bag and redistributes the forces, providing equal distribution of support over the remaining zonules [54]. At minimum, overlap of the end terminals is needed to provide complete circumferential support. CTR is indicated when there is evidence of severe, but localized zonular dialysis (<4 h) or mild degree of generalized zonular weakness [54]. The CTR can be inserted manually with forceps or with injectors into the capsule bag before or after lens extraction.

The CTR has intra- as well as post-operative advantages. By expanding the bag, it reduces the risk of further zonular damage. Also, it minimizes the risk of potentially aspirating the bag during the surgery. Post-operatively, CTR reduces the risk of IOL decentration and tilting [55]. It offers the advantage of preventing capsule wrinkling and facilitate recentering a mildly subluxed capsular bag. Further, it may decrease the prevalence of posterior capsule opacification or the incidence of capsular phimosis [56].

When there is a profound zonular insufficiency and a severely subluxed capsular bag, a standard CTR may not supply enough intraoperative and postoperative support to maintain the desired orientation of the capsular bag. To deal with these problems, scleral-fixated devices such as the modified CTR (M-CTR) or the capsular tension segment (CTS) must be used [57]. Iris chafing from the fixation eyelet and chronic uveitis could occur with small capsulorhexis, thus an adequate size capsulorhexis (5.5 mm) should be performed [54].

Correction of astigmatism during cataract surgery

Corneal astigmatism can be measured by multiple techniques including manual keratometry, autokeratometry, optical biometery and corneal topography. Topographic measurement of corneal astigmatism is currently the standard of care. Corneal topographic measurements identify irregular astigmatism that may limit optimum results.

Management of corneal astigmatism at the time of cataract surgery is an area of increasing importance and active research. Several approaches to correct corneal astigmatism have been successfully tried. These include main corneal incision-placement on the steep axis of the cornea, single or paired peripheral corneal relaxing incisions (PCRIs) and/or toric IOL implantation. Corneal incisions do not change the spherical equivalent power of the cornea enough to affect IOL power calculations. Because of the coupling effect, they flatten the meridian where they are placed and steepen the meridian 90° away.

For corneal astigmatism <1 D, placing the main corneal incision on the steep axis could be performed. With 1-1.5 D of astigmatism, peripheral corneal relaxing incisions may be utilized. Toric IOL is used for >1.5 D of astigmatism [58].

On axis corneal incision

A full thickness corneal incision for cataract surgery flattens the cornea in the meridian of the incision and therefore can reduce preexisting astigmatism. The incision is made on the steep axis of astigmatism. This is a good approach for correcting small amounts of against-the-rule astigmatism with a temporal incision.

Peripheral corneal relaxing incisions

Peripheral corneal relaxing incisions (PCRIs) are called limbal relaxing incisions (LRIs) in older literature, but this term is inaccurate because the limbus is not incised. The incisions reduce corneal astigmatism by flattening the cornea in the steep meridian and steepening the cornea in the flat meridian. PCRIs are useful for treating 1-1.5 D of regular corneal astigmatism when implanting non toric IOLs. Beyond 1.5 D, the risks associated with PCRI use begin to outweigh the potential benefits compared with toric IOLs. To achieve consistent incision depth, PCRIs should be performed at the beginning of surgery before altering the intraocular pressure. Unwanted under corrections may occur if relaxing incisions are made after a globe is penetrated [59]. Also, the axis marking should be placed while the patient is in the upright position to prevent axis misalignment due to cyclorotation of the eye in the supine position. An axis misalignment of LRI of just 5° results

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