

Advanced Intraocular Lens Designs

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Abstract

Intraocular lenses (IOLs) have evolved since their introduction and spherical monofocal designs are no longer the only pseudophakic option. IOLs with a toric surface are able to correct astigmatism, but are dependent on the accuracy of placement. Haptic design is very important with toric IOLs as different designs demonstrate different post-operative rotational stability. Multifocal IOLs produce multiple focal points within the eye and so provide the capacity for simultaneous distance and near vision. Various mechanisms for creating these focal points exist, which determine how light is distributed. Accommodating IOLs use the optic shift principle in order to restore the accommodative response. Single and dual optic variations exist; however, the restoration of accommodation has been limited and variable with the current generation of these IOLs. Aspherical IOLs are designed to improve the optical quality of the image created by the IOL. Aspherical correcting IOLs are dependent on their centration and tilt. New phacoemulsification technology allows cataract removal through a sub-2mm incision, and microincisional IOLs can be implanted through these incisions, which results in minimal surgical impact on the cornea. Blue- and violet-blocking IOLs have been introduced, which might help prevent the development of age-related macular degeneration. Light-adjustable lenses are a relatively new technology and allow non-invasive post-operative adjustment of the IOL's refractive power. This is a fast-moving area of research and development due to the high demands of clinical practice.

Keywords

Intraocular lenses, multifocal, accommodating, blue-blocking, aspherical, toric, microincisional, light-adjustable

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Since the implantation of the first intraocular lens (IOL) in 1949, there have been significant improvements in their design, which have led to cataract surgery being transformed into a precise refractive surgical technique. The evolution of IOL designs has been rapid, and extensive development of new advanced IOLs has occurred in recent years.

The term 'premium IOL' encompasses any non-conventional monofocal IOL. As with most new technologies, premium IOLs are currently more expensive than the conventional designs. Where a country has a social healthcare system, the state covers the cost of conventional monofocal IOL implantation. Premium IOLs may not be provided for under these systems, and an extra payment by the patient may be required for their implantation. However, in many healthcare systems an extra payment is not accepted and premium IOLs are only available privately, with the patient covering the costs of both surgery and IOL.

This article discusses the types of premium IOL available at present. Different varieties of premium lens may be available from various manufacturers. However, the intention of this article is to discuss the principles behind the lenses rather than individual designs.

Toric Intraocular Lenses

Corneal astigmatism greater than 1.50D is prevalent in approximately 22.2% of patients attending for cataract surgery.¹ With high levels of astigmatism, toric IOLs are the correction of choice as they are not

dependent on the healing response of the cornea. In comparison with corneal-relaxing incisions, toric IOLs have proved to be a more effective and stable method of correction;² however, they are dependent on their rotational stability and any axis misalignment results in a reduction of astigmatism correction. If a toric IOL rotates more than 30°, the residual post-operative astigmatism will be higher than the level of corneal astigmatism.³

Toric IOLs have two markings present on the optic demarcating the axis of astigmatism. Once in the eye, a toric IOL needs to be rotated until these markings align with the corneal astigmatic axis. Reference markers need to be placed on the eye to aid with alignment. Eye rotation greater than 10° can occur when assuming a supine position, so these reference markers need to be established before the patient is on the surgical table.⁴ There are several ways of establishing these reference markers: a slit lamp, a slit-beam axis graticule or an eyepiece graticule can be used to determine where to mark the cornea.⁵ Marking devices are also available as one- or two-step systems and can be used to mark the cornea.⁶ Alternatively, the natural landmarks of the iris can be used to determine IOL placement.⁷

Careful wound construction is especially important in toric implantation as hypotony, as a result of wound leakage, destabilises the anterior chamber, increasing the risk of rotation.⁸ Careful choice and removal of the ophthalmic viscoelastic device (OVD) is another

important aspect of toric implantation. It is believed that a dispersive OVD poses more risk of rotation, as it is more difficult to fully remove from the anterior chamber.⁹

Different IOL designs demonstrate varying levels of rotational stability in the early and late post-operative periods. In the early post-operative period, before the lens capsule contracts to lock the IOL in place, friction between the lens and crystalline bag prevents rotation. Lens material has an effect on friction: silicone lenses generate less friction compared with acrylic and polymethylmethacrylate (PMMA) lenses and so result in a higher risk of rotation.¹⁰ Lens size in relation to capsular bag size is also important: if the IOL is too small, there is a lack of contact between lens and bag, resulting in a lack of friction;⁹ if the IOL is too large, it can stretch and distort the bag.¹¹ In the late post-operative period, rotation can occur either through ocular trauma⁸ or as a result of capsular contraction.¹²

Open-loop haptics demonstrate excellent rotational stability in the early period in comparison with plate haptics, as loop haptics are longer, ensuring immediate contact with the capsular bag.¹³ However, open-loop haptics are more susceptible to late rotation caused by contraction of the capsular bag. Provided the loop haptics are inserted in a clockwise direction, under compression the lens optic is forced clockwise.¹² Plate haptics have no such preference of direction as they have no haptic loops. To assist with stability, positioning holes on the haptic allow lens epithelial cells to migrate through, further sealing the lens in place.¹⁴

Toric IOLs with closed-loop haptics were introduced relatively recently. These loops have a second insertion on the IOL, which may provide some resistance against the effects of capsular compression. The devices have demonstrated early promise, but more research is required to prove their stability.¹⁵

Multifocal Intraocular Lenses

Multifocal IOLs (MIOLs) are popular lenses for surgical correction of presbyopia as their mechanism of action is independent of ciliary body function. MIOLs provide high levels of spectacle independence¹⁶ and are currently the most reliable lens for attaining both distance and near vision. MIOLs create at least two focal points within the eye, corresponding to different working distances.

Several mechanisms can be employed to create the simultaneous vision. It is important to consider an MIOL's method of action as each lens has its own unique optical properties. The design of the lens determines how the light is distributed, how many focal points are created, the distance of their separation and the quality of the images created.

MIOLs can be divided into diffractive and refractive designs. Refractive designs can be subdivided into concentric and sectorial, while diffractive designs can be categorised as fully diffractive or partially diffractive.

Concentric Refractive Multifocal Intraocular Lenses

Refraction occurs when light is transmitted through a lens surface. The curvature, thickness and refractive index of the IOL determines the amount by which light is refracted. Refractive MIOLs have several concentric zones that differ in curvature, creating the varying refractive powers. These zones create multiple focal points within the

eye. All concentric refractive MIOLs are pupil-dependent as the refractive zones are relatively large in size. The majority of commercially available refractive MIOLs are of a centre distance design, which ensures that good distance vision is preserved even with the smallest of pupils.¹⁷ Refractive MIOLs do not split the light precisely into two focal points; instead, there is a small spread of light around the near focal point area. The spread results in increased range of near visual acuity (VA) rather than the precise optical quality obtained with a single precise focal point.¹⁸

Sectorial (Rotationally Asymmetrical) Refractive Multifocal Intraocular Lenses

Sectorial MIOLs are a new addition to the multifocal market. These lenses have the external appearance of a C-type bifocal spectacle lens, but their mechanism of action, like all MIOLs, is simultaneous vision rather than translating vision. All of the near light distribution is located on a wedge and currently it is recommended to position the lens in the inferior portion of the eye. Early results with this lens show two precise pupil-independent focal points; however, the lens is dependent on a regular pupil position. Due to its non-concentric nature, this lens does not produce the conventional halo effect; instead, glare is restricted to an area matching the position of the segment.¹⁹

Concentric Fully Diffractive Multifocal Intraocular Lenses

Diffractive MIOLs have many concentric rings across their entire surface. Each ring has a discrete border, which creates a diffraction pattern. By controlling the width of each zone, the diffraction pattern can be used to create two focal points within the eye. Traditionally, diffractive MIOLs were known as bifocal IOLs and split the light equally between distance and near vision. Asymmetrical diffractive MIOLs create an unequal split of light and transmit a higher distribution of light to either distance or near depending on their design.²⁰ With fully diffractive MIOLs, the concentric rings cover the entire optic of the IOL.

These lenses are therefore pupil-independent and the equal split of light is maintained regardless of pupil size.¹⁸ These lenses create two definitive peaks at two specific focal distances, creating two precise, clear images.¹⁸ Careful selection of the reading addition is critical with these lenses as the precise focal points provide clear images over a reduced range in comparison with a refractive MIOL.

Partially Diffractive Multifocal Intraocular Lenses

Unlike fully diffractive MIOLs, partially diffractive MIOLs have the diffraction pattern over only a specific area of the optic. An example of this type of diffraction pattern is with appodised diffractive MIOLs, where the diffractive pattern is present only on the central 3.6mm of the optic. These lenses feature 12 concentric rings over this diffractive area. The centre distributes light equally between distance and near vision; moving towards the periphery of the IOL, each ring progressively distributes more light to the distance. Surrounding this diffractive area is a single refractive surface dedicated to distance vision. It is a pupil-dependent lens: as the pupil size increases, more light is distributed to distance. In mesopic and photopic conditions, the lens provides more vision for distance when the pupil is large.²¹

Pupil Size and Multifocal Intraocular Lenses

It is vital that pupil size is considered when selecting an MIOL. Pupil-dependent MIOLs should not be considered with atypical pupil sizes or pupil positions as their mechanism of action is interrupted.

Excessively small pupil size is a contraindication to multifocal use as the splitting of light should be discouraged when light propagation through the pupil is already low.²² A reduced pupil aperture results in natural increased depth of focus, so these subjects attain near vision regardless of the type of IOL.²³

Choice of Near Addition

Choice of the appropriate near addition for the patient is important and should be undertaken in accordance with individual needs. A common complaint with MIOL implantation is the lack of intermediate vision, and this is especially true with diffractive high-addition MIOLs. A current trend in MIOL design is to have a relatively lower reading addition. This results in a longer working distance for the patient but an improvement in intermediate vision.²⁴

Mixing and Matching Multifocal Intraocular Lenses

'Mixing and matching' MIOLs refers to the implantation of two MIOLs in contralateral eyes. Opinions differ greatly with respect to this approach as it has both advantages and disadvantages. The purpose of mixing and matching is to extend the range of clear vision for the patient and to tailor vision to individual needs. Mixing and matching involves implanting two lenses with either different additions or different designs.²⁵ Combining a diffractive with a refractive MIOL is common as the diffractive lens creates a high-quality near focal point and the refractive lens extends the range of focus. However, this approach highlights the differences between the optical properties of the lenses. In these cases it is common for patients to compare vision between eyes and to feel dissatisfaction if one lens appears to perform worse than the other.²⁶ Patient education is important to prevent unnecessary dissatisfaction: patients need to be aware of the reason behind the implantation of different lenses as well as of the differences between the lenses.

Complications of Multifocal Intraocular Lens Implantation

All MIOLs create two or more simultaneous focal points within the eye. Therefore, at any one time at least one focal point will not be convergent on the retina. This defocused image causes a reduction in contrast and a distinctive photopic phenomenon.^{16,27}

The use of aspherical IOLs has been shown to improve contrast sensitivity (CS) in monofocal IOL implantation. This has led to many modern MIOLs incorporating an aspherical surface to maximise optical quality.²⁸

Photopic phenomena, often described as haloes, are a common complaint with multifocal implantation. It is well established that the effect of haloes reduces over time as adaptation to the phenomenon occurs.²⁹

Accommodating Intraocular Lenses

It has become clear that in the presbyopic eye the ciliary muscle is still active, and with accommodative effect it is possible for a conventional monofocal IOL to move anteriorly.³⁰ It was then hypothesised that if an IOL were developed with an optic designed to shift forwards with ciliary muscle contraction, accommodation could be restored. Current commercially available accommodative IOLs are based on this theory, which has become known as the 'optic-shift principle' and is dependent on the assumption that Helmholtz's theory of accommodation is correct.

Single Optic Accommodative Intraocular Lenses

Single optic accommodative IOLs are designed to translate anteriorly with accommodative effort. This forward movement increases the effective lens power at the spectacle plane. The mechanism of action varies between the various single optic accommodative IOLs, and is dependent on ciliary muscle contraction either producing an increase in vitreal fluidic pressure³¹ (pushing the lens forward) or releasing the zonule tension and allowing the elastic capsular bag to press upon the IOL haptics.³² The accommodative amplitude of these IOLs is limited by the power of the IOL and can be reduced further with capsular opacification, as this reduces capsular bag elasticity.³³

Objective measures of accommodation with accommodating IOLs have demonstrated positive but relatively small amounts of accommodation.³⁴ However, subjective measures are higher and there is ongoing work as to whether the pseudo-accommodation is related to changes in higher-order aberrations rather than true accommodation.

Dual Optic Accommodative Intraocular Lenses

A dual optic system is designed to fill the capsular bag. These lenses have a high-powered positive anterior optic and negative posterior optic. The lens haptic attaches to both optics and keeps the lenses separated. In an unaccommodated state, the capsule holds the lenses close to each other. Accommodation releases the zonules, leaving the capsule to compress the haptics, thus moving the anterior lens forwards. The anterior lens of a dual optic has a higher power than the optic of the single lens system; this means that these lenses are able to produce higher accommodative power.³⁵ Publications examining the effectiveness of this lens are scarce as this is still a relatively new concept. However, these early results have been promising compared with a monofocal control.³⁶

Aspherical Intraocular Lenses

Higher-order aberrations result in a reduction of VA and CS. The average human cornea induces positive spherical aberration (SA) into the eye's optical system. In the youthful eye, the crystalline lens compensates for this SA; however, with age the balance is lost as the crystalline lens starts to induce its own positive SA.³⁷

A spherical IOL also induces positive SA and so compounds rather than reduces the positive SA of the cornea.³⁸ To compensate for this, two forms of aspherical IOL were introduced: aberration-control aspherical IOLs and aberration-neutral aspherical IOLs.

Aberration-control Aspherical Intraocular Lenses

Aberration-control aspherical IOLs induce negative SA to compensate for the positive SA of the cornea. Reducing overall levels of SA can result in improved CS and VA.²⁸ These aberration-control lenses correct a specific amount of SA despite levels of corneal aberration being variable,³⁹ and in a proportion of patients the negative SA of the IOL may not be beneficial to the patient.

Aberration-control aspherical IOLs are dependent on the centration of the IOL in relation to the visual axis. If an aspherical IOL is decentered by more than 0.5mm, its ability to reduce spherical aberration is lost; additionally, if decentration is coupled with tilt, the effects are compounded.⁴⁰ Modern IOLs are centrationally stable, which has increased the popularity of aspherical IOLs. However, in the presence of small pupils any advantages of aspherical lenses may be lost and these lenses may perform like spherical IOLs.

Aberration-neutral Aspherical Intraocular Lenses

Aberration-neutral aspherical IOLs are designed to be aberration-free. They do not introduce any aberration into the eye, but equally do not compensate for the positive SA of the cornea. These IOLs are affected less by centration in comparison with aberration-control aspherical IOLs.⁴⁰ The aberration-neutral aspherical IOLs show superior results compared with monofocal IOLs.⁴¹

In order to achieve optimum visual results, SA needs to be effectively and predictably controlled. Ideally, corneal SA would be measured pre-operatively and a lens could be selected in accordance with this measured level of aberration.⁴²

Microincisional Intraocular Lenses

Debate is ongoing over what exactly constitutes a microincision. However, in cataract surgery it is generally referred to as the removal of a cataract through a sub-2mm incision. Microincisional IOLs have been designed for implantation through these incisions without the need for enlargement,⁴³ although this is not always possible, as IOL development has lagged behind the development of the phaco-emulsification equipment. Theoretically, the smaller the incision, the less impact it has on the cornea, resulting in quicker healing times and less surgically induced astigmatism (SIA), although the exact size of incision at which these effects stop having any incremental effect is unknown.⁴⁴ Microincisional IOLs are available in monofocal, multifocal, toric, accommodative and multifocal toric varieties.

If a corneal incision is placed on the steepest axis, it can reduce corneal astigmatism – and the larger the incision, the greater the level of astigmatism that can be corrected.⁴⁵ Hence, to correct moderate to high levels of corneal astigmatism, microincisional IOLs should be coupled with limbal-relaxing incisions or with a toric optic.

Microincisional IOLs have been shown to produce similar to better visual outcomes compared with standard non-microincisional IOLs. As well as reducing SIA, microincisions reduce the level of higher-order aberrations and provide more rapid post-operative visual stability.⁴⁶ As the availability of microincisional surgery increases, the use of microincisional IOLs will become more common.

Blue- and Violet-blocking Intraocular Lenses

Early IOLs provided no filtered protection. It was soon concluded that the addition of an ultraviolet light (UV) filter to an IOL would prevent retinal photodamage. The definite and conclusive benefits led to the dominant use of UV-filtering IOLs.

The crystalline lens is known to yellow with age, which consequently reduces the transmission of short-wavelength light in the visible spectrum. It has been proposed that chronic exposure to this short-wavelength light is a risk factor for age-related macular degeneration (AMD).⁴⁷ However, the evidence proving that the use of blue- and violet-blocking IOLs can reduce the risk of AMD is equivocal. Epidemiological studies have failed to find conclusive evidence demonstrating a link between light exposure and AMD.⁴⁸ Laboratory studies are largely responsible for establishing the link between blue light and AMD. These studies examined the acute effect of phototoxicity rather than demonstrating the chronic mechanism of AMD development.⁴⁹

There are concerns over the effect of blue- and violet-blocking lenses on mesopic and scotopic vision. When light levels are already low, it

is undesirable to reduce them further with the use of a filter. However, studies examining the effects of blue- and violet-blocking IOLs on mesopic vision found no significant deterioration.⁵⁰ Similarly, it has been demonstrated that these lenses provide similar visual acuity, colour vision and CS to a standard monofocal.⁵⁰

Furthermore, there are theoretical concerns regarding the effect of blue- and violet-blocking IOLs on sleep patterns, as blocking short-wavelength light may affect the circadian cycle. However, *in vivo* studies found no difference in comparison with monofocal IOLs.⁵¹

Until extensive, prospective, randomised, long-term studies examine the effect of blue-/violet-blocking lenses on the development of AMD, their use will remain controversial and debatable.

Light-adjustable Intraocular Lenses

The accuracy of IOL implantation with current biometry techniques has improved greatly with the introduction of optical coherence interferometry and the use of modern IOL calculations. The position of the IOL within the eye is now one of the main causes of refractive error. To increase the accuracy of the refractive outcomes of cataract surgery, an IOL that has a power that is adjustable post-operatively has been created. The light-adjustable lens (LAL) is a silicone IOL whose power can be adjusted using a laser. The LAL has a silicone matrix imbedded with silicone macromers. Irradiation of the IOL polymerises the macromers. If this irradiation is localised, polymerisation is also localised, resulting in a lower concentration of macromers in this region. A diffusion gradient is created: untreated macromers migrate to the polymerised region, creating a localised swelling of the IOL. To create a more positively powered IOL, irradiation is applied to the central area of the IOL; to make the lens more negative, irradiation is applied to the periphery of the lens. Once the required power has been achieved, the entire lens is irradiated, locking the refraction in place. The amount of adjustment is dependent on the amount of localised irradiation and the length of time between initial irradiation and final treatment.⁵² Specific irradiance patterns can be projected onto the LAL in order to correct for higher-order aberrations or astigmatism, or to create a multifocal surface.⁵³

Initial results of LAL implantation have been promising. The LAL polymerisation treatment has demonstrated its effectiveness at treating a range of post-operative refractive errors ranging from +2.00D to -1.50D; this has the potential to reduce the impact of refractive surprises caused by calculation error.^{54,55}

LALs have the potential to non-invasively customise visual correction post-operatively. This has exciting prospects; however, as with all emerging technologies, the current technology is expensive. With time these costs will decrease, although it remains to be seen whether the initial results on implantation are as tight as with conventional monofocal IOLs. Further work is also needed on the potential toxins released from the polymerisation process and whether they have any effect on the eye.

Summary

The evolution of IOL technology has been pronounced in recent years, the end goal being to create an IOL that can predictably and safely correct for any prescription while fully restoring accommodation. It is clear that we are not yet at this point. However, the rapid development of IOL technology appears set to continue in the future. ■

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