which are placed in the anterior chamber of the eye between the iris and the cornea, and posterior chamber IOLs, which are placed in the posterior chamber behind the iris and rest against the capsular bag. Procedures for implanting the IOLs and technologies for manufacturing them in various sizes, thicknesses, and forms as well as with various materials progressed tremendously in the last decade. Multifocal IOLs are one of the important signs of this progress. While monofocal IOLs, the most commonly used, are designed to provide clear vision at one focal distance, the design of multiple optic (multifocal) IOLs aims to allow good vision at a range of distances.

INTRAOCULAR LENSES: WHAT AND WHY?

An intraocular lens, commonly called IOL, is a tiny artificial lens implanted in the eye. It usually replaces the faulty (cataractous) cristalline lens. The most common defect of the natural lens is the cataract, when this optical element becomes clouded over. Prior to the development of IOLs, cataract patients were forced to wear thick coke bottle glasses or contact lenses after the surgery. They were essentially blind without their glasses. In addition to IOLs replacing the crystalline lenses, a new family of IOLs, generally referred to as phakic lenses, is nowadays subject of active research and development. (Phakos is the Greek word for lens. Phakic is the medical term for individuals who have a natural crystalline lens. In Phakic IOL surgery, an intraocular lens is inserted into the eye without removal of the natural crystalline lens.) These IOLs are placed in the eye without removing the natural lens, as is completed in cataract surgery. They are used to correct high levels of nearsightedness (myopia) or farsightedness (hyperopia).

An IOL usually consists of a plastic lens with plastic side struts called haptics to hold the lens in place within the capsular bag. The insertion of the IOL can be done under local anesthesia with the patient awake throughout the operation, which usually takes <30 min in the hands of an experienced ophthalmologic surgeon (Fig. 1).

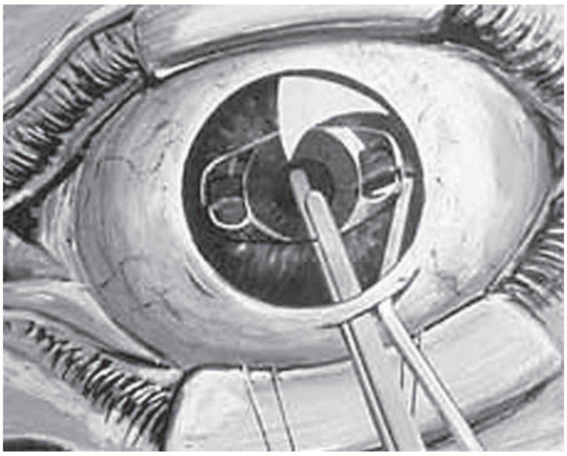

Figure 1. Implantation of an IOL: Since the natural lens is left undistrubed, the operation is much simpler than a cataract operation. The entire procedure consists of making a small incision at the edge of the cornea and placing the appropriate tiny plastic lens in the space between the iris and the cornea, (the anterior chamber). Stitches are used to close the incision.

HISTORICAL OVERVIEW

The idea of the IOL dates back to the beginning of modern cataract surgery when Barraquer developed keratomileusis (1). However, the first implantation of an artificial lens in the eye was probably attempted in 1795 (2). References to the idea of the IOL before World War II in ophthalmic literature are rare. There has been mention of limited animal experiments using both quartz and plastic material performed in the 1940s, but nothing had come of these efforts (3).

The most important step toward the implantation of IOLs came as a result of World War II pilots, and the injuries sustained when bullets would strike the plastic canopy of their aircraft (Fig. 2), causing small shards of plastic to go into their eye. In the late 1940s, Howard Ridley was an RAF ophthalmologist looking after these unfortunate pilots and observed, to his amazement, little or no reaction in cases in which the material had come from Spitfire planes. He then concluded the poly(methyl methacrylate) (PMMA) material of the canopies (windshield) was compatible with eye tissue (4). This observation sparked the idea for inserting an artificial lens in the eye. Ridley, who was convinced this lens should be placed in the posterior chamber, designed a disk-shaped lens, much like the natural lens, with a small peripheral flange allowing him to hold the lens with forceps (4). The artificial lens, made entirely of PMMA, weighed slightly >100 mg in air and was $\sim$8.35 mm in diameter. In several cases, he attempted to implant the lens following intracapsular surgery using the vitreous base for support (5). On November 29, 1949, the first successful IOL implantation was performed at St. Thomas Hospital in London (6,7). While far from perfect, the procedure worked well enough to encourage

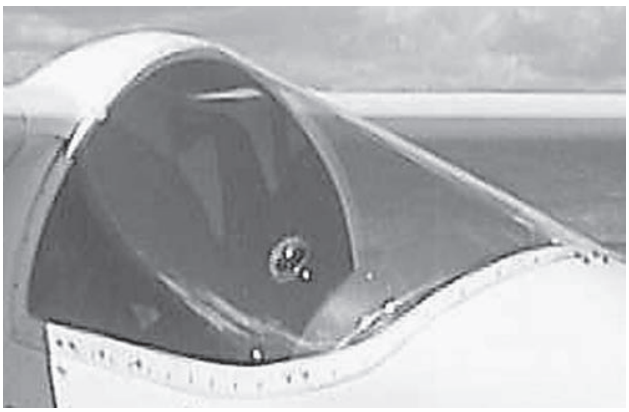

Figure 2. Invention of the IOL: During World War II, Fighter pilots were sometimes involved in accidents where the plastic windshield (canopy) of their aircraft was shattered. Doctors found that fragments of the canopy that entered the eye were tolerated by the eye tissues. They might remain inside the eye for years, and the eye would not react.

further refinement. Then, over a decade, Ridley implanted several hundred IOLs (8).

Though Ridley was ahead of his time, his method was subject to serious criticism. Complications were common and failure rates $> 50\%$ were often contemporaneously quoted. Fixation was dependent on the formation of adhesions between the iris and the capsule. Several ophthalmologists strongly opposed to his procedure. Implantation in the anterior chamber was technically easier and was compatible with intracapsular surgery. Also, fixation could be achieved at the time of implantation by adding haptic struts to the lens that could be wedged into the angle. The first anterior chamber lens was implanted by Baron in 1952 (8).

To make intraocular lens implantation safe, developments in lens design and surgical techniques were required. Lens implantation did not become widely adopted as an integral part of cataract surgery until the 1980s. Key advances were the introduction of viscoelastic fluids to protect the cornea during implantation and flexible haptics to enhance long term stability of the IOL (9).

With traditional single vision monofocal IOLs, people generally experience good vision after surgery at a single focal point, either near or at a distance. The multifocal IOL (10) was designed in the mid-1990s to provide a full range of vision with independence from glasses in most situations.

Besides, the invention of phakic lenses is no less important than Ridley's invention. These IOLs were introduced by Strampelli (11) and later popularized by Barraquer in the late 1950s (12). Phakic IOLs are becoming more popular because of their good refractive and visual results and because they are easy to implant in most cases (13). In the beginning, the design was a biconcave angle-supported lens. These lenses were abandoned following serious angle- and endothelium-related complications. By the late 1980s, Baikoff (14,15) introduced a myopia lens with Kelman-type haptics (16). This design had many problems, leading to its design modification a number of times. Fyodorov, the inventor of radial keratotomy (17), introduced the concept of a soft phakic lens in the space between the iris and the anterior surface of the crystalline lens (18).

Based on earlier works of Worst, winner of the Binkhorst Award for innovation in ophthalmology in 1976, Fechner introduced phakic myopia lens of iris claw design in 1986 (19). This IOL is then referred to as Worst–Fechner lens (20). Many companies around the world manufactured it in various models. Today, people usually identify it by the name of Artisan IOL.

MATERIAL OF THE IOL

Many factors, such as the optical quality of the system of the eye (aberrations, ...), presence of inflammation, cost, and wound size, depend on the material and the form of the IOL.

From the point of view of flexibility, there are two families of IOLs: foldable and inflexible lenses. Foldable IOLs are generally made of acrylic or silicone. They can be rolled up and inserted through a tube with a very small incision not requiring any stitches. Inflexible IOLs, typically made of PMMA, require a larger incision because they are unfoldable. Most lenses are biconvex, thus optically equivalent upside down. However, most lenses have haptics which are generally angled to push the posterior optics.

Four basic materials are used for IOLs: PMMA, silicone, acrylic and collamer. Other materials are also used. For example, some manufacturers replace silicon by a hydrophilic biocompatible polymer, called collamer. Many IOLs have been made from PMMA plastic, the same plastic the original hard contact lenses were made of. Silicon IOLs are foldable. Folding an IOL allows it to be inserted through a smaller incision. A smaller incision heals faster and induces less postop astigmatism. Some foldable lenses are now being made of acrylic plastic. While acrylic and silicone lenses are very popular, PMMA is the time-tested material but, as stated above, requires a large incision. Silicone oil is also a problem for silicone IOLs in that the view of the fundus can be severely degraded. This is less so for PMMA and hydrophobic acrylic IOLs and least for hydrophilic acrylic. Although this is a relative contraindication for silicone IOLs in the face of significant vitreoretinopathy, a solvent exists that eliminates the problem (21). Collamer is a new hydrophilic material just recently released that has shown some interesting properties. It has been shown to exhibit less internal reflectance than other lens materials including silicone, acrylic, and PMMA (22). It reduces the risk of long-term inflammation (23). Table 1 summarizes the characteristics of the four materials.

VARIOUS PARAMETERS FOR IOLs

Are age, race, and sex important parameters for IOL implantation? Age at which surgery is performed turned out to be of great importance (24–28). The ideal age should be at around 18 years when the refraction stabilizes. However, in specific circumstances, in the interest of the minor patient, the parents and the surgeon can opt to perform phakic lens implantation at an earlier age. Studies

Table 1. Four Commonly Used IOLs Materials and their Advantages and Drawbacks

Material	Flexibility	Advantages	Drawbacks
PMMA	Rigid	Low cost, less inflammation, long-term experience, good bicompatibility	larger incision, not foldable
Silicone	Foldable	Smaller incision, injectable	high cost, more inflammation, cannot use with silicon oil
Collamer	Foldable	Smaller incision, less inflammation, very good bicompatibility	high cost, short term experience
Acrylic	Foldable	Smaller incision, less inflammation, high refraction index (thin IOL), good bicompatibility	high cost

of the suitable age of IOL implantation in children have been carried out (24). A 3-year-old child has been qualified with IOL implantation, the child younger than 9 years old should be implanted with a normal adult IOL and then corrected with glasses, and a child after 10 years old should be directly implanted with a proper dioptric IOL (24). Some researchers evaluated the influence of cataract surgery on the eyes of children between 1 and 5 years old. They concluded that cataract surgery, either extraction with or without IOL implantation, did not retard axial elongation in children above 1 year old (25). Comparisons between children with congenital or developmental lens opacities who underwent extracapsular cataract extraction and children with normal eyes have been carried out (26). The pattern of axial elongation and corneal flattening was similar in the congenital and developmental groups to that observed in normal eyes. No significant retardation or acceleration of axial growth was found in the eyes implanted with IOLs compared with normal eyes. A myopic shift was seen particularly in eyes operated on at 4–8 weeks of age and it is recommended that these eyes are made 6 D hyperopic initially with the residual refractive error being corrected with spectacles (26).

To our knowledge, IOL implantation does not depend on race and sex.

OPTICAL QUALITY

Two optical qualities are distinguinshed: the intrinsic optical quality of the IOL and the optical quality of the system of the eye including the IOL. Many factors, such as the material and the geometrical profile of the IOL, influence the intrinsic quality of this optical element. Axial shift (decentration), transversal rotation (not around the optical axis), and deformation (mechanical stresses, . . .) of the IOL are examples of factors affecting the optical quality of the whole system of the eye even in case the IOL alone is a perfect optical element. Thus, the optical quality of the IOL is certainly important. However, for vision, the determinant factor is the optical quality of the whole system of the eye in which the IOL is implanted. Several studies have been undertaken to assess the optical quality of the IOL and the optical quality of the whole system of the eye. Before progressing in this section, let us briefly introduce the notion of optical quality.

Aberrations

Stated in wave optics, the system of the eye should transform the input wavefront into a perfect convergent spherical wavefront that has the image point as center (29–31). Note that an optical wavefront represents a continuous surface composed of points of equal phase. Thus all image-forming rays, which travel normal to the exit spherical wavefront, meet in the focal point in phase, resulting in maximum radiant energy being delivered to that point. In reality, this situation never occurs. The rays modified by the optical system do not converge entirely to a common point image. For one object point correspond several image points that form a blurred image. This deviation from the ideal case is called optical aberration, or merely aberration, and is a measure of the optical quality of the system. Aberration can be quantified either with respect to the expected image point or to the wavefront corresponding to this ideal point. If the real output wavefront is compared to the ideal one, it is called the difference between them wavefront aberration (29). All human eyes suffer from optical aberrations that limit the quality of the retinal image (32–36). Several metrics have been proposed to measure the optical quality of the system of the eye (37–41). Let us return back to IOLs now. Optical quality of multifocal IOLs will be treated in the section devoted to this kind of lens.

Optical Quality of the IOL

The optical quality of IOL was the subject of intensive studies. Several common but some contrasted results have been obtained. An exhaustive study goes beyond the scope of this document. We limit our attention to some recent results. Tognetto et al. (42) evaluated the optical quality of different IOLs by using an optical test bench. The purpose of the study was to evaluate the optical quality of IOLs and not to evaluate the optical performance of these lenses once implanted. Three randomly acquired samples of 24 different models of foldable IOLs were compared. The conclusion is that different IOLs can transmit different spectra of spatial frequencies. The best frequency response was provided by acrylic IOLs, particularly those with an asymmetrically biconvex profile. This could be due to a reduction of optical degradation provided by this type of profile. A lens with a higher frequency response should create a better quality of vision once implanted, and the frequency response should therefore be considered when choosing the intraocular lens model (42).

Negishi et al. (43) evaluated the effect of chromatic aberrations in pseudophakic eyes with various types of IOLs. Their results show that longitudinal chromatic aberrations of some IOLs may degrade the quality of the retinal image. They concluded that attention must be paid to the detailed optical performance of IOL materials to achieve good visual function.

In a comparative study (44), Martin found that the collamer IOL reduced the number of induced higher order aberrations when compared with acrylic and silicone lenses. Indeed, he found that the collamer IOL has 55–117% fewer induced higher order aberrations than acrylic or silicone materials. As a consequence, it produces less postop glare. He concluded the collamer lens provides clearer vision than the other lenses.

Optical Quality of ARTISAN Lenses

Brunette et al. (45) evaluated the optical quality of the eye before and after the insertion of an ARTISAN phakic intraocular lens for the treatment of high myopia (range −20.50 to −9.75D). Consecutive patients implanted with the ARTISAN lens by a single surgeon were prospectively enrolled. One eye per subject was tested. The wavefront aberration was calculated from images recorded with a Hartmann-Shack sensor (46,47). The PSF and the MTF were also computed from the wavefront aberration. It was concluded that preliminary data using the Hartmann–Shack wavefront sensor have not revealed a tendency toward deterioration of the optical performance following the insertion of an ARTISAN lens for the treatment of high myopia. The Hartmann–Shack sensor is a useful tool for the objective assessment of the image optical quality of eyes with a phakic intraocular lens.

MULTIFOCAL IOLs

Unlike the natural lens, the curvature of current intraocular lenses cannot be changed by the eye. Standard intraocular lenses provide good distance vision, and the patient needs reading glasses for near vision. Newer bifocal intraocular lenses give distance vision in one area and near vision in another area of the vision field. How does it work?

The basic idea consists in providing a lens with two posterior focal points instead of one. The IOL is no longer monofocal. It becomes bifocal. Two solutions are possible: refractive or diffractive bifocal lens. A third solution consists in combining both approachs together.

Diffractive Lenses

The idea comes from the principle of the Fresnel zone plate. It consists in designing a binary diffractive phase element so when the incident wave comes across this diffractive element, all the resulting waves, coming from all points of the zone plate, arrive in phase at a certain (focal) point. They then superimpose constructively, yielding a focusing behavior. As shown in Fig. 3, waves traveling along various segments arrive in phase at the focal point since the optical paths differ by a multiple of the wavelength. To fulfill this condition, the thickness d is chosen so that it introduces a phase shift of π: $d = (2k+1)\lambda/[2(n-1)]$ (optical path: $(2k+1)\lambda/2$). In Fig. 3, $k = 0$, yielding $d = \lambda/[2(n-1)]$, where n is the refraction index of the diffractive lens. The radii of the rings (Fig. 3) verify the following rule: $r_m = \sqrt{m}\cdot r_1 = \sqrt{m\lambda f}$, where r_1 is the radius of the smallest circle and f is the focal length. Without grooves on the diffractive, the waves traveling along the segments, represented by dashed lines in Fig. 3, would arrive in phase opposition with respect to other waves. In reality, the binary form (two phase levels) of the diffractive lens does not fully ensure the condition of coming in phase at the focal point. For rigor, several phase levels are required (Fig. 4). In general, the diffraction efficiency η, which is defined as the ratio of the focused energy to the incident energy, increases with the number of phase levels L according to the following formula (48): $\eta = \sin^2(\pi/L)/(\pi/L)^2$. Using two phase levels (binary), only 41% of the energy is focused. The rest is scattered in space. A four level diffractive lens focuses 81% of the input energy (it scatters only 19% of the incident energy).

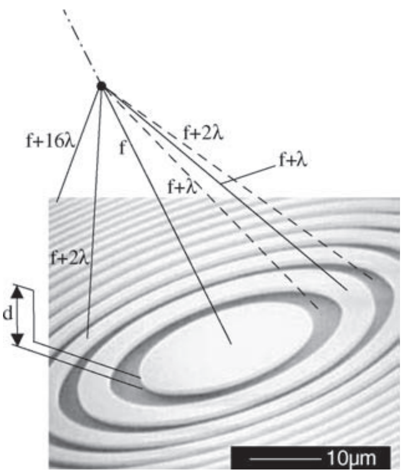

Figure 3. Binary diffractive phase element: Fresnel zone plate. Waves traveling along various segments arrive in phase at the focal point since the optical paths differ by a multiple of the wavelength. To fulfill this condition, the thickness d is chosen so that it introduces a phase shift of π: $d = (2k + 1)\ \lambda/[2(n-1)]$ (optical path: $(2k + 1)\ \lambda/2$): In the figure, $k = 0$.

To obtain a bifocal diffractive lens, we need to focus rays on two focal points at distances f_1 and f_2. It can be done by providing two series of zones (rings). The first series, the inner one, involves radii verifying $r_m^{(1)} = \sqrt{m\lambda f_1}$ (with $m = 1,2,\ldots, M$), whereas the radii in the second series, the outer one, satisfy the condition $r_p^{(2)} = \sqrt{p\lambda f_2}$ (with $p = M+1,\ldots, P$). To obtain a multifocal diffractive lens, we need more series of radii.

Refractive Lenses

An alternative to obtain a multifocal length consists in modifying the surface profil of a conventional biconvex lens so that it provides two or more different focal points for light convergence. The technique consists in designing a spherical refractive surface that has additional refracting surfaces to give a near add (Fig. 5), or a near and intermediate add. The principle of multifocal refractive lenses is illustrated in Fig. 6a. Refractive IOLs with several focal points are commercialized in various models. For example, one of the models includes five refractive zones targeting distance, intermediate and near vision (Fig. 6b). The IOL uses continuous aspheric optics to ensure that 100% of the light entering the eye reaches the retina. The lens uses five concentric zones with the first, third, and fifth zones being far dominant and second and fourth zones being near dominant (49). The light distribution is arranged so that 50% of light is distant focussed, 13% is focussed for intermediate vision and 37% for near vision. The near add

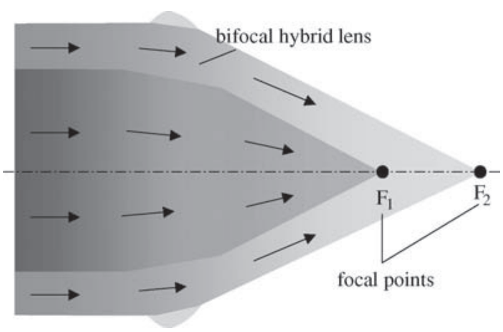

Figure 4. Bifocal hybrid refractive/diffractive IOL: Anterior surface broken up into a refractive zone and a second zone composed of concentric diffractive rings.

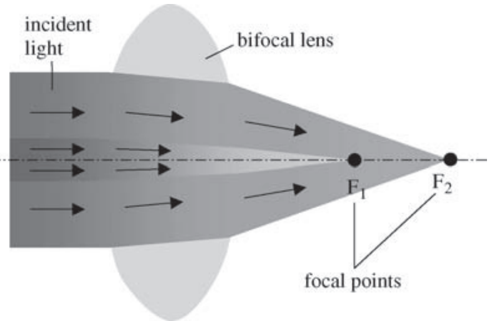

Figure 5. Bifocal refractive IOL: Spherical refractive surface that has additional refracting surfaces to give a near add.

comprises of 3.5 dioptre intraocular power equivalent to a 2.75–2.85 add in the spectacle plane (49).

Optical Quality of Refractive and Diffractive Lenses

This discussion will be limited to some recent results. Pieh et al. (50) compared the optical properties of bifocal diffractive and multifocal refractive intraocular lenses. The IOLs were manufactured by different companies. A model eye with a pupil 4.5 mm in diameter was used to determine the point spread function (PSF) (30,51) of the distance focus and near focus of the IOLs to compare them with PSFs of foci of corresponding monofocal lenses. For interpreting the PSFs the through focus response, the modulation transfer function (MTF) (51), and the Strehl ratio (51) were evaluated. They concluded the modulation transfer functions

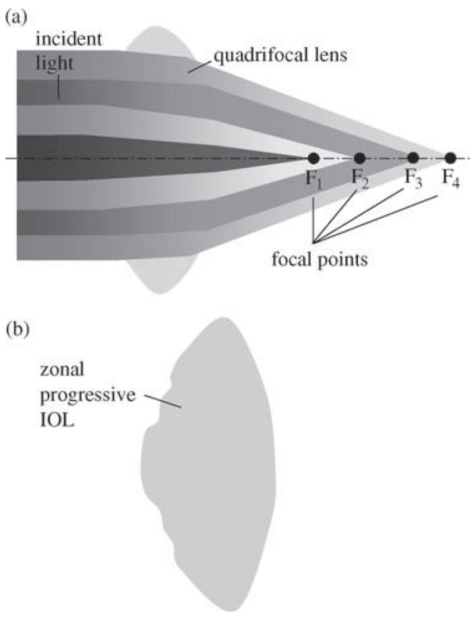

Figure 6. Multifocal refractive IOLs: (a) several refractive surfaces with different curvatures. Each one provides a focal point (b) a commercial zonal progressive IOL with five concentric zones on the anterior surface. Each zone repeats the entire refractive sequence corresponding to distance, intermediate and near vision, resulting in wide-range vision.

reveal comparable properties for distance vision and a superiority of the bifocal diffractive lens over the refractive multifocal lens for near vision. This mean due to the fact that the incoming light is distributed over different zones in the refractive lenses.

Hybrid Lenses

Diffractive and refractive optics (Fig. 4) can be combined. In this type of lens, the basic spherical refractive surface is broken up into a refractive zone and a second zone composed of concentric diffractive rings. This combination of zones creates two different focal points for light convergence, one for near objects and one for distant objects. Hybrid IOLs are basically bifocal lenses (Fig. 4). The usual strategy has been to have a distance component with a near component targeting the usual near distance. However, multifocal hybrid lenses are possible.

IOLs AND ACCOMODATION

New research into accommodating intraocular lenses indicates that many patients who get these implants will enjoy good distance and near vision (52). The first hint that intraocular lens implants could accommodate came back in 1986, when Thornton used A-scan biometry to report on anterior movement of a three-piece loop IOL (53). He found that this forward movement allowed some patients to have good uncorrected distance and near vision simultaneously.

The mechanisms of presbyopia remain incompletely understood. A review of the variety of such mechanisms has been presented by Atchison (54). Accommodation in the youthful, phakic human eye is accomplished by contraction of the ciliary body and subsequent release in the resting tension of the zonular fibers by which the crystalline lens is suspended, resulting in increased lens curvature (55–57). The weight of current evidence seems to suggest that although some loss of ciliary body action might contribute to reduced accommodation (58), significant ciliary body function persists into advanced maturity, and that loss of lens and capsule elasticity in concert with changes in the geometry of zonular attachments are probably most culpable in producing the distress of presbyopia (59). If so, replacement of the crystalline lens with a lens that responds to ciliary body contraction should restore accommodative function (60). Attempts to replace the crystalline lens by refilling the capsular bag with appropriately deformable gels have been made (59,61,62). McLeod et al. aimed at designing an accommodating intraocular lens with extended accommodative range that can be adapted to current standard phacoemulsification and endocapsular implantation technique (60). They concluded that a dual optic foldable IOL design can increase the optical effect of a given displacement and suggests improvements for accommodating intraocular lenses.

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