INVITED REVIEW

Presbyopia Correcting Intraocular Lenses

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ABSTRACT

Presbyopia is a global condition increasingly affecting the aging population. In recent years, rapid progress in intraocular lens (IOL) technology has expanded the options available for presbyopia correction. Advances in optical design, including aspheric, diffractive, refractive, and extended depth-of-focus (EDOF) concepts, aim to provide a broader range of vision while minimizing visual disturbances such as halos, glare, and loss of contrast. These innovations have also been supported by the use of novel biomaterials and enhanced haptic designs to improve intracapsular stability and long-term safety. However, the increasing diversity of IOL platforms has created challenges in terminology, classification, and clinical decision-making.

This review seeks to clarify the main optical principles underlying current presbyopia-correcting IOLs, summarize reported clinical outcomes, and highlight their respective advantages and limitations. Careful patient selection, combined with an understanding of the latest IOL technologies, remains essential to achieving optimal postoperative satisfaction and spectacle independence.

Keywords: Extended depth of focus intraocular lenses, monofocal plus lenses, multifocal lenses, premium intraocular lens, presbyopia

BACKGROUND

Refractive lens exchange and modern presbyopia-correcting intraocular lenses (IOLs) have advanced considerably in recent years, with the primary goals of improving visual outcomes, reducing procedure-related complications, and enhancing postoperative quality of life. [1]

Presbyopia has become a very important problem today with increasing life expectancy, a decrease in the normal amplitude of accommodation with age, the inability to meet the needs of the individual at near- vision distance, and increasing expectations of individuals. Many patients expect to be able to see up close, as well as comfortably see at near, far, and intermediate distances and live a spectacle-free life. Following lens extraction during cataract surgery, the eye loses approximately 20-30% of its total refractive power, however IOL implantation can correct refractive deficit.[2] The 'ideal' correction of presbyopia should restore correct focus and sustain the emmetropic level for decades.

Monofocal IOLs remain the most frequently implanted lenses worldwide. With monofocal lenses, the best corrected visual acuity (BCVA) can be obtained at a fixed distance, but they do not not provide correction at close and intermediate distances, and the person is dependent on glasses. Mini-monovision with monofocal lenses, in which the dominant eye is set for distance vision and the non-dominant eye is set for intermediate distance or near vision, is an option for intermediate distance and near vision, but it has many limitations, such as stereopsis loss.[3]

With the development of technology, there have been revolutionary developments in IOLs, and they continue to increase daily. Successful outcomes rely on selecting an appropriate IOL through a clear understanding of the patient's visual requirements as well as the strengths and lim-

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itations of the available lens technologies. Despite all these developments, it still needs to be possible to produce IOLs that provide perfect images of different targets at various distances without increasing aberrations and loss of light energy.

The literature contains many studies and reviews comparing and describing the materials, focal points, and optical designs of different IOLs. This review aims to describe the premium IOLs used in presbyopia correction by categorising them according to their optical properties and revealing their superiority or weakness compared to each other and the existing studies.

1. Multifocal IOLs (MfIOLs)

In MfIOLs, multiple focal points are obtained through diffractive rings on the anterior surface of the lens in diffractive lenses and through optical regions with different refractive indices in refractive lenses. Therefore, they are more susceptible to residual refractive errors than monofocal IOLs, which affects patient satisfaction and visual quality.[4, 5] Decreased visual quality is associated with reduced contrast sensitivity and increased halo and glare rates.[6] Trifocal IOLs function by splitting light into 3 focal points, optimising visual acuity for various degrees of distance, and serving as near, intermediate and distance pre-vision.[7] Studies in the literature indicate that trifocal lenses are superior to monofocal and multifocal lenses in near and intermediate distance vision.[8, 9] Several studies have shown that the diffractive design of trifocal IOLs splits incident light more than bifocal IOLs, potentially decreasing contrast sensitivity and increasing photic phenomena.[10-12] Recent progress in IOL design has facilitated the evolution of MfIOLs and contributed to enhanced visual performance. In this review, MfIOLs are classified into refractive, diffractive, and hybrid refractive-diffractive optical types, and their design and characteristics are systematically summarized (Table 1).

Table 1. *Classification of Multifocal Intraocular Lenses (MfIOLs) Based on Optical Design Types*

Category of Multifocal IOLs (MfIOLs)	**Lenses (Manufacture)**
Refractive MfIOLs	
Rotationally Symmetric Refractive MfIOLs	Array SA40N (AMO), ReZoom NXG1 (Advanced Medical Optics), M-flex 630 (Rayner), FIL611PV (Soleko Ltd.)
Rotationally Asymmetric Refractive MfIOLs	Lentis Mplus series (Teleon), SBL-3 (Lenstec Optical Group)
Diffractive MfIOLs	
Bifocal Diffractive MfIOLs	Tecnis series (ZKB00, ZMB00, ZLB00) (Johnson & Johnson Vision), MicroSilâ 612 DAY (Human Optics)
Trifocal Diffractive MfIOLs	FineVision series(POD F, Micro F, POD F GF) (Physiol), RayOne Trifocal (Rayner), AT LISA tri 839MP (Carl Zeiss Meditec Company), Enova Maestro (VSY biotechnology), Intensity SeeLens (Hanita Lenses RCA)
Hybrid Refractive- Diffractive MfIOLs	
Bifocal Hybrid MfIOLs	AcrySof ReSTOR (e.g., SN6AD1, SV25T0) (Alcon), AT LISA 809M (Carl Zeiss Meditec Company), Eyecryl Acty (Biotech Vision Care), Acriva Reviol MfIOLs (VSY biotechnology), OptiVis (Aaren Scientific), Acri.LISA 366D (Acritec Industries), Acri.Twin system 737D and 733D (Acritec Industries), AcriDiff (Care Group), iDiff Plus 1-R and 1-P (Care Group)
Trifocal Hybrid MfIOLs	AcrySof IQ PanOptix TFNT00 (Alcon), TRIVA-aA (HumanOptics), TriDiff (Care Group), Tecnis Synergy (Johnson & Johnson Vision)

1.1. Refractive MfIOLs

Progressive or zonal refractive MfIOLs use concentric zones to increase dioptric power on the anterior lens surface, with the highest dioptric power at the centre of the lens. The design increases accommodative power in response to myosa with near reflex, as a smaller pupil allows light to pass through refractive zones of higher dioptric power located in the centre of the lens.[13]

1.1.1. Rotationally symmetric refractive MfIOLs

The second-generation silicon MfIOL, AMO® Array SA40N, was first introduced in 1997.[14] This IOL optic is characterised by 5 concentric aspheric refractive zones that split the incident light between near, intermediate and far foci, thus allowing focusing at different distances.[15] Sen et al. demonstrated that Array SA40N IOLs provide visual superiority over monofocal IOLs at near and far distances and patient satisfaction despite reduced contrast sensitivity.[16] However, capsular opacification due to these lenses has been reported as an essential problem.[17]

The ReZoom NXG1 IOL (AMO, USA) is a promising solution to reduce photic disturbances. This second-generation refractive IOL incorporates a modified square-edge design aimed at lowering the risk of posterior capsular opacification (PCO), while also refining certain features of the original Array lens.[15] The design increases the size of the second and third zones, decreases the extent of the fourth and fifth, and introduces an aspheric transition across the zones. Although it provides functional vision at distance, intermediate, and near ranges, its performance is constrained by pupil size because of the lens's zonal design. It has demonstrated superior distance performance in photopic conditions and less favorable performance in mesopic conditions.[18] Gierek-Ciaciura et al. found that ReZoom NGX1 lenses outperformed Array SA40N lenses in uncorrected distance visual acuity (UDVA) but were not as effective as diffractive and hybrid refractive-diffractive lenses in uncorrected near visual acuity (UNVA).[19]

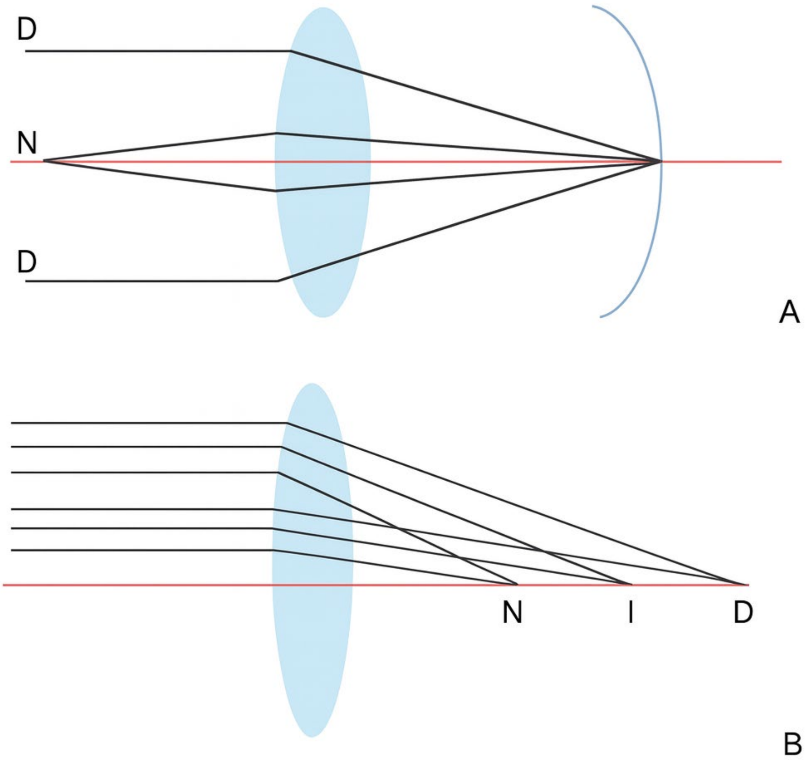
The M-flex 630 series of MfIOLs, developed by Rayner IOLs Ltd. in the United Kingdom, demonstrated favorable outcomes in both distance and intermediate visual acuity following implantation. This series provided different near additions ranging from 30 to 50 cm. In the study by Rabsilber et al., the +3.0 D model was found to be significantly superior in uncorrected intermediate visual acuity (UIVA), nstilling confidence in its performance. Another model of refractive MfIOLs, FIL611PV, was shown to offer worse UDVA and UNVA than diffractive MfIOLs.[20, 21]

In summary, rotationally symmetric MfIOLs show great potential, offering improved distance visual acuity and some restoration of near visual acuity compared to other MfIOLs. However, the additional focus may lead to a decrease in contrast sensitivity, an increase in photic disturbance, and a reduction in spectacle independence at close distances. While some refractive MfIOLs with aspheric surfaces can enhance visual quality, it's important to remember that visual quality deterioration is a possibility when issues such as pupillary dependence, tilt, and decentration arise.[21] Salati et al. reported that photic phenomena decreased and satisfaction with visual results increased in elderly patients with pupil diameter of less than 3 mm.[22]

1.1.2. Rotationally asymmetric refractive MfIOLs

Rotationally asymmetric refractive MfIOLs incorporate two optical segments with distinct refractive powers, one optimised for distance and the other for near vision.[23] The aspheric junction of these segments modifies the path of incoming light relative to the optical axis, minimising visual blur induced by diffraction and interference.[23] At the same time, rotational asymmetric refractive MfIOLs lack a concentric ring for refraction or diffraction, which is expected to minimize the formation of photic phenomena such as glare and halo formation. With the improved optical design, asymmetric refractive MfIOLs unequivocally outperform symmetric MfIOLs, providing better visual outcomes in terms of refraction, contrast sensitivity and patient satisfaction.[23]

The Teleon Lentis (Netherlands) Mplus series were the first lenses commercially available as asymmetric refractive MfIOLs. These biconvex acrylic one-piece IOLs are characterized by an innovative sector-shaped near vision segment with a seamless transition zone between the near and far vision zones.[24] Numerous studies have shown that Mplus series lenses offer significantly improved distance vision, high contrast sensitivity, and notably less halo and flare.[6, 25, 26] The series includes the LS-312 model with C-loop haptic and the LS-313 model with flat haptic. In a study comparing LS-MF15 IOL and LS-MF30 IOL models



Figures 1A and B: *(A) Ray tracing of a basic refractive bifocal IOL. (B) Ray tracing of a multifocal IOL with multiple aspheric zones (D: Distance I: Intermediate N: Near)*

with different near insertion powers as +1.5 D and +3. D, it was found that LS-MF30 IOL was more successful for UDVA and UNVA, and LS-MF15 IOL was more successful for UIVA. [26, 27]

In 2016, Lenstec Optical Group Ltd. (United Kingdom) introduced another segmented refractive MfIOL, the SBL-3 (ClearView 3). It features a sector-shaped far-vision zone at the top of the front surface and a sector-shaped near-vision zone at the bottom, providing a continuous and variable dioptri.[28] This unique feature, unlike other Lentis Mplus lenses, places the near segment in the inferior nasal part. While SBL-3 IOLs deliver satisfactory distance and near visual acuity, they show no significant difference when compared with other Lentis Mlus series lenses.[29] According to the metanalysis by Xu et al., Mplus IOLs demonstrate superior performance in intermediate visual acuity, but fall short in distance visual acuity compared to monofocals and in near visual acuity compared to bifocal IOLs.[26]

1.2. Diffractive MfIOLs

Diffractive MfIOLs, a pioneering development in the field, are based on the Huygens-Fresnel principle. When light encounters obstacles, diffraction occurs if the size of the obstacles is close to or smaller than the wavelength (Figure 2). Diffraction is one way of guiding light.[30] According to Whitman's diffraction principle, diffractive MfIOLs incorporate elements from both monofocal and toric designs and utilize a diffractive component to split the incident light into multiple focal points.[9] This process generates four diffraction orders: the 0th order for distant vision, the first order for near vision, and additional orders that do not converge at a specific focal point, typically leading to higher-order aberrations (HOAs).

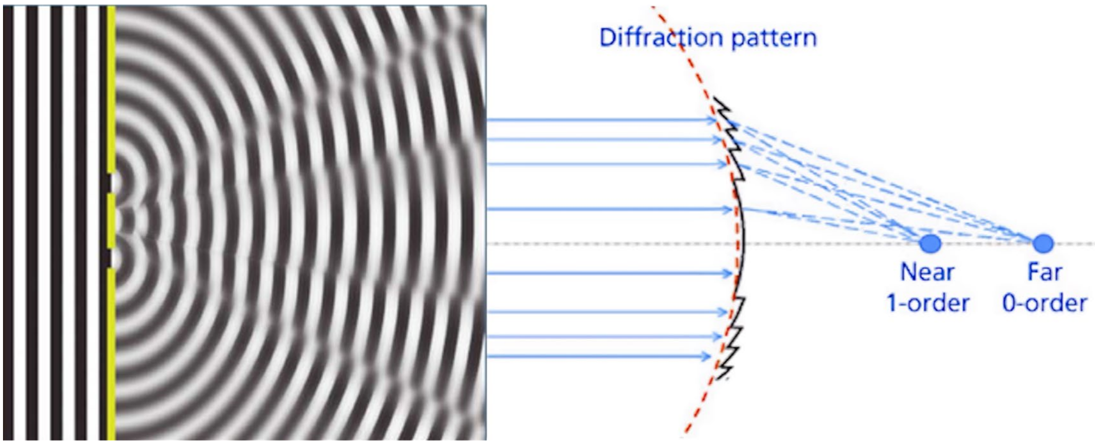


Figure 2. *Schematic representation of the diffractive lens principle. Incident parallel light is modulated by concentric diffractive zones, producing constructive interference that directs energy into discrete diffraction orders, with the first-order focus corresponding to near vision and the zero-order focus corresponding to distance vision.*

1.2.1. Bifocal diffractive MfIOLs

The Tecnis diffractive MfIOL (Johnson & Johnson (J&J) Surgical Vision, Inc., Santa Ana, CA, USA) is an acrylic lens with an aspheric front surface and a back surface with diffractive rings that focus both near and far light regardless of pupil size.[31] The ZM900, ZMA00, and ZMB00 models have high close insertion strength (+4.0 D), and the ZLB00 and ZKB00 models have lower close insertion strengths of +3.25 and +2.75 D, respectively[9]. When Tecnis ZMB00 was compared with other models, there was no significant difference in UDVA, but UNVA was found to be better than the others at 33 cm.[32] Given that the typical working distance for most individuals ranges between 40 and 60 cm, IOLs with low near additions can provide a degree of enhancement in intermediate visual performance.[33]

Another bifocal diffractive MfIOL is the HumanOptics MicroSilâ 612 DAY, which has 25.5 D optical power and +3.5 D near addition. It is made of silicone material and has a biconvex shape with an aspherical surface and a diffractive profile on the front surface of the lens.[31]

1.2.2. Trifocal diffractive MfIOLs

Although the near, intermediate, and distance visual acuity of bifocal multifocals are acceptable, trifocal lenses have been produced to meet this need, especially as the need for intermediate vision has increased with the changing lifestyle.

The Physiol FineVision is a diffractive trifocal lens and offers patients sharp near and distance vision plus good intermediate vision with virtually no change in distance vision under mesopic conditions. It combines two overlapping diffractive profiles, one with +1.75 D addition for intermediate vision and one with +3.50 D addition for near vision, providing three useful focal points. There are 3 forms, hydrophilic (FineVision POD F and FineVison Micro F) and hydrophobic (FineVision POD F GF), with similar design and refractive strengths. In comparative studies between hydrophilic and hydrophobic versions of the lens, it was concluded that there was no significant difference between them in terms of visual and refractive results.[34, 35] Micro F's with larger optics have been shown to provide the best vision for patients requiring large lenses.[36] In a prospective study involving eyes undergoing cataract or refractive lens exchange surgery with Physiol FineVision IOL implantation, 87% of patients reported achieving complete spectacle independence, a significant improvement in their quality of life. In addition, only 10% of patients reported seeing halos around lights at night, and no patients reported seeing ghostly images.[37]

Another trifocal lens with a fully diffractive design is the RayOne lens produced by Rayner. The lens, which has fewer rings than other trifocal lenses, is specifically designed to enhance night vision and reduce potential visual disturbances. With 16 diffractive rings in the central optical zone of 4.5 mm on the front surface, it effectively divides the incoming light energy for 52% distance, 22% intermediate, and 26% near vision through a 3 mm pupil. This design ensures a vision from 37.5 cm to 75 cm with +1.75 D intermediate vision addition and +3.50 D near vision addition, providing a secure performance in low light conditions.[9, 38] In a prospective and randomized study comparing FineVision POD F, RayOne Trifocal, and AcrySof IQ Panoptix IOLs, there were no statistically significant differences between the groups in distance, intermediate, and near vision. Except for the difference in depth perception intensity between RayOne IOL and POD F, which was less in RayOne IOL group, there was no significant difference between the groups in scotopic contrast sensitivity and visual quality with and without glare.[38] Another study comparing the RayOne IOL to the FineVision series found no significant differences in defocus curves or visual quality across all distances. However, the RayOne Trifocal demonstrated a more favorable manifest spherical equivalent and was associated with fewer issues related to depth perception compared to the FineVision POD F group.[39]

Manufactured by Carl Zeiss Meditec Company, the AT LISA tri 839MP MfIOL with diffractive design, non-apodised, aspheric, and toric options, has +3.33 D near addition and +1.66 D intermediate distance addition. In order to provide adequate light distribution to near distances even in mesopic conditions, only the central 4.34 mm diameter area functions as trifocal, while the peripheral one is bifocal, and thus pupil independent vision is aimed.[40] AcrySof® IQ ReSTOR +3.0 D and +2. 5 D MfIOLs, AT LISA tri 839MP IOL and FineVision Micro F12 trifocal IOLs were evaluated for resolution, image quality and photic phenomena. The AT LISA tri and FineVision trifocal IOLs provided an effective additional focus for intermediate vision; however, they were linked to more pronounced halos and a reduction in distance vision quality when compared with ReSTOR +2.5 D and +3.0 D MfIOLs.[41] Carson et al. compared optical bench performance for PanOptix, FiveVision, and AT LISA.[41] Contrast sensitivity was evaluated with the optical modulation transfer function (MTF). Panoptix had a higher MTF value than the other 2 trifocals in both intermediate and intermediate foci, while AT LISA was found to be higher than the others in the near focus.[41] Another diffractive MfIOL manufactured by Zeiss Meditec Company is the AT ELANA 841P. Its optical design, based on the AT LISA 839MP, has been significantly improved to have higher light transmission efficiency and a higher allocation of light to near vision, instilling confidence in its ability to improve near and intermediate vision without compromising distance vision. It has a spherical aberration-neutral optic with diffractive rings on the entire surface. Zeiss' patented smooth micro phase (SMP) manufacturing technology minimizes light scattering and associated visual symptoms.[42]

VSY biotechnology's Enova Maestro trifocal diffractive lens has a sinusoidal vision technology (SVT), unlike other MfIOLs (Figure 3). It is claimed that SVT provides the right amount of light for optimum distance, intermediate,

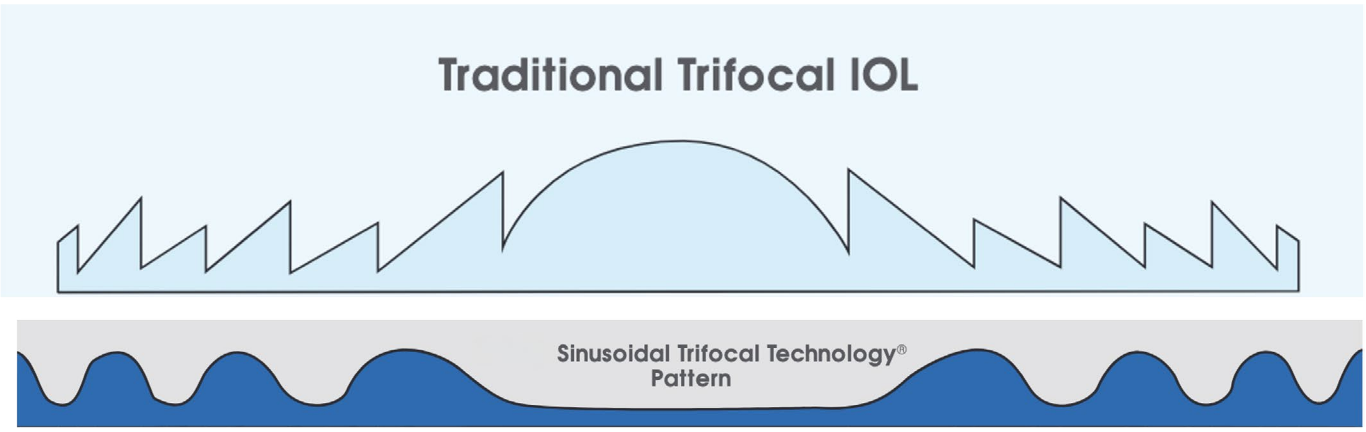


Figure 3: *The conventional trifocal diffractive lens design is shown on the top and the Enova Maestro lens design of sinusoidal vision technology (SVT) is shown on the bottom.*[43]

and near vision with a smooth transition between profile elements. It thus has unique light distribution and significantly reduces halo and glare. It was reported that the best visual acuity was obtained at 80 cm for pupil independent vision and intermediate distance and 40 cm for near distance. However, the literature has yet to be studied in which the clinical results of Enova Maestro have been published and compared with other IOLs.[43]

Intesity SeeLens (SL) MfIOL, launched by Hanita Lenses RCA Ltd, has a hydrophilic, aspheric diffractive back surface and a spherical front surface, and has a modified sinusoidal profile with 12 soft steps at different heights in the diffractive zone between 1 and 5.2 mm in diameter. With this sinusoidal profile, negative diffraction orders are also utilised, unlike most lenses on the market that use 'saw-tooth' profiles, which only use positive diffraction orders. The use of negative diffraction may increase the risk of increased chromatic aberration; however, since the material of this lens has a high Abbe number of 55 and thus shows much lower chromatic dispersion, the manufacturer's laboratory studies have reported that the colour dispersion at order -2 is comparable to the zero order of commonly used trifocal IOLs (such as FineVision; PhysIOL or AcrySof IQ PanOptix).[44, 45] In a review study in which ocular straylight was compared after uncomplicated cataract surgery involving several MfIOLs, Intensity SL IOL was shown to have the lowest straylight rate. In the results of the study, hydrophobicity was mentioned as a factor of postoperative straylight elevation. However, while the data for Intensity SL comes from much fewer sources, there are many more and different centred studies for other IOLs. It was stated that this may affect the study's results.[46]

1.3. Hybrid refractive-diffractive MfIOLs

The main disadvantages are pupil dependence in refractive IOLs and loss of energy transmitted to the retina in diffractive IOLs. Side effects such as increased dysphotopsia and reduced contrast sensitivity relative to monofocals can impair visual performance and reduce the quality of life of patients.[47] In the search for solutions to these problems, the emergence of designs with combined diffraction and refraction has provided valuable information. These hybrid designs can redistribute incident light between different foci, offering a potential solution to these issues.[48]

1.3.1. Bifocal refractive-diffractive MfIOLs

The AcrySof ReSTOR® (Alcon) apodized diffractive IOL received Food and Drug Administration (FDA) approval in 2005.[49] Its optical concept relies on apodization, employing a centrally near-focused zone encircled by concentric rings of gradually reduced step heights, which distribute light to both near and distant foci. Different near addition options (+2.5 D SV25T0, +3.0 D SN6AD1, and +4.0 D SN6AD3) are offered to match the individual patient's visual needs.[3, 50] The lens's general shape is symmetrical biconvex with a spherical aberration of -0.1 µm, and the apodised diffractive structure is located on the front aspheric surface.[31, 50] The anterior surface incorporates negative spherical aberration, counterbalancing the cornea's positive aberration. In the SN6AD1 model, 9 diffractive steps are closer to each other, and 60% of the central diffractive zone with a diameter of 0.86 mm is devoted to near focus and 40% to far vision. In the SV25T0 model, 7 diffractive steps are closer, and the central refractive zone with a diameter of 0.94 mm is completely designed for distance vision.[33, 41, 51] In a study comparing these two models, SN6AD1 provided better vision at a distance of 30-40 cm, while SV25T0 provided better vision at a distance of 50-70 cm.[52]

Another hybrid MfIOL manufactured by Carl Zeiss Meditec Company is the AT LISA 809M bifocal model. The preloaded lens with flat haptics is made of hydrophilic acrylic material. In a prospective randomized study conducted by Maurino et al. the AT LISA 809M and AcrySof Restor SN6AD1 models were compared in terms of satisfaction, visual complaints, and visual function measurements after being implanted bilaterally. The study's findings, which showed no significant difference in terms of patient satisfaction, visual function, and photopic complaints in both groups. However, in a small but significant minority of patients with photopic complaints, there was no regression in complaints in 4-8 months, and this situation caused dissatisfaction.[53]

Eyecryl (Biotech Vision Care, India) Actv is a bifocal MfIOL with a diffractive-refractive design, rotationally symmetric, sharp-edged, +3.0 D near insertion option. According to Haldipulkar et al., both Eyecryl and AcrySof lenses yielded comparable results for BCVA, photopic contrast, defocus curves, reading indices, stereopsis, and perceived visual quality. The Eyecryl lens, however, provided enhanced mesopic contrast sensitivity and reduced unwanted visual phenomena[48]

Acriva Reviol MfIOLs made from hydrophobic acrylic material and manufactured by VSY biotechnonology (Netherlands), are available in three forms: MFM 611, MFB 625, and MF 613. In the study published by Turhan and Toker, the reading performances of Acriva Reviol MFM 613 MfIOL and AcrySof ReSTOR SN6AD1 MfIOLs in the first 12 months after implantation were compared. Although both MFIOLs perform well, Acriva Reviol MFM 613 MfIOL has been shown to be superior in intermediate vision and AcrySof ReSTOR SN6AD1 MfIOL in near vision.[54] However, today, VSY biotechnonology has stopped the production of Acriva Reviol MfIOLs.

Another hybrid-designed bifocal MfIOL is the OptiVis MfIOL manufactured by Aaren Scientific. It is designed to compensate for spherical aberration to achieve outstanding optical performance for distance vision, even in clinically occurring cases of IOL misalignment and/or tilt. It has a central 1.5 mm progressive refractive zone surrounded by a 1.5 mm to 3.8 mm diameter diffractive zone for good performance in pupil independent distance and near vision. The apodised diffractive design minimises the loss of outside light. In addition, the aspheric lens periphery improves image contrast in large pupils for corneal asphericities.[47] In a study by Park et al. comparing the early clinical results of OptiVis and AcrySof ReSTOR D1 MfIOLs, OptiVis was more successful at intermediate distance, while no statistically significant difference was found in terms of distance and near distance, wavefront aberration, contrast sensitivity and IOL position.[55]

The Acri.LISA 366D, a product of Carl Zeiss Meditec, stands out with its hybrid concept. This design has proven successful in achieving clear vision at far, close, and intermediate distances in numerous studies.[56, 57] The optic surface is separated into main zones and phase zones, with the latter possessing an average refractive power that matches the zero-order diffractive power of the main zones. The IOL power responsible for distance vision is simultaneously diffractive and refractive.[58] To further enhance its performance, Acritec Industries introduced the Acri. Twin system, consisting of the 737D and 733D models, to minimize visual complaints. This twin system was designed based on the evaluation of 343 consecutive patients who underwent asymmetric bifocal implantation of the far-sighted 737 D and near-sighted 733D Acri.Twin system by Alfonso et al.[56] Binocular assessment has shown that the lens provides effective distance and near vision simultaneously, along with enhanced contrast sensitivity under both photopic and mesopic conditions. However, discrepancies in visual acuity and contrast sensitivity between monocular and binocular conditions have been reported, likely resulting from unequal light allocation among the lenses.[56]

AcriDIFF (+3.25 near insertion) and iDiff Plus 1-R and 1-P (+3, +3.5, +4.0 D near insertion) IOLs manufactured by Care Group are rotationally symmetric bifocal MFIOLs with refractive-diffractive design. AcriDiff incorporates a yellow tint for blue light filtration, with transition zones of increasing height on the front surface and an aspherical back surface. In IDiff Plus MfIOLs, the increased step height and diffractive pattern, along with the greater step angles between transition zones, facilitate balanced light distribution and achieve higher modulation transfer function (MTF) values.[59, 60]

1.3.2. Trifocal refractive-diffractive MfIOLs

Developed in 2015 by Alcon Laboratories (USA), AcrySof IQ PanOptix TFNT00 IOL is a non-apodized MfIOL with a central biconvex optic with an inner diffractive and an outer refractive zone.[40].Splits incoming light with three focal points from far to mid and near to create mid and near add powers of +2.17 D and +3.25 D, respectively, enabling optimum close reading distances at 60 cm and 42 cm.[61] The anterior surface is shaped to introduce a negative spherical aberration term, which counteracts the cornea's average positive spherical aberration.[40]

The PanOptix IOL features a quadrifocal design and incorporates ENLIGHTEN, a unique technology that shifts the intermediate focal point at 120 cm to the distant focal point, improving visual performance. Its central optical zone includes a 4.5 mm non-apodized diffractive region, which transmits 88% of light to the retina when the pupil is 3.0 mm in size. This design ensures efficient light utilization and consistent performance across various lighting conditions, as it is minimally affected by pupil size.[40, 62] Additionally, a toric version is available to address astigmatism.

In an international multicentre, prospective study, Kohnen et al. published 1-year visual results of AcrySof IQ Pan Optix trifocal IOL and an evaluation of the safety of the IOL.[63] The safety of the lens was evaluated by looking at many factors, including complete ophthalmoscopic examination, secondary surgical interventions, IOL observations and damage, IOL decentralization and tilt, intraocular pressure, surgical complications, and posterior capsulotomy. Bilateral eyes of 145 patients were included in the study. According to the study, PanOptix IOL was shown to provide an excellent safety profile with satisfactory visual acuity results during the 12-month follow-up after implantation. In addition, good intermediate visual acuity was obtained under photopic conditions; the defocus curve showed visual acuity of 20/25 Snellen and better at near and intermediate distances. In a study comparing AcrySof IQ PanOptix and AT LISA tri 839 MP, PanOptix was shown to have better visual results at intermediate and distance with higher contrast sensitivity under different conditions.[64]

Another hybrid design trifocal lens TRIVA-aA (HumanOptics Holding AG, Erlangen, Germany) is a MFIOL with a diffractive aspheric front surface in the center and a non-aberration design with refractive optics in the periphery. The peripheral refractive optical design is aimed at reducing photic phenomena and achieving near-perfect distance vision even under mesopic conditions. The achromatic central diffractive field has been developed to increase the extended focal range and reduce halos and glare. The lens with +1.75 D intermediate distance addition and +3.5 d near distance addition is also available in toric form for patients with astigmatism.[65] Pastor-Pascual et al. reported that 95.65% of the patients had high or very high satisfaction, and 74% had no visual problems in their daily lives after bilateral implantation of Triva -aA IOL.[66]

MfIOL TriDiff is a refractive-diffractive designed MfIOL manufactured by Care Group (India). The TriDiff IOL contains two diffractive patterns with an aspheric posterior surface on the anterior surface, which provides optimum optical quality at all distances and is thought to minimise the effects of light scattering, such as glare, halos, and reduced contrast sensitivity. It provides an additional +3.5 D for near and +1. 80 D for intermediate distance and is pupil independent.[67]

Approved in 2019 in Europe under the Conformité Européenne mark and approved by the US Food and Drug Administration (FDA) in 2021, Tecnis Synergy (J&J Vision, Santa Ana, CA, USA) is a hybrid-design MfIOL that incorporates both diffractive extented depth of focus (EDOF) and bifocal technology in the rear optics to provide a range of vision for remote collars.[68] The aspheric anterior surface counteracts the mean ocular spherical aberration, while an advanced high-resolution coating minimises light scatter, and the addition of a violet-filtering chromophore enhances contrast sensitivity under low-light conditions.[69] Benyoussef et al. compared the reading performance of FineVision Hp trifocal IOL, a trifocal diffractive lens, and Tecnis Synergy IOL, a hybrid design, after bilateral implantation.[70] Synergy IOL has been reported to provide better reading speed and to be less sensitive to refractive error. In a prospective case series comparing the refractive and visual outcomes of Tecnis Synergy, AcrySof PanOptix, and FineVision POD F MfIOLs, it was reported that minimum incidence of photic phenomena and effective visual rehabilitation were achieved with all three IOLs.[70] However, it has been noted that there is a tendency to obtain a wider functional focal range with the Tecnis Synergy IOL.

Palomino-Bautista et al. published their results using different criteria to evaluate the depth of field (DOF) provided by different presbyopia-correcting IOLs and to define defocus tolerance . A total of 150 eyes in which 6 different MfIOLs, namely LISA Tri (Carl Zeiss Meditec), PanOptix (Alcon Laboratories), FineVision (PhysIOL), Miniwell (SIFI MedTech), Tecnis Symfony (J&J Vision), and Tecnis Synergy (J&J Vision) were implanted were included in the study. According to the results, both objective and subjective measurements showed that Tecnis Symfony and Tecnis Synergy IOLs had a greater DOF tendency compared to most other trifocal diffractive designs, except PanOptix. There was no statistical difference between PanOptix and Tecnis Synergy and Tecnis Symfony.[71]

1.4. New generation hybrid MfIOLs

At the 2024 ESCRS (European Society of Cataract and Refractive Surgery) Congress, Rayner introduced the RayOne Galaxy, the first IOL worldwide to incorporate a spiral optic design. This novel lens was developed using proprietary machine learning algorithms, which enabled the evaluation of millions of potential design variations to optimize performance. Through this data-driven process, the complex spiral optic was realized, providing an extended range of vision while significantly reducing dysphotopsia. The use of advanced computational modeling also greatly accelerated the development timeline. Similar to other hydrophilic RayOne IOLs, the Galaxy is manufactured from Rayner's long-established Rayacryl® hydrophilic acrylic material. It also incorporates the Amon-Apple 360° enhanced square edge, designed to minimize posterior capsule opacification, as well as Anti-Vaulting Haptic technology to ensure intracapsular stability. A key feature of the Galaxy IOL is its smooth, non-diffractive spiral optic, which plays a critical role in lowering the incidence of dysphotopsia. Unlike traditional diffractive FROF (full range of focus) lenses, this design eliminates abrupt optical transitions and concentric diffractive rings, thereby reducing photic disturbances, particularly under mesopic conditions. Furthermore, the refractive spiral configuration ensures 100% transmission of incoming light, avoiding the energy losses typically associated with diffractive optics.[72]

The TECNIS Odyssey™ IOL is a next-generation presbyopia-correcting IOL built on J&J's proven TECNIS platform. It integrates a wavefront-designed aspheric anterior surface with a digitally optimized freeform diffractive posterior surface, thereby providing a seamless range of vision. The lens is composed of violet-light–filtering, UV-absorbing hydrophobic acrylic and incorporates proprietary achromatic technology to reduce both spherical and chromatic aberrations. Structurally, it features a 6.0 mm optic within a 13.0 mm overall diameter, a frosted continuous 360° square edge, and a Tri-Fix haptic configuration, all of which contribute to enhanced intracapsular stability and long-term safety. The reduced step-height diffractive profile is specifically engineered to mitigate dysphotopsias, including halos and glare, while preserving contrast sensitivity and visual acuity across varying lighting conditions. Manufacturer indicates that the Odyssey provides a wider functional range, improved tolerance to residual refractive error, and superior visual quality relative to conventional trifocal IOLs, with consistently high rates of spectacle independence. Collectively, these optical and surgical advancements position the TECNIS Odyssey IOL as a reliable and high-performance option within the expanding category of presbyopia-correcting IOLs.[73]

1.5. Summary of MfIOLs

The selection of MfIOLs extends far beyond refractive targets, requiring a comprehensive assessment of multiple parameters including the patient's age, occupational demands, lifestyle, pupil dynamics, corneal aberration profile, ocular surface health, neuroadaptation capacity, and tolerance for photic phenomena (Table 2). Refractive MfIOLs, due to their pupil-size–dependent optical designs, provide

Table 2. *Some of multifocal intraocular lenses (IOLs)*

Multifocal IOL	MFR	IOL material	IOL total/ optic diameter (mm)	Intermed/ Near Add. (D)	Optical principal	Asphericity	Pupil dependent (Yes/No)	Positive dysphotopsia	Toric version (Yes/ No)
Array SA40N	AMO	Silicon optic and PMMA haptics	13/6 mm	0/+3.50	Bifocal, refractive, rotationally symmetric	Neutral	Yes	Yes (53%)[22]	No
The ReZoom NXG1	AMO	Hydrophobic acrylic	12/6 mm	0/+3.50	Bifocal, refractive, rotationally symmetric	No	Yes	Yes [18]	No
M-flex series (580F,630F)	Rayner Ltd.	Hydrophilic acrylic with hydrophobic surface	12.5/5.75 mm 12/ 6.25 mm	0/+3.0, +4.00	Bifocal, refractive, rotationally symmetric	Neutral	Yes	Low [74]	Yes
FIL611 PV	Soleko	Hydrophobic acrylic	11/6 mm	0/+3.0	Bifocal, refractive, rotationally symmetric	-0.11 µm	Yes	Yes	No

Table 2. *Some of multifocal intraocular lenses (IOLs)*

Multifocal IOL	MFR	IOL material	IOL total/ optic diameter (mm)	Intermed/ Near Add. (D)	Optical principal	Aspheri-city	Pupil depen-dent (Yes/No)	Positive dysphotopsia	Toric version (Yes/ No)
LENTIS Mplus series (LS-312 MF15, LS-312 MF30, LS-313 MF30, LU313 MF30)	Oculentis	Hydrophilic acrylic with hydrop-hobic surface	11/6 mm	0/+1.5, +3.0	Bifocal, refractive, rotationally asymmetric	Neutral	No	Low [75] (13%) [76]	Yes
SBL-2 and 3 (ClearView)	Lenstec Inc.	Hydrophilic acrylic	11/5.75 mm	0/+2.0 and +3.0	Bifocal, refractive, rotationally asymmetric	-0.11 µm	Yes	Low [3]	Yes
Tecnis ZMB00; ZLB00; ZKB00	J&J, Inc.	Hydrophobic acyrilic	13/6 mm	0/+4.0; +3.25; +2.75	Bifocal, diff-ractive	−0.27 µm	No	Yes (30%- 67%) [3]	Yes
Bi-Flex M 677MY [77]	Medicon-tur	Apodized, hydrophilic, acyrilic	13/6 mm	0/+3.50	Bifocal, diff-ractive	Yes	No	Mod (21%) [3]	Yes
MicroSila 612 DAY	Human Optics	Hydrophobic acyrilic, silicon optic, PMMA haptics	12/6mm	0/+3.50	Bifocal, diff-ractive	Neutral	Yes	Not published	Yes
FineVision POD F, Micro F and POD GF	PhysIOL	Hydrophilic, acyrilic	11.4/ 6mm	+1.75/+3.50	Trifocal, diff-ractive	-0.1 µm	Yes	Low [3, 78]	Yes
RayOne	Rayner Ltd.	Hydrophilic acrylic	12.5/6 mm	+1.75/+3.50	Trifocal, diff-ractive	Neutral	Relati-vely No	Low [79]	Yes
AT LISA tri 839MP	Carl Zeiss Meditec	Hydrophilic acrylic with hydrophobic surface	11/6 mm	+1.66/+3.33	Trifocal, diff-ractive	−0.18 µm	No	Low- Mod [3]	Yes
AT ELANA 841P	Carl Zeiss Meditec	Hydrophobic acyrilic	13/6 mm	+1.66/+3.33	Trifocal diff-ractive	Neutral	No	Low-Mod [42]	Yes
Enova Ma-estro	VSY Bio-technology	Hydrophobic Acrylic	13/6 mm	+1.80/ 3.60	Trifocal diff-ractive, sinu-soidal vision technology	-0.10 µm	No	Not published	No
Intensity SeeLens	Hanita Lenses RCA Ltd.	Hydrophilic acyrilic	13/6 mm	+1.50/+3.0	Trifocal Diffractive, modified sinusoidal profile	-0.13µ	No	Low [44]	Yes

Table 2. *Some of multifocal intraocular lenses (IOLs)*

Multifocal IOL	MFR	IOL material	IOL total/ optic diameter (mm)	Intermed/ Near Add. (D)	Optical principal	Asphericity	Pupil dependent (Yes/No)	Positive dysphotopsia	Toric version (Yes/ No)
AcrySof ReSTOR (SN6AD1 and SV25T0)	Alcon	Hydrophobic acrylic, glistening free	13/6 mm	0/+3.0 and +2.5	Hybrid, bifocal, refractive-diffractive	-0.10 µm	Yes	Yes [53]	Yes
AT LISA 809M	Carl Zeiss Meditec	Hydrophilic acrylic with hydrophobic surface	11/6 mm	0/+3.75	Hybrid, bifocal, refractive-diffractive	Yes	No	Yes [53]	Yes
Eyecryl Actv	Biotech Vision Care	Hydrophilic acyulic with hydrophobic surface	12.5/6 mm	0/+3.00, +3.75	Hybrid, bifocal, refractive-diffractive	Yes	No	Very Low [48, 80]	Yes
Acriva Reviol MF 613MFB 625, MFM 611	VSY Biotechnology	Hydrophobic acrylic	13/6 mm 12.5/6 mm 11/6 mm	0/+3.75	Hybrid, bifocal, refractive-diffractive	Yes	No	46% [81]	No No Yes
OptiVis	Aaren scientific	Hydrophobic acrylic	11/6 mm	0/+2.80	Hybrid, bifocal, refractive-diffractive	Yes	No	Low- Mod [82]	No
The Acri. LISA 366D	Carl Zeiss Meditec	Hydrophilic acrylic material with a hydrophobic surface	11/6 mm	0/+3.75	Hybrid, bifocal, refractive-diffractive	Yes	Yes	43% [81]	Yes
AcriDIFF; iDIFF Plus 1-R, 1-P	Care Group	Hydrophobic acrylic; Hydrophilic acrylic	12.5/6 mm; 12.5/6 mm, 11/6 mm	0/+3.25; 0/+3.00, +3.50, +4.00	Hybrid, bifocal, refractive-diffractive	Yes	No; Yes	Yes	Yes
AcrySof IQ/ Clareon PanOptix	Alcon	Hydrophobic acrylic/ Combining a hydrophilicpolymer (hydroxyethyl methacrylate [HEMA]) and a hydrophobic component (phenylethyl acrylate [PEMA])	13/6 mm	+2.17/ +3.25	Hybrid, trifocal, refractive- diffractive	-0.10 µm	No (up to 4.5 mm) [3]	Mod- High/ Very Low [83]	Yes
TRIVA-aA	Human Optics	Hydrophilic acyrilic	12.5/6 mm	+1.75/ +3.50	Hybrid, trifocal, refractive- diffractive	Yes	No	Yes [66]	Yes

Table 2. *Some of multifocal intraocular lenses (IOLs)*

Multifocal IOL	MFR	IOL material	IOL total/ optic diameter (mm)	Intermed/ Near Add. (D)	Optical principal	Asphericity	Pupil dependent (Yes/No)	Positive dysphotopsia	Toric version (Yes/ No)
TriDIFF	Care Group	Hydrophobic Acrylic	10.75-11.25/6 mm	+1.80/ +3.50	Hybrid, trifocal, refractive- diffractive	Yes	No	Not published	Yes
Tecnis Synergy	J&J	Hydrophobic acrylic	13/6 mm	UNK	Hybrid, diffractive	-0.27 µm	Low [84]	Low [71]	Yes
Galaxy [85]	Rayner	Rayacryl hydrophilic acrylic	12.5/6 mm	UNK	Hybrid, non-diffractive spiral optic	Yes	UNK	Low [85]	Yes
Odyssey [73]	J&J	Hydrophobic acrylic	13/6 mm	UNK	Hybrid diffractive	-0.27 µm	No (up to 5 mm)	Not published	Yes

AMO: Abbott Medical Optics J&J: Johnson& Johnson Intermed: Intermedier IOL: Intraocular lens MFR: Manufacturer Mod: Moderate UNK: Unknown

high contrast sensitivity under well-illuminated conditions and generally exhibit lower rates of halos and glare compared with diffractive designs, making them advantageous for patients with larger pupils, those prioritizing night-driving performance, and those whose primary goal is distance vision. Rotationally asymmetric refractive designs tend to minimize photic phenomena while preserving distance and intermediate contrast sensitivity. In contrast, diffractive MfIOLs distribute light to multiple focal points via concentric rings on the lens surface, functioning independently of pupil size and offering balanced vision at near, intermediate, and far distances. However, the division of light may reduce contrast sensitivity and increase the incidence of halos and glare. Trifocal diffractive lenses, in particular, are beneficial for active individuals seeking high levels of spectacle independence, with improved intermediate vision performance between 40 and 80 cm -especially advantages for computer use- though often at the expense of some contrast sensitivity and with a higher frequency of photic phenomena. Hybrid refractive-diffractive designs combine the benefits of both optical principles, delivering extended depth of focus, satisfactory contrast sensitivity, and functional visual acuity, and are a rational option for patients with moderate tolerance for photic phenomena and a desire for multifocal vision performance. Ultimately, rather than a single "ideal" model, optimal surgical outcomes and patient satisfaction are best achieved through alignment of the optical design's strengths and limitations with the patient's individualized visual priorities.

2. Extended Depth of Focus MfIOLs

There is a growing interest in the technology of EDOF lenses designed to overcome the problems associated with MfIOLs and provide spectacle independence over a broader range than conventional monofocal IOLs, correcting presbyopia and minimizing optical phenomena such as halo and glare.[86] The basic optical principle of EDOF IOLs is to increase the depth of focus and create a single extended focal point without overlapping images, which creates both refractive and diffractive multifocality, unlike monofocal IOLs where light is focused on a single point or MfIOLs with multiple focal points. The focal lengthening in EDOF lenses is a result of the linear distribution of light energy rather than its travelling to one or different foci. However, this can result in a deterioration in the retinal optical quality of the image, with a potential reduction in contrast sensitivity.[1] It should be noted that increased depth of field can lead to a deterioration in the quality of vision and, especially if the aberration size is enormous, can lead to a decrease in the quality of the distant image and the phenomenon of dysphotopsia.[87]

EDOF IOLs may not have the same clarity in near vision as MfIOLs, but they are attractive, with reduced aberrations and improved intermediate vision without compromising distance visual acuity or causing the disturbing positive dysphotopsia that can be associated with some multifocal lenses. In addition, LASIK patients with small epiretinal membranes or high-grade aberrations may be suitable for the EDOF lens, even if MfIOLs are not suitable for their use.[88]

The number of lenses marketed as EDOF lenses is increasing. However, when evaluated in detail, not all of them fall within the definition of EDOF in terms of technology and optical design. Although there are many points that distinguish EDOF lenses from monofocal plus lenses, there are also overlapping aspects. Therefore, these lenses can be considered as a subgroup of EDOF lenses or a different group of premium lenses.[89] As debate has grown regarding which IOLs can be classified as EDOF, the US FDA, in collaboration with the American Academy of Ophthalmology (AAO), introduced specific clinical benchmarks in the 2018 ANSI/AAO Standard, formulated through a task force consensus.[90] Based on these criteria, EDOF IOLs are expected to deliver a monocular negative depth of focus which refers to the range of distances over which an object appears in focus, not less than 0.5 D greater compared with a monofocal control, evaluated at a visual acuity of 0.2 logMAR (Snellen 20/32). In addition, the monocular photopic distance-corrected mean visual acuity at 66 cm should be superior to a monofocal lens, with at least 50% of eyes achieving a visual acuity of 0.2 logMAR or better. Ultimately, the average monocular photopic BCVA must be at least equivalent to that achieved with a monofocal control IOL. Monocular mesopic contrast sensitivity and visual symptom questionnaires should be evaluated, but specific criteria for visual quality or visual disturbances are not specified in detail.[90] In order for a lens to be called EDOF IOL, the optical profile must be continuous, and there must be no uniformly refractive or diffractive change in the transition.

According to the ideal EDOF principle, the lens concentrates light into a focal line that remains in focus over a broad range of distances along the visual axis, thereby bringing distant, near, and intermediate objects into sharp focus. While some objectives of the ideal EDOF lens may be attainable by focusing incoming light into a narrow channel that spans a broader range of distances, this remains challenging due to the inherent physical limitations of light. Advances in technology have enabled the application of different optical concepts in the design of EDOF IOLs. These include non-diffractive strategies such as small-aperture optics, modulation of spherical aberration, and wavefront-shaping, as well as diffractive approaches. (Figure 4.).[91] Thus, the concept of pure EDOF emerged and the concept of hybrid EDOF was first used by Kanclerz et al.[92] Later, Alio et al. made a new classification and grouped EDOF lenses into 5 categories (Table 3).[1, 87]

Type 5 EDOF lenses in the EDOF classification of Alio et al. are referred to as 'enhanced monofocal' in many studies in the literature. This lens group is also referred to as 'monofocal plus' or 'mono-EDOF'.[89] Although this lens group is not accepted as EDOF because it does not meet one of the 4 elements of ANSI criteria, it is included in Alio's classification. However, although Alcon AcrySof IQ and Clareon Vivity IOL type 5 are included in the subgroup in this classification, it has been shown in many studies that the Vivity IOL using Alcon's proprietary X-WAVE technology, which extends and shifts light without splitting and has a separate change in radial curvature of about 2 mm, meets the ANSI criteria for an EDOF lens.[93-95] In other approaches, EDOF lenses can be grouped as diffractive and non-diffractive. As can be seen, with the differences in lens production technologies and the increasing diversity, a clear distinction of EDOF lenses is impossible. However, in light of the existing classifications, the most commonly used EDOF lenses are included in this review. Enhanced monofocal lenses classified as Type 5 will be covered in a separate sub-heading.

The Tecnis Symfony (ZXR00; J&J Surgical Vision) with achromatic diffractive design was the first EDOF lens to

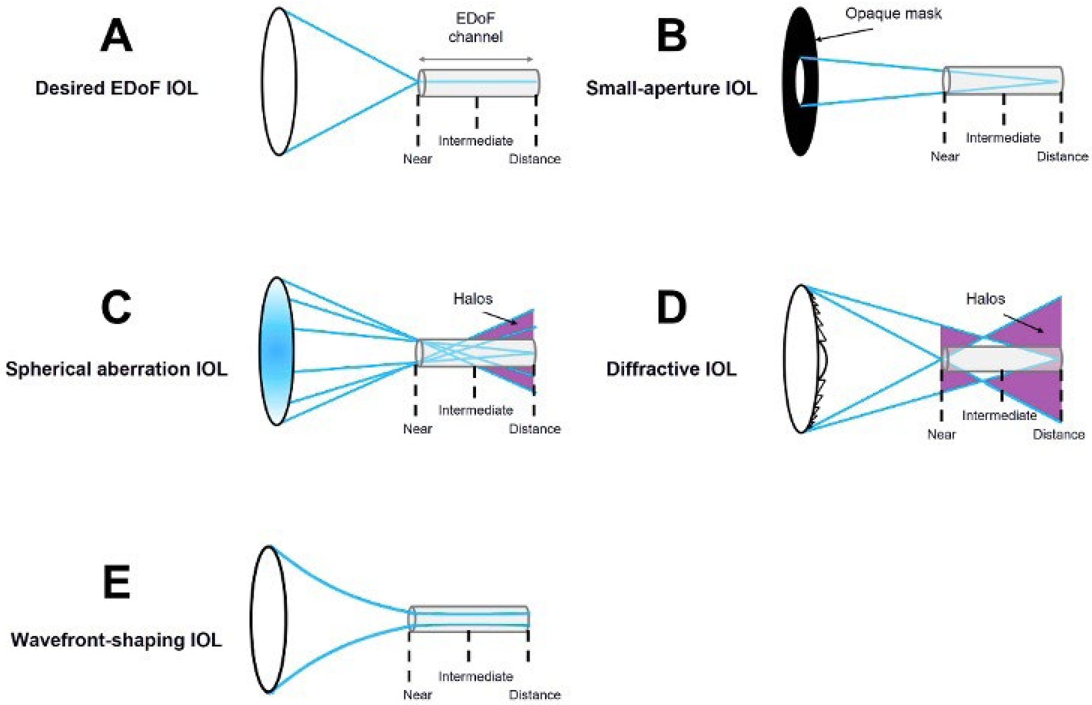


Figure 4: *Light path (A) of the ideal EDOF lens and optical principles of currently available IOLs (B, C, D, E) 90*

Table 3: *Alio's EDOF IOL classifications with subgroups by optical design 1*

Subgroups	Features	IOls
Type 1	Pure EDOF IOLs based on SA (Based on positive or negative (or both) SA to increase DoF)	Mini Well Ready (SIFI; Medtech), Wichterle Intraocular Lens-Continuous Focus (Medicem)
Type 2	Based on pinhole effect lenses (Small aperture)	IC-8 AptheraTM (AcuFocus Inc.), XtraFocus Pinhole Implant (Morcher GmbH)
Type 3	Mf lenses with low power near-vision addition (either refractive or diffractive)	Lentis Comfort, LS-313 MF15 (Teleon Surgical), Acunex Vario AN6 V (Teleon Surgical), AT LARA 829 MP (Carl Zeiss Meditec)
Type 4	Hybrid Mf-EDOF: Combination of SA with modest power addition for near	FineVision Triumf POD L GF (PhysIOL), Tecnis Symfony ZXR00 (Johnson & Johnson Vision), Lucidis (Swiss Advanced Vision, SAV-IOL SA), Supraphob Infocus IOL (Appasamy Associates), EDEN (Swiss Advanced Vision, SAV-IOL SA), Harmonis (Swiss Advanced Vision, SAV-IOL SA), Synergy ZFR00 (Johnson & Johnson Vision)
Type 5	Modified Central Optical Profile Lenses, either a greater power WF modulation to cause DoF increase	Eyhance ICB00 Tecnis lens (Johnson & Johnson Vision), AE2UV (Eyebright Medical Technology Inc.), distributed in Europe under the tradename ZOE (Ophthalmo Pro GmbH), Synthesis PLUS (Cutting Edgence), Acrysof IQ Vivity DFT015 (Alcon), LuxSmart (Bausch & Lomb), RayOne EMV (Rayner Intraocular Lenses Limited), IsoPure (Physiol), Lentis Quantum (Teleon Surgical)

DoF: Depth of Focus, Mf: Multifocal, SA: Spherical Aberration, WF: Wavefront.

be marketed and remains popular worldwide.[68] Manufactured from hydrophobic-acrylic and UV-filtered material, the lens has an anterior aspheric surface with a biconvex wavefront design and a posterior achromatic diffractive pattern with an echelette design and belongs to the type 4 hybrid Mf-EDOF group. The integration of achromatic optics with negative spherical aberration adjustment enhances the quality of the simulated retinal image, while preserving depth of field and stability against decentration.[3] The lens is available in a spherical power range from +5.00 D to +34.00 D with +1.75 D insertion in the IOL plane. Importantly, previous investigations indicate that the Tecnis Symfony IOL is highly safe and associated with minimal posterior capsule opacification (PCO) and side effect rates, providing reassurance about its reliability.[32, 96] In a meta-analysis of studies comparing trifocal lenses with EDOF lenses, only Tecnis Symfony was included in the EDOF group, while AcrySof IQ PanOptix, FineVision Micro F, FineVision Pod F, and AT LISA tri 839MP IOLs were included in the trifocal group. The results showed that Tecnis Symfony IOL provided significantly better intermediate distance but worse near vision than trifocal IOLs. The meta-analysis revealed no significant differences between the groups in terms of spectacle independence, contrast sensitivity, or patient satisfaction.[96] Rodov et al. compared Tecnis Symfony with Fine Visio Micro F and showed that postoperative halo and glare were significantly higher in trifocal IOL compared to EDOF.[97] In a study comparing Tecnis Symfony and Tecnis Synergy, it was reported that Synergy was better in intermediate and near vision, while Symfony offered much better optical quality.[68] In a prospective series published by Mencucci et al., the results of bilateral IOL implantation with the EDOF lens Tecnis Symfony and trifocal IOLs PanOptix IQ and AT LISA tri 839 MP were compared. Mesopic intermediate vision results of Tecnis Symfony IOL were found to be much more successful than trifocals. Under photopic conditions, trifocal IOLs showed better near vision than Tecnis Symfony IOL. However, the contrast sensitivity of Tecnis Symfony IOL was significantly better than trifocals under both photopic and mesopic conditions.[12] In contrast, Webers et al. compared Tecnis Symfony and AT LISA tri 839MP IOLs in a prospective randomised study and found no statistical difference in contrast sensitivity and incidence of photopic phenomena such as halo and glare.[98] In this case, it can be said that Tecnis Symfony type hybrid EDOF lenses do not provide an advantage over trifocals in the problem of dysphotopsia.

Lucidis (Swiss Advanced Vision, SAV-IOL SA) is another type of hybrid refractive EDOF IOL. It is a 360-degree square-edge design lens with a central aspheric element surrounded by an outer ring, with an add power of +3.00 D and a spherical power range of +5.00 D to +30.0 D. The 1mm area in the central aspherical zone acts as an axicon so that the resulting light forms a Bessel beam and results in a beam of focal areas that provide an uninterrupted view from mid-distance to short distance. The manufacturer claims this design will achieve the same optical quality and visual acuity for distance vision compared to conventional monofocal lenses. Despite this design, one study reported that uncorrected distance visual acuity results were lower than other EDOF lenses.[99] However, low glare rates and satisfactory refractive results of Lucidis EDOF IOL have also been reported in the literatüre.[100]

Mini Well Ready (SIFI; Medtech) type 1 is an aberration-based IOL with a double aspheric optical design produced on the principle of pure EDOF. The optics of the Mini Well IOL consist of 3 regions: an outer monofocal region responsible for creating the distance focus and inner and middle regions where different SAs with the opposite sign are applied to increase the depth of focus of the lens. The middle region has a negative SA that contributes to the near focus, and the innermost region has a positive SA that creates the intermediate focus.[1, 101]

Another IOL in this group is the Wichterle Intraocular Lens- Continuous Focus (Medicem, Kamenné Žehrovice, Czech Republic) (WIOL-CF). This lens is classified as a bioanalogical lens. It possesses a polifocal optic, and in theory, the IOL is designed to alter its shape during accommodation. Nevertheless, possible accommodation is one of the three steps that enable vision at all distances. The other two steps are polifocality, which provides the high depth of focus provided by hyperbolic optics, and pseudo accommodation, which is provided by the combination of polifocality and pupillary reflex. The WCIOL-CF lens mimics the natural crystalline lens with its three modes of action: hydrogel material, lens optics, and geometry. The haptic-free structure, hyperbolic back surface, large optics, and hyperbolic back surface of the lens greatly resemble the shape of a natural crystalline lens, resulting in an infinite number of foci. The smooth hydrogel surface provides maximum biocompatibility, elimination of cell adhesion, and resistance to calcification.[102] Studeny et al. evaluated the results after bilateral implantation of the WIOL-CF lens and reported that the incidence of photopic phenomena was low in addition to good vision at distance, intermediate, and near.[102] However, it was discontinued in 2018 due to reports of poor results related to excessive SA induced by the lens.[87]

Based on the equation presented by Campbell more than 50 years ago, it can be said that depth of field and depth of focus decrease as pupil size increases. Furthermore, according to Stiles-Crawford, when light of equal intensity enters the eye near the center of the pupil, a more enormous photoreceptor response is produced compared to light entering from the edge of the pupil. Considering these theorems, EDOF IOLs with a mechanism targeting a more significant depth of focus have been introduced to the market with the Type 2- pinhole effect principle, and this group includes the IC-8 (AcuFocus Inc., Irvine, Ca, USA) and the XtraFocus (Morcher) lenses. However, the disadvantages of this group of lenses, such as implantation through a 3.5 mm^2 corneal incision and visual disturbances such as halo in mesopic conditions and in patients with large pupils, should be kept in mind. The small optical diameter causing DoF reduction is also one of the disadvantages.[103]

IC-8 is a one-piece, hydrophobic acrylic lens with small aperture optics combined with a monofocal IOL (Figure 5-A). Evidence indicates that IC-8 implantation, whether unilateral with a contralateral lens or performed bilaterally, yields favourable visual outcomes at near, intermediate, and distance ranges.[104-106] Furthermore, the design of this IOL offers the opportunity to improve vision in patients with ocular trauma or corneal irregularities.[107] XtraFocus is a hydrophobic-acrylic IOL with pinhole effect, designed to be implanted in the ciliary sulcus of pseudophakic eyes in a piggyback configuration (Figure 5-B).[1]

It is still debatable whether the group of lenses in Type 3 with diffractive and/or refractive near vision additions should really be included in the EDOF category because they resemble low power multifocal lenses. Lentis Comfort, LS-313 MF15 (Teleon Surgical) is a rotational asymmetric MfIOL with +1.50 d near addition. Although studies reported high contrast sensitivity, very low incidence of photic phenomena, and high patient satisfaction, +1.50 D addition was reported to be insufficient for reading small print in near vision.[108, 109] The in vitro performance of the lens under polychromatic light showed that in addition to the low additive value, the segmented bifocal design imparts EDOF character to the lens. Another IOL in Type 3 is AT LARA 829 MP (Carl Zeiss Meditec), a hydrophilic acrylic lens with aberration-neutral and chromatic aberration correction, diffractive and aspheric optical design. In a prospective randomized study comparing 3 EDOF and 1 monofocal lens (AcrySof IO SN60WF) including AcrySof IQ Vivity (Non-diffractive/ Refractive EDOF), AT LARA 829 (Mf), Tecnis Symfony ZXR00 (Hybrid EDOF) IOLs, there was no statistically significant difference in visual acuity between the groups, Halo and glare rates with EDOF

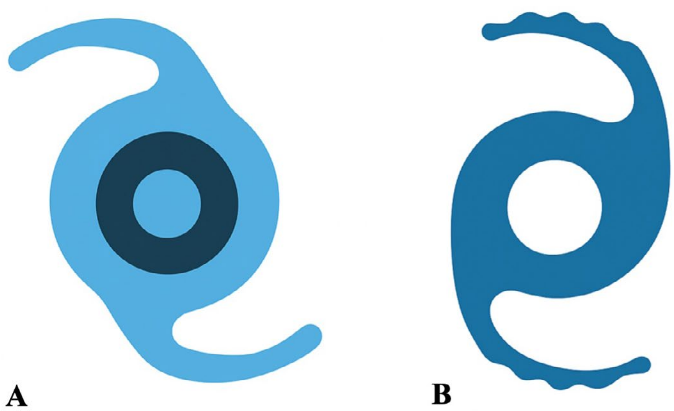


Figure 5: *IC-8 small aperture intraocular lens (IOL) (AcuFocus Inc.) (A) and XtraFocus Pinhole Implant (Morcher) (B) 1*

Vivity IOL were close to monofocal lenses but significantly lower than other EDOF lenses.[110]

Enova Advanced (VSY biotechnology), one of the newly introduced EDOF lenses, is an asymmetric, biconvex, and neutral bi-aspheric IOL with a non-diffractive hydrophobic material. The manufacturer claims that the lens has a minimal spherical aberration design due to the light adaptive structure of the lens and that photopic phenomena such as halo glare are very few, and the quality of vision is very good at far, intermediate, and near distances. However, there are no studies in the literature that include the results of this lens and compare it with existing EDOF IOLs.[111]

The new pure refractive EDOF IOL, Tecnis PureSee (DEN00V), newly manufactured by J&J, features an improved anterior surface to compensate for spherical aberration and a posterior refractive surface designed to increase the depth of focus. The first article on Tecnis PureSee by Alarcon et al. showed that this new IOL provided a visual range similar to Tecnis Symfony but had a better dysphotopsia profile than a monofocal IOL.[112] Subsequently, in a multicentre clinical randomised trial by Corbett et al. comparing Tecnis PureSee with Tecnis Eyhance, an 'enhanced monofocal' lens, Tecnis PureSee demonstrated a wider visual range and statistically superior intermediate and near performance compared to the enhanced monofocal lens. In addition, distance visual acuity, contrast sensitivity, and dysphotopsia profile were similar to the enhanced monofocal IOL.[113] Although Tecnis PureSee has reliably good visual results and fewer photopic phenomena in the light of existing studies, studies comparing it with the results of existing multifocal and EDOF IOLs are needed.

The AcrySof IQ and Clareon Vivity (Alcon), both classified as type 5-modified central optical lenses according to Alio's et al. classification, use Alcon's proprietary X-WAVE technology, which extends and shifts light without splitting and has a discrete change in radial curvature of approximately 2 mm. Studies have shown that the Vivity IOL meets ANSI criteria for an EDOF lens.[1, 114] The aspheric design of the Vivity corrects the -0.20 μm primary spherical aberration. The manufacturer states that the Vivity lens incorporates two transition elements, with a central spacing of 2.20 mm. The initial transition element induces wavefront stretching, generating an extended focal range. In this process, light is elongated toward both the myopic and hyperopic directions; however, the hyperopic component falls behind the retina and therefore does not contribute to vision. Through the action of the second transition element, the wavefront is advanced and light is redirected from the hyperopic to the myopic focus, ensuring that the entire light energy is effectively utilised. The aspheric front lens surface and spherical back surface provide an extended depth of field. The lens made of hydrophobic acrylate/methacrylate copolymer is pupil independent.[115] The lens offers distance vision of similar quality to monofocal lenses, good quality intermediate distance vision, and satisfactory near vision, all with a tolerably low incidence of photopic disturbances, supported by many comparative studies.[93, 110] In a study comparing the glistening rates of ReSTOR+3 SN6AD1, SN60WF, PanOptix TFNT, and Vivity DFT015 IOLs, Vivity was found to be the least glistening IOL.[116] In a study by Pastor-Pascual et al. evaluating the results of AcrySof Vivity Toric DFT215 IOL, Vivity toric IOL provided good visual quality at different distances and excellent rotational stability in patients with low astigmatism.[117] In a study comparing bilaterally implanted AcrySof IQ Vivity or Vivity Toric IOLs with PanOptix Trifocal, ReStor 2.5 Active Focus and ReStor 3.0 MfIOLs, AcrySof IQ Vivity was shown to offer a wider range of vision and better spectacle independence than typically achieved with conventional monofocal IOLs, with high satisfaction rates and a favorable dysphotopsia profile compared to diffractive MfIOLs.[118]

On the other hand, although it was described as a non-diffractive/refractive lens until recently, NIMO analysis (in vitro optical analysis) has shown that the lens has a diffractive element due to its 2.2 mm central shaping.[119] This finding is significant as it challenges the previous understanding of the lens and has important implications for its clinical use. This is of particular clinical importance when comparing Vivity with non-diffractive enhanced monofocal lenses. In a case-control study, Vivity IOL with EDOF and enhanced monofocal Tecnis Eyhance results were compared, and distance and intermediate visual acuity were very good in both lenses, with higher spectacle independence in Vivity. There was no difference in patient satisfaction and photopic disturbances such as glare.[120] However, in a single-center randomized study, the results of which were just published in October 2024, the results of bilateral Acrysof IQ Vivity DFT015 (EDOF) and RayOne EMV RAO200E (Rayner) (enhanced monofocal) lenses were compared in both groups with mini-monovision. There was no significant difference in binocular visual acuity between the lenses, but a significantly smaller halo size was reported in the RAO200E group. In addition, Vivity IOL showed a significantly better defocus curve at -2.5, -2.0, and -1 D defocus compared to the RayOne group.[121]

2.1 Enhanced Monofocal IOLs

The development of various EDOF lens designs has introduced a distinction between lenses that meet ANSI criteria and those that do not, further highlighting the differences between EDOF lenses and enhanced monofocal lenses (monofocal plus). However, these two groups also have overlapping aspects. However, whether enhanced monofocal lenses are, a subgroup of EDOF lenses or a different premium lens group is still controversial. Advanced monofocal lenses are expected to provide a reasonable quality distance and functional intermediate vision without causing photic phenomena. The modification of non-diffractive technology with an aspheric front surface has been used to achieve this goal with a continuous power profile. Prominent lenses in this group include Tecnis Eyhance (J&J), IsoPure (Physiol), Lux Smart (Bausch & Lomb), Zoe (OphthalmoPro GmbH), RayOne EMV (Rayner), Evolux (Sifi) and Vivinex Impress (Hoya).

Tecnis Eyhance offers a smoothly increasing refractive power from the periphery to the center with no refractive line and aims to compensate for positive spherical aberration in the cornea and good intermediate distance vision (at 66 cm). Defocus measurements show that the Tecnis Eyhance has a more extensive 'landing zone' than the Tecnis monofocal lens and provides excellent distance vision (0.0 logMar).[122, 123] In the study by Auffarth et al., it was shown to have an extended imaging capacity compared to the monofocal lens of the same company and a low potential for induction of photic phenomena similar to monofocal.[124] In different clinical studies, Tecnis Eyhance was compared with Technis Symfony, the EDOF lens of the same company, and it was shown that Tecnis Eyhance offered good quality distance vision with non-inferior intermediate vision and was not inferior to Symfony in terms of spectacle independence. Tecnis Eyhance also provided a lower subjective perception of halo and glare.[125, 126] In a study comparing the results of bilateral Eyhance IOL implantation with mini-monovision monofocal Tecnis 1-piece IOL implantation, binocular distance, intermediate visual acuities, contrast sensitivity, patient satisfaction, and incidence of photic phenomena did not differ between the groups. In contrast, binocular near visual acuity was significantly better in the mini-monovision group.[127]

RayOne EMV (Rayner) is an aspheric monofocal IOL with neutral aberration in the periphery, but it differs from other IOLs with its increased positive spherical aberration. While the plano target is maintained in the dominant eye, 1D power offset is applied in the non-dominant eye. According to the manufacturer, this provides a depth of focus extension of 2.25 D. In a prospective study by Garcia-Bella et al. reporting 3-month follow-up results after bilateral RayOne EMV implantation, it was shown that this lens provided excellent distance and intermediate vision with a high level of satisfaction with emmetropia as the target.[128]

IsoPure 123 (PhysIOL) is a hydrophobic acrylic monofocal IOL with 4 closed haptics and increased negative spherical aberration on both anterior and posterior surfaces. In studies comparing it with standard monofocal lenses, it has been shown to provide similar distance vision and good quality intermediate vision with minimal effect on contrast sensitivity, without increasing optical aberrations or causing any photic symptoms, ensuring a comfortable and safe experience for the patient.[129, 130]

LuxSmart IOL (Bausch& Lomb GmbH, Berlin, Germany) is a new acrylic hydrophobic and aspheric IOL generation. The lens design in the type-5 EDOF group in the classification of Megiddo-Barnir and Alio is based on the principle of pure refractive EDOF.[1] In the central 2 mm of the lens, there is a combination of spherical aberration of the 4th and 6th order with opposite signs; in the immediate periphery, there is a transition zone designed to smoothly reduce the optical vergence from the center to the periphery, and in the periphery, there is a refractive aspheric surface. According to the manufacturer, this transition is designed to control the trajectory of light rays to ensure that no light is outside the field of view.[1, 131] Campos et al. published the preliminary clinical results of the LuxSmart IOL and reported that it is a safe option that provides spectacle independence in the distance and intermediate vision without increasing dysphotopsia and provides higher performance in near vision than the conventional monofocal lens.[132] In the first published prospective study, it was shown that it provided a very high intermediate visual distance with uncorrected distance visual acuity similar to standard monofocal lenses and caused mild photopic phenomena.[133]

Vivinex Impress XY1-EM (Hoya Surgical Optics) is a single-piece hydrophobic acrylic IOL with aspheric optics and extended depth of focus for intermediate vision. In a study comparing the visual performance and optical quality between Eyhance, Isopure, and Vivinex Impress XY1-EM, no statistically significant difference was found between the groups.[86]

Synthesis Plus IOL (Cutting Edge) is an enhanced monofocal lens with a 4-point fixed haptic structure. In addition to the patented transition zone and monofocal optical periphery, the 4th and 6th spherical aberrations in opposite directions provide increased depth of field. Thus, the lens can provide continuous high-contrast vision from far vision to intermediate vision while maintaining a functional near vision quality and maintaining ocular optical quality within an acceptable range to prevent the induction of photopic disturbances.[134]

The number of improved monofocal lenses is increasing daily, and their classification is still controversial. These lenses are often preferred because of their far vision quality, which is competitive with standard monofocal lenses, their significant improvement in the intermediate distance, and their low incidence of photopic phenomena such as halo and glare. In addition, improved monofocal lenses may be a good choice in the presence of the patient's occupational expectations, lifestyles, personality characteristics, or concomitant ophthalmic pathologies such as retina or glaucoma.

3.Add- on MfIOLs

The sulcoflex trifocal lens (Rayner, United Kingdom), with its diffractive structure and annular design similar to the RayOne Trifocal lens, is a piggyback MfIOL for the ciliary sulcus. Its 6.5 mm round-edged optical design aimed to reduce the risks of pupillary block, photic effect, and optic-iris capture and minimize edge-related glare and associated dysphotopsia.[135] In a study by Levinger et al. involving 15 eyes, Sulcoflex IOLs were shown to be a safe and preferable option for the correction of refractive error after cataract surgery.[136]

4. Accommodative IOLs

They are lenses designed to respond to the accommodative effort by producing a change in dioptric power with the help of ciliary muscle contractions and to maintain the natural accommodative ability of the refractive system.[9] There are many different principles of accommodative IOL technology and accommodative IOLs. However, the only accommodative IOL approved by the FDA is the Crystalens IOL (Bausch and Lomb) with 4.5 mm optics, which has two haptic plates and four polyamide rings that help to fix it in place within the capsular sac.[137] Positioning the lens within the capsular bag enables it to mimic the eye's natural accommodative mechanism by altering power in response to ciliary muscle activity.[137] Crystalens accommodative IOL provides the advantage of good distance vision and less visual disturbance compared to MfIOLs. Since the lens is made of 3rd generation silicone elastone, it should not be used in patients with asteroid hyalosis and in patients who may require vitrectomy surgery.

It is predicted that the function of accommodative IOLs may be limited by fibrosis of the capsular bag. This problem can be overcome with accommodative IOLs placed in the ciliary sulcus. Accommodative IOLs have the potential to eliminate the neuroadaptations period that patients experience after MfIOLs.[6, 138]

5.Other IOL Technologies

The RxSight Light Adjustable Lens takes cataract surgery differently by shifting important decisions regarding final lens power to the ideal postoperative period. According to the manufacturer, this approach provides unparalleled precision as it considers lens shift and refractive changes that may occur during the healing process to achieve the best possible results. The FDA approved the RxSight Light Adjustable Lens in November 2017 for use in patients with corneal astigmatism and no macular disease. Implanted in a standard cataract procedure, this monofocal IOL made of light-reactive material is adjusted within the first 17-21 days after surgery to correct refractive error and provide optimized vision with an ultraviolet (UV) light treatment performed by a Light Delivery Device™ (LDD™), tailored to the patient's experience and life. This treatment is FDA-approved for postoperative residual refractive spherical and/or cylindrical correction up to 2 D.[33, 59]

Refractive Index Shaping (RIS) technology, currently under development by Perfect Lens, is a promising advancement that involves repowering an implanted IOL. Preclinical studies have shown that it can effectively resolve spherical, toric, and multifocal issues in acrylic IOL material, all within a short office setting.[139] This method, which typically uses ultrafast femtosecond laser technology and an optical focusing device, is designed to modify postoperative refraction. RIS is an exciting development that has the potential to precisely change IOL power, offering a new level of control in cataract surgery. Unlike traditional methods, this technology is based on a device rather than a lens. The prospect of resolving residual surprises after cataract surgery with a minimally invasive treatment is indeed promising.

The Real-Time Autofocus Servo Control lens, for which research is still ongoing, is planned to be designed to perform the accommodation function using a solar energy capture technology paired with a variable focus lens to allow real-time focus adjustment according to the imaged object, and its project has been announced by Swiss Advanced Vision.[59]

CONCLUSION

Presbyopia-correcting IOLs have seen remarkable advancements in recent decades, offering patients improved visual outcomes and reduced dependence on spectacles. MfIOLs, EDOF lenses, and emerging enhanced monofocal lenses each have distinct characteristics suited to different patient needs. While MfIOLs provide good distance and near vision, they may cause side effects like glare and halos. EDOF lenses aim to improve intermediate vision and provide a smoother range of focus, though they are not immune to HOAs. The intrinsic limitations of MfIOLs, including light energy loss, and the possible complications of EDOF optics, such as HOAs, remain unresolved, and there is still insufficient global awareness of the distinct types of MfIOLs. Recent studies suggest that future priorities in the MfIOL market are likely to continue focusing on enhancing intermediate vision, achieving a full range of vision, and ensuring continuous focus.. Monofocal Plus lenses, with slightly extended depth of focus, offer a balance between simplicity and functionality, appealing to patients seeking an alternative to traditional monofocal lenses.

The key to successful outcomes lies in careful patient and lens selection. Factors such as ocular health, lifestyle requirements, and visual priorities must be assessed, and strong patient motivation for spectacle independence is crucial. Clear communication about the benefits and limitations of each lens type is essential to align expectations and enhance satisfaction.

Looking ahead, the field of IOL technology continues to evolve, with innovative designs and materials being developed to address current limitations, such as IOL misalignment, posterior capsular opacity, and unpredictable refractive outcomes. Future advancements promise even greater customization and visual performance, heralding a new era in refractive cataract surgery and presbyopia correction.

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