A review of the surgical options for the correction of presbyopia

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ABSTRACT
Presbyopia is an age-related eye condition where one of
the signs is the reduction in the amplitude of
accommodation, resulting in the loss of ability to change
the eye’s focus from far to near. It is the most common
age-related ailments affecting everyone around their mid-
40s. Methods for the correction of presbyopia include
contact lens and spectacle options but the surgical
correction of presbyopia still remains a significant
challenge for refractive surgeons. Surgical strategies for
dealing with presbyopia may be extracolular (corneal or
scleral) or intraocular (removal and replacement of the
crystalline lens or some type of treatment on the
the crystalline lens itself). There are however a number of
limitations and considerations that have limited the
widespread acceptance of surgical correction of
presbyopia. Each surgical strategy presents its own unique
set of advantages and disadvantages. For example, lens
removal and replacement with an intraocular lens may
not be preferable in a young patient with presbyopia
without a refractive error. Similarly treatment on the
crystalline lens may not be a suitable choice for a patient
with early signs of cataract. This article is a review of the
options available and those that are in development
stages and are likely to be available in the near future for
the surgical correction of presbyopia.

INTRODUCTION
Presbyopia is an age-related reduction in the amplitu-
de of accommodation and leads to the loss of
ability in changing the eyes’ focus between far and
near. The correction of presbyopia without resorting
to spectacles and contact lenses (CLs) remains the
Holy Grail for refractive surgeons as well as the
billions of patients with presbyopia.

Numerous accommodative and pseudoaccommoda-
tive approaches to treat presbyopia surgically
exist. Each has its own benefits and limitations, and
may involve some degree of compromise between
the distance and near visual acuities (VA). Accommodative approaches attempt to restore the
true, dynamic and continuous range of the defocus-
ing ability of the eye. Pseudoaccommodative approaches provide functional near vision from a
variety of non-accommodative factors.

This review provides an overview of the options
that are currently available for the surgical manage-
ment of presbyopia.

PSEUDOACCOMMODATIVE APPROACHES
Corneal approaches
Excimer laser procedures
Monovision

Monovision with an excimer laser is a well-
established technique that corrects one eye for
distance vision (usually dominant eye) and the
other eye for near vision, resulting in intentional
anisometropia.¹ This aim is to give functional near
and distant VAs without the need for glasses. The
mechanism that enables monovision to succeed is
interocular blur suppression.

Studies have reported success rates ranging from
80–98%¹–³ for monovision post laser vision correc-
tion (LVC), 91% for monovision after cataract
surgery and 95% following clear lens extraction⁶
with good satisfaction. Surgically induced monovi-
son is associated with a higher success rate than
with CLs (91–98%), but it is unclear whether this
is because it is harder to reverse the procedure or
because of a multifocal corneal shape in LVC.

Limitations of monovision include compromising
visual function, such as reduced low contrast VA
and contrast sensitivity (CS), inability to incorpo-
rate an intermediate vision correction without com-
promising distance vision or near vision, reduced
stereopsis, and small-angle esotropic shift.⁷–⁹

Multifocal corneal ablation
Multifocality achieved by excimer ablation some-
times known as presbyLasik, is interesting to refract-
ive surgeons because it is familiar, seems less
invasive than intraocular surgery and could theoret-
ically be more controllable. However, this is against
the conventional thinking for LVC where one
usually attempts to minimise the higher order
aberrations.

A variety of presbyopic LVC procedures exist.¹⁰–¹²
In peripheral presbyopic LVC, the peripheral cornea
is ablated to create negative peripheral asphericity.
Thus the central cornea is for distance vision and
the mid-peripheral cornea for near vision (eg, Nidek
Advanced Vision Excimer Laser; (NIDEK,
Gamagori, Japan).¹¹ In central presbyopic LVC, the
central area is ablated for near vision and the periph-
ery for distance vision (eg, Supracor, Technolas
Perfect Vision GmbH, München, Germany); and
Pulsar (CustomVis, CV Laser, Perth, Australia).

Although optically the results are predictable and
good, some patients find it difficult to adapt to the
compromise and others are dissatisfied because
the minor loss of distance VA.¹²,¹³

Presbyond Laser Blended Vision (Carl Zeiss
Meditec, Jena, Germany) is an optimised laser
treatment method attempting to improve on con-
ventional monovision. The dominant eye is treated
for distance vision to almost plano and the non-
dominant eye is corrected to be slightly myopic
for near vision to –1.5 D. This monovision treatment
is enhanced by the use of a wavefront-optimised
ablation profile to create a continuous refractive
power gradient for the whole optical zone of the


CrossMark
cornea. Studies show that this treatment is a well-tolerated and effective procedure for treating patients with presbyopia.14–16

More recently, SCHWIND eye-tech-solutions (Kleinostheim, Germany) introduced its PresbyMAX software. This is a biaxial cornea modulation technique, based on the creation of a central hyperpositive area for near vision and leaving the pericentral cornea for far vision. Uthoff et al17 reported good distance and near visual outcomes in a 6-month follow-up study (table 1).

While multifocal LVCS represent a promising avenue for future presbyopic correction, outcome data is relatively sparse compared with other modalities.24

Conductive keratoplasty
Conductive keratoplasty (CK) is the successor of laser thermo-keratoplasty. CK uses the application of low frequency radio waves to ‘shrink’ collagen fibrils within the mid-peripheral cornea. This causes a net steepening on the central cornea and thus increases the positive power of the eye. Radiofrequency energy is typically 0.6 W with a 0.6-s treatment time,25 delivered through a fine tip inserted into the peripheral corneal stroma in a ring pattern outside of the visual axis. Eight to 32 treatment spots are placed in up to three rings in the corneal periphery (6-mm, 7-mm and 8-mm optical zones) and striae form between the spots and create a band of tightening to steepen the cornea primarily to create monovision. Although this has shown to be a relatively safe technique and may present theoretical advantages over flap creation techniques (less invasive and no flap-related complications), long-term studies report high rate of regression and hence this is not a popular technique at present.26–28

Intrastromal femtosecond ring incisions
Although the primary application of femtosecond laser has been its use in the creation of Laser-Assisted in situ Keratomileusis (LASIK) flaps, its precision and safety features makes it a useful tool for many types of corneal refractive surgery, including intrastromal treatments. Typically, five concentric rings in the cornea stroma between 2 mm and 4 mm from the line of sight are created using a femtosecond laser. Studies with INTRACOR (Technolas Perfect Vision GmbH, München, Germany) have shown the technique to be efficient and safe.29–30

The main advantage of INTRACOR is that the corneal surface is not cut. The ring structure induces a localised biomechanical change in the tissue causing a slight central steepening of 1–2 dioptres (D). This steepening changes the spherical aberration (SA) and corneal asphericity, resulting in improvement in the near vision.29–32 To date, the results reported have shown an overall improvement of uncorrected near VA (UCNUVA).19 29–32 However, some studies report no improvement in UCNUVA at 1 month,19 33 reduced best distance corrected VA (BDCVA),19 31 and anterior corneal protrusion after hyperopic LASIK followed by INTRACOR.13 The treatment is usually performed in the non-dominant eye only. Further study is required on this treatment modality.

Corneal inlays
Corneal inlays (CIs) are intrastromal implants which are placed underneath a LASIK flap or into a femtosecond laser created corneal pocket. The pocket technique has a number of potential advantages: the majority of peripheral corneal nerves are preserved, allowing corneal sensitivity to be maintained, they are additive, do not remove tissue, preserve future options for presbyopic correction and may be used in pseudophakia and/or combined with IVC.34 In addition, they are all removable. The LASIK flap could be created with a microkeratome or with a femtosecond laser.

Complications reported with CI include hyperopic shift, haloes, a decrease in photopic and mesopic CS, corneal thinning and melting, broadened defocus curve and reduced simulated retinal blur in the implanted eye (Kamra Inlay, AcuFocus, Irvine, California, USA).22 35–37 With all inlay designs, centration is critical for proper performance, and a small displacement can make a clinically significant difference.38

At present, there are three types of corneal inlays:

- CIs that alter the index of refraction with a bifocal optic. The Flexivue Microrels, (Presbia, Los Angeles, California, USA) and Icolens (Neoptics AG, Hunenberg, Switzerland) are currently in clinical trials although several studies have been presented. The Flexivue (precursor was the Invue) is the only CI using a refractive addition power.29 30 The Icolens is a new CI and recently Baily has reported the 1-year visual outcomes (table 1).23

- The Raindrop Near Vision Inlay (ReVision Optics, Lake Forest, California, USA) is a CI that changes the corneal curvature. Garza et al20 reported good and stable results at 1 year.

- The Kamra CI relies on small-aperture optics to increase the depth of focus. Most of the published data demonstrates that monocural implantation of a small-aperture inlay results in sustained improvement in near vision and intermediate vision while maintaining good distance vision,22 35–37 However, the size, material and visibility of the Kamra CI can be a disadvantage compared with the other CIs.

Lenticular approaches
The ultimate goal of cataract extraction and clear lens extraction is to replace the crystalline lens with an intraocular lens (IOL) that simulates the original function of the crystalline lens and provides the patients with a full range of functional vision for all distances. Currently, the available IOLs can be grouped into accommodating (AIOLs) or pseudoaccommodating IOLs (although the mechanism of action of some ‘accommodative lenses’ may be pseudoaccommodative in nature). With pseudoaccommodative multifocal IOLs (MIOLs), the patient has two or three points in focus but primarily perceives only the focused image of interest.39 40

Precise biometry, accurate IOL power calculation, good surgical technique as well as patient selection are crucial in achieving the best visual outcome and patient satisfaction.

Pseudophakic multifocal intraocular lens
Multifocal intraocular lenses are used following patients with cataract or in clear lens extraction and excellent clinical outcomes have been reported.42–44 However, patient dissatisfaction and secondary procedures, including IOL exchange, can also be significant.45–47 Some of the MIOLs are based on multifocal CL designs, however the visual results may differ between them. First, CLs and IOLs are placed in different locations in the eye which results in different plane corrections, and second, the CL moves during the blink versus the stability of the IOL. These differences could lead to different visual outcomes.

Complications of these MIOLs include reduction in quality of vision, especially loss of CS, dysphotopsia, and reduced intermediate vision and near vision.48–50

The discussion below is not an exhaustive list of the IOLs available or publications (it is beyond the scope of this article) but is representative for the common lenses used.
<table>
<thead>
<tr>
<th>Author</th>
<th>Procedure</th>
<th>Study design</th>
<th>Number of eyes</th>
<th>UCNVA</th>
<th>BDCNVA</th>
<th>Additional tests</th>
<th>Complications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Levinger et al</td>
<td>Monovision induced by LASIK</td>
<td>1 year</td>
<td>38</td>
<td>0.06 logMAR (binocular)</td>
<td>Not available</td>
<td>▶ CS reduced in mesopic condition.</td>
<td>Not reported</td>
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<td></td>
<td>▶ 85.2% of satisfaction</td>
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<td>Greenbaum</td>
<td>Monovision pseudophakia</td>
<td>1 year</td>
<td>120 cataract/20 CLE</td>
<td>0.0 logMAR or better (binocular) in 91% cataract and 95% CLE</td>
<td>Not available</td>
<td>▶ 91% acceptance cataract</td>
<td>▶ 1 dry eye</td>
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<td></td>
<td>▶ 95% acceptance CLE</td>
<td>▶ 1 vitreous loss</td>
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<td></td>
<td></td>
<td>▶ 1 iris atrophy</td>
<td>▶ 20% reported haloes and glare in cataract in CLE</td>
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<tr>
<td>Uthoff et al</td>
<td>Multifocal corneal ablation</td>
<td>6 months</td>
<td>20 (emmetropic), 20 (hyperopic), 20 (myopic)</td>
<td>0.18 logRAD (emmetropic), 0.24 logRAD (hyperopic), 0.12 logRAD (myopic) (binocular)</td>
<td>Not available</td>
<td>CS significantly reduced in all groups</td>
<td>Not reported</td>
</tr>
<tr>
<td>McDonald et al</td>
<td>Conductive keratoplasty</td>
<td>6 months</td>
<td>143</td>
<td>0.18 logMAR or better in 77% (monocular)</td>
<td>Not available</td>
<td>76% reported very satisfied/ satisfied</td>
<td>Not reported</td>
</tr>
<tr>
<td>Menassa et al</td>
<td>Intrastromal femtosecond Ring incision</td>
<td>18 months</td>
<td>25</td>
<td>0.2 logMAR (monocular)</td>
<td>Not available</td>
<td>▶ Corneal steepening 0.90 D</td>
<td>▶ 36% reported rings around light sources</td>
</tr>
<tr>
<td>Limnopoulou et al</td>
<td>Flexivue microlens inlay</td>
<td>1 year</td>
<td>47</td>
<td>0.14 logMAR (monocular), 0.13 logMAR (binocular)</td>
<td>Not available</td>
<td>▶ HOA increased.</td>
<td>No surgical complications</td>
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<td>▶ CS decreased.</td>
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<td>▶ 81.25% reported</td>
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<td></td>
<td>▶ UCNVA excellent</td>
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<tr>
<td>Garza et al</td>
<td>The raindrop Inlay</td>
<td>1 year</td>
<td>20</td>
<td>&lt;0.1 logMAR (monocular and binocular)</td>
<td>Not available</td>
<td>▶ Photopic CS no significant change.</td>
<td>▶ 1 patient reported severe haloes at 6 months,</td>
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<td></td>
<td>▶ 95% reported satisfied or very satisfied UCNVA, UCIVA.</td>
<td>▶ 10% inlays removed because dissatisfaction,</td>
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<td></td>
<td>▶ 100% satisfied or very satisfied UCNVA</td>
<td>▶ decentration.</td>
</tr>
<tr>
<td>Seyeddain et al</td>
<td>The Kamra inlay</td>
<td>2 years prospective</td>
<td>24</td>
<td>0.1 logMAR (monocular)</td>
<td>Not available</td>
<td>0.1 logMAR UCIVA</td>
<td>▶ 1 eye with epithelial ingrowth in the pocket</td>
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<td></td>
<td>▶ 1 eye with epithelial iron deposit</td>
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<tr>
<td>Baily et al</td>
<td>The Icolens corneal inlay</td>
<td>1 year</td>
<td>52</td>
<td>0.4 logMAR (monocular)</td>
<td>Not available</td>
<td>90% reported happy with the procedure</td>
<td>11 inlay explanted because minimal improvement UCNVA</td>
</tr>
<tr>
<td>Hipsley (ASCRS 2011)</td>
<td>The LaserACE procedure</td>
<td>18 months</td>
<td>134</td>
<td>0.18 logMAR or better in 89%</td>
<td>Not available</td>
<td>▶ 1.25–1.75 D increase in objective accommodation.</td>
<td>No major complications</td>
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<td>▶ 0.18 logMAR or better in 95% UCNVA</td>
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<tr>
<td>Berrow (2014)</td>
<td>PresVIEW scleral implant</td>
<td>3 months (ongoing 2 years FDA clinical trial)</td>
<td>28</td>
<td>Not available</td>
<td>0.3 logMAR 100% (monocular, binocular)</td>
<td>Mean lines of improvement at 2.3 monocular and 2.0 binocular</td>
<td>Not reported</td>
</tr>
</tbody>
</table>

Note: some visual acuities were converted to logMAR using the visual acuity conversion chart prepared by Jack T Holland.

BDCNVA, best distance corrected near visual acuity; CLE, clear lens extraction; CS, contrast sensitivity; FDA, Food and Drug Administration; HOA, high order aberration; LogMAR, log minimum angle of resolution; logRAD, logarithm of the reading acuity determination; UCDVA, uncorrected distance visual acuity; UCIVA, uncorrected intermediate visual acuity; UCNVA, uncorrected near visual acuity.
Refractive MIOLs

Refractive MIOLs have the incorporation of two different powers integrated into two or more typically circular refractive zones. Due to each lens zone having a different effective aperture, the image quality can depend on the pupillary response to light and the accommodation reflex.47

The ReZoom (Abbott Medical Optics (AMO), Irvine, California, USA) is a refractive MIOL (the original model being called the ARRAY) and the Food and Drug Administration (FDA) approved it in 2005. It is a three-piece MIOL and has five refractive optical zones; zones 1, 2, and 3 are adjusted for near vision, while zones 2 and 4 are adjusted for far vision. This design gives good distance vision and good intermediate-range vision although the reading performance is variable.48 Disadvantages of this lens, like many MIOLs, include dysphotopsia.49

The M-flex MIOL (Rayner IOLs Limited, Hove, UK) is based on a multizoned refractive aspherical optical technology, with either 4 or 3 annular zones (depending on IOL base power) providing +3.0 D or +4.0 D of additional refractive power at the IOL plane (equivalent to +2.25 D or +3.0 D at the spectacle plane). Cezon et al50 reported good visual performance and high rate of spectacle independence at 1 year.

Refractive MIOLs appear to be associated with more photic phenomena compared with diffractive MIOLs.51 Photic phenomena are among the most frequent reasons for patient dissatisfaction following implantation of MIOLs.52

Diffractive MIOLs

These are based on the principle of diffraction, whereby light slows down and changes direction when it encounters an obstacle.53 These lenses use microscopic steps (diffractive zones) across the lens surface. As light encounters these steps, it is directed towards the distant and near focal points (the amount of light is directly related to the step height as a proportion of wavelength). Diffractive MIOLs can be subdivided into apodised (gradual reduction in diffractive step heights from centre to periphery) or non-apodised (uniform height): both categories are limited in view of the diffractive IOLs.57 58 The prevalence of these lenses show a significant improvement in uncorrected VA at all distances. The trifocal designs may be the emerging technology in the field of the diffractive IOLs.57 58 The prevalence of complications still needs to be assessed with larger clinical studies.

Rotationally asymmetrical MIOLs

All traditional MIOLs are based on the concept of rotational symmetry. Recently, MIOLs with rotational asymmetry were introduced. One such lens, the Lentis MPlus LS-312 (Oculentis GmbH, Berlin, Germany), consists of a single-piece, aspherical surface that is independent of pupil size.59 Different near additions are available allowing customisations for each individual and can be used with a mix and match philosophy.

Results indicate good distance, intermediate and near VAs with a high level of CS.59–61 The authors recently conducted a study with the latest version: Lentis Mplus X LS-313 in 34 eyes showing excellent visual performance62 (table 2).

The SBL-3 MIOL (Lenstec, St Petersburg, Florida, USA) is another asymmetrical segmented MIOL that is also designed to improve CS, minimise dysphotopsias and provide good far vision, intermediate vision and near vision. The SBL-3 has a three-dimensional sector-shaped near vision addition with a seamless transition zone between the distance and near segments. Venter et al63 recently published a study conducted in 106 eyes showing excellent outcomes (table 2).

Rotationally asymmetrical MIOLs seem to provide a good visual outcome at distance vision and near vision with minimal dysphotopsia and retain intermediate vision. The design minimises loss of light from splitting of the incoming light. Patients also were satisfied with their uncorrected near vision. Further studies with larger cohorts and longer follow-up period are necessary.

Finally, Staar (Staar Surgical Company, Monrovia, California) is known to be developing a new multifocal phakic implantable contact lens that would potentially correct ametropia and presbyopia.

Phakic MIOL

Ametropia and presbyopia can also be corrected using an anterior chamber phakic MIOL. George Baikoff designed one of the first models64 69 and this anterior chamber multifocal design has been marketed under the trade names of Newlife (IOLTECH, SA, La Rochelle, France) and Vivarte Presbyopic (CibaVision, Duluth, Georgia, USA) and provides a single addition of +2.5 D for near vision.

Baikoff et al64 also performed the first clinical trial with this type of multifocal IOL in 55 eyes showing that this IOL was effective and gave good predictability. Alio and Mulet, in another pilot study with a multifocal phakic IOL prototype (AMO, Irvine, California, USA), also showed good results.65 However, the complications reported by these anterior phakic IOLs include endophthalmitis, surgically induced astigmatism, corneal endothelial cell loss, pupil distortion, chronic uveitis, pupillary block glaucoma, pigment dispersion syndrome and cataracts.

ACCOMMODATIVE APPROACHES

For accommodation to be restored in the presbyopic eye, it is necessary that the ciliary muscle is still able to contract with accommodative effort: there is evidence to suggest that the ciliary muscle does not undergo atrophy with age and remains functional.70 71 Although the young phakic eye may have 7–8 D of true accommodation, most patients with presbyopia would be happy with a restoration of 2–3 D of true accommodation.

Lenticular approaches

Accommodating intraocular lens

There are many different concepts and designs for AIOLs including mouldable gels, fluid displacement and flexible haptics. These IOLs are designed to use ciliary muscle contraction, capsular bag elasticity and changes in vitreous cavity pressure to induce change or movement in the shape of the IOL to produce an optical change in the eye based on the optic-shift concept, that is, on the
<table>
<thead>
<tr>
<th>Author</th>
<th>IOL</th>
<th>Design</th>
<th>Study design</th>
<th>Number of eyes</th>
<th>UCNVA</th>
<th>BDCNVA</th>
<th>Additional tests</th>
<th>Complications</th>
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<tbody>
<tr>
<td>Forte and Ursoleo</td>
<td>ReZoom</td>
<td>Refractive</td>
<td>2 years</td>
<td>55</td>
<td>0.10 logMAR</td>
<td>Not available</td>
<td>UCNA 0.07 logMAR (monocular).</td>
<td>7% patients reported moderate glare</td>
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<td>(monocular)</td>
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<td>5% patients reported moderate halo</td>
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<td>Not reported</td>
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<tr>
<td>Cezon et al.</td>
<td>Rayner M-flex</td>
<td>Refractive</td>
<td>1 year</td>
<td>32</td>
<td>0.28 logMAR</td>
<td>0.28 logMAR</td>
<td>UCNA 0.15 logMAR (monocular).</td>
<td>2 eyes implant replacements</td>
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<td>(monocular)</td>
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<td>2 eyes with cystoid macular oedema</td>
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<td>1 eye flat macular oedema</td>
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<td>1 eye macular oedema with fibrous reaction</td>
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<td>1 cystic maculopathy</td>
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<td>4 IOL explantation</td>
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<td>12.8% eyes required Yag laser</td>
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<tr>
<td>Kohnen et al.</td>
<td>AcrySof ReSTORMA60D</td>
<td>Diffractive</td>
<td>6 months</td>
<td>127</td>
<td>0.14 logMAR in</td>
<td>0.14 logMAR in</td>
<td>84.6% spectacle independence for near vision</td>
<td>Not reported</td>
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<tr>
<td></td>
<td>MA60D3</td>
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<td>66.9% (binocular)</td>
<td>71.2% (binocular)</td>
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<td>8.5% patients reported severe glare</td>
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<td>4.2% patients reported severe halo</td>
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<td>2 eyes implant replacements</td>
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<td>2 eyes with cystoid macular oedema</td>
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<td>1 eye flat macular oedema</td>
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<td>1 eye macular oedema with fibrous reaction</td>
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<td>1 cystic maculopathy</td>
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<td>4 IOL explantation</td>
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<td>12.8% eyes required Yag laser</td>
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<tr>
<td>Packer et al.</td>
<td>Tecnis multifocal</td>
<td>Diffractive</td>
<td>1 year</td>
<td>244</td>
<td>0.20 logMAR</td>
<td>0.18 logMAR</td>
<td>95.5% spectacle independency for distance vision</td>
<td>Not surgical complications</td>
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<td>(monocular)</td>
<td>(monocular)</td>
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<td>86.6% spectacle independency for near vision</td>
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<td>94.6% satisfied</td>
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<td>10.3% patients reported moderate glare</td>
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<td>2.6% patients reported severe glare</td>
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<td>84.8% spectacle independence</td>
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<td>84.8% spectacle independence</td>
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<td>UCNA 0.08 logMAR</td>
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<td>DCNA 0.08 logMAR (monocular)</td>
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<td>UCDNA 0.19 logMAR (monocular)</td>
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<td>NAVQ Rasch scores satisfaction at near 15.9 logts</td>
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<td></td>
<td></td>
<td></td>
<td>Not surgical complications</td>
</tr>
<tr>
<td>Mojzis et al.</td>
<td>AT Lisa tri 839MP</td>
<td>Diffractive trifocal</td>
<td>6 months</td>
<td>60</td>
<td>0.20 logMAR</td>
<td>0.17 logMAR</td>
<td>UCNA 0.08 logMAR (monocular).</td>
<td>Not surgical complications</td>
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<td>(monocular)</td>
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<td>DCNA 0.08 logMAR (monocular)</td>
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<td>NAVQ Rasch scores satisfaction at near 15.9 logts</td>
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<td>Not reported</td>
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<tr>
<td>Sheppard et al.</td>
<td>Finevision trifocal</td>
<td>Diffractive trifocal</td>
<td>2 months</td>
<td>30</td>
<td>Not available</td>
<td>Not available</td>
<td></td>
<td>Not surgical complications</td>
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<td>Not surgical complications</td>
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<tr>
<td>Voskresenskaya et</td>
<td>MIOL-Record trifocal</td>
<td>Diffractive trifocal</td>
<td>6 months</td>
<td>36</td>
<td>0.10 logMAR</td>
<td>0.10 logMAR</td>
<td>UCNA, DCNA 0.2 logMAR, Scotopic</td>
<td>Not surgical complications</td>
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<td>(monocular)</td>
<td>(monocular)</td>
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<td>CS 0.2 log unit below standard values at all spatial frequencies</td>
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<td>94% patients reported spectacle freedom</td>
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<td>25% patients reported haloes</td>
</tr>
<tr>
<td>Shah (2014)</td>
<td>Lentis Mplus X LS-313</td>
<td>Rotationally asymmetrical</td>
<td>3 months</td>
<td>34</td>
<td>0.18 logMAR</td>
<td>0.15 logMAR</td>
<td>NAVQ Rasch scores satisfaction at near 20.43 logts</td>
<td>Not surgical complications</td>
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<td>(monocular)</td>
<td>(monocular)</td>
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<td>UCNA 0.16 logMAR (monocular) and 0.13 logMAR (monocular)</td>
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<td></td>
<td>DCNA 0.15 logMAR (monocular) and 0.1 logMAR (binocular)</td>
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<td>94.4% satisfied or very satisfied</td>
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<td>86.8% had no difficulty at all or little difficulty performing tasks that require good close-up vision</td>
</tr>
<tr>
<td>Venter et al.</td>
<td>SBL-3</td>
<td>Rotationally asymmetrical</td>
<td>3 months</td>
<td>106</td>
<td>0.12 logMAR</td>
<td>0.11 logMAR</td>
<td>UCNA 0.16 logMAR (monocular) and 0.13 logMAR (binocular)</td>
<td>Not surgical complications</td>
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<td>(monocular);</td>
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<td>DCNA 0.15 logMAR (monocular) and 0.1 logMAR (binocular)</td>
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<td>0.08 logMAR</td>
<td>0.08 logMAR</td>
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<td>94.4% satisfied or very satisfied</td>
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<td>(binocular);</td>
<td>(binocular);</td>
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<td>86.8% had no difficulty at all or little difficulty performing tasks that require good close-up vision</td>
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<tr>
<td>Baikoff et al.</td>
<td>Anterior piOL</td>
<td>Refractive</td>
<td>1 year</td>
<td>55</td>
<td>0.23 logMAR</td>
<td>Not available</td>
<td>Efficacy ratio of 80%</td>
<td>Slight pupil ovalisation in 10% eyes</td>
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<td>(monocular)</td>
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<td>Safety ratio of 94%</td>
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<tr>
<td>Author</td>
<td>IOL</td>
<td>Design</td>
<td>Study design</td>
<td>Number of eyes</td>
<td>UCNVA</td>
<td>BDCNVA</td>
<td>Additional tests</td>
<td>Complications</td>
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<tr>
<td>Alí and Mulet</td>
<td>The AMO multifocalphakic IOL prototype</td>
<td>Refractive</td>
<td>1 year</td>
<td>34</td>
<td>0.20 logMAR (binocular)</td>
<td>Not available</td>
<td>▶ UCVA 0.00 (binocular)</td>
<td>▶ Mean endothelium cell loss less than 5% ▶ 4 IOL explantations because of dissatisfaction</td>
</tr>
<tr>
<td>Cumming et al</td>
<td>Crystalen AT-45</td>
<td>Accommodative</td>
<td>1 year FDA clinical trial</td>
<td>263 eyes</td>
<td>0.20 logMAR or better in 93.5% (binocular)</td>
<td>0.20 logMAR or better in 83.9% (binocular)</td>
<td>▶ DCVA 0.1 in 95% eyes (binocular) ▶ 25.8% patients reported spectacle freedom</td>
<td>▶ Endophthalmitis 1 eye ▶ 12 eyes IOL dislocation ▶ 2 eyes retinal detachment ▶ 1 eye iridectomy ▶ 1 eye with persistent corneal oedema ▶ 3 eyes with iritis</td>
</tr>
<tr>
<td>Sanders and Sanders</td>
<td>Tetraflex</td>
<td>Accommodative</td>
<td>1 year FDA clinical study</td>
<td>255</td>
<td>0.4 logMAR in 77%</td>
<td>0.4 logMAR or better in 67%</td>
<td>▶ 90% could read ≥ 80 wpm at the 0.2 logMAR print size ▶ 75% patients reported never or occasionally wore near glasses</td>
<td>Malpositioning of 5 IOLS ▶ Anterior and posterior opacification in 100% of cases</td>
</tr>
<tr>
<td>Mastropasqua et al</td>
<td>1CU Human Optics</td>
<td>Accommodative</td>
<td>2 years</td>
<td>14</td>
<td>Not available</td>
<td>0.2 logMAR at 6 months 0.48 logMAR at 2 years</td>
<td>AA 1.9 D at 6 months and 0.30 D at 2 years</td>
<td></td>
</tr>
<tr>
<td>Alí (2009)</td>
<td>The NuLens</td>
<td>Accommodative</td>
<td>1 year</td>
<td>10 (Cataract and atrophic macular degeneration) 6 months</td>
<td>Increase of 3.8 Jaeger rows 6 months</td>
<td>Not available</td>
<td>Cross-section measurement of IOL of 0.09 mm (equivalent to 10 D)</td>
<td>▶ 1 posterior synechia inducing IOL tilt ▶ 1 capsulorhexis edge capture by the haptic endplate inducing high myopia</td>
</tr>
</tbody>
</table>

Note: some visual acuities were converted to logMAR using the visual acuity conversion chart prepared by Jack T Holland.

AA, amplitude of accommodation; BDCNVA, best distance corrected near visual acuity; CIVA, corrected intermediate visual acuity; CS, contrast sensitivity; DCIVA, distance corrected intermediate visual acuity; LogMAR, log minimum angle of resolution; MIOL, multifocal intraocular lens; UCIVA, uncorrected intermediate visual acuity; NAVQ, Near Assessment of Vision Questionnaire; pIOL, phakic intraocular lens; UCNVA, uncorrected near visual acuity.
axial movement of the optic resulting from action of the ciliary muscle. A hinge between the optic and haptics allows the lens to move forward as the eye focuses on near objects and backward as the eye focuses on distant objects, thereby increasing the dioptrical power of the pseudophakic eye.

It has been reported that an IOL optical shift of 1.0 mm can offer about 1.0 D of accommodation in a single-optic IOL and between 2.5 D and 3.0 D in an IOL with two-lens optics.\(^72\)\(^73\) In addition, the amount of accommodative result depends on several factors, such as the position of the optics in the capsular bag, the posterior chamber and the refractive power of the IOL.

The Crystalens HD (Bausch & Lomb, Rochester, New York, USA) the Tetraflex HD (Lenstec. St Petersburg, Florida, USA) and the 1CU Human Optics (Human Optics AG, Erlangen, Germany) are examples of single-optic AIOLs and have all been extensively used.\(^66\)\(^68\) Visual performance reported with these AIOLs is promising,\(^66\)\(^68\) however capsule opacification and loss of accommodative ability with time are often present.

The single-optic passive-shift IOLs are considered pseudoad-


dominate because they have limited accommodative ability, as their anterior movement is insufficient to provide functionally sig-


nificant amplitudes of accommodation. Hence, dual-optic devices were developed such as the Synchrony IOL (AMO, Irvine, California, USA), and the Sarfarazi IOL (Shenasa Medical, Carlsbad, California, USA). The configuration of these devices with a high positively powered mobile anterior optic, connected to a stationary negatively powered posterior optic, is designed to increase the potential accommodative amplitude. Published results of both IOLs are limited but have shown positive results in small cohorts.\(^74\) They may be relatively difficult to handle, technically.

There are some IOLs, that change their shape or curvature with accommodative effort, in different stages of development. The FluidVision lens (PowerVision, Belmont, California, USA) drives fluid of a polymer-matched refractive index from the IOL’s soft haptics through channels to a fluid-driven internal activator. One-year follow-up showed that the base IOL powers were accurate and stable, VAs were good, and patients showed more than 5.00 D of accommodation on average (American Society of Cataract and Refractive Surgery (ASCRS) 2011). The NuLens (NuLens, Herzliya Pituh, Israel), a sulcus-based accommodating IOL is still under development although it has been implanted in 10 eyes with cataract and atrophic macular degeneration showing at 1 year, reporting this IOL may result in up to 10 D of accommoda-


dation.\(^73\) and the Superior Accommodating IOL (Human Optics AG, Erlangen, Germany) is designed to mimic the behaviour of natural lens and it is under development.

The lens filling techniques have been under investigation for years. It consists of replacing the lens with a soft gel that would allow modifying the shape for accommodation. The Medennium SmartLens IOL (Medennium, Irvine, California, USA) is a ‘smart’ hydrophobic acrylic material with unique thermodynamic property. When implanted into the capsular bag, the body’s temperature causes the material to transform into a gel-like polymer and take the shape of the natural lens. To the knowledge of the authors no data has been published yet. It should be noted that objective measurement of the accommodative capability of AIOLs is extremely difficult to obtain.\(^76\)

Laser-assisted presbyopia reversal

Laser assisted presbyopia reversal aims to restore dynamic accommodation increasing pliability in the sclera and net forces of the ciliary muscles on the lens facilitating accommodation. The postulated mechanism of action of laser assisted presbyopia reversal is to decrease ocular rigidity. The procedure is performed using a handheld fibre-optic handpiece that delivers pulses of an erbium:YAG laser ablating a diamond matrix pattern of nine laser spots into each oblique quadrant of the sclera. These are presumed to decrease the distance between the ora serrata and the scleral spur, restore the anatomical relationships of the system and free the ciliary muscle to contract normally. The spots delivered in a diamond matrix pattern of nine laser spots into each oblique quadrant. The results so far (in 134 eyes of 67 patients after 18 months follow-up) are promising. Hipkiss reported restoration of 1.25–1.75 D of objective accommodation, which remained stable through 18 months in initial results (2011 ASCRS meeting) (table 1).

The femtosecond laser seeks to restore the flexibility that has been lost by making precise incision patterns within the lens without opening the capsule.

Presidential studies have been performed in human cadaver and animal lens.\(^77\)\(^80\) which have demonstrated safety, increased lens flexibility and no production of cataract. A feasibility study with the LENSAR (LENSAR, Orlando, Florida, USA) in 80 subjects with cataract showed that a third showed an improvement in objective accommodation measured with the Grand Seiko WR-3100 K auto-


refractor (Grand Seiko, Fukuyama, Japan) and over 50% showed an improvement in subjective accommodation with the push-down method. Over 40% also showed an increase in the best distance-corrected near VA (results presented at ASCRS 2014).

Currently, there is another femtosecond laser-based therapy study for the treatment of presbyopia in Germany (The Human Eye study Cologne/Rostock). This clinical study is being conducted at two sites: University of Rostock University Eye Hospital, Rostock, Germany and Augenklinik am Neumarkt, Köln, Germany. Fifteen eyes in each site (n=30 eyes) have been recruited. However, to the knowledge of the authors, no data has been reported.

**Sceral modification**

Extraocular approaches have been developed based on Schachar’s theory.\(^81\) This model states that accommodation results of an increase of zonular traction at the lens equator to increase the lens diameter, therefore, presbyopia occurs as a result of increased lens growth causing a reduction in the space between the lens and the ciliary body (circumlenticular space), such that upon contraction the zonules can no longer exert their effect on the lens due to a loss of tension. MRI studies have shown that the circumlenticular space decreases with age as a result of the inward movement of the ciliary muscle ring that occurs with advancing age and an increase of the lens thickness.\(^74\) However, goniovideography, infrared photogra-


phy and MRI studies have shown that the lens decreases in diameter and surface area with accommodation.\(^82\) Despite the controversy of this theory, Schachar postulated that expanding the dimensions of the overlying scleral wall by pulling the ciliary muscle away from the equatorial edge of the lens, would reverse the process of presbyopia and increase accommodative amplitude. LaserACE (Ace Vision Group, Silver Lake, Ohio, USA) and VisAbility Implant System surgery Schelar Implants (Refocus Group, Dallas, Texas, USA) were originally developed on the basis of this theory but the actual mechanism of action is still under investigation.

*See page 138 for references.*
Scleral expansion bands

Scleral expansion band surgery for the treatment for presbyopia is based on the model of accommodation theorised by Schachar.8

Scleral expansion bands have therefore been used for this purpose, but previous studies have demonstrated mixed results and have demonstrated limited success with temporary improvement in amplitude of accommodation.8,9-13 Most recently, Refocus group has developed The VisAbility Implant System scleral implants. The technique consists of implanting four prostheses (size of a grain of rice) within elongated pockets in the sclera. The prostheses are thought to exert traction on the sclera in the region overlying the ciliary body which expands the sclera and the underlying ciliary body: thus restoring the effective working distance of the ciliary muscle and increasing the amplitude of accommodation. The actual surgical technique has evolved markedly from the initial use of manual diamond blade to the current use of disposable scleratome improving considerably the accuracy of tunnel creation. Furthermore, the original implant was a one-piece device, which was pushed into place and was difficult to thread through the tunnel. This one-single piece had a tendency to slip out of the tunnel over the long term resulting in a return or regression of patients’ preoperative near vision.

Nowadays, the implant is a two-piece locking implant that prevents the implanted device from slipping out. Currently, Refocus group is conducting a FDA clinical trial (table 1).

CONCLUSION

There have been significant developments in surgery for presbyopia over the last decade achieving relatively good outcomes but each modality has its own advantages and disadvantages and sometimes compromises. However, to properly compare interventions it is necessary to encourage researchers to report best distance-corrected near VA rather just UCVA to minimise any confounding effect of myopia and astigmatism on results.

Other options for the management of presbyopia should not be forgotten, for example, it has been suggested that the use of miotics to increase depth of focus could help those suffering from presbyopia, and this would represent a type of reversible miotics to increase depth of focus could help those suffering from presbyopia, and this would represent a type of reversible amniotic cataract surgery for presbyopia.

In the next few years it is likely that the introduction of different IOLs will be seen, as well as the development of new pharmacological treatments and technologies to provide patients with better visual outcomes and then possibly restoration of true accommodation to the presbyopic eye will be seen.

Contributors All three authors were involved in the planning, writing and reviewing of this manuscript.

Competing interests SAN and SS have received unrestricted grants or been involved in commercial studies for Bausch and Lomb, Lenstec, Abbot Medical Optics, Oculentis GmbH, FineVision, Topcon Europe Medical BV, Refocus Group and LENSAR. SS is a consultant to Lenstec, Oculentis GmbH, Topcon Europe Medical BV, Refocus Group and LENSAR and is medical director and equity holder for CustomVIS.

Provenance and peer review Not commissioned; externally peer reviewed.

REFERENCES


