Refractive Aim and Choice of Intraocular Lens

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Introduction

In recent decades, there have been revolutionary changes to the design and material of intraocular lenses (IOLs), resulting in a wide diversity of choices available in the market. Different IOLs have different properties and it is important to understand each IOL to assist for the best selection for our patients. IOL materials can be rigid, flexible or foldable. Rigid IOLs are made from polymethyl methacrylate (PMMA), foldable IOLs can be made from Silicone, hydrophilic acrylic or hydrophobic acrylic. IOL designs can be one piece or three piece, square edged or rounded, planar or angulated haptics, they can also be open loop or plate haptic designed as well as short wavelength filtered or ultraviolet filtered. As for its optical properties, it can be monofocal, multifocal or of extended depth of focus, it can also be spherical or toric, depending on the need for each patient. IOL selection is an individualised process and is largely based on the patient's visual requirements and expectations. An ideal IOL should be able to provide a satisfactory visual outcome with good visual quality to the patient, and to the surgeon, it should be easy to handle and insert, with low rates of complications and a long-term safety profile.

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IOL Biomaterials

IOL materials can be rigid, flexible or foldable. Rigid IOLs are made from PMMA, which is a transparent material with a refractive index of 1.49. Flexible IOLs can be made from silicone, which consists of polymers of silicone and oxygen, with a refractive index of 1.41–1.46. Foldable IOLs include hydrophobic acrylic and hydrophilic acrylic. Hydrophobic or hydrophilic depends on its interaction with water. Hydrophobic acrylic IOLs consists of acrylate and methacrylate with a refractive index of 1.54, whereas hydrophilic acrylic IOLs are composed of poly-hydroxyethyl-methylacrylate (HEMA) and hydrophilic acrylic monomer with a refractive index of 1.47.

PMMA

PMMA is the first material used for IOLs. It is rigid, non foldable and hydrophobic with an optical diameter of 5–7 mm. It has been shown that implantation of a foldable or rigid IOL gives similar excellent results with the advantage of being inexpensive [1]. However, due to its lack of flexibility, it requires a large corneal incision for insertion, which has caused it to grow out of favor. PMMA IOLs are also reported to have a significantly higher rate of posterior capsule opacification (PCO) than silicone or acrylic IOLs [2]. Heparin surface modified PMMA IOLs have also been used, theoretically it can reduce postoperative inflammation, and its use in uveitis patients was shown to have good results [3]. PMMA IOLs are currently considered when performing extracapsular cataract extraction, and due to their overall rigidity resulting in good centration and resistance to tilt, it is used for scleral fixating IOLs. PMMA material is also used in anterior chamber IOLs as well as iris fixated IOLs due to its inert property with minimal inflammation.

Silicone

Silicone material is flexible and hydrophobic. Because of this property, it allows a smaller corneal incision for IOL implantation. In 1980s, silicone IOLs have come into place, it is a flexible IOL with an optical diameter of 5.5–6.5 mm [4]. However, since 1990s, several case studies have reported an interaction between silicone oil used in vitreoretinal surgeries with silicone IOLs. The strong adherence of silicone droplets on the IOL have caused significant visual loss and in some cases, resulted in the need for IOL exchange [5–8]. Therefore, it is not considered in potential cases for vitreoretinal surgeries such as high myopia or eyes with proliferative diabetic retinopathy. Silicone IOLs are also not easy to handle, as they become slippery when wet, which is almost unavoidable during a cataract surgery. Another disadvantage is its rapid unfolding. Surgeons have reported

unexpected posterior capsule rupture in apparently uneventful phacoemulsifications until the IOL was injected [9].

Hydrophobic Acrylic

Hydrophobic acrylic materials are a series of copolymers of acrylate and methacrylate derived from rigid PMMA, which makes it both durable and foldable. Hydrophobic acrylic foldable IOLs were first presented in 1993 and have quickly dominated the market ever since their introduction. They have an optical diameter between 5.5 and 7.0 mm and are available in one piece or three piece designs. They have a higher refractive index, therefore allows for thinner lenses and they also have a very low water content. Although being foldable, they have a slower and more controlled unfolding rate as compared to silicone IOLs. Meta-analysis and different studies have also reported a lower PCO rate when compared with hydrophilic acyclic IOLs [10–12]. Other studies have also shown a lower incidence of Nd:YAG laser capsulotomy in hydrophobic acrylic IOLs than PMMA or silicone IOLs [13]. However, they have a disadvantage of having intralenticular changes where small water inclusions cluster together and this has been reported to cause significantly greater level of glistening than silicone and PMMA [14], leading to visual disturbance.

Hydrophilic Acrylic

Hydrophilic acrylic materials are composed of a mixture of poly-HEMA and hydrophilic acrylic monomer. They are foldable, soft, with high water content and have excellent biocompatibility due to the hydrophilic surface. They also have a slower unfolding rate as compared with silicone IOLs and are easy to handle and relatively more resistant to instrumental damage or Nd:YAG laser [15]. Postoperatively, hydrophilic acrylic IOLs have been shown to have minimal inflammatory cells on the anterior surface of the IOL, which indicates a high uveal biocompatibility [16]. The best IOL should provide optimal uveal and capsular biocompatibility, which can be determined by examining the cellular reaction on the anterior and posterior surface of the IOL [17]. The cellular reaction consists of foreign body giant cell reaction to the IOL, which is an indicator of the uveal biocompatibility. As for capsular biocompatibility, this can be determined by the proliferation of lens epithelial cells (LEC) after contact between the capsule and the IOL. When comparing with hydrophobic acrylic IOLs, hydrophilic acrylic IOLs are also shown to have better biocompatibility [18]. However, case reports have shown the presence of calcium deposition on IOL optics (under certain circumstances), which leads to decrease in visual acuity and the need for IOL exchange [19–21]. Hydrophilic acrylic material was also shown to carry a higher risk of

PCO than hydrophobic material [22], this may be explained by the higher water content which attracts LEC migration. Furthermore, hydrophilic IOL is considered contraindicated in patients with asteroid hyalosis.

IOL Optical Design

IOL evolution was driven by efforts to improve its surgical handling as well as optical performance. There is a large variety of different designs available aiming at different purposes to improve visual outcome.

Three Piece or One Piece?

Since the introduction of hydrophobic acrylic IOLs, they have become the most popular foldable IOL worldwide. In 1993, the first hydrophobic acrylic model was introduced into the market—three piece Alcon AcrySof. It quickly gained popularity due to its stable clinical results, excellent biocompatibility and low rate of PCO [23]. In 2000, Alcon introduced the one piece AcrySof (Fig. 1), aiming to allow a easier insertion through a smaller incision. Three piece IOL are made of different materials, the optic can be made of PMMA, silicone or acrylic, while the

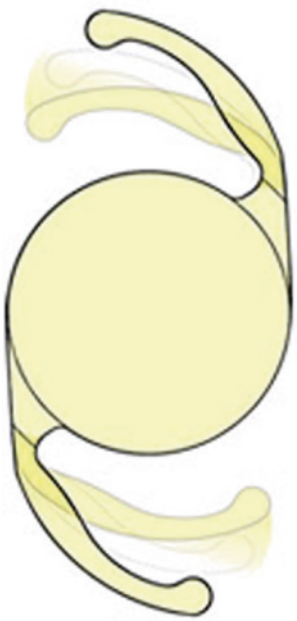

Fig. 1 Alcon® AcrySof one piece IOL

highly elastic haptics tend to be made of PMMA (Fig. 2). For a one piece IOL, it is entirely made out of one material and is usually acrylic. When compared with the three piece IOL, the one piece IOL has similar overall length and optic diameter, the optic edge is slightly thicker due to broad haptic shoulders at the transition from the optic, also, it has a flat configuration as oppose to a slight angulation in the haptics of a three piece IOL.

The first clinical comparison of the two AcrySof designs was published in 2003, the retrospective study showed similar visual acuity, centration and refractive stability between the two IOLs [24]. However, one piece IOLs were shown to have more PCO than three piece IOLs. The higher incidence of PCO was thought to be due to a lack of a sharp posterior edge, which is present in three piece IOLs, to indent the posterior capsule for a barrier to prevent migration of LEC. However, further prospective, randomized comparison showed equal stability and degree of opacification between three piece and one piece IOLs [25].

With regards to implantation, due to more rigid haptics, three piece IOLs require a larger corneal incision to reduce risk of damage to the haptics, they also carry a higher risk of posterior capsule rupture during insertion and unfolding. Therefore, in current practice, they are mainly considered when there is a need for sulcus implantation, due to better stability in the sulcus and a lower chance of iris chafing by slightly thinner haptics [26]. Indeed, the ASCRS recommended a 13.5 mm three piece IOL with posteriorly angulated haptic and rounded anterior optic edge to be inserted in the sulcus with optic capture at the anterior capsulotomy for best results.

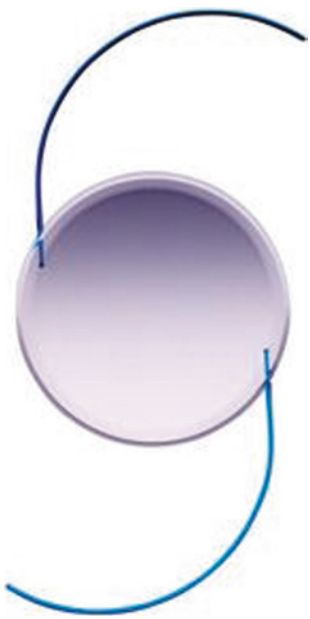

Fig. 2 Precision Lens® AR40 three piece IOL

Square Edged or Round Edged?

The incidence of PCO with AcrySof IOLs was noted to be significantly lower. Studies have been carried out to determine whether the material or the design contributes to the reduction of PCO. An animal study showed the inhibition of LEC proliferation by creating a sharp capsular bend from using square edged acrylic IOLs [27]. Another prospective study implanted otherwise identical acrylic IOLs with or without a square edge in alternate eyes and found that the eyes receiving square edged design developed less PCO [28]. Further studies have also found that PMMA or silicone IOLs with square edged designs also significantly prevents PCO [28, 29]. These findings conclude that it is the square edge rather than the IOL material that is the primary factor in reducing the formation of PCO. The rationale being that any IOL with a squared edge, regardless of the material, is able to indent the posterior capsule, which forms a mechanical barrier to prevent LEC migration and PCO formation. A meta-analysis comparing square and round edged IOLs also showed a clear beneficial effect of square edged IOLs in PCO prevention [30].

However, it is well documented that square edged designs have their specific drawbacks. Edge glare phenomenon or unwanted optical images have been reported in square edged designs [31, 32]. These unwanted images contribute to symptoms of dysphotopsia, which can be positive or negative. Positive dysphotopsia is characterized by brightness or light streaks radiating from a central source of light. Negative dysphotopsia is characterized by darkness or shadows at the temporal peripheral field of vision [33]. Dysphotopsia symptoms are thought to be due to distribution of intensified edge glare rays to the peripheral retina. Round edges provide a great reduction in potential glare by disbursing reflected edge glare rays and reducing the intensity on the retina. Edge rounding can significantly reduce the potential for unwanted optical images, however it loses the ability for a capsular bend in the prevention of PCO. As both square edged and round edged designs have their own tradeoff, further refinements in edge design will be necessary to determine the optimal design that can both minimize edge glare phenomenon and PCO.

Planar Haptics or Angulated Haptics?

Besides having a squared edge as a barrier to prevent the formation of PCO, IOL haptic designs have also been considered in PCO prevention. Haptics with a forward angulation of roughly 5–10 degrees aim to push the optic backwards against the posterior capsule to cause a barrier effect for LEC migration. However, studies have showed that angulated haptic designs do not seem to have a better PCO prevention effect than those with planar haptics [34].

Loop Haptic or Plate Haptic?

Capsule contraction syndrome was defined as a reduction in equatorial diameter of the capsular bag, fibrosis of the anterior capsule and shrinkage of its opening [35]. Shrinkage of capsule is due to an imbalance between centrifugal and centripetal forces on the capsular bag. The size of the continuous curvilinear capsulorrhexis (CCC), zonular stability, IOL material and IOL design may play a role in the formation of capsular contraction syndrome. The smaller the CCC, the greater the sphincter effect on the IOL. The weaker the zonules, the more imbalance between the forces and the capsulorrhexis perimeter. As for the IOL design, excessive capsular fibrosis has been observed more commonly with silicone IOLs, this was attributed to the chronic low grade inflammation that was seen after the implantation of silicone material intraocularly as well as a relatively flexible material which is less resistant to capsular tension [36, 37]. On the other hand, haptic design - loop haptic (Fig. 3) versus plate haptic (Fig. 4) - was shown to have a major effect on the causation of capsular contraction syndrome. A study compared a loop haptic design with a plate haptic design with almost identical optics in terms of material, diameter and thickness, the study reported a marked constriction of the CCC in the plate haptic design [38]. The authors proposed three reasons for the causation of such. Firstly, it can be explained by the large area of contact of the plate haptic with the anterior capsule that may stimulate cell proliferation and fibrosis. Secondly, the large size of the plate haptic may have prevented fusion between the

Fig. 3 Zeiss® CT Lucia loop haptic IOL

Fig. 4 Zeiss® CT Asphina plate haptic IOL

anterior and posterior capsules, such that capsule bending is not possible and this allows for LEC migration. Thirdly, the plate haptic has a small arc of contact with the fornix of the capsular bag and may inhibit the proliferation of LEC less than loop haptics.

With regards to optical performances, there have been contrasting evidences when comparing loop haptic to plate haptic designs. Studies have showed that due to a better stability, plate haptic designs result in better optical performances than loop haptic designs [39]. However, recent studies have showed similar optical performances and rotational stability when using plate haptic or loop haptic toric IOLs [40, 41].

Ultraviolet Light Filtered or with Blue Light Filtered?

Ultraviolet (UV) has been proven to be toxic to the retina due to short wavelength energy causing oxidative stress to the retina [42]. Retinal protection against UV and blue visible light is usually done by the cornea and crystalline lens. After cataract removal, the amount of light transmission to the retina increases, which leads to the creation of UV filtering IOLs (Fig. 5), and subsequently, by adding yellow chromophores to it, blue light filtering IOLs were introduced. Blue light filtering IOLs (Fig. 6) were also referred to as yellow tinted IOLs. The rationale for blue light filtering IOL is to imitate the human crystalline lens. With ageing, yellow chromophores accumulate in the lens and decrease the transmission of visible blue light which is one of the factors in the pathogenesis of age related macular degeneration (ARMD) [43]. Theoretically, with the addition of yellow chromophores, blue light filtering IOL reduces chromatic aberration, provides protection against phototoxic short wavelength light and also reduces cyanopsia, which is when patients notice a blue tinge to their vision post operatively [44, 45]. Studies have also suggested other benefits including improvement in contrast sensitivity and reduction in glare [46, 47].

Fig. 5 Alcon® AcrySof SN60WF blue light filtered IOL

Fig. 6 Bausch+Lomb® enVISTA MX60 UV light filtered IOL

Although blue light filtering IOLs have been suggested to be retinal protective and prevent the development of ARMD, firm clinical evidence is still lacking. There has been contrasting evidence on the photoprotective effect of blue light filtered IOLs. A recent small study showed strong support of a photoprotective role of blue light filtered IOL on the progression of geographical atrophy in ARMD [48]. Blue light filtering IOLs were also shown to significantly reduce blue light

induced apoptosis to the RPE cells [49, 50]. However, others reported no differences in macular changes between an ultraviolet filtering IOL and a blue light filtering IOL [51]. This finding was also supported in another study where blue filtered IOLs showed no significant clinical or optical coherence tomography (OCT) findings with respect to ARMD [52].

With regards to visual performance, recent systematic review and meta analysis showed that there is no clinically meaningful difference in visual acuity, colour vision and contrast sensitivity, both IOLs demonstrated similar visual performance [51, 53, 54]. As there is good evidence in the literature to support a similar good visual performance of blue filtering IOLs with definite and theoretical benefits of reduction in glare and filtration of short wavelength light, using blue filtering IOLs is a sensible precaution especially in cases with high risk of ARMD [55]. In current practice, surgeons opt to match the IOL with the one used in the fellow eye to avoid unwanted visual disturbances and imbalance between both eyes.

IOL Optical Properties

Nowadays, the goal of cataract surgery is to provide good visual acuity as well as visual quality preferably at all distances. Different IOLs have different optical properties. Monofocal IOLs aim at providing clear vision at one distance, which is usually for distance vision. Therefore, reading glasses will be needed for near and intermediate vision. In the last decade, many improvements have been made to allow for the development of a wide spectrum of IOLs beyond the standard monofocal IOLs. Presbyopia-correcting IOLs aim at providing clear vision for near, intermediate and distance vision, which is limited in monofocal IOLs, such that these patients can be spectacle independent at all times.

IOL Selection

Spherical Correction

Monofocal IOL

Monofocal IOL is the most common type of IOL used in cataract surgery. It has one focusing distance and it can be set to focus for near, intermediate or distance vision depending on the targeted refractive error. Most patients opt for low myope or even emmetropia to set for clear distance vision so they will be spectacle independent most of the day, however, they will need reading glasses for near and intermediate work.

Presbyopia

Presbyopia-Correcting IOLs

After cataract extraction, there is a loss of accommodation, which was present in the native lens in younger patients. The implantation of the standard monofocal IOLs can only provide clear vision at one distance, therefore, patients will still need to rely on glasses for other distances. Presbyopia-correcting IOLs were developed to combat the loss of accommodation and they can be subdivided into multifocal IOLs, accommodative IOLs and extended depth of focus IOLs.

Multifocal IOL

Multifocal IOL functions by generating different foci by either a diffractive or a refractive design, this addresses the visual limitation in monofocal IOLs. Diffractive IOLs are created by the use of concentric rings of decreasing height on the posterior surface of the IOL, which causes diffraction of light at both near and distance [56]. Diffractive IOLs can be subdivided into apodized or non apodized (Figs. 7 and 8). Apodization causes optical properties of the IOL to change

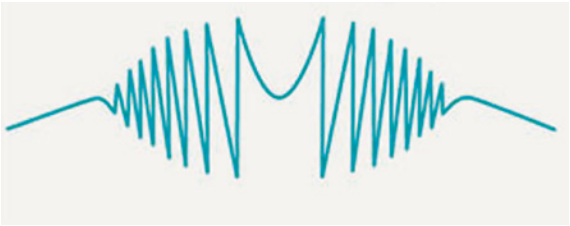

Fig. 7 Optical profile in Apodization

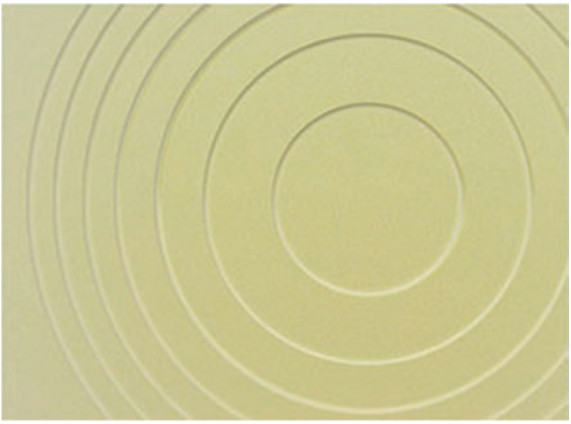

Fig. 8 Apodized Diffractive IOL

Fig. 9 Alcon® AcrySof Restor Multifocal IOL

across the optical surface from the centre to the periphery. Apodized diffractive IOLs allow for a smooth transition of the distribution of light energy between different foci, so allowing more light to near when the pupil is small, this is usually the case when carrying out near tasks, and more light to distance when the pupil is large, this is usually seen when looking at distance [57]. Apodization helps in improving image quality and to minimize visual disturbances such as halos and glares and night vision problems. Refractive IOLs function by the use of concentric refractive zones of different powers to allow for viewing at all distances [58].

Multifocal IOLs (Fig. 9) can be bifocal or trifocal. Bifocal IOLs are made of concentric rings that form two primary focal points, aiming at providing clear vision for both near and distance. Trifocal IOLs are a newer type of multifocal IOL and are designed to form three focal points to provide a better intermediate vision than bifocal IOLs, while preserving clear vision for both near and distance ranges. Although trifocal IOLs seem ideal, the addition of an intermediate focus results in an additional defocus image instead of one, which may lead to symptoms of glare and haloes [59]. Since the introduction of trifocal IOLs, it has caused a matter of concern regarding the visual performances between the two IOLs. A study has compared the visual performance after bilateral implantation of a diffractive bifocal or trifocal IOL from the same manufacturer using the same material, the study concluded that trifocal IOL can provide a significantly better intermediate vision and equivalent distance and near vision as bifocal IOL without any disturbance in visual quality [60]. Recent meta-analysis compared the visual performance of bifocal and trifocal IOLs, trifocal IOLs have a clear advantage

over bifocal IOLs in intermediate vision, however, both IOLs have similar near and distance visual performance, spectacle independence and postoperative satisfaction [61, 62].

Despite aiming to provide good vision at all distances, multifocal IOLs have their own drawbacks. Multifocal IOLs have been shown to cause a decrease in near contrast sensitivity under both mesopic and photopic conditions, and a decrease in distance contrast sensitivity under mesopic conditions [63]. This may be due to redirection of light from the other focal points causing coexisting images and a lower contrast sensitivity. A recent systematic review and meta-analysis compared multifocal IOLs to standard monofocal IOLs. With multifocal IOLs, a higher proportion of patients were able to achieve spectacle independence but at a greater risk of unwanted visual phenomena, these includes symptoms of halo and glare [64].

When comparing diffractive and refractive IOLs, diffractive IOLs can provide a slightly better near vision and less halo and glare, however they have a slightly worse intermediate vision. Refractive IOLs are more dependent on pupil diameter which may lead to night vision problems, and this is probably due to the zonal design of the IOL [58, 65]. With an attempt to incorporate the best of both diffractive and refractive IOLs, mix-and-match method has been introduced. Mix-and-match method functions by bilateral implantation of diffractive in one eye, and refractive multifocal IOLs into the fellow eye in attempt to achieve better visual outcomes. A few studies on the mix-and-match method have shown safe and good results at all distances, an increase in contrast sensitivity, a high level of patient satisfaction and a high rate of spectacle independence [66–68].

The decision to implant multifocal IOLs should be based on consideration of a patient's motivation to achieve spectacle independence, if so, pre operative counseling is of vital importance. Patients should be notified on the possible side effects such as decrease in contrast sensitivity, halos, glares, starburst, night vision problems and the need for visual adaptation.

Supplementary IOL

Refractive surprises or undesirable visual outcomes happen occasionally after multifocal IOL implantation. To address for this problem, many methods have been discussed, these include IOL exchange, refractive corneal surgery and supplementary piggyback IOLs. A retrospective analysis showed multifocal retreatment rate was 10.8%, of which supplementary piggyback IOLs consists of 89% [69]. Supplementary IOLs are implanted into the ciliary sulcus for refractive correction, Sulcoflex® IOL (Fig. 10) is one such lens. Recent studies evaluated the implantation of Sulcoflex® IOL for post operative negative dysphotopsia, these studies concluded that Sulcoflex® IOL can successfully treat negative dysphotopsia and symptoms resolved completely in all cases [70, 71]. Sulcoflex® IOL has been shown to be an effective treatment option with predictable outcome in the correction of post operative refractive surprises, it also reduces spectacle dependence and is well tolerated by implanted eyes [72].

Fig. 10 Rayner Sulcoflex® Trifocal IOL

Accommodative IOL

Accommodative IOL is designed by simulating the natural accommodative process by changing optical power in response to ciliary muscle contraction [73]. A recent systematic review and meta-analysis confirmed that accommodative IOLs can provide better distance corrected near visual acuity and results in higher levels of spectacle independence than standard monofocal IOLs [74]. Accommodative IOLs also produce minimal unwanted visual disturbances such as halos and glares and contrast sensitivity is preserved when compared with multifocal IOLs.

There are mainly two types of accommodative IOLs, the single optic and the dual optic IOLs. After a single optic accommodative IOL is placed into the capsular bag, the anterior capsule fibroses and induces pressure on the optic plate, which cause it to vault posteriorly. When the ciliary muscle contracts, it moves the optic forward and causes an axial positional change in the IOL thus adjusting its optical power. Approximately 1 mm of movement is equivalent to a 2 diopters power change [75]. The main drawback of this design is that it is very dependent on the function of the capsular bag. With time, anterior capsule fibrosis may develop, this may limit the axial movement of the IOL and progressively loses its accommodative ability. Also, the degree of refractive change differs according to the axial length in each eye, which may lead to unpredictable outcome. The dual optic accommodative IOL functions by a spring system comprising a high plus power anterior optic coupled to a compensatory minus power posterior optic. When the dual optic accommodative IOL is implanted in the capsular bag, it is compressed due to capsular tension. During accommodation, the zonules relax and the capsular tension is released, leading to an expansion of the capsular bag. Due to the spring system design, it causes a forward axial displacement of the optic and a dynamic increase in dioptric power of the IOL [76, 77]. The dual optic system is currently the most promising generation to attempt to simulate a larger degree of accommodative effect, however, larger trials with longer follow up are necessary to support clinical usage.

Fig. 11 Tecnis® Symfony Extended Depth of Focus IOL

Extended Depth of Focus IOL

As multifocal and accommodative IOLs both have their own drawbacks, the goals of spectacle independence as well as optimizing visual quality have driven the development of extended depth of focus (EDOF) IOLs (Fig. 11). EDOF IOLs provides a single elongated focal point to enhance depth of focus or range of vision. The principle behind EDOF IOL is to focus light rays in an extended longitudinal plane as opposed to monofocal and multifocal IOLs, which focus light rays at one single point or multiple points respectively. This elongated focus aims to eliminate the overlapping of near and far images created by multifocal IOLs and therefore significantly reduces potential halos and glares [78]. A recent study has shown that EDOF IOLs provide better optical quality than monofocal and multifocal IOLs [79]. Due to the novelty of this design, limited studies have been carried out, but preliminary results are promising. To date, there is only one large prospective multicenter study being performed, which reported a successful visual restoration across all distances and a minimal level of disturbing halos and glares, as well as high levels of patient satisfaction [80]. Recently, the use of 'blended EDOF' has also been discussed. Blended EDOF aims at implantation of an EDOF IOL in one eye and a multifocal IOL in the fellow eye. A recent study compared visual outcomes between bilateral implantation of a diffractive multifocal IOL with blended EDOF, results showed that blended EDOF exhibited a better performance for uncorrected distance visual acuity but slightly worse in uncorrected near and intermediate visual acuity, blended EDOF also showed better contrast sensitivity under photopic conditions [81]. EDOF IOLs have promising results, however, larger clinical trials are also needed for better evidence to support clinical implantation.

Refractive Rotational Asymmetry IOL

Nowadays, patients have high visual expectations. After cataract surgery, patients not only expect to have clear vision for all distances including presbyopia correction, they also do not expect any compromise in contrast sensitivity and dislike unwanted visual symptoms. To overcome the drawbacks of multifocal IOLs,

a new single piece refractive IOL has been introduced. The Lentis Mplus X IOL is a refractive rotational asymmetry IOL aiming at providing high contrast sensitivity and minimising halos and glare. The IOL provides multifocality by having 2 sectors with a seamless transition in between, there is an aspheric sector for distance vision and a +3.00 D sector in the lower IOL segment for near vision. This IOL is based on the concept of rotational asymmetry to reduce any potential sources of light scattering. Light is refracted to the near focus specifically in the lower sector and the rest of the lens acts as a monofocal IOL, this allows for more light to the distance focus without being scattered by diffraction, which then improves contrast sensitivity, causes less halo and glare and better image quality [82]. This IOL has a diameter of 11 mm and an optical zone diameter of 6 mm. A study with bilateral implantation of Lentis Mplus X IOL concluded that this new generation multifocal IOL was able to provide adequate distance, intermediate and near vision with high rates of spectacle independence [83]. Another study compared EDOF IOLs with Lentis Mplus X IOL, results showed that the Lentis Mplus X IOL had the highest higher order aberration in all cases [84]. However, although this new generation IOL was shown to provide a wide range of focus with no significant decrease in optical quality, IOL tilt in eyes are factors that limit its near vision outcomes [82]. Therefore, new haptic designs and a longer follow up period is needed to confirm the stability of this new generation multifocal IOL.

Monovision and Mini-Monovision

Monovision functions by using standard monofocal IOLs to correct distance vision in the dominant eye and to intentionally focus for near to intermediate vision in the non dominant eye. Monovision requires a process of neuroadaptation, which is how the brain adapts to use the dominant eye for distance image and the non dominant eye for near image to achieve a wide range of vision to achieve spectacle independence [85]. Monovision is usually achieved when the non dominant eye targets for roughly −2.50 D or more, but this is not always the case. Patient dissatisfaction usually arises from insufficient unaided reading capacity [86]. However, larger degrees of intended anisometropia come at a price, which causes a compromised visual function such as stereopsis and contrast sensitivity. Therefore, this technique is not appropriate for all patients. To address this, mini-monovision is a technique to aim at a smaller range of anisometropia, where the non dominant reading eye aims between –0.75 and –1.25 D, this provides a good distance and intermediate vision, better stereopsis, fewer optical side effects but requires spectacle wear for certain near tasks such as reading fine prints or computer work [87]. Studies have compared bilateral implantation of multifocal IOLs to the effect of using mini-monovision technique, multifocal IOLs demonstrated better near vision and higher spectacle independence rate but also more likely to undergo IOL exchange, whereas mini-monovision technique reported fewer visual disturbances with acceptable rates of spectacle independence

[88–90]. The greatest challenge of using monovision technique is patient selection. Ideally, potential patients should undergo a contact lens trial to ensure good neuroadaptation for the technique. Mini-monovision technique is a choice to consider, as it creates a lesser degree of anisometropia and provides a good balance between spectacle independence and better stereopsis. It is also more cost effective when compared with multifocal IOLs. However, patients should be warned of the potential need for spectacles for specific near tasks.

Astigmatism

Toric IOL

Corneal astigmastism correction has become an essential part of cataract surgery in order to provide the best visual outcome. Toric IOLs (Fig. 12) are currently one of the main options for astigmatic correction during phacoemulsification. Toric IOLs were first introduced in 1992 as a three piece non-foldable PMMA IOL which evolved into the first foldable one piece silicone toric IOL in 1994. Since then, many advancements have been made in improving its IOL material and design. Toric IOLs function by neutralizing regular corneal astigmatism by accurate axis placement against the steepest corneal axis. Current toric IOLs can correct up to 6D of astigmatism and can be used in both monofocal and multifocal IOL designs. However, toric IOLs depend on its rotational stability. A 5 degree rotation can cause a decay in image quality to up to 7% and a 10 degree rotation causes a decay in up to 11%. Rotations up to 30 degrees will lead to a 45% decay in image quality and will eliminate the correcting effect of the IOL [91, 92]. IOL biomaterial has a major influence on rotational stability. After implantation of a toric IOL into the capsular bag, the anterior and posterior capsule fuses with the IOL and prevents postoperative rotation. In vitro and animal studies have indicated acrylic IOLs to have the strongest adhesions with the capsular bag as compared with other biomaterials [93, 94].

Fig. 12 Tecnis® Toric IOL

Keys to success in implanting toric IOLs depend on preoperative and intraoperative measures as well as proper patient selection. Ideal patients should have at least 1–1.5 D corneal astigmatism. Preoperatively, comprehensive ocular examination and topography should be done to rule out ocular comorbidities that may interfere with postoperative outcomes. Eyes with irregular astigmatism such as corneal scars are not preferred for toric IOL implantation, eyes with a regular bowtie astigmatism are the most suitable candidates. As a stable capsular bag IOL complex is essential for rotational stability, zonular instability and posterior capsular instability are also contraindications for implanting toric IOLs. As for preoperative investigations, accurate biometry and keratometry are needed for precise IOL power calculation. Accuracy can be enhanced by taking repeated measurements and using different devices based on different principles [95]. Intraoperatively, alignment accuracy can be improved by accurate corneal marking. Various methods have been described in axis marking, these can be done either manually or by image guided systems. Manual marking can be done by coaxial slit beam, bubble marker, pendulum marker or tonometer marker. A comparative study of the four different marking techniques showed a minimal rotational deviation with pendular marker and a least vertical misalignment with the slit lamp marking technique [96]. Manual marking should be done when the patient is sitting erect with the back resting against a wall and looking straight ahead, so as to avoid any cyclotorsion which can go up to 28 degrees when there is a change in position from sitting to supine [97]. Image guided techniques include iris fingerprinting, where the iris and limbal landmarks are captured preoperatively and intraoperative image registration are used to match the images and to calculate the distance in degrees from the targeted axis [95]. Newer advancements include intraoperative aberrometry, these devices can be used to perform real time assessment of the lens status to provide an accurate toric IOL alignment.

Before the introduction of toric IOLs, preoperative corneal astigmatism was addressed by the technique of limbal relaxing incisions (LRI) during cataract surgery. LRI involves the creation of paired incisions corresponding to the steep meridian, resulting in flattening of the cornea and reducing the astigmatic power. Although LRI is easy to perform, inexpensive and effective in reducing up to 4D of astigmatism, it carries the risk of corneal perforation. Also, LRI results are often unpredictable, as it depends on the rate and degree of corneal healing and remodeling. Moreover, LRI is unable to correct high astigmatisms as in toric IOLs. When comparing toric IOLs and monofocal IOLs with LRIs, study have showed that toric IOLs are able to provide a more effective and predictable outcome when compared to LRIs [98]. A recent systematic review and meta-analysis also showed that toric IOLs provide better uncorrected distance visual acuity, greater spectacle independence and lower amounts of residual astigmatism [99]. Although toric IOLs are more expensive than monofocal IOLs, economical analyses have demonstrated that lifetime costs are reduced with the use of toric IOLs because of the reduced need for spectacles [100]. Toric IOLs should be considered in cases with astigmatism of over 1D as it effectively neutralizes astigmatism and provides a good visual outcome.

Aniridic IOLs

Aniridia can be due to congenital conditions or it may be acquired after ocular trauma. Aniridia affects visual quality and leads to significant photophobia as well as symptoms of halo and glare, it can also lead to poor cosmesis. In aniridia cases, if lens extraction is needed, implantation of an aniridic IOL can be considered. An aniridic IOL is an IOL with a black diaphragm, manufactured by Morcher GmBH (Stuttgart, Germany) and they are available in several types. BDI consists of a clear central optic (4.5, 5 or 6.5 mm diameter), surrounded by a black diaphragm and 2 haptics (12.5 or 13.5 mm) with the latter built with a hoop in the haptic to allow for scleral fixation (Fig. 13). Due to its large optical diameter, a large corneal incision is required for BDI placement.

BDIs are shown to effectively improve visual acuity, decrease photophobia and resolve cosmetic issues in most both congenital aniridia and traumatic aniridia cases [101, 102].

BDIs can have potential complications, one being corneal decompensation from endothelial cell loss, this can be due to mechanical damage from insertion of a large IOL, postoperative persistent inflammation or high intraocular pressure [103]. A large study reported long-term follow up in eyes with congenital aniridia and identified glaucoma as a major long-term complication [104]. Although these eyes were already at risk of developing glaucoma, other contributing factors were hypothesized to be due to a direct compression onto the trabecular meshwork by the haptics, which was especially true in cases where BDIs were placed in a relatively anterior position as seen with ultrasound biometry. However, high intraocular pressure was also noted in cases with a normal BDI position. This was thought to be due to chronic postoperative inflammation or a large IOL size impairing aqueous outflow.

BDIs seem to be a safe and effective IOL in aniridic eyes, however, long-term follow up is needed for its potential complications.

Fig. 13 Morcher® Aniridic IOL

Adjustable IOLs

Nowadays, a patient who wishes to undergo cataract surgery often has high expectations and demand for accurate refractive outcomes. However, realistically, these cannot always be achieved and will often lead to patient dissatisfaction. The introduction of adjustable IOLs aims at improving refractive accuracy, visual outcome and patient satisfaction. The idea is to allow patients to choose their specific refractive outcomes and to allow for post op adjustment accordingly, so to deliver accurate results. Light adjustable lenses (LAL) consist of photosensitive silicone macromers diffused over the IOL, irradiation of the LAL with ultraviolet light causes photosensitive macromers to polymerize. This polymerization causes the formation of silicone polymers in the irradiated region, a diffusion gradient between the radiated and non-radiated portions will then be created, this allows macromers to migrate towards the irradiated portion and leads to lens swelling and refractive power increment [105]. As with other IOLs, LALs are implanted into the capsular bag with standard phacoemulsification techniques. Roughly around one month after the operation, the patient will undergo refraction, a light delivery device system will then be used to deliver ultraviolet light at the slit lamp to induce predictable and precise changes to the shape and refractive power of the IOL optic to allow for post operative fine refractive adjustments. After the new refractive power is confirmed, a lock in procedure will be carried out with the light delivery device to allow irradiation to the entire lens to polymerize all remaining macromers, this will not cause any diffusion gradient and will not result in any lens power change, thus preventing additional changes to the refractive outcome. A recent study concluded that light adjustable IOLs are able to achieve accurate refractive outcomes to around emmetropia with good uncorrected distance visual acuity, which remained stable over time [106]. Another study also concluded that light adjustable IOLs are able to reduce postoperative spherical and cylindrical errors to up to 2D. There was significant improvement in uncorrected distant visual acuity and the refractive changes were stable [107]. LALs seem to be a promising IOL with good refractive results, however, long term results are needed for evidence of a stable refractive outcome.

Special IOL Techniques

Piggyback IOL

In patients with extreme refractive errors, a single high power IOL may not be adequate to provide sufficient power, the use of piggyback IOLs help by implanting two IOLs to correct these high powers. Piggyback IOLs can also be considered in cases of undesirable optical results, the procedure carries a lower risk than IOL exchange, especially in cases when the IOL has already been fibrosed in the

capsular bag, the optical result is often also more predictable and accurate [108, 109]. Piggyback IOLs are usually done with one IOL implanted into the capsular bag and a second IOL implanted in the sulcus.

In cases of extreme high powers, the image quality of piggyback IOL is superior to that of a single IOL, as with a single IOL, a steep radius is needed to provide high powers which will contribute to significant spherical abberations and will lead to severely distorted image quality [110]. The optimal image quality that can be achieved in eyes with extreme axial length was found to be by a piggyback IOL system. Piggyback IOL also provides additional benefit in terms of depth of focus. This was hypothesized to be due to the presence of a contact zone between the two IOLs being implanted, which was surrounded by concentric Newton rings [111]. The size of the contact zone depends on the curvature of the IOL and its material, and causes a pressure forcing the IOLs together. The Newton rings surrounding the contact zone are due to the presence of a very thin gap between the two IOLs, causing possible interference. Within the contact zone, the lens curvature is flatter than that outside of the zone, which then provides a lower refractive power. Therefore, this design principle simulates that of a multifocal IOL, where the central zone with less refractive power can be used for distance viewing and the non-contact zone with more refractive power can be used for near distance viewing. Defocus curves in piggyback IOLs have been shown to have a greater depth of focus than those in single IOLs.

However, piggyback IOLs have their own drawbacks. The presence of Elschnig pearls and intralenticular opacification have been reported between the interface of the piggyback IOLs [112, 113]. These membranous formations affect visual acuity and also cause late refractive surprises [114]. To prevent intralenticular opacification, meticulous polishing of the anterior capsule has been recommended to eliminate residual LEC, a large capsulorrhexis can also prevent migration of LEC into the intralenticular space [115]. Vaulting to avoid IOL-IOL contact can eliminate interlenticular opacification.

Anterior Chamber IOLs

Anterior chamber IOLs are considered in myopia correction by phakic IOLs or aphakic correction when the IOL is considered not suitable to be placed in the capsular bag. Anterior chamber IOLs can be angle supported or iris supported. Angle supported IOLs are fixed with four haptic points in the anterior chamber. Iris supported IOL is positioned in the anterior chamber and held in place by fixation to the mid-peripheral iris stroma. When comparing angle supported IOL and iris supported IOLs, although angle supported IOLs are technically easier, they have a significantly higher rate of endothelial cell loss [116], and also leads to higher rates of glaucoma. Therefore, angle supported IOLs are often not the desired choice and are contraindicated in young patients, eyes with preexisting glaucoma or corneal endothelial pathologies.

As for iris supported IOLs, they are shown to be safe, efficacious, predictable and stable in correcting high or severe myopia with significant gains in visual

acuity [117, 118]. Postoperative complications include glare and halos from poor centration or from implantation in eyes with large pupil sizes, other complication includes the formation of cataract in phakic IOLs. Another important issue is also the rate of endothelial cell loss. A four year endothelial study has reported endothelial cell loss rate to be 3.85% at 6 months to 13.42% at 4 years [119]. Due to its anterior position, there are a few recommendations before considering implanting of iris supported IOLs. Firstly, an anterior chamber depth of at least 3.2 mm is required before considering its implantation. Secondly, preoperative specular microscopy is also essential in excluding eyes with preexisting compromised endothelial cell count. Lastly, extra caution has to be taken in considering the implantation in young patients due to a potential risk of corneal decompensation in the future.

Retropupillary iris supported IOLs have been designed aiming to reduce the rate of loss of endothelial cell count, however, a retrospective analysis has showed that the technique does not have a significant effect on decreasing the rate [120]. Other studies have also showed pigment dispersion to be a potential complication with retropupillary placement [121].

Scleral Fixating IOLs

In cases of inadequate capsular support after cataract surgery, choices of angle supporting IOLs, iris supporting IOLs or scleral fixating IOLs (SFIOL) can be considered. A literature review was conducted to determine the safety and efficacy between the three types of IOL fixation methods in eyes with inadequate capsular support, it was concluded that there is insufficient evidence to demonstrate the superiority of one lens type or fixation method over another [122].

Regarding scleral fixating IOLs, its surgical techniques have evolved over the past decades. Scleral fixating IOLs can be fixated to the sclera by sutures or by tunneling the haptics without the use of sutures or by the formation of terminal bulbs on the haptic ends to avoid suture usage as well. SFIOL techniques can largely be grouped into sutured or sutureless techniques.

For sutured techniques, suture was used to fix the haptics of the IOL to the sclera at 3 and 9 o'clock positioned 2 mm posterior to the limbus. As sutures are tied onto the sclera, there is a risk of suture exposure and conjunctival erosion. Symptoms of foreign body sensation have also been reported due to exposed suture ends. To improve this, scleral flaps were fashioned to cover the suture knots to avoid exposure or irritable symptoms [123]. However, scleral flap technique requires a conjunctival peritomy and can be problematic in patients requiring future glaucoma filtration surgeries. Therefore, the introduction of Hoffman's pouch aims at creating scleral pockets without the need of conjunctival peritomy and allows adequate suture knot coverage [124]. In the recent decades, the Lewis technique has been widely used, a 10-O polypropylene suture with a straight needle was passed from one scleral side to the opposite and the needle was turned around and passed back into the eye and emerged at the original scleral bed. Both

sutures were withdrawn and cut and tied to the eyelet of the IOL and IOL was inserted through the corneoscleral wound. The sutures were then tied and knots rotated and covered with conjunctiva. A recent study demonstrated long-term stability with the Lewis technique, although knot erosion is not uncommon, the IOL remains stable due to a fibrotic process around the sutures and the IOL haptics [125]. To enhance durability of the sutures, thicker materials such as Gore-Tex have been used. A recent series using 7-O Gor-Tex suture reported no cases of suture breakage during a 33 months follow up period [126]. Long-term studies of sutured SFIOL have reported it to be a safe and effective technique, however potential risks include suture erosion and breakage leading to IOL dislocation or lens tilt and suture exposure causing endophthalmitis [127].

For sutureless techniques, intrascleral fixation, fibrin glue assisted or the Yamane technique have been described. Intrascleral fixation was described by Scharioth [128], which creates sclerotomies 2 mm posterior to the limbus then partial thickness scleral tunnels parallel to the limbus at the original sclerotomy sites. A three-piece IOL was inserted into the eye and the haptics were externalized through the sclerotomy incisions and placed into the scleral tunnels. The Scharioth technique was shown to provide exact centration and axial stability and prevented distortion in most cases. Fibrin glue has also been used to secure haptics to the sclera. Scleral flaps were fashioned and fibrin glue was applied to the bed of the flap to allow the haptics to be fixed in place, the scleral flap was positioned over the haptic to seal the flaps. Studies have shown one year results to be promising, however long term results are lacking [129]. The Yamane technique was recently described, the technique first introduced a three-piece IOL into the anterior chamber, then a 27-G needle was used to create a scleral tunnel posterior to the limbus, the haptic was then introduced into the lumen of the needle and externalized. Cautery was applied to the ends of the haptic to allow formation of a terminal bulb to secure the IOL in place, conjunctiva was mobilized onto the bulb ends to prevent erosion [130].

Currently, there are limited studies comparing one type of SFIOL technique with another, there is limited long-term evidence to support the superiority of any one technique.

Rare IOL Related Complication

IOL Opacification

The opacification of IOLs is a rare complication and usually occurs during the late post operative period [131]. The exact cause and mechanism is still unknown. IOL opacification may cause decreased post operative visual acuity, reduction in contrast sensitivity and symptoms of glare, in severe cases, it requires explantation and IOL exchange [132]. Explanted opacified IOLs have been sent for analysis using light and scanning electron microscopy, results revealed numerous fine,

granular, crystalline like deposits on both the anterior and posterior surfaces of the IOLs [132]. A report related its cause to individual manufacturers in relation to the differences in the water content of hydrophilic acrylic materials [133]. Another report attributed IOL opacification to primary calcification which was found in a significant number of patients implanted with hydrophilic-hydrophobic acrylic IOLs and had a significant effect on their vision [134]. Other surgical interventions with injection of foreign material into the anterior chamber such as air or gas, also seem to increase the risk of IOL opacification [135]. There have been increasing reports on hydrophilic IOL opacification after endothelial keratoplasty with intracameral instillation of air or gas [136–139]. IOL explantation is the only treatment choice in severe cases, however it is often associated with increased complication rate [140]. A recent study even recommends to avoid hydrophilic acrylic IOLs in procedures that will require intracameral air or gas injection such as endothelial keratoplasty [141]. Although IOL opacification is a rare late post operative complication, it can lead to severe undesirable visual outcome requiring IOL explantation, which can be a high risk procedure.

Conclusion

With the evolution of IOLs, there is currently a large diversity of IOLs available in the market. IOL selection is an individualized process and should be based on the patient's motivation for spectacle independence, activities of daily living and visual expectations. Although newer IOLs seem to show favorable outcomes, they will need larger clinical trials for better evidence in support of clinical usage.

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