Intraocular lens correction of presbyopia

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Abstract:
The continued development of intraocular lens (IOL) technology has led to a dramatic improvement in refractive outcomes. New and innovative ways of achieving the desired postoperative refractive goals continue to be developed. This article aims to review the currently available IOL modalities for correction of presbyopia at the time of cataract surgery, including reference to high-quality comparative studies, where available, and discussion of strengths as well as limitations of the currently available IOL technologies. It has been shown that multifocal compared to monofocal IOL was associated with higher rates of spectacle independence, but higher rates and severity of symptomatic glare as well as reduced contrast sensitivity. Within multifocal IOLs, diffractive compared to refractive IOLs tended to have better near vision and a lower rate of symptomatic glare. Extended depth-of-focus IOLs compared to diffractive multifocal IOL demonstrated equal or superior intermediate visual acuity, with less than or equal rates of glare. Accommodative IOLs represent a broad range of technologies that continue to develop, and new technologies offering opportunities for postoperative adjustment of refractive outcome are emerging.

Keywords: Accommodative intraocular lens, cataract surgery, extended depth-of-focus intraocular lens, intraocular lens, intraocular lens technology, lens, multifocal intraocular lens, premium cataract surgery, presbyopia correction, refractive cataract surgery

Introduction

Cataract is estimated to affect 52.6 million people worldwide and is globally estimated to cause 33% of total visual impairment and 51% of total blindness.¹,² With 83% of total cases of blindness considered to be preventable, cataract is the number one cause not only of blindness but of preventable blindness globally.¹,² As major efforts continue to reduce this disease burden, with increasing rates of cataract surgery and improving refractive postoperative outcomes, rates of global blindness due to cataract have been declining.³ As paradigms in management strategy for patients with cataract shift from a focus on anatomic resolution of disease toward patient-centered care responsive to individual patient wants and needs, refractive considerations are increasingly important in preoperative evaluation and surgical planning.⁴ Patients not accustomed to corrective spectacle wear preoperatively tend to have greater expectations of postoperative spectacle independence for both distance and near vision after cataract surgery.⁵ Due to the popular desire for spectacle independence postoperatively, use of intraocular lens (IOL) for presbyopia correction in the setting of cataract surgery is an increasingly prevalent aspect of premium cataract surgery practice. IOL technology has advanced significantly over the past several decades, and an increasingly diverse set of options for IOL correction of presbyopia has become available to physicians. An understanding of the relative strengths and weaknesses of each IOL technology is fundamental to proper patient selection, preoperative counseling, and surgical planning. This review describes...
current IOL technology for presbyopia correction in cataract surgery, quality comparative information where available, and new IOL technologies currently in development.

Monovision

Monofocal IOLs are spherical IOLs that produce focus at one point. Historically, both eyes have often been set for the same refractive target. Some patients may prefer emmetropia for distance, with use of reading glasses for near work, but others may prefer to be free of spectacles for reading, relying instead on corrective lenses for distance. In cases of nonrefractive low vision such as advanced macular degeneration, a patient may desire induction of high myopia with cataract surgery to obviate the necessity for the use of low-vision aids for reading. For correction of presbyopia, use of multifocal IOLs to create “monovision” has long been a popular choice for select patients. Monovision is created with induction of monocular myopia for near or intermediate work. The “dominant” eye is chosen using the Miles test, and that eye is often targeted for emmetropia. Trial contact lens inducing myopia in the nondominant eye should be performed preoperatively to ensure tolerance of anisometropia and associated aniseikonia prior to undergoing cataract surgery with a monovision target. Limitations of monovision include interference with stereoaucy, aniseikonia, subjective visual disturbance, and limitation to use only in the population of patients tolerant of induction of monovision.

Multifocal Intraocular Lens

The first of its kind, multifocal IOLs for correction of presbyopia were first implanted in human eyes in 1986 but were initially slow to be widely adopted.[6,7] A large variety of multifocal IOLs have been developed. Although early models such as the BioFilmCon have been discontinued, many multifocal IOLs remain widely available worldwide, though only a select few have been Food and Drug Administration (FDA) approved for sale in the United States [Table 1].[8,9] Multifocal IOLs may be categorized as refractive and diffractive as well as bifocal and trifocal. Refraction and diffraction refer to the physical mechanism used by the lens to cause bundling of light at distinct points.[10] IOLs may have both refractive and diffractive design components. Bifocal and trifocal describe the number of distinct focal points at which this light is bundled. Simultaneous perception of disparate images from these multiple focal points can be initially disturbing to patients and require a months-long period of neuroadaptation postoperatively.[11] Certain lenses are rotationally asymmetric, with an inferior segment containing the refractive power required for good near vision; positioning of this segment inferiorly, superiorly, temporally, or nasally has not been found to significantly affect visual performance.[12] Extended depth of focus (EDOF) refers to a longitudinally extended continuous focal point and is discussed separately.

Refractive

Progressive or zonal refractive multifocal IOLs use concentric zones of increasing dioptic power on the anterior lens surface, with highest dioptic power at the center of the lens. The goal of this design is to increase accommodative power in response to miosis with the near reflex, as a smaller pupil will allow light to pass through those refractive zones with higher dioptic power located at the center of the lens. The distribution of light passing through the lens varies between distance and near according to variation in pupil size. For example, an analysis of the bifocal refractive AMO Array SSM 26NB IOL demonstrated 50%–60% light allocation for distance, 22%–38% for near, and 15%–18% at intermediate foci.[13]

Diffractive

Diffractive IOLs rely on concentric diffractive surfaces on the posterior portion of the lens; this causes interference of optic wavefronts, designed such that interference between diffracted light rays may reduce but remains incapable of eliminating glare and higher order aberrations associated with multifocal IOLs. Apodized diffractive IOLs, such as progressive refractive IOLs, rely on pupil size to influence light distribution between distant and near focal points. Again, light passing through the lens is distributed between distance, near, and other foci. For example, the first ever 3 M diffractive bifocal IOL allocates 41% of incident light to distance and near focus, with 18% of light distributed to higher order diffraction.[13]

Refractive compared to diffractive

Refractive compared to diffractive IOLs tend to have greater frequency of symptomatic glare, haloes, and higher order aberrations.[14] Meta-analysis demonstrates refractive multifocal IOL tend to produce better-uncorrected distance visual acuity (UDVA) compared to diffractive multifocal IOL.[14] Diffractive multifocal IOL performed better than the refractive multifocal IOL in uncorrected near visual acuity (UNVA), reading acuity, reading speed, smallest print size, spectacle independence, halo, and glare rate.[14] There was no significant difference between the two groups with regard to uncorrected intermediate visual acuity (UIVA).[14]

Apodized versus nonapodized diffractive and progressive versus nonprogressive refractive

Apodized diffractive and progressive or zonal refractive IOLs rely on pupil size changes to mimic accommodation, whereas constant multifocal lenses have the same optical property over the entire optic surface. It is important to note that IOL decentration and pupil size affect
| Manufacturer   | IOL brand | IOL model | Material          | Pieces | Haptic design | Haptic angulation (degrees) | IOL (mm) | Optic (mm) | Focallity  | Optical Principle | Symmetry | Structure | Intermediate add (D) | Near add (D) | Incision Size (mm) | FDA Approved | Pupil Dependence | Location | Toric version |
|---------------|-----------|-----------|-------------------|--------|---------------|-----------------------------|----------|------------|------------|-------------------|----------|-----------|---------------------|-------------|-------------------|-------------|------------------|----------|---------------|
| 1°Q           | AddOn     | Hydroporphic acrylic | 1 Square, 4-flex haptics | Not published | 13.0 | 6.0 | Bifocal | Diffractive | Rotationally symmetric, convex -concave | Apodized | 0 | +3.00 | Not published | No | Yes | Subcus | Yes |
| Basis         | BasisQ    | Hydroporphic acrylic with hydrophobic surface | 1 4 double-loop haptics | 0 | 13.0 | 6.0 | Bifocal | Diffractive | Rotationally symmetric | Apodized | 0 | +3.00 or +3.5 | Not published | No | Yes | Bag | No |
| Basis         | Basis.Z   | Hydroporphic acrylic with hydrophobic surface | 1 Z-loop haptics | 0 | 13.0 | 6.0 | Bifocal | Diffractive | Rotationally symmetric | Apodized | 0 | +3.50 | Not published | No | Yes | Bag | Yes |
| Aaren scientific |        |            |                    |        |                |                             |          |            |           |                   |          |           |                      |             |                   |             |                 |          |               |
| Aquavision     | OptiVis MF | Hydroporphic acrylic | 1 4 double-loop haptics | 5 | 11.0 | 6.0 | Bifocal | Refractive | Rotationally symmetric | Apodized | 0 | +2.8 | 2.2 | No | No | Bag | No |
| AMO           | ReZoom    | Hydrophilic acrylic with PMMA haptics | 3 Modified C-loop haptics | 5 | 13.0 | 6.0 | Bifocal | Refractive | Rotationally symmetric | Progressive | 0 | +3.5 | 3.2 | No | Yes | Bag | No |
| TECNIS        | ZKB00     | Hydroporphic acrylic | 1 Modified C-loop haptics | 0 | 13.0 | 6.0 | Bifocal | Diffractive | Rotationally symmetric | Constant | 0 | +2.75 | 2.2 | Yes | No | Bag | No |
| TECNIS        | ZLB00z    | Hydroporphic acrylic | 1 Modified C-loop haptics | 0 | 13.0 | 6.0 | Bifocal | Diffractive | Rotationally symmetric | Constant | 0 | +3.25 | 2.2 | Yes | No | Bag | No |
| TECNIS        | ZMB00     | Hydrophilic acrylic | 1 Modified C-loop haptics | 0 | 13.0 | 6.0 | Bifocal | Diffractive | Rotationally symmetric | Constant | 0 | +4.0 | 2.2 | No | No | Bag | Yes |
| TECNIS        | ZMA00     | Hydrophilic acrylic | 3 Modified C-loop haptics | 0 | 13.0 | 6.0 | Bifocal | Diffractive | Rotationally symmetric | Constant | 0 | +4.0 | 2.2 | No | No | Bag | No |
| TECNIS        | ZM900     | Silicone | 3 Modified C-loop haptics | 0 | 12.0 | 6.0 | Bifocal | Diffractive | Rotationally symmetric | Constant | 0 | +4.0 | 2.2 | No | No | Bag | No |
| Alcon         | AcrySof IQ | Hydrophilic acrylic | 1 Modified L haptics | 0 | 13.0 | 6.0 | Bifocal | Refractive | Rotationally symmetric | Apodized | 0 | +2.5 | 2.2 | Yes | Yes | Bag | Yes |
| AcrySof IQ    | ReSTOR    | Hydrophilic acrylic | 1 Modified L haptics | 0 | 13.0 | 6.0 | Bifocal | Refractive | Rotationally symmetric | Apodized | 0 | +3.0 | 2.2 | Yes | Yes | Bag | Yes |
| AcrySof IQ    | ReSTOR    | Hydrophilic acrylic | 1 Modified L haptics | 0 | 13.0 | 6.0 | Bifocal | Refractive | Rotationally symmetric | Apodized | 0 | +4.0 | 2.2 | Yes | Yes | Bag | No |
| AcrySof IQ    | ReSTOR    | Hydrophilic acrylic | 1 Modified L haptics | 0 | 13.0 | 6.0 | Bifocal | Refractive | Rotationally symmetric | Apodized | 0 | +2.17 | +3.25 | 2.2 | No | No up to 4.5 mm | Bag | Yes |
| AcrySof IQ    | PanOptix  | Hydrophilic acrylic | 1 Modified L haptics | 0 | 13.0 | 6.0 | Trifocal | Refractive | Rotationally symmetric | Constant | +2.17 | +3.25 | 2.2 | No | No up to 4.5 mm | Bag | Yes |

Contd...
| Manufacturer | IOL brand | IOL model | Material | Pieces | Haptic design | Haptic angulation (degrees) | IOL (mm) | Optic (mm) | Focallity | Optical Principle | Symmetry | Structure | Intermed add (D) | Near add (D) | Incision Size (mm) | FDA Approved | Pupil Dependence | Location | Toric version |
|--------------|-----------|-----------|----------|--------|---------------|-----------------------------|---------|-----------|----------|-----------------|----------|----------|----------------|-------------|----------------|-----------|--------------|----------|--------------|
| Alsanza      | Alsafit   | Fourier   | Hydrophobic and hydrophilic acrylic with hydrophobic surface | 1 | Square edge (FINS4FIT) haptics | 0 | 11.0 | 6.0 | Trifocal | Diffractive | Rotationally symmetric | Apodized | +1.77 | 1.8 | No | Yes | Bag | No |
| Alsiol       | 3D VF     | Hydrophilic and hydrophilic acrylic with hydrophobic surface | Modified loop haptics (FINS2FIT) | 0 | 13.0 | 6.0 | Bifocal | Diffractive | Rotationally symmetric | Not published | 0 | +3.75 | 2.0 | No | No | Bag | No |
| Biotech      | Eyecryl Actv | DIYHS 600 ROH | Hydrophilic acrylic with hydrophilic surface | 1 | Double C-loop haptics | 5 | 12.5 | 6.0 | Bifocal | Diffractive | Rotationally symmetric | Constant | 0 | +3.75 | 2 | No | No | Bag | No |
| Care group   | AcriDIFF  | Hydrophilic acrylic | Modified C-loop haptics | 5 | 12.5 | 6.0 | Bifocal | Refractive-diffractive | Rotationally symmetric | Constant | 0 | +3.25 | 2.0 | No | No | Bag | Yes |
| iDiff        | 1-R       | Hydrophilic acrylic | Double loop haptics | 0 | 12.5 | 6.0 | Bifocal | Refractive-diffractive | Rotationally symmetric | Progressive | 0 | +3.0, +3.50, +4.0 | 2.0 | No | Yes | Bag | Yes |
| iDiff        | 1-P       | Hydrophilic acrylic | Plate haptics | 0 | 11.0 | 6.0 | Bifocal | Refractive-diffractive | Rotationally symmetric | Progressive | 0 | +3.0, +3.50, +4.0 | 2 | No | Yes | Bag | Yes |
| Preziol      | Multifocal Foldable IOL | Hydrophilic acrylic | Double C-loop haptics | 0 | 12.5 | 6.0 | Trifocal | Refractive | Rotationally symmetric | Progressive | +1.0 | +4.0 | 2.8 | No | No | Bag | No |
| Preziol      | Multifocal PMMA | Hydrophilic acrylic with hydrophilic surface | C-loop haptics | 0 | 12.5 | 6.0 | Trifocal | Refractive | Rotationally symmetric | Progressive | +1.0 | +4.0 | 2.8 | No | No | Bag | No |
| Carl Zeiss Meditec | AT LISA 809MP | Hydrophilic acrylic with hydrophilic surface | Plate haptics | 0 | 11.0 | 6.0 | Bifocal | Diffractive | Rotationally symmetric | Constant | 0 | +3.3 | 1.8 | No | No | Bag | Yes |
| AT LISA      | t l 809MP | Hydrophilic acrylic with hydrophilic surface | Plate haptics | 0 | 11.0 | 6.0 | Trifocal | Diffractive | Rotationally symmetric | Zonal | +1.67 | +3.3 | 1.8 | No | No | Bag | Yes |
|             |           |           |           |        |               |               |         |          |           |                 |          |          |                |             |                |            |              |          |              |          |              |
| Manufacturer          | IOL brand         | IOL model       | Material                  | Pieces | Haptic design | Haptic angulation (degrees) | IOL (mm) | Optic (mm) | Focallity | Optical Principle | Symmetry          | Structure    | Intermed add (D) | Near add (D) | Incision Size (mm) | FDA Approved | Pupil Dependence | Location | Toric version |
|-----------------------|-------------------|-----------------|---------------------------|--------|---------------|----------------------------|----------|------------|-----------|-------------------|-----------------|-------------|-----------------|--------------|-------------------|--------------|------------------|----------|---------------|
| Cristalens Reverso    | Hydrophilic       | 1               | C-loop haptics; Piggyback lens | 10     | 13.8          | 6.5                        | Bifocal  | Diffractive | Rotationally symmetric | Not published | 0           | +3.0            | 2.0          | No                | Not published | Sulcus           |          |               |
| Artis                | Hydrophobic       | 1               | 4 double -loop haptics     | 5      | 10.8          | 6.0                        | Bifocal  | Diffractive | Rotationally symmetric | Not published | 0           | +3.0            | 2.0          | No                | Not published | Bag               | Yes       |               |
| Hanita               | Seelens MF        | 1               | Modified C-loop haptics    | 5      | 13.0          | 6.0                        | Bifocal  | Diffractive | Rotationally symmetric | Apodized      | 0           | +3.0            | 1.8          | No                | Yes          | Bag              | No        |               |
| BinnyLens MF         | Hydrophilic       | 1               | 4-point double loop haptics| 5      | 11.0          | 6.0                        | Bifocal  | Diffractive | Rotationally symmetric | Apodized      | 0           | +3.0            | 1.8          | Yes               | Bag          | No               | No        |               |
| Hoya Surgical Optics | AF-1 iSii         | HY-60           | Modified C-loop haptics    | 3      | 12.5          | 6.0                        | Trifocal | Refractive  | Rotationally symmetric | Not published | 0           | +3.0            | 2.5          | No                | Bag          | No               | No        |               |
| Human Optics         | Diffractiva       | 1               | C-loop haptics             | 0      | 12.5          | 6.0                        | Bifocal  | Refractive  | Rotationally symmetric | Apodized      | 0           | +3.5            | 2.2          | No                | Yes          | Bag              | Yes       |               |
|                      | Diff-s, Diff-sA,  | 3               | C-loop haptics             | 0      | 14.0          | 6.0                        | Bifocal  | Diffractive | Rotationally symmetric | Apodized      | 0           | +3.5            | 2.2          | No                | Yes          | Sulcus           | Yes       |               |
|                      | Diff-sY, Diff-sAY |                 |                            |        |               |                            |          |            |                       |                |             |                 |              |                  |              |                  |           |               |
|                      | Add-On            |                 | Undulating C loop haptics, piggyback IOL | 5      | 14.0          | 7.0                        | Bifocal  | Diffractive | Rotationally symmetric | Apodized      | 0           | +3.5            | 2.2          | No                | Yes          | Sulcus           | No        |               |
| Lenstec Inc          | SBL 2             |                 | Plate haptics              | 0      | 11.0          | 5.75                       | Bifocal  | Refractive  | Rotationally asymmetric | Segmental     | 0           | +2              | No           | yes               | Bag          | No               | No        |               |
|                      | SBL 3             |                 | Plate haptics              | 0      | 11.0          | 5.75                       | Bifocal  | Refractive  | Rotationally asymmetric | Segmental     | 0           | +3              | No           | No                | Bag          | No               | No        |               |
| Medicontur           | Bi-Flex M         | 677 MY          | Double C-loop haptics, posteriorly vaulted | 0      | 13.0          | 6.0                        | Bifocal  | Diffractive | Rotationally symmetric | Apodized      | 0           | +3.5            | 1.8-2.2      | No                | No           | Bag              | Yes       |               |
| MTO                  | Presbysmart       |                 | Modified C-loop haptics    | 0      | 13.0          | 6.0                        | Bifocal  | Diffractive | Rotationally symmetric | Apodized      | 0           | +3.0, +3.5      | 2.2          | No                | Yes          | Bag              | Yes       |               |
|                      | Crystal Evolution |                 | Plate haptics              | 0      | 11.0          | 6.0                        | Bifocal  | Diffractive | Rotationally symmetric | Not published | 0           | +3.0, +3.5, +4.0 | 1.5          | No                | No           | Bag              | No        |               |
| Manufacturer | IOL brand          | IOL model         | Material                  | Pieces | Haptic design | Haptic angulation (degrees) | IOL (mm) | Optic (mm) | Focallity | Optical Principle | Symmetry | Structure | Interface add (D) | Near add (D) | Incision Size (mm) | FDA Approved | Pupil Dependence | Location | Toric version |
|--------------|--------------------|-------------------|---------------------------|--------|---------------|-----------------------------|----------|------------|-----------|------------------|----------|-----------|------------------|-------------|-------------------|-------------|------------------|----------|---------------|
| MBI         | PreciSAL M302A     |                   | Hydrophobic acrylic       | 1      | Modified C-loop haptics | 0              | 13.0    | 6.0       | Bifocal  | Diffractive      | Rotationally symmetric | Not published | 0          | +3.0             | 2.2         | No                | Not published | Bag              | No       |               |
| Oculentis   | LENTIS MF30 (X)    |                   | Hydrophilic acrylic       | 1      | Plate haptics   | 0              | 11.0    | 6.0       | Bifocal  | Refractive       | Rotationally symmetric | Segmental     | 0          | +3               | 2.0         | No                | No         | Bag              | Yes      |               |
| Oculentis   | LENTIS MF20        | SQFL 600DF        | Hydrophilic acrylic       | 1      | Plate haptics   | 0              | 11.0    | 6.0       | Bifocal  | Refractive       | Rotationally symmetric | Segmental     | 0          | +2               | 2.0         | No                | No         | Bag              | Yes      |               |
| OmniLens    | Revive             |                   | Hybrid acrylic            | 1      | Double loop haptics | 5              | 12.5    | 6.0       | Bifocal  | Diffractive      | Rotationally symmetric | Apodized      | 0          | +3.5             | 2.2         | No                | Yes        | Bag              | No       |               |
| PhysIOL     | FineVision Micro F |                   | Hydrophilic acrylic       | 1      | 4 double -loop haptics | 5              | 10.75   | 6.15      | Trifocal | Diffractive      | Rotationally symmetric | Apodized      | +1.75      | +3.5             | 1.8         | No                | Bag        | No              | No       |               |
| PhysIOL     | FineVision Pod F   |                   | Hydrophilic acrylic       | 1      | 4 single -loop haptics | 5              | 11.4    | 6.0       | Trifocal | Diffractive      | Rotationally symmetric | Apodized      | +1.75      | +3.5             | 2.0         | No                | Yes        | Bag              | YES      |               |
| Rayner      | M-Flex Sulcolex    | Multifocal        | Rayacryl, hydrophilic acrylic | 1      | Piggyback lens; modified undulating C-loop haptics | 10             | 14.0    | 6.50      | Bifocal  | Refractive       | Rotationally symmetric | Not published | 0          | +3.5             | 2.0         | No                | Yes        | Subcus           | Yes      |               |
| Rayner      | M-Flex Sulcolex    | Trifocal          | Rayacryl, hydrophilic acrylic | 1      | Piggyback lens; modified undulating C-loop haptics | 10             | 14.0    | 6.50      | Trifocal | Diffractive      | Rotationally symmetric | Apodized      | +1.75      | +3.5             | 2.2         | No                | Yes        | Subcus           | Yes      |               |
| Rayner      | M-Flex 580-F       |                  | Rayacryl, hydrophilic acrylic | 1      | Double loop haptics | 0              | 12.0    | 5.75      | Bifocal  | Refractive       | Rotationally symmetric | Zonal         | 0          | +3, +4           | 1.8         | No                | Yes        | Bag              | Yes      |               |
| Rayner      | M-Flex 630-F       |                  | Rayacryl, hydrophilic acrylic | 1      | Double loop haptics | 0              | 12.5    | 6.25      | Bifocal  | Refractive       | Rotationally symmetric | Zonal         | 0          | +3, +4           | 1.8         | No                | Yes        | Bag              | Yes      |               |
| Rayner      | RayOne             |                   | Rayacryl, hydrophilic acrylic | 1      | Closed loop haptics | 0              | 12.5    | 6.0       | Trifocal | Diffractive      | Rotationally symmetric | Apodized      | +1.75      | +3.5             | 1.8         | No                | Yes        | Bag              | Yes      |               |
| Soleko      | Review FIL 611 PV  |                   | Hydrophilic acrylic       | 1      | 4 double -loop haptics | 5              | 11.0    | 6.0       | Trifocal | Refractive       | Rotationally symmetric | Not published | +2.1       | +3.75            | 2.0         | No                | Not published | Bag              | Yes      |               |
| Review      | FIL 65 PVS         |                   | Hydrophilic acrylic       | 1      | Double -loop haptics; pediatric lens | 5              | 12.5    | 5.0       | Bifocal  | Refractive       | Rotationally symmetric | Not published | +2.1       | +3.75            | 3.0         | No                | Not published | Bag, sulcus, or scleral fixation | Yes      |               |

*Contd...*
refractive outcomes for both nonapodized and apodized diffractive, as well as progressive and nonprogressive refractive lenses.[15] Refractive outcome after monofocal IOL implantation is less sensitive to pupil size and IOL centration compared to multifocal IOL.[16]

**Bifocal versus trifocal**

Meta-analyses showed that trifocal IOLs demonstrated a small but statistically significant improvement in UDVA compared to bifocal IOL, but this difference is unlikely to represent a clinical advantage.[17-19] There was no significant difference in UNVA between bifocal and trifocal IOLs. There were no conclusive differences between bifocal and trifocal IOLs with regard to contrast sensitivity, subjective visual disturbances, spectacle independence, and patient satisfaction.[17-19] UIVA has been variably shown to be equivalent or better with trifocal compared to bifocal multifocal IOL.[17-19]

**Monofocal intraocular lens versus multifocal intraocular lens**

High-quality data exist in the comparison of monofocal IOL monovision with multifocal IOL and has been the subject of meta-analysis as well as a Cochrane review. Compared to monovision, patients receiving multifocal IOLs were less likely to be spectacle dependent but more likely to report glare, with no significant difference in UDVA.[20] Cochrane review and meta-analysis both demonstrated higher rates of spectacle independence with multifocal IOL compared to monovision.[20,21] However, multifocal IOL compared with monovision was not shown to provide meaningfully different UDVA, UIVA, and UNVA.[20] According to the Cochrane review, monovision demonstrated fewer symptomatic higher order aberrations compared to multifocal IOL, though with high estimate uncertainty.[21] Meta-analysis indicated that subjective visual disturbances including glare and haloes were both more common and more bothersome in patients receiving multifocal IOLs compared to monovision.[20]

Compared to multifocal IOLs, monofocal IOLs are not considered to cause reduction in contrast sensitivity, and thus may be a better choice in patients suffering from glaucoma, macular degeneration, or other diseases causing reduced contrast sensitivity.[22] There have been reports of multifocal IOL interfering with fundus visualization during vitrectomy; small-scale animal studies do not bear this out and more research is needed in this area.[23,24]

**Extended Depth of Focus Intraocular Lens**

EDOF IOLs have a longitudinally extended continuous focal point, rather than biphasic or triphasic peaks of best acuity as in bifocal or trifocal multifocal IOLs, and may use multifocal or pinhole optical designs to achieve this effect [Table 2].[8,9,25] The elongated focal point of manufacturing the IOLs, making them suitable for patients with reduced contrast sensitivity.
EDOF IOLs is designed to reduce overlap of near and far images as in multifocal IOLs, and theoretical studies using interferometry suggest that EDOF lenses provide better image quality at points between intermediate and near.\[^{28}\]

**Extended depth of focus compared to multifocal intraocular lens**

Although EDOF IOLs are relatively new technology compared to multifocal IOLs, multiple comparative studies have already been performed. Of note, the currently available safety and efficacy studies of EDOF IOLs and the only available randomized controlled trial do not meet quality criteria laid out in the American Academy of Ophthalmology Task Force consensus statement on EDOF lenses.\[^{25,27}\]

EDOF IOLs' accommodative effort, with a change in dioptric power, is possible that ciliary sulcus placement may confer improved refractive outcomes, and some accommodative IOLs are designed to be placed into the ciliary sulcus. An additional advantage of accommodative IOL technology is the potential to obviate the need for patients to experience the often-difficult period of neuroadaptation that is required with multifocal IOL.\[^{11,36}\] Currently, only Crystallens has been the FDA approved for sale in the United States; a much larger variety of accommodative IOLs are available worldwide. Although promising, many new accommodative IOLs are still in development. More research is needed to further develop and refine accommodative IOL technology.

**Accommodative Intraocular Lens**

Accommodative IOLs are designed to respond to accommodative effort, with a change in dioptric power, and represent a diverse group of technologies that defy generalization [Table 3].\[^{9,31}\] There are multiple principles, on which the current and past accommodative IOL technologies have been proposed to work, including position-changing single- or dual-optic IOLs, overlapping dual-lens varifocal IOLs, liquid-containing shape-changing IOLs, fluid interface changing IOL, and surgical techniques to fill the capsular bag with synthetic material.\[^{38}\]

Accommodative IOLs should by definition demonstrate anatomically measurable changes in dioptric power in reaction to accommodative efforts.\[^{32}\] Accommodation may be measured objectively with videorefractometry or streak retinoscopy, subjectively with convergence on a target or induction of defocus, or through simulation with topical pilocarpine.\[^{32,33}\] Some accommodative IOL designs are predicated on accommodative ciliary muscle contraction causing IOL optic movement anteriorly, increasing dioptric power. For 1.0 mm of anterior optic movement, single-optic IOLs produce 1.0D of accommodation, whereas dual-optic IOLs produce 2.5–3.0 D of accommodation.\[^{33,34}\] The amount of dioptric change in response to topical pilocarpine application as documented in the literature for each IOL is listed in Table 3. Small degrees of objectively measured accommodation with accommodative IOLs have been noted to be discordant with measured UNVA and distance-corrected near visual acuity (DCNVA), and pseudoaccommodative factors may also contribute to the near visual acuity measured in studies of accommodative IOLs.\[^{35}\]

Fibrosis of the capsular bag is believed to limit the accommodative functions of accommodative IOLs. It is possible that ciliary sulcus placement may confer improved refractive outcomes, and some accommodative IOLs are designed to be placed into the ciliary sulcus. An additional advantage of accommodative IOL technology is the potential to obviate the need for patients to experience the often-difficult period of neuroadaptation that is required with multifocal IOL.\[^{11,36}\] Currently, only Crystallens has been the FDA approved for sale in the United States; a much larger variety of accommodative IOLs are available worldwide. Although promising, many new accommodative IOLs are still in development. More research is needed to further develop and refine accommodative IOL technology.

**Accommodative intraocular lens compared to monofocal intraocular lens**

Meta-analyses have been performed comparing accommodative IOL to monofocal IOL. The majority of accommodative IOLs examined in studies included in these meta-analyses relies on single-optic forward motion within the capsular bag, and include the ICU lens, AT-45 Crystallens, and the BioComFold IOL. Accommodating IOLs demonstrated improved DCNVA and were associated with greater anterior lens shift in response to accommodation than monofocal IOLs. However, the degree of anterior shift of accommodating IOL with pilocarpine stimulation was estimated by meta-analysis to provide <1.0 D of accommodation.\[^{37}\] Spectacle independence was greater with accommodating IOLs than with monofocal IOLs.\[^{38,39}\] There was no significant difference in corrected distance visual acuity and contrast sensitivity between accommodating IOLs and monofocal IOLs.\[^{38}\]
| Manufacturer   | IOL brand | IOL model | Material                     | Number of pieces | Haptic Design | Haptic Angulation (degrees) | IOL diameter (mm) | Optic diameter (mm) | Optical principle | Symmetry            | Structure           | Intermediate add (D) | Near add (D) | Incision size (mm) | FDA approved | Location | Toric version |
|---------------|-----------|-----------|------------------------------|------------------|---------------|-----------------------------|-------------------|---------------------|-------------------|---------------------|----------------------|----------------------|---------------|---------------|--------------|------------|----------------|
| AMO           | TECNIS    | ZXR00     | Hydrophobic acrylic          | 1                | C-loop haptics | 0                           | 13.0              | 6.0                 | EDOF; diffractive  | Rotationally symmetric | Achromatic          | +1.78                | 0             | 2.2           | Yes          | Bag        | Yes          |
| Acufocus      | IC-8      | Biocompatible hydrogel (acrylic) | 1                | C-loop haptics | 5                           | 12.5              | 6.0                 | Pinhole; 3.23     | Rotationally symmetric | Pinhole              | 0                      | 0             | 3.5           | Bag          | No         | No           |
| Medicem       | WIOL-CF   | Methyacrylic copolymer (acrylic) | 1                | Bioanalog optic without haptics | n/a                     | 10.0              | 8.9                 | Axial motion (EDOF, refractive) | Rotationally symmetric | Progressive          | +1.5                    | +2.5                  | 2.5          | No           | Posterior capsule | No         | No           |
| Morcher       | Xtrafocus | Pinhole Implant | Black hydrophobic acrylic | 1                | Modified C-loop haptics     | 14               | 14.0              | Pinhole; 1.3 mm aperture | Rotationally symmetric | Pinhole              | N/A                    | N/A                    | 2.2          | No; approved outside of US for treatment of irregular corneal astigmatism | Sulcus | No           |
| Oculentis     | LENTIS    | Comfort LS-313 MF15 | Hydrophobic acrylic | 1                | Plate haptics               | 0                | 11.0              | 6.0                 | EDOF refractive    | Rotationally asymmetric | Segmental             | +1.5                | 0             | 2.2           | No          | Yes        |               |
| Sifi meditec  | Mini well | Copolymer      | Copolymer         | 1                | Fenestrated haptics         | 5                | 10.75             | 6.0                 | EDOF, refractive   | Rotationally symmetric | Progressive           | 0                      | +3.00            | 2.2           | No          | Bag        | Yes        |

AMO=Abbott Medical Optic, EDOF=Extended depth of focus, IOL=Intraocular len, N/A=Not available, FDA=Food and Drug Administration
Table 3: Accommodative Intraocular Lenses

| Manufacturer         | IOL brand    | IOL model | Material          | Number of pieces | IOL design | IOL diameter (mm) | Optic diameter (mm) | Optical principle | Measured accommodation (D) | Incision size (mm) | FDA approval | Location | Toric version |
|----------------------|--------------|-----------|-------------------|------------------|------------|-------------------|---------------------|-------------------|------------------------|-----------------|--------------|----------|---------------|
| AMO                  | Synchrony    | Synchrony | Silicone          | 1                | 2 optics   | 9.8               | 6.0                 | Dual-optic motion   | 1                      | 3.8            | No          | Bag      | No            |
| AkkoLens International | Lumina      | Lumina   | Acrylic           | 2                | 2 optics slide across one another, connected by spring-like haptics at lens edge | not published | Customized | Alvarez principle | 2–3                   | 2.8            | No          | Sulcus  | No            |
| Bausch + Lomb        | Crystalens   | Crystalens| Silicone optic with polymide haptics | 3                | Single optic with biconvex hinged plate haptics | 0           | 12.0         | Single-optic forward motion | >0.4                  | 2.8            | Yes         | Bag     | Yes           |
| Bausch + Sarfarazi   | Sarfarazi    | Elliptical| Silicone          | 1                | 2 optics connected by 3 spring haptics | not published | 9.0         | Single-optic forward motion | 4.0                  | No             | Bag         | No       | No            |
| Herzliya Pituah      | NuLens       | Dynacurve | PMMA-Silicone     | 2                | 4 PMMA haptics with posterior HEMA piston pressurizing silicone optic gel | not published | 10.0        | Axial motion          | 50-70                  | 5              | No          | Sulcus  | No            |
| Human Optics         | Akkomodative | 1CU Lens | Hydrophilic acrylic | 1                | Single optic with 4 flexible haptics | not published | 9.8         | Single-optic forward motion | 1.36–2.25             | 1.8            | No          | Sulcus  | No            |
| Lenstec, Inc.        | Tetraflex    |           | Hydrophilic acrylic | 1                | Single optic, closed loop haptics | 5          | 11.5         | Single-optic forward motion | 2                    | 2.8            | No          | Bag     | No            |
| Medennium            | SmartIOL     | SmartIOL  | Hydrophobic acrylic; gel at body temperature | 1                | Gel filling capsular bag | n/a       | 9.5         | Accommodation            | 3.5                   |                |             | Bag     | No            |
| Morcher              | BioComFold   | 43A, 43E | PMMA-acrylic      | 1                | Single optic connected to 3 circumlinear broad, perforated haptics | 12         | 10.2         | Single-optic forward motion | 0.7                  | No             | Bag         | No       | No            |
| PowerVision, Inc.    | FluidVision  | Hydrophobic acrylic fluid | 1                | Single optic and 2 C-loop haptics filled with fluid | 0          | 10.0         | Fluid movement within the IOL/Helmholtz theory | 3                    | 3.5            | No          | Bag     | No            |
| Soleko               | Optoflex     | FIL618    | Acrylic           | 1                | Single optic with 3 haptics connecting to annular ring | 5          | 10.4         | Single-optic forward motion | 0.23                  | 2.5            | No          | Bag     | No            |
| Tekia, Inc.          | Tek-Clear    | Hydrophilic acrylic | 1                | Single 360° full bag optic with circumferential plate haptic | 11.0       | 5.5         | Single-optic forward motion | NA                    | 2.8            | No          | Bag     | No            |

AMO=Abbott Medical Optics, IOL=Intraocular lens, NA=Not available, FDA=Food and Drug Administration, PMMA=Polymethylmethacrylate
Accommodative intraocular lens compared to multifocal intraocular lens

One randomized controlled trial compared the 1CU accommodative IOL, array multifocal IOL, and Clariflex monofocal IOL. In this trial, distance-corrected binocular near visual acuity was similar among accommodative and multifocal IOLs; both were superior to monofocal IOL. Spectacle independence and accommodative range were superior in the multifocal IOL compared to accommodative IOL and superior in the accommodative IOL compared to monofocal IOL. Rates of glare were similar among accommodative and monofocal IOL and were lower than with multifocal IOL. Due to the variety of accommodative IOL technologies, the findings of this study may not be readily generalizable to all accommodative IOLs.

New Intraocular Lens Technologies

Noninvasive postoperative refractive adjustment

The RxSight Light Adjustable Lens was the FDA approved for sale in the United States in November, 2017 for patients with corneal astigmatism and without macular disease [Table 4]. This is the first IOL approved in the United States capable of noninvasive postoperative refractive adjustment. This monofocal IOL is made of material reactive to ultraviolet (UV) light delivered by the light treatment device within the first 17–21 days after surgery. Refractive adjustments are made over 7–14 days postoperatively, with 3–4 light treatment sessions lasting 40–150 s each, capable of adjusting both sphere and cylinder to best fit patient preference. This treatment is the FDA approved to correct up to 2 D of residual postoperative refractive sphere and/or cylinder. Patients in clinical trials receiving this IOL gained 1 line of UDVA compared to controls. Contraindications to use of the RxSight IOL include medication use that would increase sensitivity to UV light exposure and history of ocular herpes simplex virus infection.

Refractive index shaping uses another kind of light to alter refraction postoperatively, that of an ultrafast femtosecond laser combined with an optical focusing device. This technology has the additional advantage of potentially creating multifocal refractive surfaces postoperatively. This promising technology is currently in development by two companies: Perfect Lens in association with the University of Utah and Clerio Vision in association with the University of Rochester. Unlike the RxSight lens which is currently the FDA approved for use in humans, refractive index shaping technology is still being refined in animal models.

Advantages of noninvasive postoperative refractive adjustment of an already implanted IOL include the ability to overcome unexpected refractive changes...
related to effective lens position. Refractive index shaping, though still a budding technology, may have the potential to make refractive lens adjustments or even create lens multifocality long after implantation of the original IOL.

**Adjunct intraocular implant**

The Omega Gemini Capsule, currently undergoing investigational use in humans in the United States, is a refractive capsule with internal shelf-like spaces designed to be implanted into the capsular bag, allowing controlled placement of an IOL into a specific location within the capsular bag [Table 4]. This in principle works to reduce unexpected postoperative shifts in effective lens position. Theoretically, the Gemini Capsule also creates the possibility of additional intracapsular IOL insertion if desired within this larger intracapsular space. In addition, an IOL placed within the shelves of the device could theoretically be moved later onto a different position to effect a refractive change as a patient ages. Although investigational implantation in humans has begun, this device is not yet in clinical trials.

**Electronic intraocular lens**

Still in the research fundraising phase, Swiss Advanced Vision recently announced the launch of a project to develop the Real-Time Autofocus Servo Control lens. Theoretically, this lens would be designed to fully restore accommodative function using a solar energy capture system paired with a varifocal lens to allow real-time focus adjustment based on the object being viewed. This technology is also advertised to potentially allow augmented reality, apps, or other interactive features to be incorporated into development of the IOL. Developing this technology successfully necessitates creation of stable, biologically inert intraocular electronic circuitry and associated self-sustaining power source. This technology remains at a very early and theoretical stage in development.

**Patient Selection**

This is perhaps more appropriately termed patient election, as not only selecting the most desirable method of presbyopia correction but also choosing to undergo cataract surgery at all is an elective decision that must be made by the patient. Patients undergoing cataract surgery with placement of a presbyopia-correcting IOL must be motivated to be spectacle independent. In addition, patient personality must also be considered during preoperative counseling.

Multifocal IOLs by design divide light entering the eye into different focal points, causing the brain to perceive multiple images simultaneously. Processing these disparate images requires central adjustment of neural visual inputs, and this process of neuroadaptation can be time-consuming and frustrating for patients. The success of neuroadaptation to multifocal IOL is dependent on individual as much as refractive factors; patients with personality traits of compulsive checking, orderliness, competence, and dutifulness have been found to be more likely to experience glare and haloes postoperatively, possibly as a result of failure of neuroadaptation. Failure of neuroadaptation after multifocal IOL placement can lead to patient frustration. The most frequently reported indications for explantation of multifocal IOL are blurry vision, glare, and haloes.

Far more common than need for IOL exchange, however, is patient dissatisfaction. In one case series, the most common cause of dissatisfaction with multifocal IOL was ametropia. Postoperative ametropia is influenced by the accuracy of preoperative biometry, as well as effective lens position. In the case of multifocal IOLs, effective lens position affects the near focal distance as well. Globe size also influences near focal distance outcomes; in general, the greater the distance between the cornea and the multifocal IOL, the farther the near focal distance is likely to be postoperatively. Pupil size may also influence refractive outcome, and IOL selection must be undertaken carefully in patients with large pupils. Larger pupil size has been shown to improve contrast sensitivity and improve UDVA but lessen UNVA in multifocal diffractive IOL. Posterior capsular opacification may also contribute to postoperative visual disturbance, and must be distinguished from higher order aberrations and associated issues with neuroadaptation related to the IOL itself. Management of patient dissatisfaction must be performed with care, and YAG capsulotomy delayed while lens exchange remains a possibility. Patient lifestyle must also be discussed, as eye trauma postoperatively may lead to lens decentration or dislocation.

Nonrefractive conditions limiting visual acuity must be evaluated and ruled out prior to pursuing presbyopia correction with IOL placement. It is necessary to exclude conditions such as amblyopia, optic neuropathy, or retinal disease that would preclude “good” vision even in an optically perfect environment. It is also necessary to exclude corneal conditions such as keratoconus, corneal scar, and other causes of irregular astigmatism that would compromise refractive outcome. In patients suffering from retinal disease, wherein detailed examination of the retina may be necessary for optimal medical and surgical management, IOL selection should be considered carefully.

**Surgical Planning Considerations**

Accurate preoperative biometry and lens calculations are of paramount importance in ensuring expected and
desired refractive outcomes. To ensure optimal refractive outcome when using a presbyopia-correcting IOL, it is important to ensure that astigmatism has been treated to within 0.5 D. Any patients with 0.5 D or greater of regular preoperative astigmatism may benefit from toric IOL placement or limbal relaxing incisions. To this end, proper lens centration within the capsular bag is also important to refractive outcome. Although presbyopia-correcting IOLs function through a variety of optical mechanisms, all are susceptible to tilt and decentration leading to compromised optical performance. In the case of Crystalens, the only FDA approved accommodative IOL available in the United States, the risk of capsular contraction syndrome (also known as Z syndrome) must be mitigated with use of central capsulorrhexis, adequate anterior capsular coverage of plate haptics, and fastidious cortex removal.\[36\]

**Conflicts of interest**

The authors declare that there are no conflicts of interests of this paper.

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