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Restoration of accommodation: surgical options for correction of presbyopia

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Accommodation is a dioptric change in the power of the eye to see clearly at near. Ciliary muscle contraction causes a release in zonular tension at the lens equator, which permits the elastic capsule to mould the young lens into an accommodated form. Presbyopia, the gradual age-related loss of accommodation, occurs primarily through a gradual age-related stiffening of the lens. While there are many possible options for relieving the symptoms of presbyopia, only relatively recently has consideration been given to surgical restoration of accommodation to the presbyopic eye. To understand how this might be achieved, it is necessary to understand the accommodative anatomy, the mechanism of accommodation and the causes of presbyopia. A variety of different kinds of surgical procedures has been considered for restoring accommodation to the presbyopic eye, including surgical expansion of the sclera, using femtosecond lasers to treat the lens or with so-called accommodative intraocular lenses (IOLs). Evidence suggests that scleral expansion cannot and does not restore accommodation. Laser treatments of the lens are in their early infancy. Development and testing of accommodative IOLs are proliferating. They are designed to produce a myopic refractive change in the eye in response to ciliary muscle contraction either through a movement of an optic or through a change in surface curvature. Three general design principles are being considered. These are single optic IOLs that rely on a forward shift of the optic, dual optic IOLs that rely on an increased separation between the two optics, or IOLs that permit a change in surface curvature to produce an increase in optical power in response to ciliary muscle contraction. Several of these different IOLs are available and being used clinically, while many are still in research and development.

Key words: accommodation, ageing, intraocular lenses, lens, presbyopia

There is tremendous and growing interest in the prospects for restoring accommodation to the presbyopic eye. Accommodation is defined as a dioptric change in the power of the eye.[1,2] This means that the young eye undergoes a true increase in optical power to focus at near. Restoring accommodation means not simply providing the distance corrected presbyopic eye with functional, static near vision, such as can be achieved with bifocal spectacles, multifocal intraocular lenses or monovision but restoring the true, dynamic and continuous range of focusing ability of the eye. While it is well established that passive optical methods of treating presbyopia, such as monovision, multifocality and bifocal or progressive addition lenses provide functional distance and near vision to presbyopes, these do not restore the active change in power of the eye that occurs during accommodation in the young eye. The optical factors that contribute to functional distance and near

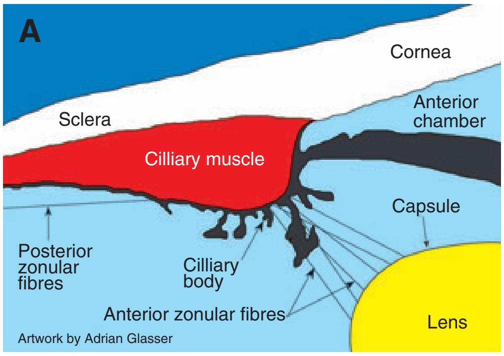


Figure 1A. Schematic diagram of the accommodative structures

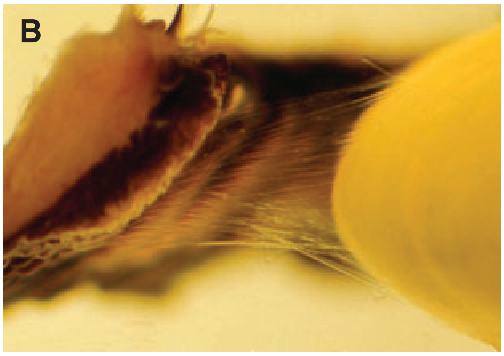


Figure 1B. Photograph of a partially dissected human eye-bank eye showing the accommodative structures (reprinted from Glasser and Campbell[4] with permission from Elsevier)

vision with multifocal intraocular lenses, for example, are described as pseudo-accommodation because they provide functional near vision from a variety of non-accommodative factors. Optical multifocality effectively increases the depth of field of the eye by increasing the range of distances in object space over which the eye cannot perceive a clear change in focus. Multifocal intraocular lenses accomplish this with multiple simultaneous foci for different distances. This results in a compromise to the quality of the near and far images, resulting in a decrease in contrast sensitivity and acuity for all viewing distances. Other factors that can increase the depth of field of the eye include small pupils and optical aberrations, such as spherical aberration or astigmatism. While passive optical factors such as monovision, multifocality, bifocal or progressive addition lenses may be considered as appropriate methods for treating the symptoms of presbyopia, they are very different from restoring the true, dynamic dioptric change in power that occurs during accommodation in a young eye. If it were possible to restore true accommodation to the presbyopic eye, this would provide a range of clear vision such as is available to the young, emmetropic eye and this may become the future mainstay for treating presbyopia.

It is now well established that presbyopia is in large part, if not entirely, due to an increased stiffness of the lens.[3–8] Therefore, the prospects exist for restoring the accommodative capacity to the eye by either restoring the accommodative ability to the presbyopic lens or by replacing the presbyopic lens with an artificial intraocular lens that is capable of producing an optical change in power of the eye.

To understand if accommodation can be restored to the presbyopic eye, it is necessary to understand the accommodative anatomy, the accommodative mechanism, the causes of presbyopia, the accommodation restoration approaches under investigation and how to measure accommodation objectively. These topics will be addressed.

ACCOMMODATIVE ANATOMY

Perhaps the most important accommodative anatomical structure is the ciliary muscle that resides beneath the anterior sclera at the limbal region of the eye, posterior to the scleral spur and anterior to the ora serrata of the retina (Figure 1). The ciliary muscle is composed of muscle fibres of three differing orientations, longitudinal, radial and circular and serves as the engine that drives accommodation. Although fibres of three different orientations can be distinguished microscopically, the entire ciliary muscle is a single functional entity with the muscle fibres contracting as a unit. The ciliary muscle is surrounded on the inner surface by the highly vascularised ciliary body, which provides oxygen and nutrients to the ciliary muscle. The ciliary body is subdivided anatomically into the anterior pars plicata (the ciliary processes) and the posterior pars plana region, which extends to the ora serrata. There are two groups of fine, elastic zonular fibres. The anterior zonular fibres insert into the lens capsule all around the lens equator and they extend across the circumlental space to attach along the walls of the ciliary processes of the anterior ciliary body. The posterior zonular fibres extend from the walls of the ciliary processes of the ciliary body, posteriorly towards the posterior insertion of the ciliary muscle near the ora serrata. The thin elastic capsule surrounding the lens is an important anatomical component of the accommodative apparatus, as is the lens itself. The lens can be broadly differentiated into the inner nucleus and the surrounding cortex.

ACCOMMODATIVE MECHANISM

Accommodation is widely accepted to occur essentially in accordance with the mechanism originally described by Helmholtz (Figure 2).[9–10] Other theories of accommodation have been proposed including those described by Tscherning,[11] the more recent variant of this theory proposed by Schachar[12,13] and

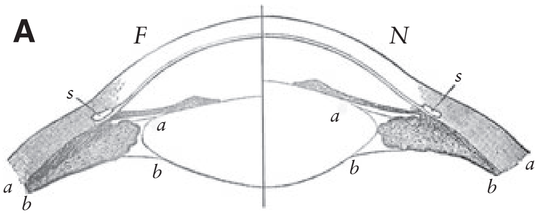


Figure 2A. Schematic diagram of the accommodative mechanism as originally described by Helmholtz who believed the posterior lens surface was stationary during accommodation (reprinted from Helmholtz[9] with permission from The Continuum International Publishing Group)

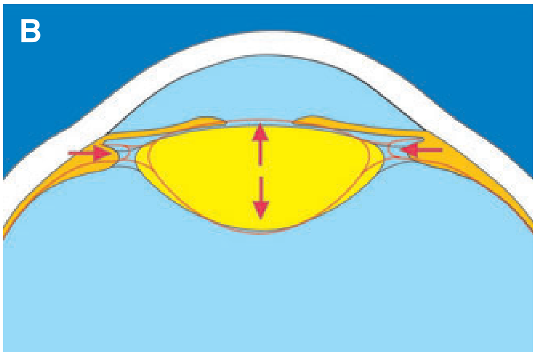


Figure 2B. Schematic diagram showing modification of the Helmholtz theory showing a posterior movement of the posterior lens surface based on recent experimental findings (reprinted with permission from Glasser A. Physiology of accommodation and presbyopia. In: Sher NA, ed. Surgery for Hyperopia. Thorofare: Slack Incorporated, 2004. p 11–21)

Coleman's catenary theory of accommodation.[14–16] Although there has been much recent discussion of these alternative theories, there is considerable credible evidence against them, which supports the Helmholtz theory. These alternative theories of accommodation are addressed where relevant to the discussion of various accommodation restoration concepts. Under the Helmholtz accommodative mechanism, when the eye is at rest and focused for distance, the ciliary muscle is relaxed. Resting tension on the anterior zonular fibres around the lens equator holds the lens in a relatively flattened and unaccommodated state. When the eye makes an effort to focus on a near object, the ciliary muscle contracts. This causes the bulk of the anterior ciliary body to move forward and towards the axis of the eye,[10,17–19] resulting in a release in tension on the zonular fibres around the lens equator. The elastic capsule surrounding the lens is then able to mould the young, soft lens into a more spherical and accommodated form.[4,20–23] For a five dioptre accommodative response, lens equatorial diameter decreases by about 3.5 per cent,[19,24,25] lens thickness increases by about 300 microns, the anterior lens surface moves forwards towards the cornea by about 250 microns and the posterior lens surface moves backward towards the retina by about 50 microns.[26–28] This would result in a net forward movement of the middle of the lens by about 100 microns. Most importantly, for the accommodative increase in power of the eye, the anterior and posterior surfaces of the lens undergo an increase in curvature.[29,30] The increase in surface curvatures causes an increase in optical power of the lens and therefore an increase in power of the eye.

The relaxation of accommodation (also referred to as disaccommodation) takes place when the ciliary muscle contraction ceases. The elasticity of the posterior attachment of the ciliary muscle and the posterior zonular fibres pull the ciliary muscle backward into an unaccommodated configuration. This increases tension on the zonular fibres at the lens equator. The increased tension in the zonular fibres pulls on the equatorial region of the lens capsule to pull the lens into a flattened and unaccommodated state. There is an increase in lens diameter, a decrease in lens thickness and a flattening of the anterior and posterior lens surface curvatures. The lens and eye then undergo a decrease in optical power.

CAUSES OF PRESBYOPIA

Many aspects of the accommodative structures undergo changes with age. This includes a configurational change in the ciliary body,[19,31,32] anterior shift of the zonular insertion onto the lens,[33] changes in thickness and elasticity of the capsule[34–36] and continued growth in size and mass of the lens.[3,37] Of all the documented changes, the most significant change contributing to presbyopia is undoubtedly stiffening of the lens.[3,6–8] Certainly, if no other aspect of the accommodative apparatus changed with age but the lens stiffness increased progressively as it does, this would ultimately lead to a lens that is too stiff to undergo the changes in shape required for accommodation.[3,4] It has also been suggested that lens growth results in an age-related increase in lens equatorial diameter.[38] Studies show that although the lens growth results in an increase in axial thickness, there is no corresponding increase in lens equatorial diameter.[19] Schachar's ill-conceived notion that the lens equatorial diameter grows, comes from a statement in a book chapter that there appears to be an increase in lens equatorial diameter with increasing age.[39] Rafferty[39] cites an original study by Smith,[37] in which lens diameter was measured in isolated lenses from human eye bank eyes. Those original data show an increase in lens diameter as a function of age, however, Smith[37] recognised (as Schachar[38] and Rafferty[39] do not) that the isolated lens diameter does not represent the diameter of the lens in the living eye because, when the zonular fibres are cut and the lenses are removed from the eye, the young lenses undergo an accommodative decrease in lens diameter but the older, presbyopic lenses do not. Therefore, measurements of lens diameter from isolated lenses are from maximally accommodated young lenses and unaccommodated older lenses. These measurements do not reflect the lens diameter in the unaccommodated, living eye and therefore, do not represent growth related changes in lens diameter.[37] In fact, the lens diameters from isolated lenses very closely parallel MRI measurements of accommodated lens diameter in the living eye.[19,37,40]

RESTORATION OF ACCOMMODATION

For accommodation to be restored to the presbyopic eye, it is necessary that the ciliary muscle should still be able to contract with an accommodative effort. It has been suggested that the ciliary muscle may atrophy from disuse but that, if the accommodative ability were restored to the lens, with training the ciliary muscle could regain its contractile strength to again produce accommodation. It is unlikely that the ciliary muscle is quiescent or atrophied in the presbyopic eye. It is well known that the iris continues to contract in response to light, even in a presbyopic eye and that the iris in a presbyopic eye constricts with an effort to accommodate.[41] The ciliary muscle, like the iris, is an intraocular muscle, so if the iris remains functional, so too may the ciliary muscle. The accommodative pupillary constriction and contraction of the ciliary muscle, in conjunction with the convergence response from the two eyes, is known as the accommodative or near triad.[42,43] Accommodation, the accommodative pupil constriction and convergence are neurologically coupled in the brain.[44,45] An effort to accommodate causes all three responses to occur. Stimulating convergence alone also causes activation of the near triade and produces pupil constriction and contraction of the ciliary muscle. Therefore, even in a presbyopic eye, it is unlikely that the ciliary muscle is inactive. Every effort to focus at near would produce a pupillary constriction and may produce a ciliary muscle contraction. Even while wearing near reading spectacles, the act of convergence, which is necessary to maintain single vision on a near object, would be likely to produce a pupil constriction and an accommodative contraction of the ciliary muscle. There are several lines of evidence that suggest that the ciliary muscle does not atrophy with increasing age and does remain functional. There is no age-related loss of contractility of the isolated rhesus monkey ciliary muscle.[46] Similarly, when the presbyopic eye makes an effort to accommodate, the ciliary muscle contracts,[18,19] although the lens shows no accommodative change.[19] Furthermore, the ciliary muscle continues to contract with an accommodative effort even in the pseudophakic eye.[32] The continued contractility of the ciliary muscle in the presbyopic eye is good news for the prospects for restoring accommodation to the presbyopic eye because it means that the engine that drives accommodation continues to remain functional.

Other aspects of the accommodative structures that must remain viable to restore accommodation to the presbyopic eye will depend on how much the restoration relies on these structures. For example, intraocular lenses placed within the capsular bag may use forces from the elasticity of the capsule. Although there are significant age changes in capsular elasticity, some elasticity remains after the age at which accommodation is lost. For low strains relevant to accommodation, Young's modulus of the capsule increases with age until about age 35 and thereafter remains constant.[34–36] Therefore, the capsule may become increasingly effective at producing forces required to produce accommodation in the lens and may even counteract the presbyopic progression to some extent. The elasticity and integrity of the zonular fibres may also be critical to successful restoration of accommodation. Zonular-ciliary body attachment strength may decrease with age.[47,48] The zonular insertion onto the lens equator also changes with age, undergoing an anterior shift on the lens, presumably as the lens capsule shifts around as the lens grows within the capsule.[33] Obviously, such changes in the zonular orientation or elasticity could impact accommodative performance.

While the young phakic eye may have seven to eight dioptres of true accommodation, it should not be necessary to attempt to restore as much as this to the presbyopic eye to achieve successful restoration of accommodation. Certainly, no presbyope would complain at having seven dioptres of accommodation but likewise, most presbyopes would be perfectly content with successful restoration of only three dioptres of true accommodation. With the extra one to two dioptres of pseudo-accommodation afforded by factors, such as the near pupillary constriction, that increase the depth of field of the eye, this would meet the needs of just about all normal everyday near tasks. Therefore, given the apparent viability of the accommodative physiology in the presbyopic eye and the relatively modest and seemingly achievable goals, there would appear to be great hope for the prospects of restoring accommodation to the presbyopic eye.[49]

SCLERAL APPROACHES

Scleral approaches for restoring accommodation are based on ill-conceived, revisionist notions of the mechanisms of accommodation and presbyopia.[38,50,51] Schachar's theory suggests that accommodation occurs from an increase in zonular traction at the lens equator to increase lens diameter, rather than from the decrease in zonular traction and a decrease in lens diameter that is widely documented to occur.[10,24,52] Schachar's theory of presbyopia suggests that presbyopia occurs from a progressive growth in the lens equatorial diameter and not from the increase in stiffness of the lens that has been widely documented.[3,6–8] The growth in lens diameter is suggested to result in gradual slackening of the zonular fibres extending from the lens equator to the ciliary body. This slackening of zonular fibres would not permit the required increase in zonular traction during accommodation. Surgical expansion of the sclera is suggested to restore zonular tension thought to be lost with the supposed increased growth of the lens equatorial diameter.

The idea behind the scleral approaches is that radial slits in the sclera (radial sclerotomy) or polymethyl methacrylate (PMMA) scleral expansion bands inserted into four scleral tunnel incisions overlying the ciliary muscle will expand the diameter of the sclera over the ciliary muscle (Figure 3). PresVIEW scleral implants are being manufactured (Refocus Group, Dallas, TX) and information from the company states that Phase III United States Food and Drug Administration clinical trials were started in the United States in August 2005. These clinical trials are ongoing.

As the theoretical mechanisms of accommodation and presbyopia on which the scleral approaches are based are incorrect, it is not surprising that accommodation is not restored with these approaches. Objective measurements of accommodation in scleral expansion band patients show either a complete absence of accommodation or accommodative amplitudes similar to those in age-matched control subjects.[53,54] Subjective measurements of accommodation are suggested to show some short-term improvement as well as an improvement in the contralateral unoperated eye.[55] The improvement in the unoperated eye points to a possible placebo effect. Even results from subjective measurements of accommodation are not uniformly good with some studies reporting effects in only some patients and regression after several months and other studies reporting no benefits.[56,57] These scleral surgical procedures are also prone to complications, such as thin scleral pockets and extrusion of the bands, anterior chamber perforation, ischaemia, scleral thinning and axial myopia.[55,57,58] Disregarding the ill-founded theories of accommodation and presbyopia, on which these scleral approaches may be based, in the face of the clear and pronounced increase in lens stiffness with increasing age, surgical expansion of the sclera cannot restore the accommodative ability to the presbyopic lens and therefore, cannot restore accommodation to the presbyopic eye.

CORNEAL APPROACHES

Many corneal surgical procedures are being used to alleviate the symptoms of presbyopia. These include multifocal corneal refractive surgical procedures (AMO, Santa Ana, CA), monovision through corneal refractive surgery or Near Vision Conductive Keratoplasty (NearVision CK) (Refractec, Irvine, CA) or a pinhole corneal inlay (AcuFocus, Irvine, CA), for example. These all rely on pseudo-accommodation by increasing the depth of field of the eye. None of these corneal procedures and, in fact, no other corneal procedures known to this author, are directed at the active restoration of accommodation. Although the avian eye is known to undergo changes in corneal curvature during accommodation, as a natural part of the accommodative response,[59] the normal changes in corneal curvature that have been documented to occur with accommodation in humans are essentially negligible and serve no functional role in accommodation.[60–62] As the corneal procedures for treating presbyopia are not intended to, nor could they, restore active and dynamic accommodation, they will not be addressed further here. Because changes in corneal curvature are not a natural part of the accommodative response, it seems unlikely that surgical manipulation could induce significant changes in corneal curvature of human eyes to restore accommodation.

LENTICULAR APPROACHES

Pharmacological interventions to ‘soften’ the lens are being discussed and patents for this exist, however, there appear to be no peer-reviewed published papers that address this topic. The concept is that eye drops could be developed that act selectively on the lens to break molecular or cellular bonds that may have formed to stiffen the lens. A conceivable disadvantage of this approach may be the need to apply eye drops for a considerable number of years, possibly before presbyopia begins. As compliance is an issue with many patients for devastating and potentially life-threatening diseases such as tuberculosis, it is hard to imagine patients taking therapeutic eye drops for many years to stave off the progression of something as benign as presbyopia, of which they are not yet aware. Pharmacological interventions, if they are to prove successful, will not only have to effectively soften the lens but will have to do so without inducing lens opacities or other ocular complications. They will also have to do so rapidly or meet the significant compliance challenges.

An alternative approach to restore accommodation to the presbyopic lens is the use of laser energy to ‘treat’ or ‘soften’ the lens. Preliminary studies[63–66] have investigated this approach in living and excised animal and human cadaver lenses. These studies suggest that femtosecond lasering does not produce cataract and can soften the lens and increase the accommodative potential of presbyopic lenses. Future testing will demonstrate if this is feasible for restoring accommodation *in vivo*. Challenges faced by this procedure include the fact that the older, presbyopic lens is larger and thicker than a young lens due to the continued growth and it is not clear that laser-induced mechanical changes would allow this larger lens to undergo accommodative changes. Laser cuts in the lens would be at a multicellular rather than at a single cell or subcellular level and although this may produce mechanically advantageous changes to the lens, it will not do so by reversing the cellular and subcellular changes that result in the age-related stiffening of the lens. Further, studies show that the accommodative changes in curvature in the natural young lens occur due

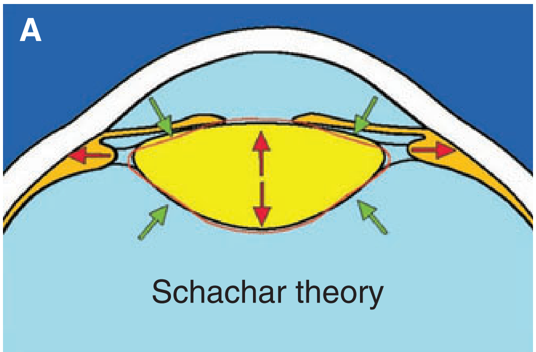


Figure 3A. Schematic diagram showing the Schachar theory of accommodation

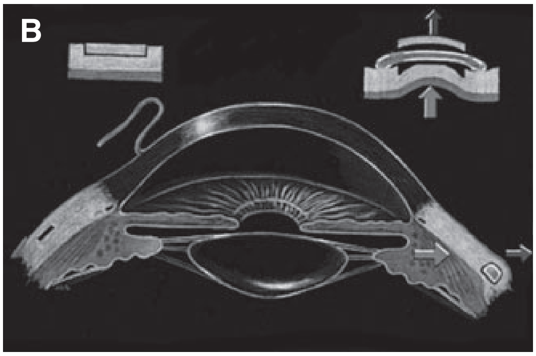
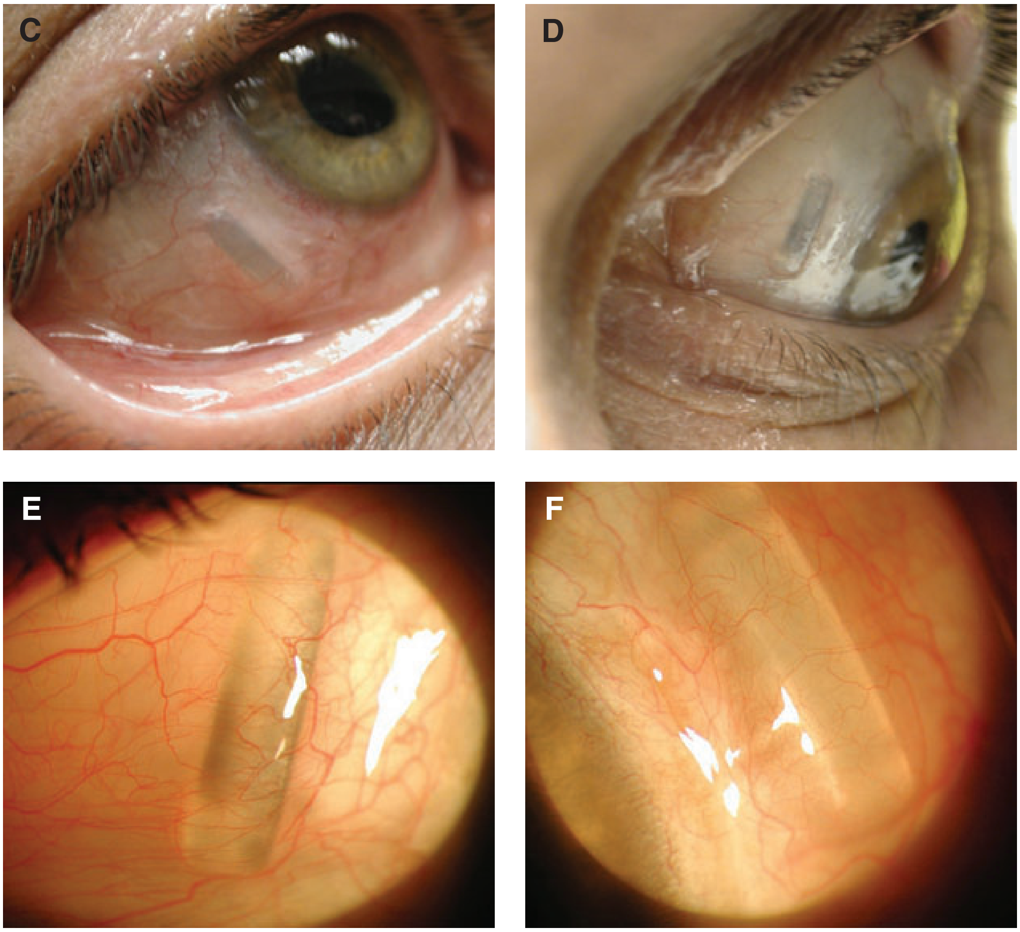


Figure 3B. The scleral expansion band surgical procedure (reprinted from Kleinmann G, Kim HJ, Yee RW. Scleral expansion procedure for the correction of presbyopia. *Int Ophthalmol Clin* 2006; 46: 1–12. With permission from Elsevier.)



Figures 3C, 3D, 3E, 3F. Photographs showing the appearance of scleral expansion bands in the eyes of a patient (reprinted from Ostrin, Kasthurirangan and Glasser[54] with permission from Elsevier)

to an increase in thickness of the nucleus rather that the cortex[67,68] and the aging lens nucleus undergoes a greater increase in stiffness than the cortex.[6,8] Therefore, laser treatments would need to be directed at the lens nucleus for maximum effect but would have to avoid inducing opacities, if vision is to remain uncompromised. If this is achieved, one benefit of laser treatment is that it is non-invasive. Provided the lens capsule is not affected and phakoemulsification can still be performed when required, it is potentially a benign procedure because a cataractous lens would ultimately be removed anyway.

ACCOMMODATING LENS IMPLANTS

It may be possible to restore accommodation to the presbyopic eye by replacing the crystalline lens with an artificial intraocular lens (IOL) that produces an optical change in the eye. Typically, such IOLs would be used in standard cataract surgery, in which a capsulorhexis is made in the anterior capsule and the crystalline lens is removed leaving an empty capsular bag, into which the IOL is placed. These IOLs are designed to use some part of the accommodative physiology, such as ciliary muscle contraction, capsular bag elasticity and/or suggested changes in vitreous cavity pressure to induce a movement or a change in shape of the IOL to produce an optical change in the eye. A variety of different IOLs have been designed that rely on a variety of different mechanisms of action.[49,69–72] The IOLs can be categorised broadly as single optic IOLs that are designed to undergo a forward translation of the optic, dual optic IOLs that are designed to undergo an increased separation of the two optics, or IOLs that are designed to undergo an increase in curvature to produce an optical change in power.

SINGLE OPTIC IOLS

Single optic accommodative IOLs include the HumanOptics AG Akkommodative 1CU accommodative IOL (Erlangen, Germany), the eyeonics Crystalens AT-45 (with a 4.5 mm diameter optic) and the newly released Crystalens AT-50 (with a 5.0 mm diameter optic) (Aliso Viejo, California), the Lenstec Kellan Tetraflex (KH-3500, St. Petersburg, Florida), the Bausch & Lomb OPAL (Rochester, New York), Acuity C-Well accommodative intraocular lens (OrYehuda, Israel), the Morcher BioComFold 43E (Stuttgart, Germany), the AMO/Quest Vision lens (Santa Ana, California).[72–75] Of these, the Crystalens AT-45 and AT-50 are the only accommodative IOLs approved by the FDA for clinical use in the USA. The Lenstec Tetraflex is undergoing US FDA clinical trials. The Morcher BioComFold 43E, the Human Optics 1CU and the Lenstec Tetraflex have been or are being used clinically in Europe. The Bausch & Lomb OPAL, the Acuity C-Well, and the AMO/Quest Vision lens are believed to be in the research and development stage only and may have been used clinically on a limited basis, if at all.

Not all of these IOLs rely on exactly the same mechanism of action to perform their accommodative function. All are designed to be implanted within the capsular bag. The eyeonics Crystalens has hinged plate haptics (Figure 4). It is designed to be implanted in the capsular bag in a posteriorly vaulted position with the optic against the posterior capsule and vitreous face. Initially, the surgical protocol included the need for post-operative cycloplegia to allow the anterior and posterior capsular bag surfaces to fibrose around the haptics and seal the IOL within the fibrotic capsule. The haptic and optic sealed within the fibrotic capsule serves as a single entity diaphragm against the vitreous face. The mechanism of action suggested by the manufacturer is that an accommodative effort causes a bulking up of the ciliary muscle within the vitreous cavity, which increases the vitreous pressure against the posteriorly vaulted optic, causing a temporary forward movement of the optic. The Lenstec Tetraflex is suggested by the manufacturer to work on a similar principle, although not through hinged haptics. The flexible plate haptics are suggested to facilitate a forward movement of the optic within the capsule, also induced through an increase in vitreous chamber pressure during accommodation. The other single optic IOLs, (the Bausch & Lomb OPAL, the HumanOptics 1CU, the Acuity C-Well and the Morcher BioComFold) to the extent that it is known or can be gauged from their designs rely on a decrease in the capsular bag diameter in accordance with the natural accommodative mechanism to produce a lever of fulcrum action of the haptics on the optic to invoke a forward translation of the optic.

The single optic IOLs are designed to rely on a forward translation of the optic or in some cases flexing or bending of the optic with an accommodative effort to induce an increase in power of the eye. If a single optic were translated forward along the optical axis, this would produce an increase in optical power of the eye. Simple schematic eye calculations can provide some indication of the change in ocular power that can be expected from a forward translation of an optic. The overall power of the optic required to achieve an emmetropic eye is dictated by the corneal curvature, the axial length of the eye and the ultimate postoperative position of the IOL in the eye. These will also dictate how much power change can be achieved by a given forward shift. Using a Bennett and Rabbetts schematic eye,[76] one millimetre of forward shift of a one millimetre thick optic could result in 0.8 D of accommodation in a long eye (26.04 mm), 1.3 D in an average eye (24.09 mm) or 1.85 D of accommodation in a short eye (22.04 mm). Therefore, in general, it is theoretically possible for single optic IOLs that rely solely on a forward shift to induce a change in power of the eye of about one dioptre of accommodation.[77–80] A forward movement of an optic by one millimetre would represent an extremely large forward movement relative to the magnitude of the lens movements that occur in the young phakic eye during accommodation. The phakic lens does not rely on forward movement to produce the accommodative change but rather on changes in surface curvature. The natural lens thickness increases only by about 300 µm and there is an approximately 100 µm net forward movement of the natural lens with five dioptres of accommodation.[26–28] The 100 µm for-

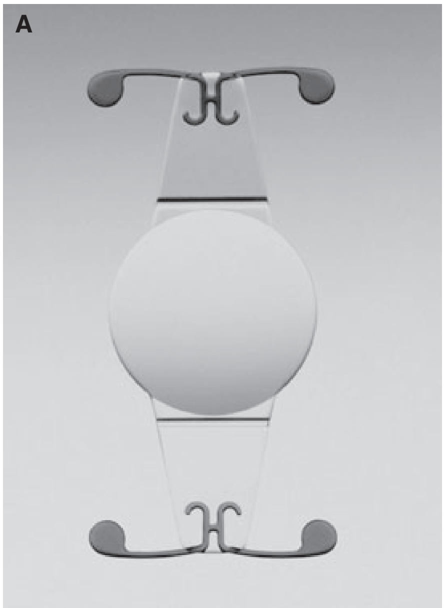
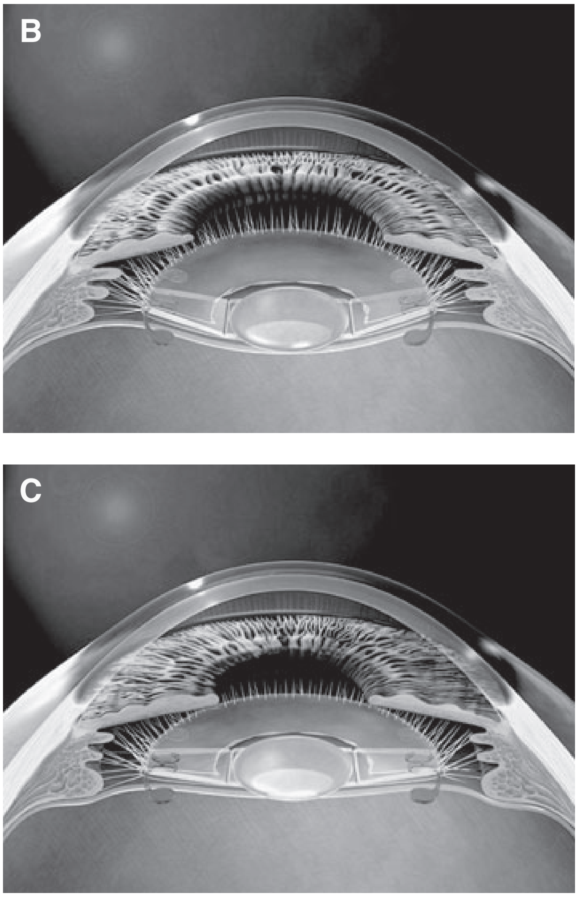


Figure 4A. Photograph of the eyeonics Crystalens AT-45 (reprinted from Cumming JS, Slade SG, Chayet A. Clinical evaluation of the model AT-45 silicone accommodating intraocular lens: results of feasibility and the initial phase of a Food and Drug Administration clinical trial. *Ophthalmology* 2001; 108: 2005–2009. With permission from Elsevier.)



Figures 4B and 4C. Schematic diagrams showing the theory of its function (figures courtesy of eyeonics, inc)

ward movement of the crystalline lens imparts a negligible contribution to the refractive change of the eye. Therefore, given the small magnitude of the accommodative biometric changes in the young phakic lens, it is doubtful that an optic would routinely be likely to move by as much as one millimetre in a pseudophakic eye.[81] Although an average anterior movement of the eyeonics Crystalens from cyclopentolate cycloplegia to pilocarpine stimulated accommodation of 0.84 mm has been reported from 10 eyes,[73] measurements of volitional accommodation suggest about 0.35 mm of forward movement may occur.[82] Other studies with pilocarpine stimulated accommodation have shown posterior optic movements.[83]

A secondary mechanism of action of some of these single optic IOLs is suggested to be a flexing, bending, buckling or arching of the optic, caused either by the vitreous forces or by the haptic forces on the relatively soft optics.[73] Such changes in the optic could result in changes in power or changes in aberrations of the optic. Patients with the eyeonics Crystalens and the Lenstec Tetraflex IOLs have been suggested to benefit from the optical effects caused by such accommodative flexing or arching. If this occurred, it could introduce increased aberrations to the eye, which could have a beneficial effect of increasing the depth of field of the eye and thereby contributing to the pseudo-accommodative effects in addition to any possible power changes or axial translations of the optic that may occur.

For those single optic IOLs that rely on vitreous pressure, it is not clear to what extent the vitreous pressure increases in the pseudophakic eye during accommodation. Coleman's catenary suspension theory of accommodation suggests that an increase in vitreous pressure serves as the primary motivational force to produce accommodative changes in the natural lens.[14–16] The suggestion is that the ciliary body, the zonular fibres and the hyaloid membrane between the vitreous body and the posterior lens surface form a diaphragm or catenary structure that together with the vitreous support, determines the shape of the lens. It is suggested that a contraction of the ciliary muscle causes a pressure differential between the anterior and vitreous chambers that together with the hyaloid membrane catenary structure causes the lens surface curvatures to become more steeply curved. Data exist to suggest that there is a pressure differential between the anterior and vitreous chambers during accommodation in the phakic eye but the empirical data are limited.[15,16,84] It is not clear to what extent the pressure differential may be a cause or a consequence of the accommodative mechanism. The fact that the posterior surface of the natural lens moves posteriorly towards the retina during accommodation[26–28] suggests that the vitreous has little influence on the crystalline lens and that the posterior movement of the posterior lens surface could cause the increase in vitreous pressure. Finite element modelling suggests that a vitreous force is unable to produce the required accommodative changes in the lens.[85] Evidence against a role for the vitreous in accommodation comes from the observation that the accommodative amplitude was the same in the two eyes of a 32-year-old patient in whom the vitreous had been removed from one eye.[86] Further, it is well established from *in vitro* experiments that normal accommodative changes occur in the crystalline lens due to the forces exerted on the lens by the lens capsule, without the vitreous being present,[4,21,23,87] thus rendering it doubtful that the vitreous plays an active role in accommodation of the crystalline lens. It remains unclear if the reported accommodative increase in vitreous pressure in the phakic eye occurs in the pseudophakic eye or if a pressure differential or the vitreous plays a role in producing accommodative changes in IOLs.

Those single optic IOLs that are designed to use the elasticity of the capsular bag to induce an accommodative movement of the optic typically rely on contraction of the elastic capsule and a decrease in equatorial diameter to act on the haptics with a centripetal force. This motivates a forward movement of the optic through lever- or hinge-like action from the haptics. The challenge faced by these IOLs is that the capsular elasticity should remain viable in the presbyopic eye and after a cataract surgical procedure, phakoemulsification and removal of the lens substance. Age-related changes in capsular elasticity and the capsular fibrosis, lens epithelial cellular proliferation and capsular shrinkage that typically occur after cataract surgery may render capsular elastic forces impotent. Further, the equatorial, centripetal elastic force that the equatorial capsule normally exerts to produce accommodation on the crystalline lens, occurs in part because the capsule is distended by the lens substance. A young lens in the living eye is held in a flattened and unaccommodated state by the zonular tension on the lens equator. When the zonular fibres are cut the lens becomes more spherical and assumes a maximally accommodated state due to the elastic forces of the capsule.[22.23] If the capsule is then carefully cut and removed, the isolated lens substance again assumes a more flattened and unaccommodated form.[3,22] The crystalline lens is about 3.5 to 4.0 mm thick and has an equatorial diameter of approximately 9.0 to 9.5 mm.[19] When the lens substance is removed and an IOL one to two millimetres thick is placed inside the capsule, the IOL of diminished volume and axial thickness would cause the capsular diameter to increase to 10 mm or larger. This would result in a loss of the normal unaccommodated resting zonular tension and may completely alter the fine balance of capsular forces that normally serves to cause the lens to become accommodated. IOLs that do not fill the capsule in the same proportions as the crystalline lens may therefore also render impotent the accommodative capsular elastic forces that are required to act on the IOL.

DUAL OPTIC IOLS

The first dual optic IOL was developed in 1990[88] and subsequently implanted into rabbit eyes.[89] The Sarfarazi Elliptical Accommodative IOL[90] and the Synchrony Dual Optic Accommodative IOL (Visiogen, Irvine, CA) have been developed more recently (Figure 5).[91–94] Bausch & Lomb licensed the rights to the Sarfarazi Accommodative IOL in 2003 but it is uncertain if they are continuing to pursue further development. According to Visiogen, the Synchrony IOL received CE mark approval for use in Europe in June 2006 and has been implanted in more than 400 eyes worldwide. Visiogen started Phase III US FDA clinical trials in 2006 and has received approval from the FDA for full expansion of its Phase III US FDA clinical trials with the Synchrony IOL in 2007.

These dual optic IOLs are open chamber IOLs in that they fill the capsular bag but retain a fluid space between the two optics. They have a high positive bi-convex anterior optic (approximately 32 D) and a weaker negative meniscus-concave posterior optic (approximately -12 D) joined by ‘spring haptics’.[90,91,94] They are designed to be used with a standard cataract procedure where the crystalline lens is removed from the capsule via an approximately four millimetre diameter anterior capsulorhexis. The spring haptics are designed to keep the two optics separated and to allow the optics to move with respect to each other from the capsular forces during accommodation. The Synchrony IOL is implanted with a dedicated injector through a 3.6 to 3.8 mm corneal incision and unfolds within the capsule. The IOL is designed to retain the natural dimensions of the capsular bag in terms of axial thickness and equatorial diameter.

Theoretical calculations show that if, in the unaccommodated state, the dual IOL system has an axial thickness of three millimetres with a separation between the optics of 0.5 mm and that with an accommodative change it undergoes an increase in separation of the two optics by one millimetre, this could produce about 2.0 to 2.5 D of accommodation.[90,91,94] The expectation is that in the unaccommodated state the outward directed tension on the capsular bag from the zonular fibres would hold the IOL in the unaccommodated state with a relatively small separation between the two optics. With an accommodative effort, as zonular tension is released, the elasticity of the capsular bag would decrease the equatorial diam-

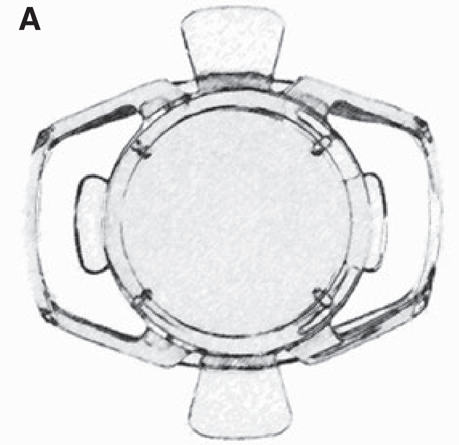


Figure 5A. Diagram Visiogen Synchrony Dual Optic Accommodative IOL (reprinted from McLeod and colleagues[94] with permission from Elsevier)

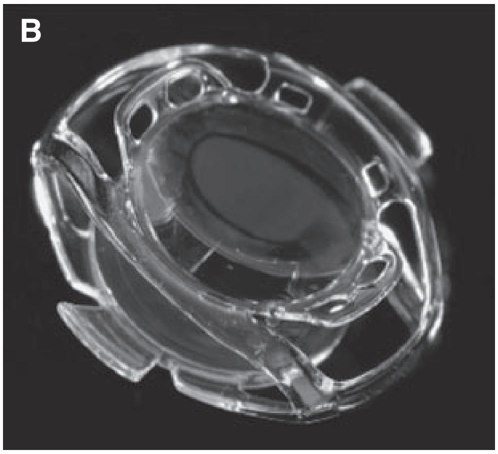


Figure 5B. Photograph of the Visiogen Synchrony Dual Optic Accommodative IOL (reprinted from McLeod and colleagues[94] with permission from Elsevier)

eter of the capsule to act on the spring haptics to increase the separation of the two optics, in particular allowing the anterior optic to translate forward with respect to the stationary posterior optic.[94] Flow of aqueous humour into and out of the capsule is expected with the accommodative action. In the case of the Visiogen Synchrony IOL, provision for this has been made by the inclusion of structures designed to tent the anterior capsule to prevent the anterior capsule from sealing against the anterior optic to facilitate fluid exchange.

As with the single optic IOLs that rely on the elasticity of the capsule to produce the accommodative change, post-operative changes in the capsule caused by fibrosis, lens epithelial cellular proliferation and capsular shrinkage and achieving the correct post-operative refraction may be the most significant challenges. In cases of posterior capsular opacification, YAG laser capsulotomy may be contraindicated with these IOLs that are so reliant on the capsule for their function. They are designed to be unstable and to move with an accommodative effort in response to forces from the capsule. There is some inherent variability in the size of the capsular bag among individuals that is unlikely to be dependent on the axial length or overall power of the eye. Placing a one-size-fits-all IOL into these capsules may result in variations in the separation of the optics, which would result in variability in the resting, unaccommodated refraction. Although the IOL is designed with a range of different powers on the posterior optic to account for these individual needs,[94] it may be a significant clinical challenge to predict the exact distance of separation of the optics in the unaccommodated state within the capsule for each eye. Further, if the capsule undergoes post-operative shrinkage, this could result in changes in unaccommodated refraction and aberrations, such as astigmatism and the accommodative potential. Initial clinical results in 24 eyes show that mean post-operative spherical equivalent was within 0.5 D in 50 per cent of eyes and within 1.00 D in 70 per cent of the eyes at six months.[92,94] Although other one year data were reported, the one year spherical equivalent data were not. It was also suggested that some initial, limited fibrosis and shrinkage of the capsule around the IOL could benefit the mechanical system and aid in keeping the accommodative function stable.[92] Maintaining an opening in the capsular bag, through which the aqueous humour can freely flow, and having an IOL that fills the capsule may help to prevent epithelial cellular proliferation and capsular opacification, fibrosis and shrinkage.[92,95] There is little benefit in an accommodative IOL if a stable refractive state cannot be achieved and maintained or if the IOL fails to undergo accommodative changes. Achieving and maintaining targeted refraction may be as difficult as achieving a lasting accommodative response from these IOLs.

CURVATURE CHANGE IOLS

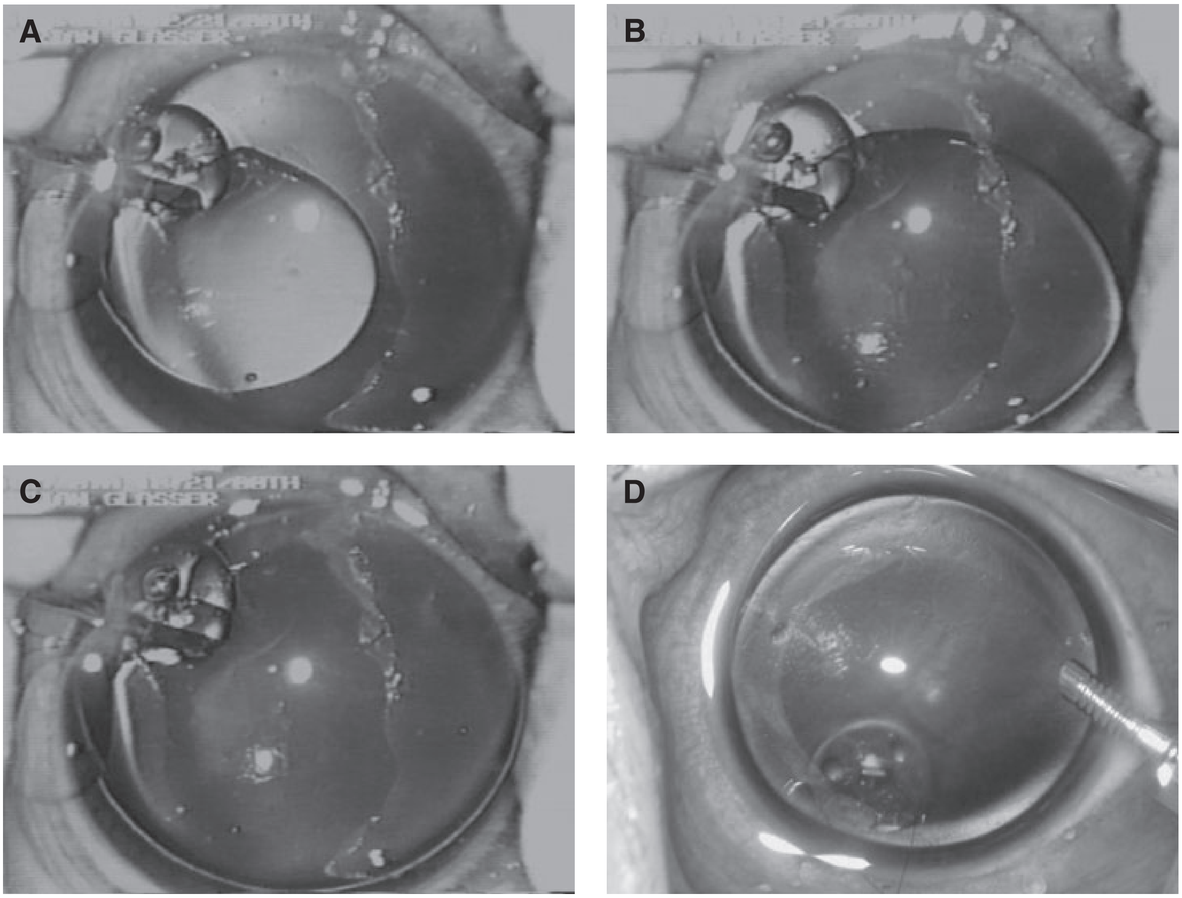
In the crystalline lens, five dioptres of accommodation results in a 300 μm increase in lens thickness[26–28] and a 300 μm decrease in lens diameter.[24] These relatively small physical changes impart a relatively strong change in optical power through an increase in lens surface curvatures. A system that is able to produce a change in surface curvature is extremely efficient as it can produce a relatively large change in optical power with relatively small physical displacements. Accommodative IOLs that are designed to take advantage of the accommodative mechanism to produce a change in surface curvature would therefore, be the most efficient way to produce a change in optical power. Four different designs that rely on change in surface curvature are known to be under development or to have undergone animal testing or limited human clinical trials. For the first two of these designs, no peer-reviewed publications are available.

The PowerVision FluidVision IOL (Belmont, CA) is a fluid-filled, capsule filling device designed with hollow haptics and optics as a fluid reservoir with contiguous fluid channels between the optic and the haptics. It is designed to be implanted within the capsular bag during standard cataract surgery. In the unaccommodated eye, resting tension on the zonular fibres holds the equatorial edge of the capsule, so that there is limited force on the haptics, which remain relatively engorged with fluid. With an accommodative response, the zonular tension is released and the equatorial diameter of the capsule decreases, applying pressure on the haptics. This displaces fluid from the haptics into the optic to cause an increase in volume within the optic and an increase in the anterior surface curvature. Conceptually, filling the capsular bag with such a device is likely to retain the fine balance of forces to permit the capsule to act on the peripheral haptics. Certainly, if sufficient fluid can be displaced from the haptics to the optic, this could produce the curvature change to produce a significant change in power of the optic.

The Medennium SmartLens (Irvine, CA) received attention several years ago but is not known to have been developed further. This soft thermoplastic hydrophobic acrylic lens is moulded into the form of a capsule filling biconvex lens with dimensions similar to the natural human lens. The refractive properties (refractive index, surface curvatures and thickness) could be adjusted, but would be predetermined and the lens moulded. At room temperature, the soft lens can then be squeezed into the shape of a two-millimetre diameter rod. Once chilled, the rod retains this shape. It is injected through a corneal micro-incision into the capsule after standard cataract surgery. During the injection process, the rod is exposed to body temperature and returns to the shape of the original lens in about 30 seconds. The soft lens is designed to fill the capsule and to respond to accommodation and through the capsular forces undergo a decrease in equatorial diameter, an increase in axial thickness and an increase in surface curvature similar to the crystalline lens. Although the surgical technique has been tested successfully in human eye bank eyes, no further information is available regarding the performance of the SmartLens. This is an interesting method to get a full-sized lens into the capsular bag during standard cataract surgery. An apparent advantage of such a lens design may appear to be that the power of the lens can be moulded before the lens is implanted into the capsule. However, if the lens is made of a soft, malleable material, the shape and power of that lens is likely to be altered on insertion into the capsular bag and the change would be dependent on how well the lens is sized for the particular capsule. Further, there is a question of whether such a lens should be formed in the accommodated or unaccommodated state, for the power may change considerably or little when the lens is inserted into the capsule. This may undermine any possible predictability in post-operative refraction that may at first appear to be available from such a premoulded lens.

A third approach that has received attention over many years is injection of a liquid polymer into the capsular bag. Initial studies were conducted more than 20 years ago in rabbit eyes.[96–100] The crystalline lens is removed via a small (one to two millimetre) peripheral capsulorhexis, which is plugged or sealed and a transparent, liquid polymer is injected past the plug to refill the capsule to recreate an optically clear and soft, accommodating lens (Figure 6). Further experimental work has been done in rabbits,[101] primates,[101] dogs,[101] human cadaver eyes, enucleated pig eyes, rabbits and cats[102–104] and in monkey eyes.[105–108] A suggested variant was to refill the capsule with a silicone endocapsular balloon and then inject a silicone polymer into the balloon. This has been performed in rabbits and enucleated pig eyes[109] and in rabbits and primates.[110,111] In many of the live animal studies, it was not possible to follow the post-operative refractive or accommodative outcomes due to post-operative capsular opacification.[105,106] In polymer refilling studies in adolescent, non-presbyopic monkeys with 12 to 15 D of accommodation, only roughly 20 to 40 per cent of the preoperative accommodative response was available after polymer filling.[107,108,111] In the only study conducted in older monkeys, although the accommodative change could not be measured due to capsular opacification, accommodative changes in lens thickness were observed in the refilled lens up to four years post-operatively but not in the presbyopic crystalline lens in one monkey.[106]

Another IOL design that also relies on a change in curvature is the NuLens accommodative intraocular lens (Herzliya Pituah, Israel).[112,113] This is based on the accommodative mechanism in the cormorant eye, where a constriction of the highly muscular iris results in the bulging of the anterior lens surface or anterior lenticonus.[114,115] The NuLens optic has an aperture in a solid, transparent material behind which is a soft gel. A solid base against the posterior surface of the gel completes the piston-like design of this IOL. Applying a pressure behind the piston causes the gel to be pushed through the aperture to give a steepening of the anterior surface curvature (Figure 7). Haptics are attached to this optic to hold the lens in the ciliary sulcus behind the iris. This system does not reside inside the capsule. Once the lens substance is removed from the capsule, the anterior capsule is collapsed against the posterior capsule to form a diaphragm. The lens is then sulcus fixated with this capsular diaphragm behind the piston of the lens. A unique feature of this IOL is that the principle of operation is such that it works opposite to the normal accommodative mechanism, in that focus for near is achieved when the ciliary muscle is relaxed and focus for distance when the ciliary muscle is contracted. When the ciliary muscle is relaxed, zonular tension would hold the capsular diaphragm in a relatively taught state. This applies a force against the posterior surface of the piston, forcing the gel through the aperture into a convex bulge. Hence, the lens has maximal power in this state and the eye would be focused for near. When the ciliary muscle contracts, zonular tension and the tension on the capsular diaphragm would be released. This relieves the pressure on the posterior



Figures 6A, 6B and 6C. Original video images of the polymer lens refilling procedure in a monkey eye
Figure 6D. Photograph of the polymer lens refilling procedure in a monkey eye (reprinted from Koopmans and associates[108] with permission from the Association for Research in Vision and Ophthalmology)

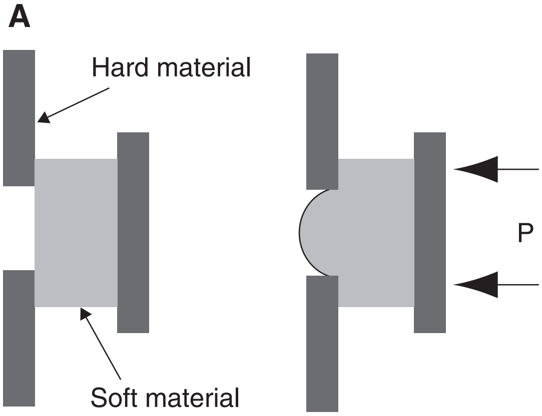


Figure 7A. Diagram of the mechanism of function of the NuLens Accommodative IOL (reprinted from Ben-Nun and Alió[112] with permission from Elsevier)

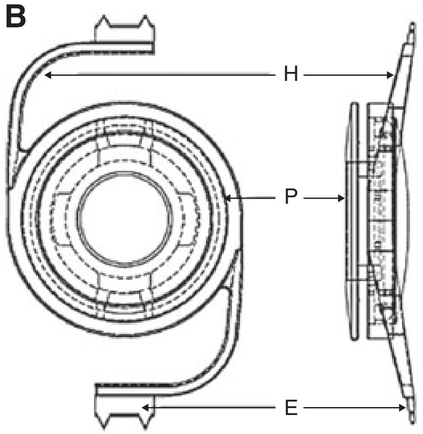


Figure 7B. Diagram of the design of the NuLens Accommodative IOL (reprinted from Ben-Nun and Alió[112] with permission from Elsevier)

piston and allows the gel to recede from the aperture, thereby flattening the gel surface curvature within the aperture. The eye would be focused for distance in this state. A prototype mechanical device and this IOL have been implanted in monkey eyes to demonstrated feasibility. Pharmacologically stimulated accommodation produced the expected change in surface curvature of the gel as measured with ultrasonic biomicroscopy. Calculations suggest this could produce 40 D of accommodation. Although this lens has been implanted into human eyes in preliminary clinical trials in Spain, no data have been published.

The obvious challenge for this design is how the patient can function with the eye focused for near, when accommodation is relaxed and focused for far, when accommodated. It is not only the focus of the eyes that presents a problem, but also how the eye would maintain single binocular vision on a near object while accommodation is relaxed and the eyes are divergent or on a distant object while the eyes are maximally accommodated and converged. As accommodation and convergence are coupled, the brain would have to learn to uncouple them. The designers have suggested that patients can learn to reverse the neurophysiology of accommodation in time,[112] but this is doubtful and one wonders how patients would function from the time of surgery until they have relearned this reverse accommodative ability. As with the other accommodative IOLs, the system is designed to be inherently unstable to permit accommodation to occur and it relies on a fine balance of forces between the viscosity of the polymer and the tension from the capsular diaphragm. Targeting and maintaining post-operative refraction and achieving a long lasting accommodative response with the capsular fibrosis and shrinkage that would be expected, even with the collapsed capsule, would undoubtedly present challenges.

CHALLENGES FOR ACCOMMODATIVE LENS IMPLANTS

Ideally, the amplitude of the accommodative response should be similar in the two eyes. This is certainly the case in young phakic eyes but this may be difficult to achieve with accommodative IOLs for a variety of reasons. Accommodative IOLs may be used in cases following cataract surgery. Cataracts do not often occur simultaneously, bilaterally. Implanting an accommodative IOL in only one eye could cause visual symptoms, such as diplopia due to aniso-accommodation if the accommodative response amplitude were especially high. Even if bilateral implants are performed, the accommodative response could be different in the two eyes due to differences in the surgery or post-operative recovery responses. The extent to which visual symptoms due to aniso-accommodation may be problematic is difficult to gauge. Monovision is a relatively standard treatment for presbyopia and some patients appear to tolerate a degree of induced anisometropia reasonably well. Further, ‘mix and match’ procedures are being used in patients with a multifocal IOL in one eye and the Crystalens in the other eye and some clinicians report patient satisfaction with this combination. Therefore, if aniso-accommodation is occurring in these patients, visual symptoms do not appear to be a problem.

All of these accommodative IOLs are designed to move in response to the forces exerted by the accommodative structures to produce a refractive change in the eye. Therefore, targeting an emmetropic post-operative refraction may be challenging with these IOLs. Each of the single optic, dual optic and curvature change IOLs has its own unique benefits and disadvantages, which depend on the specific design characteristics of each IOL. In general, single optic IOLs may be the most stable and least susceptible to post-operative surprises, in part because of their relatively limited range of motion. Capsular bags will have different sizes in different individuals, so one size IOL may not fit uniformly well into all capsules. The dual optic and curvature change IOLs may be at a particular disadvantage in this regard, as the separation of the two optics or the optic curvature determines the post-operative refraction and this depends on how well the IOL fits into the capsular bag. This variability could be reduced if the accommodative IOLs were manufactured with a range of physical dimensions. Rather than a one-size-fits-all IOL, with some relatively simple pre-operative or intra-operative ocular biometric measurements, the best-fitting IOL could be selected and used for each patient. As polymer refilling procedures create the lens inside the eye, over- or under-filling the capsule is likely to result in an over- or under-powered lens. Intraoperative refractive monitoring would be useful to determine when to terminate the refilling process when a targeted refraction is achieved. The refractive index of the polymer could be adjusted prior to injection in proportion to the volume of polymer to be injected to achieve an emmetropic refraction.

Post-operative changes could have devastating consequences for any of these accommodative IOLs. Lens epithelial cellular proliferation, capsular fibrosis and capsular shrinkage are often encountered after cataract surgery. With non-accommodative IOLs, YAG laser ablation of the opacified posterior capsule is the standard treatment. This may be contraindicated with some of the accommodative IOLs. Single optic IOLs are relatively insensitive, in terms of refractive changes or subjectively measured accommodative response, to YAG laser capsulotomy.[116] Performing capsulotomies on dual optic IOLs or curvature change IOLs may be more problematic. The polymers used to fill the capsules are soft and could either bulge or leak out following a capsulotomy, thus precluding this intervention in the case of posterior capsular opacifications.

Further, the anterior capsule is intact in the polymer filling procedures with only a small peripheral capsulorhexis, thus raising the possibility of both anterior and posterior capsular opacifications. In conjunction with polymer refilling, several agents have been tested to prevent capsular opacification.[117,118] This may be especially easily achievable with a small capsulorhexis, which could be readily sealed and the agent injected into the sealed capsule. An added level of complexity for the polymer injection procedure is that the surgical procedure differs from standard cataract surgery. The capsulorhexis is small, the crystalline lens must be removed through this small capsulorhexis, which would be especially challenging in the event of a dense cataract, and the use of the capsular plug and the polymer injection must be mastered by the surgeon. Resistance might be encountered in adopting polymer injection into the domain of routine ophthalmic practice if the surgical procedure is more complex, riskier and takes longer to perform. The development of finer surgical instruments, smaller diameter phakoemulsification probes and new laser-based phakoemulsification techniques may help to alleviate some of the surgical challenges.

The loss of capsular elasticity consequent to fibrosis or shrinkage could also result in secondary presbyopia, that is, loss of the specific function for which the IOL was used. Although this may not be considered devastating, given the additional costs, risks and possible surgical complications that the accommodative IOLs may incur, their long-term efficacy should be of paramount importance. Complete removal of the living cellular contents of the capsule in conjunction with chemical or drug treatments could help to prevent the post-operative fibrotic changes and ensure the longevity of the accommodative performance.

OBJECTIVE MEASUREMENT OF ACCOMMODATION

Ultimately, to evaluate any accommodation restoration concept, it is a fundamental necessity to employ objective techniques to measure accommodation. The point of accommodation restoration concepts is to restore the active, dynamic, accommodative change in power to the presbyopic eye. Many optical approaches are being used to 'treat' presbyopia by providing functional near and distant vision through multifocality, progressive addition lenses or monovision. These approaches can be effective for treating the symptoms of presbyopia. However, none of these approaches are directed at restoring accommodation. There is a fundamental distinction between 'treating presbyopia' and 'restoring accommodation'. The presbyopia treatments are certainly best evaluated and possibly can only be evaluated using subjective means such as near and distance acuity, contrast sensitivity, reading speed and patient satisfaction. Equally, it is important to evaluate the performance of the patients for everyday tasks and patient satisfaction. These subjective tests cannot differentiate between benefits that may be afforded by multifocality, depth of field or other ocular aberrations and a true accommodative change in power of the eye. There is no substitute for the use of objective accommodation measurements to evaluate if accommodation is restored. Such objective techniques are directed at measuring a true dioptric refractive change or changes in wavefront aberrations, as the eye focuses from distance to near. These objective tests should be done in conjunction with the subjective testing of distance and near visual ability and patient satisfaction. In fact, the United States Food and Drug Administration is mandating that such testing be included in future clinical trials of accommodation restoration concepts to meet the claims of restoring accommodation.

Objective measurement of accommodation in the phakic eye is a simple task and can be done reliably with any objective optometer, autorefractor or wavefront aberrometer, which permits the patients to fixate and focus on near and far targets.[119–126] The myopic shift that occurs in a young patient with the effort to focus at near is also reliably measured with an autorefractor or an aberrometer. Therefore, objective measurements can readily be made with clinically available autorefractors or aberrometers in the phakic eye, such as in the scleral expansion approaches[53,54] or the approaches directed at softening the natural lens with drugs or lasers.

Some minor challenges may exist when measuring accommodation in patients with pseudophakic accommodative intraocular lenses. Generally, these IOLs are made of high refractive index materials (such as silicone or PMMA). The refractive index difference between the aqueous humour and the IOL is therefore far greater than would occur in the phakic eye between the aqueous humour and the anterior surface of the crystalline lens. Such a high refractive index interface can cause bright Purkinje III images to be reflected off the anterior surface of the IOLs. The light sources from autorefractors or aberrometers may create spuriously reflections and stray light in pseudophakic eyes, which may complicate the measurements. Despite these possible complications, many studies have used a variety of autorefractors and aberrometers to objectively measure accommodation in pseudophakic patients.[78,127–129] Challenges exist but these by no means represent significant or insurmountable impediments to objective accommodation measurements.

CONCLUSIONS

There is clearly considerable interest in the prospects for restoring accommodation to the presbyopic eye. Potentially, this could be achieved in a number of different ways. Those developing these concepts should pay close attention to the generally accepted anatomy of the accommodative apparatus, mechanism of accommodation and causes of presbyopia for these concepts to succeed. The several different accommodative IOLs offer some interesting prospects, although the clinical data are relatively sparse and the limited objective measurements of accommodation do not suggest that much accommodation is restored. Although some of the concepts have been explored for decades, significant challenges still remain. Technological advancements in terms of surgical instruments, biomaterials, engineering and surgical capabilities have undoubtedly moved surgical restoration of accommodation from a theoretical concept more into the realm of mainstream ophthalmic practice but much work remains before this is likely to become the mainstay for treating presbyopia.

CONFLICT OF INTEREST

Dr Adrian Glasser in the past five years has served or currently serves as a consultant to the following companies: eyeonics/ Bausch & Lomb, Advanced Medical Optics, Alcon, PowerVision, LensAR, Visiogen, Vision CRC, Vistakon, CIBA Vision, Intralens Vision Inc, HyperBranch Medical Technology Inc. In addition, the author has stock options with LensAR through his consulting agreement.

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