

## Optics of Ideal Intraocular Lens

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### Abstract

The lens is able to refract light because its index of refraction-normally about 1.4 centrally and 1.36 peripherally-is different from that of the aqueous and vitreous that surround it. In its non-accommodative state, the lens contributes about 15-20 diopters [D] of the approximately 60 D of convergent refractive power of the average human eye; the air-cornea interface provides the rest, or 40-45 D. The aim of this essay is to discuss the optical properties of ideal intraocular lens for cataract surgery patients that meet their visual needs. Cataract is the most leading cause of blindness in the world. Treatment of cataract is done by its surgical extraction. In the past, cataract surgery patients were left aphakic and that was associated with many drawbacks of aphakia correcting glasses.

### 1. Introduction

The history of IOL [intra ocular lens] implantation begins long before the 1940s.

The first reported IOL implant occurred in 1795, when Casaamata, an Ophthalmologist in Dresden, Attempted to use an IOL to correct aphakic vision. The result was not successful and no further attempt reported until 150 years later.

In the late 1940, the first modern intraocular lens - the disk-shaped Ridley lens- was developed. Since that time, lens designed has undergone many modifications, as researchers have developed a better lens [1].

Ideal IOL for a patient should satisfy patient's visual needs as regard the following:

Correct any refractive error the patient has, this is achieved by proper power calculation and applied toric IOL in patients with astigmatism more than 1.25 D of cylinder [2].

Eliminate Ultra violet rays and high energy blue light, blue light filter IOL has this benefit. It is indicated for patient with dry or wet macular disease as blue light, which ranges from 400-500 nanometers in the visible light spectrum, may cause retinal damage and play a role in the onset of age related macular degeneration [2].

Easy implantation and centration and good stability, this depends on many factors as IOL design and material of manufacture. Produce less post-operative complications, as decreasing the possibility for posterior capsular opacification [PCO], and incidence of haloes and glare [2].

### 2. Normal Crystalline lens Anatomy, Accommodation and Optics

#### 2.1 Anatomy

The lens is able to refract light because its index of refraction-normally about 1.4 centrally and 1.36 peripherally-is different from that of the aqueous and vitreous that surround it. In its non-accommodative state, the lens contributes about 15-20 diopters [D] of the approximately 60 D of convergent refractive power of the average human eye; the air-cornea interface provides the rest, or 40-45 D [4]. The lens continues to grow throughout life and at all decades from 10 to 70 years; the male

lens is heavier than its female counterpart [3]. At birth, it measures about 6.4 mm equatorially and 3.5 mm anteroposteriorly and weighs approximately 90 mg. The adult lens typically measures 9 mm equatorially and 5 mm anteroposteriorly and weighs approximately 255 mg. With age, the relative thickness of the cortex increases; the lens also adopts an increasingly curved shape so that older lenses have more refractive power. However, the index of refraction decreases with age, probably as a result of the increasing presence of insoluble protein particles. Thus, the eye may become either more hyperopic or more myopic with age, depending on the balance of these opposing changes [4].

#### 2.2 Accommodation and Presbyopia

Hardening of the lens with age is the principal cause of this loss of accommodation, which is called presbyopia. Once an individual is about 40 years of age or older, the rigidity of the lens nucleus reduces accommodation, as contraction of the ciliary muscle no longer results in increased convexity and dioptric power of the anterior surface of the lens. This decreased accommodation then becomes clinically significant. Studies have shown that, throughout life, the hardness or stiffness of the human lens increases more than 1000-fold. Researchers continue to explore other factors that may contribute to presbyopia, such as changes in lens dimensions, in the elasticity of the lens capsule, and in the geometry of zonular attachments with age [5].

### 3. History of IOL Development

An intraocular lens [IOL] is a lens implanted in the eye to treat refractive errors. IOLs usually consist of small optics with side structures, called haptics, to hold the lens in place inside the eye [6].

Before 1949, cataract surgery resulted in aphakia, and patients were destined [unless highly myopic] to wear high hyperopic spectacles that were of considerable weight and that caused image magnification and distortion to the sides. Scleral contact lenses and eventual corneal contact lenses were used when available and possible [4].

The development of modern IOL implantation began in 1949. The first IOL was implanted by Sir Harold Ridley on 29 November 1949, at St Thomas' Hospital in London [6]. Harold Ridley, an English ophthalmologist, observed that PMMA fragments from airplane cockpit wind shields were well tolerated in the anterior segment of the eyes of injured World War II pilots. He placed a disk-shaped PMMA lens into the posterior chamber of a 45-year-old woman after he performed an extra capsular cataract extraction [ECCE] [Fig. 6] [4]. While there were no surgical problems with this operation the refractive error was grossly overcorrected and the patient ended up with some 20 Dioptres of myopia [7].



**Fig (1)** Original Ridley lens, first implanted by Harold Ridley in November 1949 [4].

#### 4. Intraocular lens materials and designs

##### 4.1 Intraocular lens materials

The earliest IOLs were made of polymethylmethacrylate (PMMA), the plastic that IOL inventor Harold Ridley had noticed to be inert in eyes of World War II aviators struck by flying plastic during combat. With the introduction of phacoemulsification and the possibility to remove the cataract through smaller incisions, foldable materials were developed for IOLs such as hydrophobic acrylic, hydrophilic acrylic (or hydrogel), and hydrophobic silicone, the three main material groups in use today.

##### 4.1.1 Materials used in IOLs

One of the difficulties faced by ophthalmologists when implanting IOLs is tissue complications induced by poor biocompatibility of various polymers used in IOLs' manufacture. Hence, it is important to clinically evaluate and study the biocompatibility of various polymeric materials before using them to produce IOLs. Several articles have reviewed the evolution of the materials used in IOLs [8]. Table 3 lists the materials commonly used in IOLs. Depending on the design, all these materials could be further categorized into optical materials and supporting

materials. Here is a list of several prominent materials used in IOLs.

#### 4.2 Intraocular Lens Design

The design options of making an IOL can be given in many ways, eg. multipiece or monobloc; plate or open-loop style; angulated or planar haptics; special haptics for certain indications such as sulcus, anterior chamber angle, or iris fixation; optic shape and edge design; and optic geometry for certain indications such as toric, aspheric, or multifocal IOLs.

##### 4.2.1 Intraocular Lens Overall Length

The overall length of IOLs is from 10 to 13 mm (averagely 10.4mm) [6]. It appears that the main reason for such oversizing is the need for the IOL to also be suitable for sulcus placement, even though a larger diameter would be preferable for this occasion [9].

##### 4.2.2 Haptic design

The haptic style of plate or open-loop is always compared by researchers to investigate the capsular bag stability and posterior capsule opacification (PCO) [10].

##### 4.2.3 Haptic angulation

The PCO preventative effect of sharp-edge optics suggests that it might be useful to maximize the barrier effect to migrating LECs at the posterior optic edge by pushing the IOL backward against the posterior capsule. This can be achieved with angulated haptic designs [11].

##### 4.2.4 Intraocular lens optic design

###### 4.2.4.1 Edge design

During the past decade it has become clear that optic edge design plays an important role in the prevention of PCO [12].

###### 4.2.4.2 Optic geometry

###### 4.2.4.2.1 biconvexity

Most IOLs on the market have a symmetrically biconvex optic, meaning that the radius of curvature of the front and back surface are identical. In a symmetrically biconvex lens with no angulation, the IOL could be implanted front to back without a change in optical power. [9].

###### 4.2.4.2.2 Optical zone

Most IOLs have a full-size effective optical zone of 6 mm in the main range of IOL powers. Therefore, the higher powered IOLs will have a thicker optic than the lower powers. [9].

###### 4.2.4.2.3 Special Optics

###### 4.2.4.2.3.1 Multifocal intraocular lenses

Multifocal IOLs [mIOL] are designed to overcome the postoperative lack of accommodation by dividing the incoming light onto two or more

focal points. One of these is used for distance vision, the other for near or intermediate vision. These IOLs have shown to reduce the need for spectacle correction in daily life [13]. However, good refractive outcome and low residual astigmatism after surgery are keys to success. Therefore, meticulous biometry and power calculation are needed. Additionally, since the light is divided and also some light [about 20%] is lost to higher orders of diffraction, patients have reduced contrast sensitivity. Small amounts of PCO may cause substantial loss in visual functions and Nd:YAG capsulotomy may need to be performed earlier than usual. Additionally, the blurred nonfocused image will overlay the focused image and can cause the photic phenomenon of halos seen around light sources especially at night with a larger pupil. These can be disturbing to patients and are the main reason for explantation of mIOLs [2].

In general, diffractive mIOLs usually have very well near vision outcomes; however, intermediate vision is poor. In contrast, refractive mIOLs usually have good intermediate vision but relatively poor near vision. In an attempt to get the best of both worlds, a strategy called "mix-and-match" with implantation of a refractive mIOL into one eye and a diffractive mIOL into the contralateral eye has been developed. Another strategy to avoid mIOLs and their potential drawbacks as mentioned above is monovision where both eyes receive standard monofocal IOLs. The dominant eye receives an IOL power to achieve good distance vision and the contralateral eye is made about 1.25 diopters more myopic to allow intermediate vision. With both eyes open, the patients usually have satisfactory near vision, at least under good lighting conditions[9].

Whether using mIOLs or monovision, patient selection and extensive preoperative counseling are key factors for a good outcome. It appears that patient motivation to achieve spectacle independence may be the critical deciding factor for success [14].

## 5. Futuristic intraocular lenses

Cataract surgery provides generally a high rate of patient satisfaction. However, there is no universally accepted and standard validated measure of patient satisfaction after cataract surgery. With current premium IOLs, appropriately selected patients can achieve spectacle independence and good visual outcomes at both near and distance [15].

Improvement in IOL design and perhaps the appearance of effective accommodative IOLs that would be widely commercially available will be the endpoint of clinical use of monofocal as well as premium IOLs available today [2].

### 5.1 Injectable polymers

Several companies are working to provide an injectable polymer with light adjustable technology. The problem with these efforts resides in the fact that it requires a lens extraction through an approximately 1mm capsulorhexis, and this indeed is very difficult to do [11].

### 5.2 Accommodative intraocular lenses

At the present moment, Accommodative Intraocular Lenses [AIOLs] are still a developing topic. Implantation inside the capsular bag does not seem to be the most successful approach. The sulcus is probably the best location for the newest generation of AIOLs. Further properly performed clinical research has to confirm those models that are under development today [2].

One of the major advantages of this type of lenses is that they do not produce a halo effect or reduce contrast sensitivity as is the case with multifocal lenses. On the contrary, near vision is not as good as with multifocal lenses. The use of glasses may be necessary occasionally to see smaller letters although these lenses do considerably reduce dependency on glasses [16].

#### 5.2.1 Crystalens IOL

It is manufactured from high-refractive-index silicone material containing an ultraviolet [UV] filter. To decrease the resistance of the optic to forward motion, the lens incorporates hinges adjacent to the optic across the plates Fig (20). Fixation within the capsular bag is ensured by the presence of small, T-shaped haptics at the end of the plates [2].

#### 5.2.2 AG Akkommodative 1CU lens

It is made of a hydrophilic acrylic material. The principle action of this lens is based on the anterior movement of the optic secondary to the ciliary muscle contraction. The haptics of the lens are modified with transmission elements at their fusion with the optic [2].

#### 5.2.3 Kellen Tetraflex accommodating lens

It is a one-piece highly flexible hydroxyl ethyl methacrylate [HEMA] lens. The lens haptic was designed to take advantage of how the crystalline lens moves during accommodation according to the Helmholtz theory. It is not based on a hinge principle, but rather on a haptic configuration to allow the lens to move with the entire capsular bag [17].

A final concern raised with this lens was its vulnerability to the contraction of the capsular bag due to its highly flexible hydrophilic acrylic material, with a subsequent anterior flexing of the lens haptic component requiring the exchange of the AIOL in many cases [18].

### 5.2.4 Synchrony dual optic IOL

It is a dual-optic silicone lens. It has 2 main components [anterior and posterior] each component has the general design of a plate haptic silicone IOL, with a bridge between them with a spring function connecting the 2 components [2].

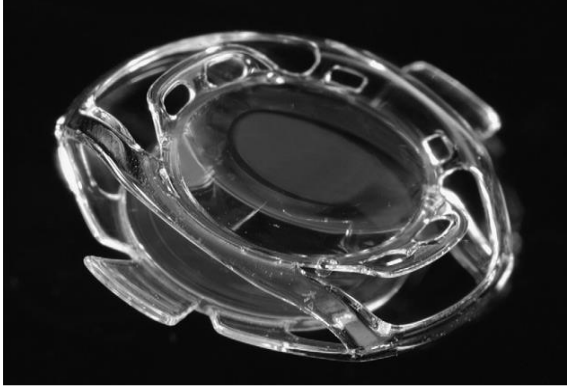


Fig (2) Synchrony dual-optic accommodating IOL [19]

### 5.3 A new generation of accommodative IOLs

Nowadays, a controversial topic is whether an AIOL should be placed inside [the classic approach] or outside the capsular bag. The capsular bag is the basal membrane of the lens epithelium, and once it is emptied its fibrosis and atrophy are unavoidable as it has no function to accomplish and no anatomic structure to support [20].

#### 5.3.1 Lumina AIOL

The lens is manufactured with an acrylic hydrophilic polymer material. The optics provides a fixed optical power: the anterior element is designed to provide 5 D while the posterior provides between 10 to 25 D, depending on the correction needed for the patient after the lens removal. The size of the IOL is personalized based on the sulcus-to-sulcus measurement of each patient. The surgical technique for the IOL implantation is similar to a standard cataract surgery procedure differing only in the placement of the IOL i.e., in the ciliary sulcus. The IOL can be implanted through a corneal incision between 2.8 and 3.0 mm [21].



Fig (3) Lumina AIOL [21].

#### 5.3.2 NuLens AIOL

The mechanism of action of the IOL is as follows: when the ciliary muscle contracts, the forces are transmitted to the piston that induces the gel component to bulge. The optical power of the IOL will increase depending on the magnitude of the silicone bulge due to the contraction of the ciliary muscle. In relation to the surgical technique, the IOL must be implanted through a limbal incision of approximately 9 mm in length. Two serious adverse events observed during the follow up: one posterior synechiae and a capsulorhexis edge capture by the haptic. Both adverse events were resolved after a minor intervention. A large reduction of the endothelial cell count was also found at three months after IOL implantation that steadily stabilized over time with no significant change from the 6 to 12 months follow up period. Finally, there was a 60% rate of posterior capsular opacification during the follow up period, which were successfully treated with Nd:YAG laser capsulotomy [2].

#### 5.3.3 WIOL-CF AIOL

The Wichterle intraocular continuous focus lens has a polyfocal optic that, in theory, changes shape during the accommodation process Fig (4).

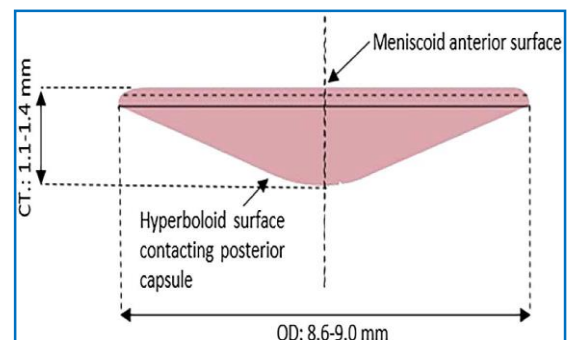


Fig (4) Schematic of the geometry of the WIOL-CF [22]

#### 5.3.4 FluidVision IOL

The FluidVision IOL incorporates a novel design with a 6-mm central optic surrounded by a peripheral reservoir that is filled with isorefractive index silicone oil [Fig. 5]. The hydrophobic acrylic lens is placed in the capsular bag [23].

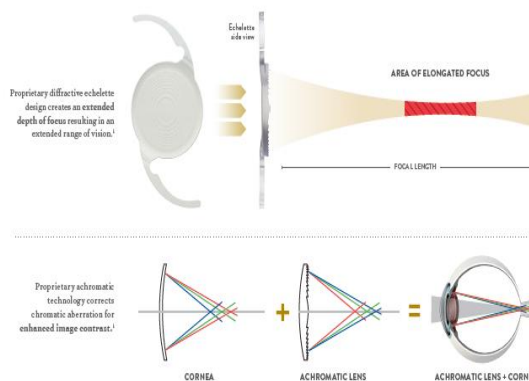


Fig (5) The FluidVision accommodative IOL[23]

#### 5.4 Extended Depth of Focus Intraocular Lens

In an attempt to achieve good quality of vision at all distances, while avoiding undesirable photic phenomena, a new generation of IOLs was introduced, the extended depth of focus [EDOF] IOL also referred to as extended range of vision [ERV] IOLs. The EDOF technology is based on the elongation of the distance the eye remains in focus, through the implementation of spherical aberration created, thus aiming to provide an uninterrupted range of vision [21] [13]

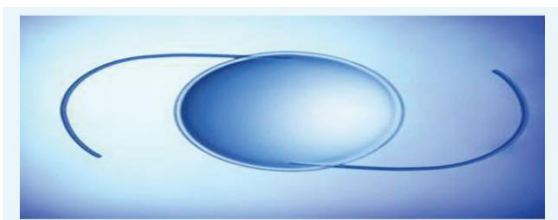
The IOL has a biconvex wavefront-designed anterior aspheric surface and a posterior achromatic diffractive surface with an echelette design [i.e. a diffraction grating designed to reflect infrared radiation] Fig (6) [13].



**Fig (6)** Optics of Symphony Etended Depth Of Focus IOL [22]

#### 5.5 Light adjustable intraocular lens

The concept behind the Light Adjustable Lens [LAL] is that spherocylindrical power modification of the IOL after implantation can overcome the inaccuracies of preoperative biometry, predictive IOL formulae, IOL power inaccuracy, healing responses, and difference in the IOL's final position compared to formulae expectation by allowing these processes to play out and stabilize Fig (7) Both spherical and cylindrical adjustments of up to 2D are possible. For these IOLs, patients are instructed to wear UV protection glasses for 2 to 3 weeks following the operation; this is essential in obtaining the desired outcome. Studies have shown good and stable refractive outcomes with high success rates and low levels of complications [23].



**Fig (7)** The Light Adjustable Lens [LAL][23]

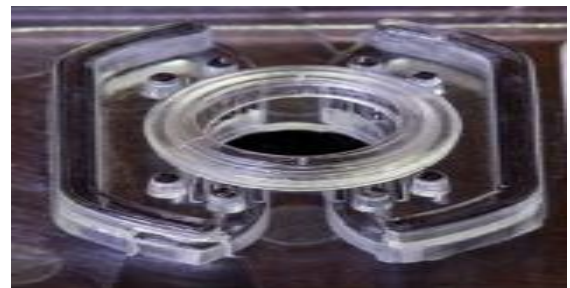
#### 5.6 Refractive Index Shaping Technology

A femtosecond laser system for IOL power adjustment based on the concept of refractive index shaping [RIS] has been developed. It uses green light [520 nm], and operates with energy levels that are below the threshold for ablation or cuts. Multiple adjustments can be performed, as they change a very thin layer within the IOL optic substance, and they are potentially reversible. [24] Furthermore, the hydrophilicity based refractive index change could be used to create a toric diopter change of up to 7.6 D in a monofocal hydrophobic acrylic lens[25].

Refractive index shaping, though still a budding technology, may have the potential to make refractive lens adjustments or even create lens multifocality long after implantation of the original IOL[26].

#### 5.7 Adjunct intraocular implant

The Omega Gemini Capsule, currently undergoing investigational use in humans in the United States, is a refractive capsule with internal shelf-like spaces designed to be implanted into the capsular bag, allowing controlled placement of an IOL into a specific location within the capsular bag [Fig. 8]. The first human experience with the Gemini Refractive Capsule has been recently reported. Although investigational implantation in humans has begun, this device is not yet in clinical trials [26].



**Fig (8)** The Omega-4 is the latest design of the Gemini Refractive Capsule[27].

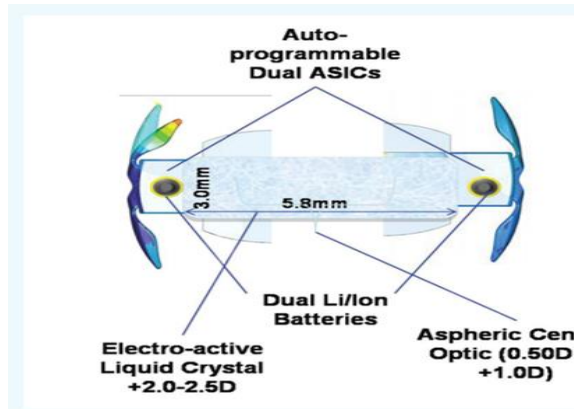
#### 5.8 Electronic intraocular lenses

The advantages of these lenses are that they do not require axial movement of the optic to achieve accommodative effect.

##### 5.8.1 Elenza sapphire autofocal iol

The Sapphire Autofocal IOL has a liquid crystal optic that automatically changes optical power in response to the change in pupillary size for the near triad Fig (9). When the pupillary photosensors are triggered on near response, the stored charge from the photovoltaic cells adjusts the optic for near vision. The power cells are rechargeable via encapsulated microcoils, which also function for two-way communication with the device and external programming. The liquid crystal,

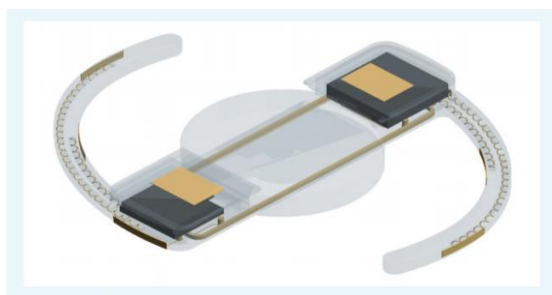
electronics, and power cells are hermetically sealed in a glass chip surrounded by an acrylic outer component. Recharging the power cells can be achieved at night by the patient's wearing a mask over the orbits. If the electronics fail for any reason, the lens defaults to a monofocal IOL. The downside is that the electro-activated process is complex; it depends on pupil size, which is highly variable and changes with age [23].



**Fig (9)** The Sapphire IOL consists of an electroactive liquid crystal, electronics, and lithium ion power cells, which are hermetically sealed in a glass wafer and surrounded by an acrylic outer component [23].

### 5.8.2 VistaLens

Vista Ocular is developing implant technologies that bypass both pupillary and ciliary muscle movement and utilize the muscle's action potential to serve as the signal for accommodation. This design also incorporates rechargeable battery power with a flexible lens system to change optical power in a variable fashion Fig (10) [23].



**Fig (10)** The VistaLens[23].

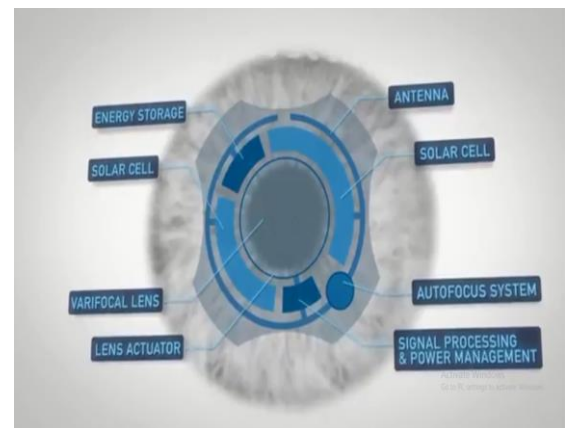
### 5.8.3 R-TASC Lens

Still in the research fundraising phase, Swiss Advanced Vision recently announced the launch of a project to develop the Real-Time Autofocus Servo Control lens [R-TASC][Fig. 11,12]. Theoretically, this lens would be designed to fully restore accommodative function using a solar energy capture system paired with a varifocal lens to allow real-time focus adjustment based on the object being viewed. Some materials used in the

device will be common to other intraocular lenses while some others required for the varifocal lens are more specific. This technology remains at a very early and theoretical stage in development. [26].



**Fig (11)** R-TASC; intraocular lens with auto-focus [28]



**Fig (12)** R-TASC Project – Active Intraocular Lens – Swiss Advanced Vision [29].

## 6. Summary

Cataract is the most leading cause of blindness in the world. Treatment of cataract is done by its surgical extraction. In the past, cataract surgery patients were left aphakic and that was associated with many drawbacks of aphakia correcting glasses.

Cataract surgery provides generally a high rate of patient satisfaction. However, there is no universally accepted and standard validated measure of patient satisfaction after cataract surgery. With current premium IOLs, appropriately selected patients can achieve spectacle independence and good visual outcomes at both near and distance. However, premium IOLs show significant sensitivity to minor ocular aberrations; therefore, adequate preoperative clinical evaluation is crucial to postoperative success. Nevertheless, despite careful selection and screening, some patients will experience unsatisfactory outcomes. Improvement in IOL design and perhaps the appearance of effective accommodative IOLs that would be widely commercially available will be the

endpoint of clinical use of monofocal as well as premium IOLs available today.

Because today's surgeons have wide selections of IOLs to choose from, patients are more often than previously to achieve optimal visual quality after cataract surgery. Additionally, because each patient's expectations and demands are unique, the IOL strategy suggested by the surgeon may not always be the same in each case.

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