Ophthalmology® ROUNDS

2014
Volume 10, Issue 6

AS PRESENTED IN THE ROUNDS OF THE DEPARTMENT OF OPHTHALMOLOGY AND VISION SCIENCES, FACULTY OF MEDICINE, UNIVERSITY OF TORONTO

Surgical Correction of Presbyopia: A Focus on New Techniques

By Raymond Stein, MD, FRCSC, and Rebecca Stein, BSc, MBChB (Candidate)

Surgical correction of presbyopia is an area of intense research and development. Although it would be ideal to prevent or reverse hardening of the crystalline lens, this is not currently a viable therapeutic option. In recent years, many different surgical procedures have been developed to allow near vision. This issue of *Ophthalmology Rounds* provides an overview of the procedures and related devices currently in use or in development for the treatment of presbyopia. All refractive and cataract patients should understand the advantages and disadvantages of the various presbyopic procedures. Although technology will continue to advance, there are real clinical benefits to the presbyopic options that can be offered today.

Over the past decade, advances in refractive surgery have significantly improved the treatment of myopia, hyperopia, and astigmatism. Surgical correction of presbyopia is considered the final frontier in the field of refractive surgery. Presbyopia is the gradual reduction in the amplitude of accommodation with aging that has already started by the early teenage years and ends sometime in the sixth decade of life with the complete loss of the ability to change the power of the eye.[1] Remedial action becomes necessary when an individual's near point has receded to an inconvenient distance.

Presbyopia, literally meaning "old eye," is the most common ocular condition in the world. With increasing longevity, most people in the western world will spend almost half their lives as presbyopes. Presbyopia currently affects around 2 billion people worldwide.[2] The first known reference to presbyopia is probably by Aristotle (384-322 BC),[3] who referred to the individual suffering from it as *presbytes* (Greek for "old man"). The basic pathophysiology involved in its development has been a matter of controversy for centuries. The treatment of presbyopia has primarily consisted of reading glasses or contact lenses. However, reading glasses only allow sharp vision at a given distance, and bifocal glasses can be difficult to use because the patient has to rotate the eyes downward instead of rotating the head. Eye care professionals and patients are searching for a safe, effective procedure to replace accommodation thus restoring the full range of vision, typically enjoyed before age 40. In addition to the goal of enhanced distance and near vision, it is important to provide functional intermediate vision. Computers, dashboards, mirrors, deskwork, and everyday facial encounters bring out the value of clear uncorrected intermediate vision.

Currently, all presbyopic nonsurgical and surgical approaches are considered compromises between benefit and adverse effect since there is no causative treatment; ie, restoration of the flexibility of the crystalline lens. It is important to keep in mind that the potential unwanted adverse effects of surgical procedures (eg, reduction in contrast sensitivity or halos at night due to a multifocal implant) must be differentiated from the inherent surgical risk to any procedure (eg, endophthalmitis or cystoid macular edema).

Refractive surgeons now have a number of different surgical modalities from which to choose, including mature technologies like monovision laser-assisted *in situ* keratomileusis (LASIK) or the creation of monovision with an intraocular lens (IOL) implant. In addition, there are corneal inlays, presbyLASIK, intrastromal correction with femtosecond technology, multifocal implants, accommodative implants, and scleral procedures. Developing procedures include photodisruption of the crystalline lens and capsular refilling.

The Underlying Problem

Modern physiological studies confirm Helmholtz's theory that progressive hardening of the crystalline lens is at the root of age-related loss of accommodation.[4] He theorized that when

Ophthalmology & Vision Sciences
UNIVERSITY OF TORONTO

Department of Ophthalmology and Vision Sciences, Faculty of Medicine, University of Toronto,
60 Murray St.
Suite 1-003
Toronto, ON M5G 1X5

The editorial content of *Ophthalmology Rounds* is determined solely by the Department of Ophthalmology and Vision Sciences, Faculty of Medicine, University of Toronto

the eye accommodates, the ciliary muscle contracts, reducing the tension on the zonules that span the circumlental space extending between the ciliary body and the lens equator. This releases the outward-directed equatorial tension on the lens capsule and allows this elastic capsule to contract, causing an increase in the anterior-posterior diameter of the lens and resulting in an increase in its optical power. Many studies based on Helmholtz's theory have attempted to explain the loss of accommodation in the aging eye. Some suggest a loss of zonules or capsule elasticity with aging; thus, when the zonules are relaxed, the lens is unable to change its shape,[5] and reports conflict on whether the ciliary muscle atrophies with age.[6]

The ideal treatment of the crystalline lens's loss of functionality would be either prevention or reversal of the hardening. Unfortunately, we are short of realizing either therapeutic option. Surgical procedures to treat presbyopia have been developed to deal with the sclera, cornea, or lens.

Surgical Corrective Procedures

Scleral procedures

Scleral procedures performed with a blade, laser, and/or insertion of scleral implants are based on expanding the distance between the lens equator and the ciliary muscle, thereby increasing zonular tension;[7] however, the mechanisms underlying this concept have yet to be proven. According to Schachar,[7] growth of the lens without concomitant growth of other ocular structures physically inhibits the movement necessary for accommodation. A sclerotomy, performed with a blade or laser, would give the lens more room for accommodation. However, physiological studies have shown that the lens does not have increased spaced to move and, additionally, does not move equatorially. Some of the early positive results with the scleral expansion procedure may be secondary to induced multifocality, which provided some enhanced near vision. Clinical outcomes with scleral expansion bands have been neither long lasting nor predictable.[8-10] Additionally, potential risks of scleral procedures include the danger of perforation, retinal detachment, choroidal or retinal hemorrhage, and ischemia, and scleral implants increase the risk of infection and may migrate and extrude.

One new laser procedure aims to correct presbyopia by modification of the scleral-ciliary complex. It utilizes an erbium yttrium aluminum garnet laser to ablate at a depth of 90% of the sclera and a width of 600 µm, with the goal to free the ciliary muscle to contract normally.[11] The spots are delivered in a matrix pattern of 9 laser spots into each oblique quadrant. After completion of the microexcisions, a collagen biomatrix filler is applied to fill the excisions to prevent fibrosis and maintain patency of the ablations. Hipsley and colleagues[12] reported restoration of accommodation of 1.25–1.50 D in 135 eyes, which remained stable through 18 months. They also reported that 89% of patients had near uncorrected visual acuity (VA) of J3 or better postoperatively and no significant loss of distance VA. Broader clinical trials are underway to corroborate these early results.

Corneal procedures

PresbyLASIK

There are 2 main approaches to creating corneal multifocality with LASIK. Peripheral presbyLASIK depends on increasing the range of pseudoaccommodation, whereas central presbyLASIK creates a bifocal. Although higher-order aberrations are responsible for decreasing the quality of vision, they can increase the depth of focus to enhance near vision. The amount of aberration that is beneficial appears to vary from patient to patient.

In peripheral presbyLASIK, the depth of focus is increased by the ablation of the peripheral cornea, inducing negative peripheral asphericity. In this procedure, the centre of the cornea is left for distance, whereas the peripheral cornea is for near.[13-15] The presbyopic correction achieved with this ablation profile is significantly influenced by the pupil diameter. If the pupil dilates, as under night conditions, more of the area of the pupil is covered by near correction, and distance vision may be compromised. Conversely, if the pupil becomes miotic, near-vision performance is reduced.

Central presbyLASIK involves the creation of a hyperpositive area for near vision in the central cornea, resulting in a surface which functions similar to a defractive multifocal IOL.[16,17] This type of ablation profile depends on pupil size for the presbyopic correction; pupil constriction enhances near vision at the expense of distance vision. One of the main advantages of this technique is that less tissue must be removed than with the peripheral technique.

Clinical outcomes for peripheral[13-15] and central[16,17] presbyLASIK have demonstrated a high percentage of patients achieving 20/25 distance VA and J2. Further studies are necessary to determine the long-term success of these techniques and to further evaluate the quality of vision under low light and low-contrast conditions.

Corneal inlays

There have been many challenges over the years in the development of corneal inlays. A clinically successful corneal inlay must be thin, have a small diameter, provide adequate nutritional and fluid permeability, and be inserted relatively deeply in the cornea of the nondominant eye under a flap or in a pocket. Impermeable intrastromal inlays can interfere with corneal metabolism and lead to overlying thinning. An adequate supply of glucose from the aqueous humor, anterior to the inlay, is critical to prevent anterior stromal necrosis. Superficial implantation can lead to abrupt surface curvature changes. Inlays also have the potential to be implanted in monofocal pseudophakic patients and post-laser vision correction patients who have become presbyopic.

The benefits of intrastromal corneal inlays for the treatment of presbyopia include potential reversibility, ease of implantation, and the potential advantage to combine them with other refractive procedures to allow the simultaneous correction of distance acuity. Early intrastromal corneal inlays had been complicated by corneal opacification, vascularization, keratolysis, and decentration. Advancements in corneal inlay technology have been

secondary to materials with enhanced biocompatibility, femtosecond lasers that facilitate the creation of intrastromal pockets, and a better understanding of wound healing responses. The success of this technology will depend on long-term studies demonstrating biocompatibility and excellent refractive outcomes. A summary of the details and features of the currently available corneal inlays is presented in Table 1.

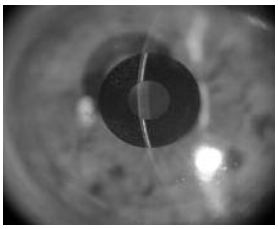
The *Kamra™ corneal inlay* (Figure 1A) is designed to increase the depth of field in the implanted eye. The inlay can enhance near and intermediate vision without a significant impact on distance acuity. Implantation can be combined with an excimer ablation to simultaneously address a refractive error and presbyopia. The inlay is implanted over the line of sight or, in cases in which there is a significant deviation between the line of sight and the centre of the pupil, an intermediate position is defined. Seyeddain et al[18] found that 96.9% of patients (N=32 eyes) could read J3 or better in implanted eyes after 24 months. Yilmaz et al[19] determined that the mean uncorrected near VA (UNVA) improved from J6 preoperatively to J1^{+} 12 months post-implant in 39 presbyopic patients (12 were naturally ametropic and 27 had ametropia from previous hyperopic LASIK). There was no significant change in mean uncorrected distance VA (UDVA) in inlayed eyes. At 4 years,[20] all patients retained a ≥2-line improvement in near vision with no significant loss in distance vision.

The *Raindrop™ corneal inlay* (Figure 1B) is intended to improve near and intermediate vision by changing the curvature of the cornea. The inlay steepens the central cornea for near vision and leaves the curvature of the more peripheral cornea unchanged for intermediate and distance vision. The material has a refractive index and water content similar to that of the human cornea. Distance acuity is minimally affected as light rays paracentral to the 2-mm inlay remain primarily focused on the retina, particularly with a mid-dilated or dilated pupil. Pupil constriction creates a pseudoaccommodative effect utilizing the steep

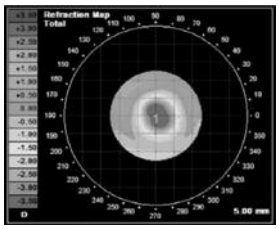
Table 1: Summary of corneal inlays for presbyopia

	Kamra™	Raindrop™	Flexivue Microlens™	Icolens™
Procedure	Modified mono-vision	Modified monovision	Modified monovision	Modifed mono-vision
Principle of action	Increases depth of focus	Steepens anterior corneal curvature	Changes refractive index	Multifocal effect
Surgery	Pocket or flap	Flap	Pocket	Pocket
Stromal depth (µm)	200	120	280–300	280–300
Inlay thickness (µm)	10	25	15–20	15
Diameter (mm)	3.8	2	3.2	3.0 m
Transparency	No	Yes	Yes	Yes

Figures 1A,B: Corneal inlays.



1A. Kamra® inlay: small aperture corneal inlay enhances the depth of focus similar to a fixed aperture camera.



1B. Raindrop® inlay: 2-mm transparent corneal inlay increases the central corneal power to allow near vision.

and central cornea to focus light rays for near. Six-month data in 30 emmetropic presbyopes from Slade et al[21] showed that mean UNVA of the treated eye was 20/25 and J1, corresponding to 4 lines of improvement. Uncorrected intermediate VA (UIVA) in the treated eye improved to 20/25; ie, 2 lines of improvement. No patient lost ≥2 lines of corrected near or distance VA. In a previous animal study,[22] the implanted eyes remained clear and free from reaction to the corneal inlay. Corneas were clear upon slit lamp examination at 1 year and histology data suggested that the inlay appeared to be inert.

The *FlexiVue Microlens™* is the only inlay that uses a refractive add power. The lens is made of a hydrophilic polymer, and it is available in +1.5 to +3.5 D refractive powers. In a study by Bouzoukis et al[23] of 43 patients with a mean preoperative UDVA of 20/20 and mean UNVA of 20/50, all patients had an increase in UNVA after 1 week. By 1 year 98% of patients had an UNVA of J2 or better, while UDVA was ≥20/40 in 93% of operated eyes.

The *Icolens™* is the newest corneal inlay in development and is designed to create a multifocal effect using a hydrophilic acrylic hydrogel. This lens combines a neutral central zone with a peripheral optical zone of 3 D. Similar to a multifocal intraocular lens, this bifocal inlay delivers 2 simultaneous images onto the retina. The peripheral positive refractive power of the inlay provides near vision. In a study by Kohnen and O'Keefe,[24] 60% of 52 implants gained ≥2 lines in near VA and 34% gained ≥3 lines. More than half (52%) of patients had no change in UDVA, 30% lost 1–2 lines, and no patient lost more >2 lines. No corneal complications or adverse events occurred. Further clinical results will be documented to determine the long-term patient satisfaction and safety level.

Corneal intrastromal femtosecond laser treatment (Intracor® procedure)

The Intracor® procedure uses a femtosecond laser to create 5 concentric rings within the stroma to induce central corneal steepening in the correction of presbyopia. There are no incisions in the epithelium or Bowman layer. The procedure takes approximately 15–20 seconds and starts in the center with a ring diameter of 1.8 mm with subsequent rings moving towards the periphery. The formation of these intrastromal rings produces a localized biomechanical change that reshapes the cornea to enhance near vision.[25,26] The procedure is typically

performed in the nondominant eye. Immediately following the procedure the intrastromal rings are clearly visible with slit lamp examination, secondary to the cavitation gas bubbles from photo disruption. These gas bubbles disappear after a few hours and the rings are barely visible within a few weeks.

This intrastromal femtosecond laser treatment was first described in 2009 by Ruiz and colleagues,[26] who reported that all 83 eyes studied had improved UNVA with minimal or no change in UDVA at 6 months postoperatively. At 12 months, 22 eyes had an UNVA of J1. Two eyes lost 2 lines of corrected distance VA at 6 months; neither was among the 22 eyes with 12-month near VA improvement. A study by Holzer et al[27] (N=58 patients) found that UNVA improved by a mean of 4 lines after 1 year. Eighteen-month data of 25 patients showed that both the median gain of 5 lines of near vision and corneal steepening remained stable.[28] Intrastromal femtosecond laser treatment has also been associated with significant adverse effects; Holzer et al[28] observed that 7.1% of their subjects lost ≥2 lines of distance best-corrected (BC) VA, 11.5% lost ≥2 lines of near BCVA, and 19.6% were not satisfied with the result at 12 months. This loss of distance BCVA is of particular concern, and long-term data on this procedure are required to identify the risk of refractive instability, as well as the potential reduction in contrast sensitivity and increased night vision disturbances.

Monovision

Classic monovision

Monovision is a well-established procedure in refractive surgery. The technique, in which the dominant eye is corrected for far vision while the nondominant eye is corrected for near vision, represents the earliest surgical attempt to deal with presbyopia. Monovision can be achieved by either corneal refractive surgery (LASIK or photorefractive keratectomy monovision) or by a monofocal implant. Prior to monovision surgery, a preoperative spectacle or contact lens trial should be implemented to ensure that anisometropia could be tolerated. The success rate in pseudophakic patients is relatively high, varying from 64% to 100%.[29] The main difficulties with the monovision technique are related to reduce stereopsis due to anisometropia, and blurred vision during night driving. A pair of glasses for night driving is helpful to allow improved visual function. The limitations include loss of fusion due to anisometropia between the 2 eyes, poor intermediate vision, reduced binocular contrast sensitivity, and reduced stereoacuity. However, recent studies have demonstrated that many of these limitations can be avoided by limiting the anisometropia to 1.25 D or 1.5 D.[29,30] It is of interest that monovision induced by refractive surgery can be tolerated by a higher portion of patients (92%) than monovision induced by contact lenses (60%).[31] It is unclear whether this may be related to problems with contact lens wear and tolerance.

Laser blended vision

Laser blended vision combines elements of monovision with increases in the depth of field by augmentation of the spherical aberration. A sophisticated excimer laser ablation profile is used to induce spherical aberration within a certain range to mitigate adversely affecting contrast sensitivity and quality of vision. The technique has demonstrated satisfactory binocular fusion and functional stereoacuity compared to classic or traditional monovision.[32,33] Reinstein et al[34] demonstrated that 94% of myopes, 80% of hyperopes, and 92% of emmetropes see 20/25 and J2.

Intraocular procedures

IOL technology continues to advance with the development of multifocal and accommodating lenses (Table 2). Each IOL design has clear advantages and disadvantages. Preoperative assessment of the patient's personality and needs is critical to determine the success with IOL technology for presbyopia.

Multifocal IOLs

Multifocal presbyopia-correcting IOLs have demonstrated a number of benefits, including spectacle independence, good near and improved intermediate acuity, depth of field, easy implantation, long-term capsular bag stability, and improvement of the symptoms of glare and halos with neuroadaptation. Potential adverse effects include limited intermediate vision, reduced contrast sensitivity compared to accommodating and monofocal lenses, and dysphotopic phenomena, such as glare, halos, and problems with night vision.[35-40] In several studies, more than 90% of patients would choose to have the same IOL implanted again. For dissatisfied patients, the cause could typically be identified and corrected in most cases. Compared to accommodative IOLs, reduced contrast sensitivity may limit multifocal

Table 2: Multifocal and accommodating intraocular lenses in Canada

	Type	Regulatory status in Canada	Contrast sensitivity
AcrySof® ReSTOR® +3.0 D +2.5 D	Multifocal – apodized	Approved	 Decrease Decrease
Tecnis® Multifocal	Multifocal – nonapodized	Approved	Decrease
AT LISA® 809	Multifocal – nonapodized	Special access	Decrease
Lentis® Mplus +3.0 D +1.5 D	Asymmetric multifocal	Approved	 Slight decrease No effect
FineVision	Asymmetric multifocal	Special access	Slight decrease
Crystalens®	Accommodating	Approved	No effect
Synchrony®	Accommodating	Special access	No effect
FluidVision®	Accommodating	Research stage	No effect
Sapphire AutoFocal®	Accommodating	Research stage	No effect

IOLs in some patients who perform low-light activities. Glare and halos may be less prevalent with the newer aspheric designs.

Multifocal IOLs are designed to have multiple focal points, which create multiple images at different focal lengths. Patients tend to perceive only the focused image of interest. Multifocal IOLs can be divided into refractive and defractive lenses. Multifocal implants should be discouraged in patients who have epithelial basement membrane dystrophy and any macular disease, such as age-related macular degeneration or epiretinal membrane. High hyperopes might face difficulties due to the large positive angle kappa that can result in multifocal intolerance. Patients receiving multifocal implants must be aware that neuroadaptation to the newly created vision might take up to 6 months.

Defractive multifocal IOLs utilize defractive zones, or microscopic steps across the lens surface.[41] As light encounters these steps, it is directed toward near and distance focal points. The amount of light directed to the near focal point is directly related to the step height, as a proportion of wavelength; at a step height of 1 wavelength, all light will be directed to the near focal point, and a step height that is a smaller proportion of the wavelength would direct more light particles to the distance focal point. This underlying principle is important in understanding the design differences of the 2 types of defractive multifocal IOLs: apodized and nonapodized.

An apodized lens has a gradual reduction in defractive step heights from the centre to the periphery.[42,43] As a consequence, as pupil size increases, more defractive zones with smaller step heights are exposed and direct a larger portion of light rays to the distant focal points. In theory, this design allows enhanced distance vision in low light situations, such as driving at night. The AcrySof® ReSTOR® implant has an apodized defractive optic zone centrally and a refractive peripheral zone (Figure 2A). This regional zone difference favours distance vision under mesopic conditions. The ReSTOR lens is available in a +3.0 model, which provides +2.25 to +2.50 D at the spectacle plane, and +2.5 model, which provides +1.75 to +2.25 D at the spectacle plane. The +2.5 model distributes more light for distance vision, has fewer diffractive zones, a larger central refractive zone, and a focal point that is about 0.50 D further out than the +3.0 model. Since visual function depends on pupil size for both implants, satisfactory reading requires sufficient light to produce a relatively small pupil. Fernández-Vega et al[44] found that UDVA was ≥20/25 in 224 myopic and hyperopic eyes (mean spherical equivalent -6.0 D and +3.9 D, respectively) 6 months after ReSTOR implantation. No myopic eye lost ≥2 lines of distance BCVA, 10 eyes gained 1 line, and 10 gained ≥2 lines. In the hyperopic group, 20 eyes gained 1 line and 15 eyes gained ≥2 lines. No eye lost >2 lines of near BCVA, 1-2 lines were lost by 10 myopic and 8 hyperopic eyes, 15 myopic eyes and 20 hyperopic eyes gained 1 line, and 5 and 16 eyes, respectively, gained 2 lines.

Nonapodized defractive IOLs are designed with defractive steps that have a uniform height from the periphery to the center, which results in an equal amount of light to near and distance foci for all pupil diameters.[42] The 2

Figures 2A,B: Multifocal IOLs

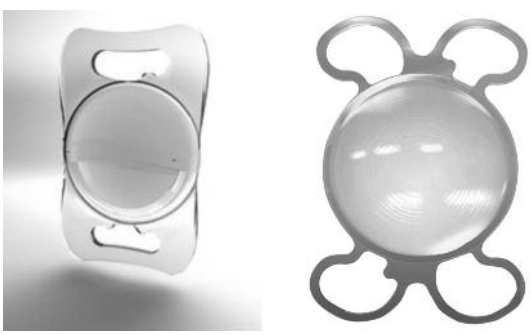
2A. AcrySof® ReSTOR® +3.0 D: apodized diffractive multifocal design

2B. Tecnis®: nonapodized diffractive multifocal design

examples of nonapodized multifocal IOLs are the Tecnis® multifocal IOL (Figure 2B) and the AT LISA® 809 IOL. Unlike ReSTOR, the Tecnis multifocal features nonapodized defractive steps on the posterior surface of the lens.[45] Implantation of Tecnis was associated with an UNVA of J1 in 93.7% of 2500 eyes and J2 in 98%.[46] Eighty-five percent of eyes achieved an UDVA of ≥20/30. The AT LISA 809 IOL, although nonapodized, directs light asymmetrically to the 2 focal points, in favour of distance vision. In a study of 45 eyes into which the AT LISA was implanted, the mean UDVA was 0.04±0.15 logMAR and 98% of eyes reached a UDVA of ≥20/40.[47] The mean UNVA and UIVA were 0.20±0.16 logMAR and 0.40±0.16 logMAR, respectively.

Rotationally asymmetric multifocal IOLs. Unlike the refractive and defractive IOLs, which are designed with rotational symmetry, a new category of IOLs utilize the concept of rotational asymmetry.[48] One such lens – the Lentis® Mplus (Figure 3A) – consists of a near section add that makes the IOL independent of pupil sizes >2 mm. It is a single-piece square-edge implant composed of hydrophilic material and is available with a +3.0 D or +1.5 D add. In a study by Venter et al[49] involving 9366 eyes (4683 patients), a binocular UDVA of ≥20/25 was achieved by 95% of eyes at 3 months. Mean binocular UNVA at 3 and 6 months were 0.155±0.144 logMAR and

Figures 3A,B: Rotationally asymmetric multifocal IOLs



3A. Lentis® Mplus +3.0 D: a rotational asymmetric bifocal design

3B. FineVision®: a rotational asymmetric trifocal design

0.159±0.143 logMAR, respectively. Patient satisfaction level was very high with 97.5% willing to recommend the procedure. Another design with rotational asymmetry the FineVision® IOL (Figure 3B); it is a trifocal design that combines 2 defractive profiles,[50] 1 for distance and intermediate vision and 1 for distance and near vision. Alió et al[51] found mean UDVA, UNVA, and UIVA of 0.18±0.13 logMAR, 0.26±0.15 logMAR, and 0.20±0.11 logMAR, respectively, in 40 eyes of 20 patients with bilateral cataracts. Monocular contrast sensitivity under scotopic conditions was within the normal range for a population older than 60 years.

Accommodating IOLs

There are 2 designs of accommodating IOLs: a single optic and a dual optic system. Single optic accommodative IOLs alter the focal length of the IOL-eye optical system, based on the anterior movement of the lens and changes in lens architecture. The dual optic accommodating IOL is designed based on the concept of not only axial movement, but on modifying the power of the implant, which changes in position.

The Crystalens® accommodating IOL, a single-optic lens, has hinges across the plate-like haptic that facilitate anterior movement of the lens. Clinical outcomes of the single optic lens have demonstrated that 88.4% of patients have achieved ≥20/40 for distance, intermediate, and near vision compared with 35.9% using the standard IOL.[52] It has been suggested that one mechanism to account for the observed accommodation or pseudoaccommodation is flexing of the optic itself, as is seen during accommodation of the natural crystalline lens.[53]

A dual-optic accommodating IOL uses 1 lens each of high and negative power, typically placed anteriorly and posteriorly, respectively.[54] An example is the Synchrony® IOL (Figure 4), whose front (+32.0 D) and posterior (variable negative power) optics are connected by spring haptics. Clinical trials have demonstrated a mean accommodative range of 3.22 ± 0.88 D.[55] This lens requires a 3.7-mm incision that can induce postoperative astigmatism.

A few new accommodative implants are currently under development. The FluidVision® lens relies on liquid to make accommodative changes. By virtue of the natural human physiological contraction and relaxation of the ciliary muscle, the fluid internal to the implant allows changes in shape like a pliable crystalline lens prior to the onset of presbyopia. The implant is acrylic and is filled with silicone oil. As the ciliary body muscle contracts and relaxes, forces are conveyed through the zonules and the capsule to the implant and the fluid in the haptics is pushed into the optic causing the anterior curvature of the optic to increase. A nonfoldable prototype of the lens was implanted in 14 sighted eyes in 2010, and an average of 5 D of accommodative amplitude was documented.[56] Another prototype implant, the electroactive Sapphire AutoFocal®, is an electromechanical lens equipped with a microscopic battery that stimulates shape change in the optic upon sensation of accommodation.[57] As the pupil changes size and becomes smaller, the liquid crystals inside the lens are stimulated by electromechanical impulses, resulting in a change in the refractive lens to provide 3 D of reading. This implant does not rely on the muscles in the eye functioning and capsular bag contraction or hardening to be effective.

Femtosecond laser photodisruption of the crystalline lens

Femtosecond laser technology is revolutionizing ophthalmic surgery by its capability to provide ultrashort laser pulses to a focal point without interacting with the surrounding transparent ocular tissues or causing collateral damage. This laser has the potential to treat the crystalline lens precisely and noninvasively, potentially restoring elasticity to the lens (Figure 5). The idea of enhancing accommodation with a femtosecond laser to soften a hard nucleus was first introduced in 1998.[58] The cutting inside the lens could be achieved by photodisruption, whereby localized laser-induced plasma is formed, followed by a shockwave and a cavitation bubble. The idea was to increase the flexibility of the lens and hence restore accommodative amplitude. A 2011 clinical study and 2-year follow up showed <1.0 D of accommodation.[59] This minimal average change suggests that further investigation is required to determine the ideal laser spot pattern. The outcomes of studies with refined algorithms are anticipated in the near future.

Figure 4: Dual optic accommodation IOL: 2 implants connected by spring haptics

Figure 5: Laser disruption of the crystalline lens. A femtosecond laser is used to cut crystalline lens fibres to enhance accommodation.

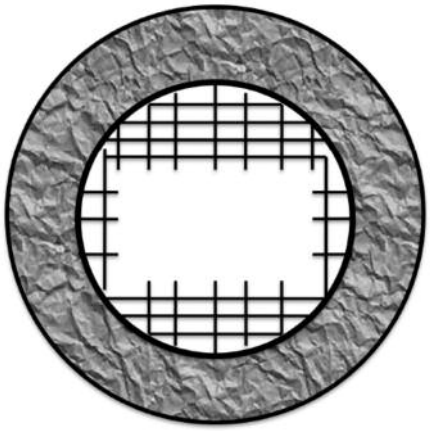
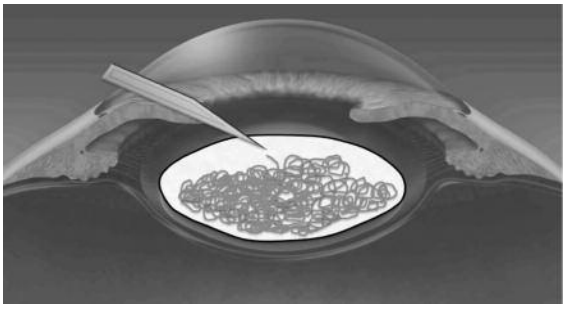


Figure 6: Lens refilling procedure: an attempt to replace the capsular bag contents with a substance to enhance accommodation.



Lens refilling

As hypothesized by Kessler in 1964,[60] an ideal option to restore accommodation would be a lens refilling procedure (Figure 6). An injectable material would replace the nucleus and cortex of the crystalline lens in the presence of a functioning ciliary muscle and capsular and zonular integrity. This procedure would create an ametropic eye, result in increasing accommodative amplitude and be viable for several decades. The refilled capsule would have the potential to restore accommodation by mimicking the mechanical properties of the youthful natural lens. Kessler's exploratory studies with beef lenses showed that the accommodative amplitude decreases significantly with capsule fibrosis, suggesting that capsule elasticity is critical in the accommodative mechanism.[60] It also has been demonstrated that the volume of the injected material is important to determine the postoperative refraction.[61] *In vivo* animal lens refilling studies the development of capsular fibrosis was seen as a major obstacle.[62] Furthermore, success of surgical attempts to eradicate regeneration of equatorial lens epithelial cells was limited. Thus, lens refilling techniques are unproven to date for the long-term restoration of accommodation.

Summary

The prevention or reversal of hardening of the crystalline lens would be an ideal approach to maintain or restore accommodation. Unfortunately, this is not a viable therapeutic option at present. Many different surgical procedures have been developed in recent years to improve near vision. These procedures include surgery on the sclera, the cornea, or the crystalline lens. The most common surgical options include monovision LASIK, monovision lens exchange, corneal inlays, presbyLASIK, and multifocal or accommodative lens implants. All refractive and cataract patients should understand the advantages and disadvantages of the various presbyopic procedures.

***Dr. Stein** is Medical Director of the Bochner Eye Institute, Cornea and Refractive Surgery Specialist, Mount Sinai Hospital, and Associate Professor, Department of Ophthalmology and Vision Sciences, University of Toronto, Ontario. **Ms. Stein** completed a BSc Honours (Medicine), Bute Medical School, University of St. Andrews, Scotland, United Kingdom, and is completing her medical degree at the University of Manchester, United Kingdom.*

References

1. Duane A. Normal values of the accommodation at all ages. *JAMA*. 1912;59:1010-1013.
2. Fricke TR, Wilson D, Holden BA. Demographics: vision impairment due to uncorrected presbyopia. In: Palikaris I, Plainis S, Charman WN, eds. *Presbyopia: Origins, Effects and Treatment*. Thorofare (NJ): Slack; 2012. Chapter 1, pp. 3-9.
3. Aristotle. *Problems*. Cambridge (MA): Harvard University Press; 1957.
4. Hartridge H. Helmholtz's theory of accommodation. *Br J Ophthalmol*. 1925;9(10):521-523.
5. Brown N. The change in shape and internal form of the lens of the eye on accommodation. *Exp Eye Res*. 1973;15(4):441-459.
6. Fisher RF. The force of contraction of the human ciliary muscle during accommodation. *J Physiol*. 1977;270(1):51-74.
7. Schachar RA. Theoretical basis for the scleral expansion band procedure for surgical reversal of presbyopia [SRP]. *Compr Ther*. 2001; 27(1):39-46.
8. Mathews S. Scleral expansion surgery does not restore accommodation in human presbyopia. *Ophthalmology*. 1999;106(5):873-877.
9. Malecaze FJ, Gazagne CS, Tarroux MC, Gorrand JM. Scleral expansion bands for presbyopia. *Ophthalmology*. 2001;108(12):2165-2171.
10. Qazi MA, Pepose JS, Shuster JJ. Implantation of sclera expansion band segments for the treatment of presbyopia. *Am J Ophthalmol*. 2002; 134(6):808-815.
11. Hipsley AM, inventor; ACE VISION GROUP INC, assignee. System and Method for Treating Connective Tissue United States patent US 7,871,404. Jan 18, 2011.
12. Hipsley AM. Laser ACE procedure for presbyopia. Paper presented at the American Society of Cataract and Refractive Surgery (ASCRS) Symposium on Cataract, IOL and Refractive Surgery. San Diego (CA): March 27, 2011.
13. El Danasoury AM, Gamaly TO, Hantera M. Multizone LASIK with peripheral near zone for correction of presbyopia in myopic and hyperopic eyes: 1-year results. *J Refract Surg*. 2009;25(3):296-305.
14. Telandro A. The pseudoaccommodative cornea multifocal ablation with a center-distance pattern: a review. *J Refract Surg*. 2009;25(1 Suppl):S156-S159.
15. Pinelli R, Ortiz D, Simonetto A, Bacchi C, Sala E, Alio JL. Correction of presbyopia in hyperopia with a center-distance, paracentral-near technique using the Technolas 217z platform. *J Refract Surg*. 2008; 24(5):494-500.
16. Jackson WB, Tuan KM, Mintsioulis G. Aspheric wavefront-guided LASIK to treat hyperopic presbyopia: 12-month results with the VISX platform. *J Refract Surg*. 2011;27(7):519-529.
17. Jung SW, Kim MJ, Park SH, Joo CK. Multifocal corneal ablation for hyperopic presbyopes. *J Refract Surg*. 2008;24(9):903-910.
18. Seyeddain O, Riha W, Hohensinn M, Nix G, Dexl AK, Grabner G. Refractive surgical correction of presbyopia with the AcuFocus small aperture corneal inlay: two-year follow-up. *J Refract Surg*. 2010; 26(10):707-715.
19. Yilmaz OF, Bayraktar S, Agca A, Yilmaz B, McDonald MB, van de Pol C. Intracorneal inlay for the surgical correction of presbyopia. *J Cataract Refract Surg*. 2008;34(11):1921-1927.
20. Yilmaz OF, Alagoz N, Pekel G, et al. Intracorneal inlay to correct presbyopia: long term results. *J Cataract Refract Surg*. 2011;37(7):1275-1281.
21. Slade ST. Early results using the PresbyLens corneal inlay to improve near and intermediate vision in emmetropic presbyopes. Paper presented at the XXVIII Congress of the European Society of Cataract & Refractive Surgery. Paris (France): September 4-8, 2010.
22. Sharma GD, Porter T, Holliday K, et al. Sustainability and biocompatibility of the PresbyLens® corneal inlay for the correction of presbyopia. Presented at ARVO 2010. Fort Lauderdale (FL):May 2, 2010. Poster D1015.
23. Bouzoukis DI, Kymionis GD, Panagopoulou SI, et al. Visual outcomes and safety of a small diameter intrastromal refractive inlay for the corneal compensation of presbyopia. *J Refract Surg*. 2012;28(3):168-173.
24. Kohnen T, O'Keefe M. ICOLENS for presbyopia. Paper presented at the American Academy of Ophthalmology 2012 Annual Meeting. Chicago (IL): November 10, 2012.

25. Guedj T, Danan A, Lebuisson DA. In-vivo architectural analysis of intrastromal incisions after INTRACOR surgery using Fourier-domain OCT and Scheimpflug imaging. *J Emmetropia.* 2011;2(2):85-91.
26. Ruiz LA, Cepeda LM, Fuentes VC. Intrastromal correction of presbyopia using a femtosecond laser system. *J Refract Surg.* 2009;25(10): 847-854.
27. Holzer MP, Knorz MC, Tomalla M, Neuhann TM, Auffarh GU. Intrastromal femtosecond laser presbyopia correction: 1-year results of a multicenter study. *J Refract Surg.* 2012;28(3):182-188.
28. Menassa N, Fitting A, Auffarth GU, Holzer MP. Visual outcomes and corneal changes after intrastromal femtosecond laser correction of presbyopia. *J Cataract Refract Surg.* 2012;38(5):765-773.
29. Jain S, Arora I, Azar DT. Success of monovision in presbyopes: review of the literature and potential applications to refractive surgery. *Surv Ophthalmol.* 1996;40(6):491-499.
30. Wright KW, Guemes A, Kapadis MS. Binocular function and patient satisfaction after monovision induced by myopic photorefractive keratectomy. *J Cataract Refract Surg.* 1999;25(2):177-182.
31. Cox C, Krueger R. Monovision with laser correction. *Ophthalmol Clin North Am.* 2006;19(1):71-75.
32. Reinstein DZ, Archer TJ, Gobbe M. LASIK for myopic astigmatism and presbyopia using non-linear aspheric micro-monovision with the Carl Zeiss Meditec MEL 80 platform. *J Refract Surg.* 2011;27(1):23-37.
33. Reinstein DZ, Couch DG, Archer TJ. LASIK for hyperopc astigmatism and presbyopia using micro-monovision with the Carl Zeiss Meditec MEL 80 platform. *J Refract Surg.* 2009;25(1):37-58.
34. Reinstein DZ, Archer TJ, Gobbe M. Aspheric ablation profile for presbyopic corneal treatment using the MEL 80 and CRS-Master laser blended vision module. *J Emmetropia.* 2011;2(3):161-175.
35. Keates RH, Pearce JL, Schneider RT. Clinical results of the multifocal lens. *J Cataract Refract Surg.* 1987;13(5):557-560.
36. Lindstrom RL. Food and Drug Administration study update. One-year results from 671 patients with the 3M multifocal intraocular lens. *Ophthalmology.* 1993;100(1):91-97.
37. Steinert RF, Aker BL, Trentacost DJ, Smith PJ, Tarantino N. A prospective comparative study of the AMO Array zonal-progressive multifocal silicone intraocular lens and a monofocal intraocular lens. *Ophthalmology.* 1999;106(7):1243-1255.
38. Knorz MC. Results of a European multicenter study of the True Vista bifocal intraocular lens. *J Cataract Refract Surg.* 1993;19(5):626-634.
39. Avitabile T, Marano F. Multifocal intra-ocular lenses. *Curr Opin Ophthalmol.* 2001;12(1):12-16.
40. Gimbel HV, Sanders DR, Raanan MG. Visual and refractive results of multifocal intraocular lenses. *Ophthalmology.* 1991;98(6):881-887.
41. Gooi P, Ahmed IK. Review of presbyopic IOLs: multifocal and accommodating IOLs. *Int Ophthalmol Clin.* 2012;52(2):41-50.
42. Davison JA, Simpson MJ. History and development of the apodized diffractive intraocular lens. *J Cataract Refract Surg.* 2006;32(5):849-858.
43. Lane SS, Morris M, Nordan L, Packer M, Tarantino N, Wallace RB 3rd. Multifocal intraocular lenses. *Ophthalmol Clin North Am.* 2006;19(1):89-105.
44. Fernández-Vega L, Alfonso JF, Rodríguez PP, Montés-Micó R. Clear lens extraction with multifocal apodized diffractive intraocular lens implantation. *Ophthalmology.* 2007;114(8):1491-1498.
45. US FDA. TECNIS Multifocal Foldable Silicone and Acrylic Intraocular Lenses P080010. 2009. Available at: http://www.accessdata.fda.gov/cdrh_docs/pdf8/P080010a.pdf. Accessed January 10, 2014.
46. Akaishi L, Vaz R, Vilella G, Garcez RC, Tzelikis PF. Visual performance of Tecnis ZM900 diffractive multifocal IOL after 2500 implants: a 3-year followup. *J Ophthalmol.* 2010;2010. Pii; 717591.
47. Visser N, Nuijts RM, de Vries NE, Bauer NJ. Visual outcomes and patient satisfaction after cataract surgery with toric multifocal intraocular lens implantation. *J Cataract Refract Surg.* 2011;37(11): 2034-2042.
48. McAlinden C, Moore JE. Multifocal intraocular lens with a surface-embedded near section: short-term clinical outcomes. *J Cataract Refract Surg.* 2011;37(3):441-445.
49. Venter JA, Pelouskova M, Collins BM, Schallhorn SC, Hannan SJ. Visual outcomes and patient satisfaction in *9366* eyes using a refractive segmented multifocal intraocular lens. *J Cataract Refract Surg.* 2013;*39*(10):1477-1484.
50. Gatinel D, Pagnoulle C, Houbrechts Y, Gobin L. Design and qualification of a diffractive trifocal optical profile for intraocular lenses. *J Cataract Refract Surg.* 2011;37(11):2060-2067.
51. Alió JL, Montalbán R, Peña-García P, Soria FA, Vega-Estrada A. Visual outcomes of a trifocal aspheric diffractive intraocular lens with microincision cataract surgery. *J Refract Surg.* 2013;*29*(11):756-761.
52. Cumming JS, Colvard DM, Dell SJ, et al. Clinical evaluation of the Crystalens AT-45 accommodating intraocular lens: results of the US Food and Drug Administration clinical trial. *J Cataract Refract Surg.* 2006;32(5):812-825.
53. Cumming JS. Performance of the crystalens. *J Refract Surg.* 2006; 22(7):633-634. Author reply. 634-635.
54. McLeod SD, Portney V, Ting A. A dual optic accommodating foldable intraocular lens. *Br J Ophthalmol.* 2003;87(9):1083-1085.
55. McLeod SD, Vargas LG, Portney V, Ting A. Synchrony dual-optic accommodating intraocular lens. Part 1: optical and biomechanical principles and design considerations. *J Cataract Refract Surg.* 2007; 33(1):37-46.
56. Roux P. Early implantation results of shape-changing accommodating IOL in sighted eyes. Paper presented at the ASCRS Symposium on Cataract, IOL and Refractive Surgery. Boston (MA): April 9-14, 2010.
57. Donnenfeld E. An "autofocal" accommodating IOL. *Cataract and Refractive Surgery Today.* 2013;13:73-76.
58. Myers RL, Krueger RR. Novel approaches to correction of presbyopia with laser modification of the crystalline lens. *J Refract Surg.* 1998; 14(2):136-139.
59. Uy H (unpublished data). 2011.
60. Kessler J. Experiments in refilling the lens. *Arch Ophthalmol.* 1964;71:412-417.
61. Nishi Y, Mireskandari K, Khaw P, Findl O. Lens refilling to restore accommodation. *J Cataract Refract Surg.* 2009;35(2):374-382.
62. Koopmans SA, Terwee T, Glasser A, et al. Accomodative lens refilling in rhesus monkeys. *Invest Ophthalmol Vis Sci.* 2006;47(7):2976-2984.

Disclosure Statement: *The authors have no disclosures to make with regard to the contents of this issue*

Change of address notices and requests for subscriptions for *Ophthalmology Rounds* are to be sent by mail to P.O. Box 310, Station H, Montreal, Quebec H3G 2K8 or by fax to (514) 932-5114 or by e-mail to info@snellmedical.com. Please reference *Ophthalmology Rounds* in your correspondence. Undeliverable copies are to be sent to the address above. Publications Post #40032303

Ophthalmology Rounds is made possible through educational support from

Novartis Pharmaceuticals Canada Inc. and Alcon Canada