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ADVANCES IN OPHTHALMOLOGY AND OPTOMETRY

Advanced Technology Intraocular Lenses

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Keywords

- Presbyopia correcting lenses • Multifocal intraocular lenses
- Extended depth-of-focus lenses • Accommodative intraocular lenses
- Phakic intraocular lenses • Light adjustable lenses

Key points

- Intraocular lenses (IOLs) have been in use since 1949 to correct for presbyopia and include accommodative, multifocal, and extended depth-of-focus lenses.
- Multifocal lenses typically are either diffractive, refractive, or use qualities of both in an attempt to achieve spectacle freedom; however, they also induce photic phenomena including glare, halos, and starbursts as a consequence of multiple images focused simultaneously on the retina.
- Extended depth-of-focus IOLs have been developed to correct presbyopia to a certain degree while reducing the risk of photic phenomena.
- Light adjustable IOLs allow the spherical and cylinder power of the implant to be adjusted after cataract surgery.
- Phakic IOLs may be considered in young patients with a clear crystalline lens who do not meet criteria for excimer laser eye surgery.

INTRODUCTION

Cataract surgery has a surprisingly long history, dating back to as early as 600 BC. Intraocular lenses (IOLs) were not introduced until 1949, when the first IOLs were created out of polymethylmethacrylate. Although riddled with

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complications such as glaucoma, inflammation, and IOL dislocations, this technology paved the way for modern cataract surgery. Monofocal lenses have a fixed power and require the use of glasses to fully correct for refractive error including myopia, hyperopia, and astigmatism.

Multiple intraocular lens technologies have been developed to help patients functionally restore the ability to see at near as well as distance to achieve partial or complete spectacle independence and improve their quality of life. The first multifocal intraocular lens was Food and Drug Administration (FDA) approved in 1997 to help provide satisfactory vision at distance, intermediate distance, and near after cataract surgery or refractive lens exchange [1,2]. Some limitations exist to the use of multifocal IOLs, namely photic phenomena including glare, halos, and/or starbursts, which are a consequence of having images simultaneously focused on the retina.

One technology emerging in the realm of presbyopia-correcting IOLs is the extended depth-of-focus (EDOF) lens. These lenses create a single elongated focal point, contrasted to the multiple foci of multifocal IOLs, and aim to reduce photic side effects such as glare and halos. The elongated focus aims to improve intermediate vision while retaining distance vision, however, often at the expense of near visual performance when compared with multifocal lenses [3].

The development of the advanced technology intraocular implants for presbyopic correction has garnered intense interest for the potential of spectacle independence after cataract surgery. The cataract extraction procedure for implantation of a multifocal and EDOF lenses is the same as that for a monofocal lens and has similar safety profiles. In this article, recent developments in advanced technology IOLs will be discussed.

Phakic IOLs have emerged for use in patients with clear crystalline lenses, allowing young patients to preserve accommodation. They are used to correct refractive error for patients that may not meet the corneal thickness or curvature requirements to safely undergo excimer laser surgery. They also have the benefit of correcting a larger refractive error, beyond the limits of safe LASIK (*laser-assisted in situ keratomileusis*) or PRK correction.

SIGNIFICANCE

Accommodative Lenses

Accommodative IOLs are either single-optic or dual-optic systems. The only available accommodative intraocular lens in the United States is the CrystaLens that uses a single-optic system. In this system, a single optic has flexible haptic that allows anterior movement of the lens to change the focal length and increase the dioptric power of the eye [1,4]. Clinical trials have demonstrated up to 1 diopter of accommodation [1].

In contrast, in the dual-optic system, as the name suggests there are two separate optic; the anterior lens has a high power, and the posterior lens has a negative power. Their relationship to each other defines the dioptric power of the eye and changes based on the zonular tension. When the ciliary muscles contract with accommodation, the zonular fibers relax, causing the lenses in the dual-optic system to separate in the anterior–posterior direction, increasing the dioptric power of the eye [1,4]. The mean accommodative range in one such lens, the Synchrony, which is not available in the United States, is 3.22 ± 0.88 diopters [1]. One disadvantage of the Synchrony is that it requires a relatively large 3.7 mm incision, which can induce unplanned postoperative astigmatism [1].

Multifocal Lenses

Multifocal lenses use light rays at distance, intermediate, and near points to be simultaneously focused on the retina. Diffractive, refractive, or hybrid physical principles are used to create multiple distinct focal points to achieve spectacle freedom [4,5]. Multifocal IOLs are additionally differentiated as either rotationally symmetric or rotationally asymmetric and apodized or non-apodized. Studies have shown multifocal IOLs to have 3 to 5 diopters between primary and secondary focal points, achieving a depth of field of 2-3x that of a monofocal IOL [6].

Diffractive IOLs are the most commonly implanted multifocal lenses [7]. These lenses have a series of concentric rings on the surface of the lens resulting in discontinuity in optical density, allowing light particles to change direction when they encounter the rings using the Huygens–Fresnel principle [6–9]. The distance between each sequential ring is called a step height [1]. Varying the size and pattern of step heights allows the relative distribution of light energy at each focal point. At the first step height, the smallest concentric ring in the center of the lens, all light rays are focused at near [1]. The step height gradually decreases toward the periphery of the lens, where a smaller proportion of the wavelength as the discontinuity in the rings causes a change in the direction and speed of the light [1,7], allowing multiple focal points rather than the one focal point seen in traditional monofocal IOLs [7].

Apodized lenses, such as the Restor (which has hybrid diffractive and refractive qualities), have a gradual decrease in diffractive step heights from the center to the periphery [7]. When looking at a near object, the pupil is miotic due to the near triad (miosis, accommodation, convergence) allowing only the central concentric rings to be exposed to light, making the focal point at near [1,7]. When looking at distance, the pupil is mydriatic allowing more of the concentric rings of smaller step heights to be exposed, allowing light to diffract at a focal point of distance [1,7]. Seeing distance targets in bright light settings is a challenge of apodized IOLs, as bright lights constrict the pupil allowing only the central rings for near targets to be exposed. In contrast, non-apodized lenses such as the Tecnis multifocal IOL, AT LISA 809, step heights are uniform from central to periphery [7]. Therefore, the light distribution is independent of pupil size, and an equal amount of light is distributed to both the near and distant focal points [1,7].

Rotationally symmetric lenses are more commonly inserted than rotationally asymmetric lenses, which have an embedded inferior add power, similar to that of a bifocal spectacle. They are available outside of the United States. Rotationally asymmetrical lenses, such as the Lentis Mplus LS-313 (a refractive IOL), were first developed in 2009; they have an embedded inferior segmental near add segment and aim to reduce the photic phenomena seen in the rotationally symmetric IOLs [2,7]. One such example is the LENTIS Mplus [1]. The IOL is independent of pupil size greater than 2 mm [1]. It is a single piece IOL with a +3.0D or +1.5D add. Despite attempts to minimize photic phenomena, asymmetrical IOLs still can have pupil-dependent photic phenomena as the center of the pupil moves slightly nasally while constricting, so the amount of light distributed between the near and distance portions of the IOL, and subsequently the vision, can be unpredictable [2] (Fig. 1).

Refractive IOLs have concentric zones of different dioptric powers [7]. This is achieved by varying the curvature of the anterior or posterior surface of the lens [6]. They are pupil dependent [7] (Fig. 2).

An example of a hybrid diffractive–refractive multifocal IOL is the Alcon Panoptix. It is a one-piece aspheric IOL [7]. It has a 4.5 mm diffractive area in the center with 15 diffractive zones and an outer refractive rim, resulting in +2.17D intermediate add power and +3.25 near add [7]. As a compromise

Fig. 1. Rotationally asymmetric multifocal intraocular lens. (*From* Pazo EE, McNeely RN, Richoz O, Nesbit MA, Moore TCB, Moore JE. Pupil influence on the quality of vision in rotationally asymmetric multifocal IOLs with surface-embedded near segment. J Cataract Refract Surg. 2017;43(11):1420-1429.)

Fig. 2. AcrySof Restor SN6AD3, an example of an apodized diffractive lens. (Alió JL, Pikkel J. Multifocal Intraocular Lenses: The Art and the Practice. Springer Nature 2014.)

for multiple focal points, there is splitting of light, with a distribution of 25% at near (40 cm), 25% at intermediate (60 cm), and 50% at distance [7]. It also employs a fourth focal point at 1.20 m due to light from the first focal point diffracting further than the focal length that is not visible but allows intermediate vision to be at a more comfortable distance [7].

Optical Side Effects in Multifocal Intraocular Lenses

Because light is distributed among multiple focal points, photic phenomena or undesired light images in the visual field occur in multifocal IOLs [7]. These include glare, halos, and/or starbursts [7]. In addition, the light in the out-of-focus image reduces the contrast of the in-focus image [1,7]. Multifocal IOLs are also associated with a reduction in contrast sensitivity as the light in the out-of-focus image reduces the contrast of the in-focus image. When comparing multifocal IOLs to monofocal IOLs, a higher incidence of reported glare and halos occurs in the multifocal groups, RR (relative risk) 1.41 (95% CI 1.03–1.93) and 3.58 (1.99–6.46), respectively [5]. Patients typically adapt to the unwanted optical phenomena in a 6-month period in a process called neuroadaptation in which the brain suppresses the unwanted image, but some patients have persistent symptoms [1,7]. Multifocal IOLs overall have a high satisfaction rate with more than 90% of postoperative patients indicating that they would choose the same intraocular lens again; however, up to 10% of patients are intolerant of the photic phenomena, and some require IOL explantation [1,9].

Extended-Vision Intraocular Lens

EDOF lenses are a new technology emerging in the realm of presbyopia-correcting IOLs. These lenses create a single elongated focal point, contrasted to the multiple foci of multifocal IOLs The elongated focus aims to improve intermediate vision while retaining distance vision; however, this often is at the cost of near visual performance when compared with multifocal lenses. They aim to reduce photic phenomena compared to multifocal IOLs.

The first EDOF IOL was produced by Johnson and Johnson Vision (Symfony) in 2014, later FDA approved for use in the United States in 2016. Since then, several EDOF IOLs have been released to the market.

Vivity is a new EDOF intraocular lens using Alcon's proprietary X-wave technology. It is a novel, non-diffractive lens with a 6-mm biconvex, aspheric optic. The lens is produced from a high refractive index hydrophobic acrylic material with blue-light-filtering properties [10,11]. The anterior surface of the Vivity lens is designed with negative spherical aberration and created using the wavefront shaping technology, and its central optical element achieves the extended depth of field vision. The light rays passing through the central 2.2 mm of the wavefront-shaping zone of the optic are stretched and shifted compared with the peripheral light rays, extending the range of focus [10]. A toric version of the Vivity is also available, which achieves astigmatic correction with the biconic structure of the posture surface of the lens [10] (Fig. 3).

The Vivity DFT015 lens provided a greater negative range of binocular defocus when compared with the SN60WF monofocal lens, with no abrupt drop in visual acuity. Clinical studies show that the Vivity lens achieved the improvement of uncorrected binocular intermediate and near visual acuity of 1 line better versus the Alcon SN60WF monofocal lens 6 months postoperatively in patients aiming for emmetropia [12]. At 6 months, the percentage of patients in the Vivity group reporting no visual disturbance was comparable to patients in the SN60WF group. The same study reported lower average mesopic contrast sensitivity in the DFT015 when compared with the SN60WF group.

Since then, other studies published have supported the improvement of intermediate vision with the DFT015 lens [13,14]. Kohnen and colleagues found that 63% of patients with bilateral Vivity IOL implantation reported no optical phenomena at 3 months postoperatively [14]. In this study, 38% of patients reported needing reading spectacles, whereas 50% of the patients are entirely spectacle independent at all distances [14]. In another study, where patients were bilaterally implanted with the Vivity IOL, with a target of emmetropia in the dominant eye and a target of −0.75 in the non-dominant eye, 76% of all patients had binocular distance-corrected VA of 0.2 logMAR (Logarithm

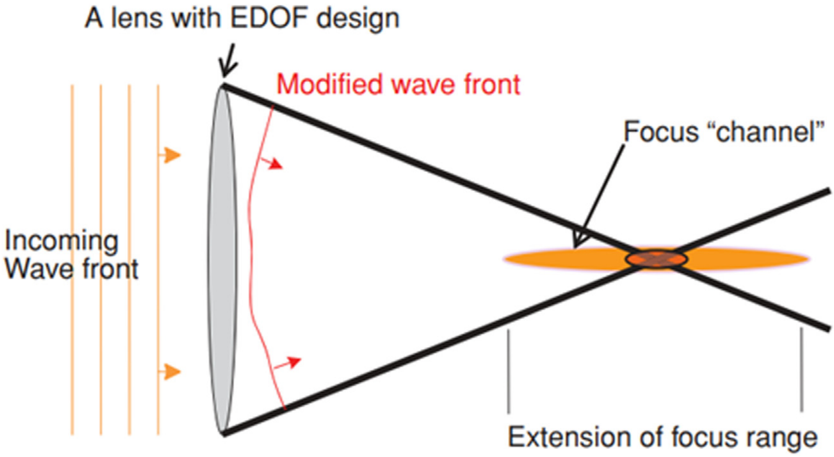

Fig. 3. Visual representation of the mechanism of an EDOF IOLan extended depth of focus IOL modifies the light wavefront and creates an elongated focal point (*From* Zeev Zalevsky "Extended depth of focus imaging: a review," SPIE Reviews 1(1), 018001 (1 January 2010).)

of the Minimum Angle of Resolution) or better at distance, intermediate, and near [15].

Monofocal Intraocular Lenses with Increased Depth of Focus

The Tecnis Eyhance is a new, advanced monofocal IOL produced by Johnson & Johnson. It is a 1-piece, biconvex aspheric lens with a 6.0 mm optic, with a continuous 360-degree posterior square edge design [16]. The lens is similar to the Tecnis monofocal lens ZCB00; however, it is distinguished by a continuous change in power from the periphery to the center of the lens. In addition to this, the lens is built with negative spherical aberration to extend its depth of focus. A study on Eyhance lens found that the power profile at the center 2 mm of the lens grants a myopic defocus of −0.5D with a 2 mm pupil [17].

Several studies have found the Tecnis Eyhance lens to be superior to the Tecnis 1-piece monofocal lens for intermediate vision without compromising distance vision while retaining a photic side effect profile similar to a traditional monofocal lens [18–22]; however, it has not yet been proven to be superior in near vision. When comparing the Tecnis Eyhance to the Tecnis Symfony (an EDOF lens), the two lenses seem to have comparable distance and intermediate vision while the Symfony achieves superior near vision and higher rates of spectacle independence [23]. This, however, is at the expense of more photic phenomena [23–25].

Light Adjustable Intraocular Lenses

Light adjustable IOLs are the only type of intraocular implants that allow adjustments of lens power after cataract surgery to improve refractive accuracy. This lens is based on the principles of diffusion. The light adjustable lens is composed of a silicone matrix embedded with photosensitive macromers. After lens implantation, ultraviolet (UV) light is directed at an area of the lens, which would turn the macromers into polymers. This creates a diffusion gradient, drawing macromers to diffuse into the light-exposed area until equilibrium is reached, resulting in a predictable shift in lens curvature and is capable of changing both the spherical and cylinder power of the lens. The adjustable range varies between −2D to +2D sphere and up to 3D cylinder. Up to four sessions of light treatment may be needed to achieve the desired lens power. After the target vision has been achieved, UV light is directed to the optic to secure the final power [26]. An FDA study of 600 participants found that those who received the light adjustable lens are twice as likely to achieve a uncorrected distance vision of 20/20 when compared with a standard monofocal lens [26].

This new technology of light adjustable lenses comes with a few caveats. Light adjustment procedures require full view of the IOL optic and require good pupillary dilation. Patients are also required to adhere strictly to full-time wear of UV-blocking glasses for several weeks after cataract surgery, as any unintended exposure may prevent future adjustments of the lens power. In addition, the implantation of this lens is contraindicated in patients with certain eye diseases such as macular disease and prior history of herpes eye infection [26].

Phakic Intraocular Lenses

An additional advanced technology utilizing intraocular lens placement is the use of phakic IOLs in patients with clear crystalline lenses. In this technique, artificial lenses are placed in phakic eyes allowing preservation of the architectural integrity of the cornea in patients who do not meet eligibility criteria for excimer laser treatment in laser-assisted in situ keratomileusis or photorefractive keratectomy [27]. In addition, phakic IOLs can correct a refractive spherical error ranging from −20D to +22D, which is a significantly larger range compared to that which can be corrected with an excimer laser (approximately −12D to +6D) [27]. Early attempts at the use of phakic IOLs started in 1950 but resulted in untoward side effects including corneal decompensation due to endothelial cell loss, uveitis-glaucoma-hyphema syndrome due to iris chafing, accelerated cataract formation, and astigmatism induced by a large surgical wound required for lens insertion [27]. In 2004, the FDA approved the first phakic IOL for use in myopia. Present day, phakic IOLs are categorized by their placement: anterior chamber supported, iris-fixated in the anterior chamber, or sulcus-fixated like in the implantable collamer lens [27]. Newer phakic lens models may still result in corneal decompensation and glaucoma like in earlier models, but improved architecture have allowed them to be safer and have predictable refractive outcomes [27].

DISCUSSION, FUTURE CONSIDERATIONS, AND SUMMARY

Over the years, new advancements in intraocular lens implant technology broadened the options for presbyopia correction in patients undergoing cataract surgery. The advent of the computer and internet age led to increasing demand for intermediate vision, as our daily lives became more intertwined with the digital screen. As the technology for modern cataract surgery has matured, new options for advanced technology IOLs have been developed.

The more commonly used presbyopia-correcting lens is the multifocal lens, which presents the earliest attempts to correct for presbyopia using IOLs. These lenses take advantage of optical properties including diffraction, refraction, or combination of the two to allow images from different distances to be simultaneously focused on the retina to try to make patients spectacle-free. As a consequence, out-of-focus images can contribute to reduced contrast sensitivity and photic phenomena, including glare, halos, and starbursts. The photic phenomena typically resolve within 6 months in a process called neuroadaptation; however, up to 10% of patients are intolerant of the side effects, and some result in lens explantation. Multifocal lenses create distinct peaks on the defocus curve correlating to improved visual acuity at determined distances, with comparatively blurrier vision in between. As a consequence, out-of-focus images can contribute to reduced contrast sensitivity. The Tecnis Synergy IOL, a hybrid diffractive multifocal and EDOF lens that was FDA approved in May 2021, has anecdotal evidence of improved contrast sensitivity compared with other multifocal IOLs, though this has not yet been formally published. In the future, it would be advantageous to create multifocal IOLs that are pupil-independent and lack the photic phenomena seen in current models.

Given the optical side effects of multifocal IOLs, eligible patients should be selected and consented carefully to ensure no preexisting ocular disease that could limit visual acuity. Lifestyle and occupational choices should be discussed with patients before implantation as patients that do activities in low light settings may be especially intolerant of the reduced contrast sensitivity [1]. A thorough slit-lamp examination and supplemental imaging should be ordered to explore pathology that could exacerbate the ability for multifocal IOLs to work most effectively. Macular pathology should be ruled out before the implantation of multifocal IOLs, such as with optical coherence tomography, as even small macular abnormalities can result in reduced contrast sensibility that can be worsened by implantation of a multifocal IOL [7]. Patients with corneal disease such as epithelial basement membrane disease, particularly in the central visual axis, should also avoid multifocal IOLs [1]. Glaucoma is a relative contraindication and may be acceptable if mild stage [7]. High hyperopes may also have a large angle kappa after implantation and centration of a multifocal IOL and may not tolerate them [1]. Lastly, as many of the multifocal IOLs are pupil dependent, pupil reactivity should be assessed before implantation [6].

Data on the CrystaLens, which is the only approved accommodating IOL in the United States, demonstrate a mean uncorrected near visual acuity of 0.19 logMAR (Snellen equivalent, 20/31), a mean uncorrected intermediate visual acuity of 0.07 logMAR (Snellen equivalent, 20/23), and a mean uncorrected distance visual acuity of 0.08 logMAR (Snellen equivalent, 20/24) [28]. Compared with monofocal IOLs, accommodative IOLs seem to allow patients to achieve better near visual acuity at 6 months postoperatively (on average, an improvement of 3.20 Jaeger units), and at 12 months postoperatively. Although accommodative lenses were found to have improved distance visual acuity at 6 months compared with monofocal lenses (0.04 standard deviations better), accommodative lenses comparatively had worse vision with time, with 12 months or more compared with monofocal lenses (0.12 log-MAR worse). The decreased vision is possibly attributed to a higher rate of posterior capsular opacification [4].

EDOF IOLs provide a wider range of uncorrected vision when compared with monofocal lenses. They provide some degree of spectacle independence by delivering improved intermediate vision without compromising distance visual acuity. As the increasing commodity of smartphone and computer use, many patients find the intermediate vision range to be increasingly important. In addition, as the Vivity EDOF uses a non-diffractive technology and does not split the light like a diffractive lens might, contrast sensitivity may be preserved [29]. All of these properties can make the EDOF IOLs an attractive option for patients who value spectacle independence at intermediate distances while reducing the chance of glare and halos.

Patients with preexisting ocular disease who might not otherwise qualify for a multifocal lens may benefit from an EDOF lens or a monofocal with EDOF properties due to its relatively preserved contrast sensitivity and reduced photic phenomenon. Additionally, depending on the specific needs of the patient, one may further extend the depth of focus by using a monovision approach with the EDOF IOLs by targeting one eye for emmetropia and the other eye for mild myopia [30,31], granting some degree of spectacle independence at near. In addition, one may take advantage of the myopic defocus curve of the EDOF to aim for true plano for distance vision, as any potential postoperative hyperopia may be tolerated thanks to the extended focus depth of the lens.

Compared with traditional monofocal IOLs, the Tecnis Eyhance provides approximately a −0.5D of myopic defocus, providing some uncorrected intermediate vision. Although its intermediate range is less than a traditional EDOF IOL, it comes with the advantage of being considered a monofocal IOL and incurs no extra out of pocket cost for the patient.

Compared with monofocal IOLs, no statistically significant difference occurs in unaided distance visual acuity in multifocal IOLs [5]. Multifocal IOLs showed the improved near vision compared with monofocal IOLs as well as a higher incidence of spectacle independence [5]. Comparing rotationally asymmetric refractive multifocal IOLs to apodized diffractive multifocal IOLs, the diffractive multifocal IOL group had better near visual acuity outcomes and a lower incidence of aberrations [28]. The rotationally asymmetric refractive multifocal IOL group had better intermediate visual acuity outcomes and contrast sensitivity [28].

Reviewing data comparing visual outcomes within the subcategory of multifocal and EDOF lenses has been challenging as the lenses have different near focal points [32]. Most studies show no statistically significant difference in best corrected distance visual acuity among the multifocal platforms [32]. For intermediate distances, all lenses have an average visual outcome in the 20/20 to 20/30 range from 50 to 80 cm [32]. Overall, studies comparing presbyopia-correcting lenses including multifocal and EDOF IOLs have demonstrated a higher prevalence of spectacle independence compared with monofocal IOLs [29,32]. Comparing the degree of visual quality at distance, near, and intermediate distances, the level of spectacle independence and side effect profile between multifocal and EDOF IOLs may be an interesting area of future research which can further delineate the differing visual profiles between the two types of IOLs.

Many new IOL technologies are on the horizon, including an intraocular capsular implant, which allows for exchange of IOLs and also may eliminate the variable of effective lens position by controlling the X, Y, and Z plane within the eye [33]. Ongoing clinical trials exist evaluating the efficacy of fluid-filled, shape-changing IOLs designed to mimic natural accommodation [34]. As developing technologies bring forth an abundance of new lens technologies to correct presbyopia, it is important to consider the patient's expectations and baseline ocular function to choose a lens which would ultimately best suit their lifestyle and visual needs.

CLINICS CARE POINTS

- Explore the patient's expectations of spectacle independence and side effect profile before choosing a presbyopia correcting intraocular lense (IOL)
- When choosing a presbyopia correcting lens, take care to review the full ocular history.
- The ideal candidate for a multifocal lens is a healthy eye with no other ocular diseases
- For patients who are not a good candidate for multifocal lenses, extended depth-of-focus IOLs may be an option to provide some level of spectacle independence for distance and intermediate tasks.

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