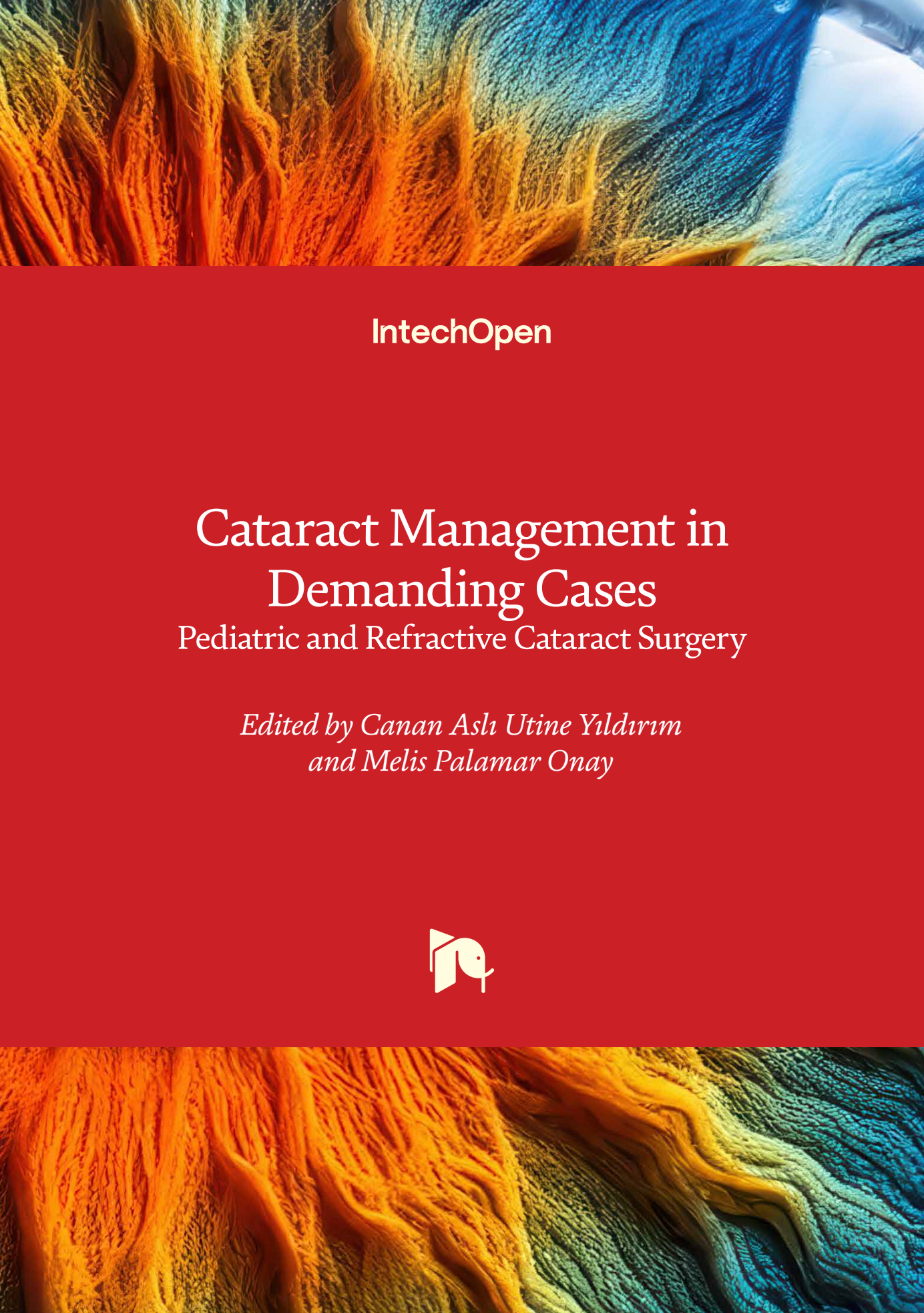




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Cataract Management in Demanding Cases

Pediatric and Refractive Cataract Surgery

*Edited by Canan Aslı Utine Yıldırım
and Melis Palamar Onay*



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Edited by Canan Aslı Utine Yıldırım and Melis Palamar Onay

Contributors

Adel Ebraheem, Amr Saad, Arañó Ferrer Jerónimo, Ata Baytaroglu, Detlev R. H. Breyer, Shimin Wu, Xiaoqin Yan

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Meet the editors



Dr. Utine Yildirim has expertise in cataract, glaucoma, and corneal transplantation, with more than 20,000 surgical cases. She performs high-risk surgeries that need a multi-disciplinary approach. She has vast experience in premium (multifocal) lens implantation for refractive cataract surgery, as well as in kerato-refractive surgery, including femto-LASIK, SMILE, and PRK; transscleral sutured intraocular lens implantation; internal fixation of subluxated or dislocated lenses; aniridia-correcting IOL implantation; and pediatric cataract surgery. Her primary expertise lies in the field of medical and surgical treatment of corneal pathologies. She holds a Master's degree in Biomedical Engineering. Currently, her h-index is 27, and her i10-index is 45. She has 2376 citations.



Melis Palamar Onay, Prof, MD, is the Secretary of the Turkish Ophthalmology Association, Cornea and Ocular Surface Division. She is an expert on Cornea and Ocular Surface, Ocular Oncology, and Ocular Infections. She has 177 articles on PubMed. Her h-index is 25, and her i10-index is 62. She has 2389 citations. She is the owner and the Assistant Editor of the journals *European Eye Research* and *European Transplant Research*.

Contents

Preface	IX
Section 1	
Pediatric Cataract Surgery – Main Principles and Challenges	1
Chapter 1	3
Preoperative Evaluation of Pediatric Cataracts <i>by Ata Baytaroglu</i>	
Chapter 2	21
Pediatric Cataract in Type 1 Diabetes Mellitus: Clinical Challenges and Surgical <i>by Shimin Wu and Xiaoqin Yan</i>	
Section 2	
Refractive Cataract Surgery with Advanced Technology	35
Chapter 3	37
Refractive Lens Exchange Indications <i>by Arañó Ferrer Jerónimo</i>	
Chapter 4	47
Advanced Techniques in Refractive Cataract Surgery (RCS): Achieving Spectacle Independence with Precision Technology <i>by Amr Saad and Detlev R.H. Breyer</i>	
Chapter 5	85
Optical Coherence Tomography in Cataract Surgery <i>by Adel Ebraheem</i>	

Preface

Cataract surgery has long been regarded as a simple procedure with excellent results. This understanding creates a massive demand and a hidden burden for surgeons. However, in some cases, such as pediatric eyes, there are inherent challenges, including differences in corneal and ocular biomechanics, incomplete development, and time constraints due to the risk of amblyopia. Furthermore, recent advancements in lens technology have paved the way to refractive excellence in far, intermediate, and near distances. This paradigm shift in cataract surgery necessitates considering additional details.

This book covers important topics about the management of cataract in pediatric eyes and in patients with high refractive demands. These include preoperative evaluation, surgical tips and techniques, and postoperative care. We believe this book will help cataract surgeons refine and polish their approaches to these complex cases, where small tips and tricks can change clinical outcomes.

We cordially thank Ms. Marica Novakovic for her tireless and dedicated help during the editorial process.

Dr. Canan Aslı Utine Yıldırım, MD, MSc
Professor,
Faculty of Medicine,
Department of Ophthalmology,
İzmir Biomedicine and Research Center,
Dokuz Eylül University,
İzmir, Türkiye

Dr. Melis Palamar Onay, MD
Professor,
Faculty of Medicine,
Department of Ophthalmology,
Ege University,
İzmir, Türkiye

Section 1

Pediatric Cataract
Surgery – Main Principles
and Challenges

Chapter 1

Preoperative Evaluation of Pediatric Cataracts

Ata Baytaroglu

Abstract

Pediatric cataracts, whether congenital or juvenile, constitute a leading cause of preventable visual loss and therefore pose serious challenges to families, clinicians, and public health systems. Early identification of pediatric cataracts and timely intervention are essential, as any delay may result in permanent vision loss and hinder a child's development. Due to the anatomy and physiology of a child's growing eye, proper preoperative evaluation is crucial for a successful surgical outcome. Preoperative evaluation of pediatric cataracts involves a thorough history and clinical examination, precise biometry for IOL planning, differential diagnosis, and active parental involvement. Challenges include managing developmental factors and postoperative complications. Technological advances have improved surgical outcomes, and early intervention is crucial for preventing amblyopia and enhancing visual and cognitive functions. The central questions of this chapter are: What are the differences in preoperative evaluation in adult and pediatric cataract cases? When and to what extent is systemic evaluation necessary? How should IOL selection and timing be after the surgical decision? What can be evaluated preoperatively to reduce postoperative complications?

Keywords: congenital, juvenile, cataracts, IOL calculation, preoperative examination

1. Introduction

The clinical management of pediatric cataracts involves several components, including skills, facilities, patient access to care, and postoperative compliance. There are varying causes and prevalences in different regions, making preoperative examination protocols even more critical. Successful surgical management and postoperative rehabilitation of pediatric cataracts depend upon the accuracy of preoperative evaluation. Visual acuity outcomes are significantly affected by age at the time of diagnosis, and improved visual acuity outcomes have been correlated with increased improvements in pediatric intraocular lens technology and small incision cataract surgeries. Although techniques such as capsulorhexis have yielded improved visual outcomes and a decrease in complication rates, posterior capsular opacification (PCO) and subsequent secondary surgery continue to be a leading concern, leading to the implementation of primary posterior capsulectomy in younger cataract patients. While better outcomes have been found in children with earlier diagnosis of pediatric cataracts who are under the age of two, optimal protocols and treatments remain a

matter of considerable debate, leaving room for future investigations in both unilateral versus bilateral cases and a more precise comparison of primary and secondary implantation techniques in pediatric cataract surgery.

2. Definition and classification of pediatric cataracts

A comprehensive definition for pediatric cataracts clarifies the two different types, congenital and juvenile, which differ in terms of clinical significance. Congenital cataracts are present at birth, and juvenile cataracts begin postnatally. This differentiation is significant because, depending on the timing of presentation, the management will differ, and the patient's vision can range from normal to the need for aggressive management. Congenital cataracts will need immediate treatment to prevent long-term visual deprivation amblyopia, and juvenile cataracts are treated more at the physician's discretion because they present more variably [1].

Centrally located cataracts with >3 mm diameter opacities are indisputably surgical, whereas peripheral, small, and partial cataracts often do not require surgery because their visual outcome is more favorable. In this chapter, the evaluation of such cases that do not require surgery but require close follow-up will not be discussed [2, 3].

Further clarification must also be provided concerning congenital versus juvenile cataracts for treatment protocol differences due to the unique presentations of congenital cataracts. When cataracts are present with microphthalmia or persistent fetal vasculature, this occurs predominantly in congenital cataracts. These cases need comprehensive evaluation, and a multidisciplinary approach with ophthalmology and other related specialists must be implemented. This approach necessitates genetic counseling and systemic evaluation, as these factors can greatly impact postoperative surgical results [4, 5].

Pediatric cataracts are also variable regarding laterality, with about 64.3% of patients having bilateral cataracts versus 35.7% with unilateral cataracts [1, 6]. Unilateral cataracts require more aggressive postoperative visual rehabilitation to ensure proper visual development. The most common morphological classification of pediatric cataracts is zonular, at 33.8%. However, there are varying morphologies, such as nuclear, polar, lamellar, and total (**Figure 1**). The morphologies have extremely variable natural histories and difficulties regarding surgery and postoperative care [4, 6–9]. An example would be a total cataract that obstructs visual stimuli from reaching the neural tissue of the eye. Immediate removal of these dense cataracts will need to be performed to preserve vision because the cataract acts as a dark barrier against visual development. Polar cataracts have some potential for visual rehabilitation while maintaining some vision due to their location (inferior polar) compared to superior polar. The location determines what kind of effects will be shown, but it should also be noted that morphological classification also helps discern between causes. For example, bilateral, symmetrical cataracts can signify genetic or systemic metabolic diseases. On the other hand, unilateral, dense cataracts presented at an early age might be from infectious and developmental causes [1].

The most significant cause of pediatric cataracts is idiopathic, at 72.5%, which means that no cause has been found upon diagnosis. Genetic and systemic causes account for 19% of secondary pediatric cataract causes. In underdeveloped countries where vaccination and health services are limited, infectious diseases may be the cause of an infantile cataract [1, 10].

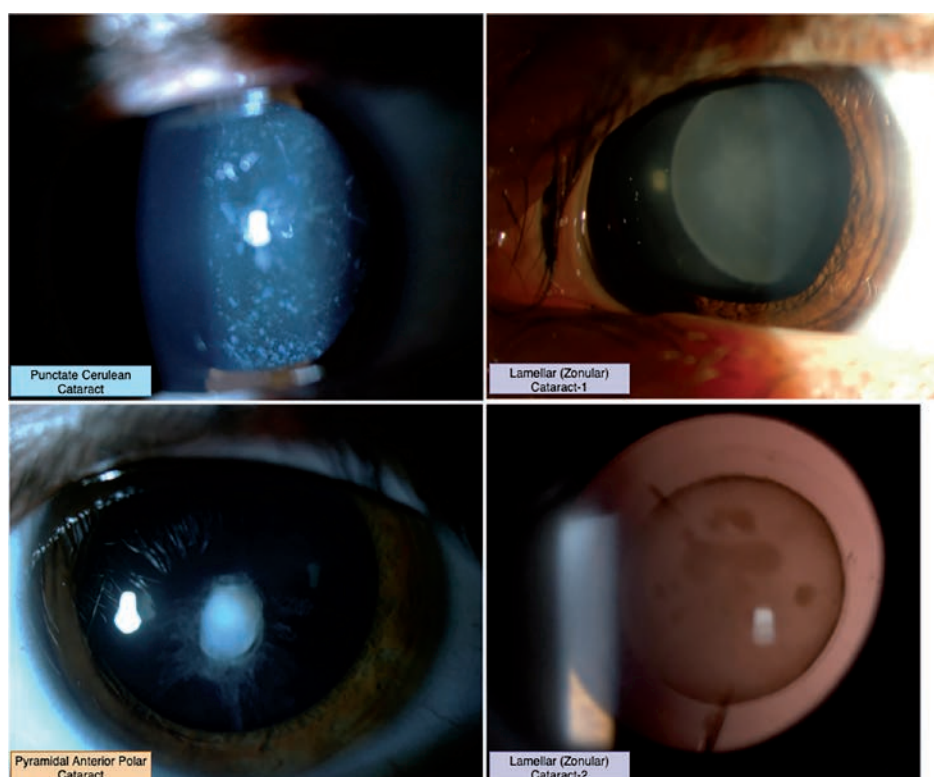


Figure 1.
Most common pediatric cataract types.

There are many associations with pediatric cataracts. Other conditions, such as strabismus (52.2%) and nystagmus (24.37%), can be identified in conjunction. Most often, strabismus and nystagmus indicate prolonged amblyopia and visual deprivation in children due to a disruption of their visual pathway neurogenesis [11–14]. In a follow-up of about 20 years, manifest nystagmus occurred in about 1/3 of the bilateral congenital cases, regardless of the timing of surgery, and surgery performed at less than 2 months of age did not prevent it. In addition, the presence of preoperative nystagmus is not necessarily a risk factor for poorer visual acuity outcome [13].

Numerous systemic conditions and congenital syndromes are also associated with pediatric cataracts. Therefore, the inclusion of both ocular and extraocular manifestations in classification and definition can help anticipate surgical complications and postoperative difficulties with visual rehabilitation. All children with pediatric cataracts should undergo a general medical workup to rule out these associations and prevent life-threatening complications.

The estimated global prevalence ranges from 1 to 15 cases per 10,000 children, with 200,000 children globally being blind secondary to bilateral cataract. These are not actual global rates due to reporting and variance in risk factors and populations in certain areas [7, 8, 15]. Globally, this underscores the need for screening and appropriate referral pathways for prompt care. Childhood cataract is the most frequent cause of treatable childhood blindness and is therefore considered a public health concern. The incidence of childhood cataract and its contribution to childhood blindness are much greater in developing countries than in the developed world, where lack

of education, late presentation, lack of specialists, and barriers to access all have an influence. In Asia alone, the prevalence of childhood blindness has surpassed the one million cases mark, and cataract accounts for a substantial percentage of this, with India, for example, contributing about 7.4–15.3% [9]. The mean age of presentation is 6 years. However, preterm children are four times more likely to develop bilateral congenital or infantile cataract if born before 33 weeks [16]. The risk of congenital and infantile cataract is also greater for children whose mothers experience pregnancy complications. Up to 67% of mothers of children with congenital cataract have had illnesses in pregnancy, and 22% have taken medicines in pregnancy. 22% of congenital cataracts have an associated systemic abnormality, and 27% are associated with ocular abnormalities [9]. Therefore, prenatal diagnosis is vital in detecting prenatal abnormalities that may increase the risk of cataract formation.

Detailed preoperative evaluation is also practical in predicting certain postoperative complications, making the preoperative evaluation the most critical period for ensuring maximum neurodevelopmental outcomes and adequate visual skills. Among the common postoperative complications, rates for postoperative posterior capsular opacification (PCO) in the pediatric population range from 21 to 51.1% [6, 12, 17]. Secondary glaucoma is not an uncommon outcome in children needing earlier surgery and, similar to PCO, this is dependent upon several factors such as etiology, age, type of cataract, etc.

3. Clinical assessment and planning

The preoperative evaluation of pediatric cataracts significantly differs from that of adults due to several unique anatomical, physiological, and developmental considerations. Since the first thing that comes to mind when we talk about cataract surgery is senile cataract in adults and elderly patients, we prefer to mention the clinical evaluation in pediatric cases, especially the important points that distinguish them from adults. A brief summary of these fundamental differences is listed in the **Table 1**.

Aspect	Pediatric cataracts	Adult cataracts
anatomy	Smaller, less rigid structures, a more elastic lens capsule	Larger and more rigid lens and ocular structures
Inflammatory response	More pronounced, higher risk of complications	Less pronounced
Systemic evaluation	Frequently required to exclude related cases	Rarely needed
IOL calculation	More complex due to ongoing eye growth	Usually standard
Timing	Urgent to prevent amblyopia	Rarely urgent
Surgical technique	Necessity for additional procedures like anterior vitrectomy, posterior capsulorhexis	Mostly standard
IOL implantation	Age-dependent, often delayed in infants	Mostly simultaneous
Post-op	Intensive, long-term follow-up, amblyopia management	Routine follow-up

Table 1.
Key differences between pediatric and adult cataracts.

Feature	Adult cataract	Pediatric cataract
Lens material	Typically hard and dense. Requires phacoemulsification to break up.	Often soft and “gummy.” Requires irrigation-aspiration or vitrectomy for removal.
Lens size	Average diameter ~ 9.3 mm at 16 years.	Average diameter ~ 6.0–7.0 mm at birth, rapidly growing in the first 2 years.
Lens capsule	Thicker and less elastic.	Thinner and more elastic, making capsulorhexis more challenging due to the tendency for “runaway” tears.
Scleral rigidity	Higher, more rigid.	Lower, more elastic, and less rigid, leading to a greater tendency for collapse during surgery and higher vitreous pressure.
Corneal rigidity	Higher.	Lower, less likely to self-seal after incisions.
Anterior chamber	More stable.	Often unstable due to low scleral rigidity and increased vitreous upthrust.
Iris	Less vascular, generally less reactive post-surgery.	Thicker and more vascular, leading to a higher incidence of postoperative inflammation.
Axial length of globe	Stable (average ~ 23–24 mm).	Rapidly growing (17–17.5 mm at birth, increasing significantly in early years), impacting IOL power calculation.
Posterior capsule opacification (PCO)	Common, but usually managed with Nd:YAG laser capsulotomy.	Much higher incidence and often more aggressive due to increased cellular proliferation; frequently requires surgical intervention at the time of initial cataract surgery.
Associated ocular anomalies	Less common, unless related to trauma or systemic disease.	More frequently associated with other ocular abnormalities like microcornea, aniridia, coloboma, and persistent fetal vasculature (PFV).
Visual pathway development	Fully developed.	Still developing, highly susceptible to amblyopia if vision is deprived by the cataract. This necessitates prompt surgical intervention for visually significant cataracts.
Postoperative inflammation	Present, but generally more predictable.	Increased tissue reactivity often leads to more significant fibrinous or exudative postoperative uveitis.

Table 2.
Differences in adult and pediatric cataracts.

Type of cataract	Associated causes	Notes
Anterior polar cataract (Figure 1)	Genetics: Often autosomal dominant inheritance, sporadic cases also exist.	- Usually small and localized. - May be associated with other anterior segment abnormalities. - Often visually insignificant, but monitor for progression.
Posterior polar cataract	- Genetics: Autosomal dominant inheritance is common, but sporadic forms occur. Genes like PITX3, MAREF, and members of the CRY (crystallin) gene family are implicated. - May also be associated with persistent fetal vasculature (PFV), posterior lenticonus/lentiglobus, aniridia, Lowe syndrome, Rothmund-Thomson syndrome.	- Central, discoid opacity at the posterior pole. - High risk of posterior capsular rupture during surgery due to strong adherence to the capsule. - Can cause significant visual impairment, even if small, due to its central location.

Type of cataract	Associated causes	Notes
Nuclear cataract	- Genetic: Mutations in crystallin genes (CRYAA, CRYAB, CRYBB1, CRYBB2, CRYGC, CRYGD, CRYGS) are common. - Metabolic: Galactosemia (classic “oil droplet” cataract), Lowe syndrome (oculocerebrorenal syndrome). - Infections: Congenital rubella syndrome (can also be lamellar or total). - Syndromes: Down syndrome.	- Opacity, primarily affecting the central nucleus of the lens. - Can be present at birth or develop later. - Varies in density and visual impact.
Lamellar (Zonular) Cataract (Figure 1)	- Genetic: Most common form of hereditary cataract, frequently autosomal dominant. Mutations in crystallin genes are often involved. - Metabolic: Hypoglycemia, hypocalcemia, galactosemia (can be lamellar in later stages). - Infections: Congenital rubella syndrome.	- Opacity in one or more concentric layers (lamellae) of the lens, typically sparing the very center (nucleus) and the outermost cortex. - Often bilateral and progressive. - Visual significance depends on the density and extent of the opacity.
Cortical cataract	- Trauma: Blunt or penetrating ocular trauma. - Metabolic: Diabetes (often bilateral, “snowflake” cataracts), hypocalcemia. - Inflammation: Chronic uveitis (e.g., juvenile idiopathic arthritis-associated uveitis). - Medications: Steroid use (especially prolonged systemic or topical use). - Radiation exposure.	- Opacities in the lens cortex, often appearing as spokes or wedges radiating inward. - Can progress to involve the entire lens.
Posterior subcapsular cataract (PSC)	- Steroid use: Most common acquired cause in children. - Trauma: Blunt ocular trauma. - Inflammation: Chronic uveitis (especially JIA-associated). - Metabolic: Diabetes. - Genetic: Some genetic syndromes (e.g., Alport syndrome, Fabry disease).	- Opacity located directly beneath the posterior capsule, often granular or vacuolated. - Can cause significant glare and reduced vision, especially in bright light or with near vision. - Tends to progress rapidly.
Total/Complete cataract	- Severe forms of other types: Any of the above types can progress to a total cataract if left untreated or if the underlying cause is severe. - Congenital Rubella Syndrome: Often causes dense, white total cataracts. - Persistent fetal vasculature (PFV): Unilateral, dense white cataract with associated retrolental fibrovascular membrane. - Severe metabolic disorders: Untreated galactosemia. - Genetic syndromes: Many severe genetic syndromes can lead to total cataracts.	- The entire lens is opaque, appearing white or milky. - Causes profound visual deprivation and amblyopia if not treated promptly.

Type of cataract	Associated causes	Notes
Membranous cataract	• Trauma: Often follows significant trauma that causes lens capsule rupture and subsequent absorption of lens material, leaving a thick fibrous membrane. • Inflammation: Severe, chronic intraocular inflammation. • Post-surgical: Can form after inadequate removal of lens material or complications. • Congenital: Less common, may result from severe intrauterine insult or complete liquefaction and absorption of lens material.	• A thin, fibrous membrane replaces the normal lens, often with minimal or no remaining lens cortex/nucleus. • Can be visually significant and challenging to manage surgically.
Punctate cataract (Figure 1)	• Genetic: Often inherited, sometimes associated with chromosomal abnormalities or syndromes (e.g., Down syndrome, Nance-Horan syndrome). • Metabolic: Hypocalcemia, Fabry disease.	• Small, discrete, dot-like opacities scattered throughout the lens. • Usually visually insignificant unless numerous and dense. •
Coronary cataract	• Genetic: Often inherited, typically not associated with systemic disease.	• Club-shaped opacities arranged radially in the deep cortex, surrounding the nucleus. • Usually develops later in childhood or adolescence. Often visually insignificant.
Sutural cataract	• Genetic: Often inherited.	• Opacities involving the Y-sutures of the lens. • Typically visually insignificant.

Table 3.
Morphological types of cataracts and their systemic associations.

3.1 Anatomy

The crystalline lens is a transparent, biconvex structure that can develop opacities that vary in morphology, including total, zonular (such as lamellar), and capsular cataracts (including both anterior and posterior subcapsular types). Morphological variations impact not only the optical quality of the lens but also surgical approaches when removal or intraocular lens (IOL) implantation is necessary [1]. Thus, for ease of understanding, we have presented the differences from adult cataract and the systemic or genetic conditions that may be associated with different cataract morphologies in **Tables 2** and **3**.

3.2 Inflammatory response

To understand the inflammatory response in pediatric cataracts, it is essential to consider both the causes and the management of inflammation post-surgery. Pediatric cataract surgery often results in a heightened inflammatory response due to the immature anatomical structures in children and the presence of other ocular

abnormalities [18]. This inflammation can lead to several complications, including posterior capsule opacification (PCO), visual axis opacification, and secondary glaucoma. The intensity of postoperative inflammation has been documented to be particularly severe in children, occurring in about 13.8% of operated eyes, a figure that increases to approximately 15.9% when anterior vitrectomy is performed [19].

Several factors exacerbate the inflammatory response following surgery. The presence of ocular trauma, commonly seen in pediatric traumatic cataracts, can significantly complicate the inflammatory landscape due to damage to corneal and uveal structures. Such cases often present with elevated inflammatory markers, increasing the difficulty of surgical interventions [20]. The surgical approach itself influences inflammation levels; for example, techniques involving intracameral injection of medications like triamcinolone acetonide have been shown to reduce postoperative inflammation effectively. Intracameral corticosteroids can lead to “quiet eyes” with minimized signs of inflammation post-surgery, suggesting their integral role in managing postoperative care [21]. Moreover, the presence of coexisting conditions, such as uveitis, can heighten the risk of developing cataracts and complicate the management of inflammatory responses. Chronic inflammatory conditions like juvenile idiopathic arthritis (JIA) can make cataract surgery more complex and increase the risk of postoperative complications [22, 23].

We believe it is essential to reiterate the importance of both preoperative and postoperative inflammation control in uveitic patients. In these cases, it is necessary to ensure that adequate immunosuppressive treatment is initiated prior to surgery using a multidisciplinary approach. Inflammation control has a dramatic impact on surgical technique, IOL selection, and implantation decisions, as well as postoperative complications in these cases. Current research recommends against the utilization of an intraocular lens (IOL) in patients exhibiting active uveitis despite optimal pharmacological intervention, very young children, hypotonic eyes, rubeotic eyes, those with uveitis of indeterminate etiology, and instances where IOL-associated complications have arisen in the contralateral eye. The data recommend less invasive small incision cataract surgery with foldable intraocular lens, particularly in unilateral cataract cases, provided that the uveitis is appropriately managed and the patient is systemically stable [22].

3.3 Systemic evaluation

Although systemic evaluation is crucial in pediatric cataract cases, underlying causes can be found in 60% of bilateral cases and 50% of unilateral cases, even in the most successful series [24]. Congenital cataract and persistent fetal vasculature (PFV) generally manifest within the first year of life and necessitate prompt surgical intervention. The age at which idiopathic and hereditary cataracts are presented varies significantly, and the time of surgery is contingent upon the visual significance of the cataract.

A pivotal aspect of managing pediatric cataracts lies in understanding their genetic underpinnings. Research has demonstrated that pediatric cataracts exhibit considerable phenotypic and genetic heterogeneity, with numerous loci identified as contributing to this disorder. Unfortunately, our current knowledge is limited, especially regarding multisystem triggers, as data on systemic associations with pediatric cataracts is still insufficient [25, 26]. Genetically, pediatric cataracts have been linked to a range of inherited conditions. Research indicates that approximately 10 to 29% of pediatric cataracts have identifiable genetic causes, with over 200 syndromes associated with their development [25, 27].

Metabolic causes represent another significant component in the multifactorial etiology of pediatric cataracts. Conditions like type 1 diabetes mellitus have been shown to precipitate cataracts in pediatric patients, occurring either at the onset of diabetes or within years following diagnosis [28]. Furthermore, metabolic disorders such as galactosemia and hereditary hyperferritinemia-cataract syndrome highlight how metabolic dysregulation can lead to cataract formation through oxidative stress and lens protein aggregation [12, 24, 25]. A comprehensive metabolic screening is thus recommended for children presenting with bilateral cataracts to rule out associated metabolic conditions. Infections encountered during pregnancy or early in a child's life, such as those caused by the rubella virus, have also been established as notable risk factors for developing pediatric cataracts [1]. Finally, acquired causes, particularly traumatic incidents, contribute significantly to the pediatric cataract population. Trauma accounts for approximately 30% of pediatric cataracts, making it a considerable factor in childhood visual impairment [29]. The recommended evaluation for bilateral cataracts in the absence of a family history comprises a urine analysis for reducing sugars, TORCH screening (toxoplasmosis, rubella, cytomegalovirus, varicella), a Venereal Disease Research Laboratory (VDRL) test for syphilis, and a blood assay for calcium, phosphorus, glucose, and galactokinase levels. Further comprehensive evaluation should be conducted in collaboration with the pediatrician and geneticist.

In summary, pediatric cataracts result from a complex interaction of genetic, metabolic, infectious, and traumatic factors. A systematic evaluation that includes genetic testing, metabolic profiling, and comprehensive clinical assessments remains crucial for developing effective treatment strategies and improving visual outcomes in affected children. However, for practical guidance, we have not included the differential diagnosis of over 100 defined syndromes here, as 60% of bilateral cataracts and 80% of unilateral cases are diagnosed as idiopathic.

3.4 Mimicking conditions

The differential diagnosis of pediatric cataracts includes a wide range of conditions such as idiopathic causes, genetic factors, maternal infections, metabolic disorders, trauma, and systemic diseases. Many diseases can also mimic cataracts. A key feature of these conditions is leukocoria. The laterality of the lesion is crucial when considering differential diagnoses. Among pediatric cases, retinoblastoma is the most critical disease to identify, as it can imitate and cause cataracts. Differentiating retinoblastoma is vital because it is a life-threatening condition that requires prompt treatment. Additionally, retinoblastoma may present with secondary glaucoma, uveitis, and other ocular issues, which could be mistaken for cataracts [30, 31].

Retinopathy of prematurity (ROP) is an important differential diagnosis for cataracts in patients with a history of premature birth, low gestational weight, and developmental delay. This is because, in most cases, by the time it appears similar to cataracts, it is accompanied by retinal detachment at stages 4–5 and indicates a poor prognosis. ROP and other retinal lesions may be linked to cataract formation, especially after surgeries like vitrectomy. Studies show that about 19% of patients who have had lens-sparing vitrectomy for ROP develop cataracts [32].

Persistent fetal vasculature (PFV) is another condition that can present with leukocoria and is also a common pseudoretinoblastoma. PFV is more frequently seen in children under 1 year old and typically presents unilaterally in full-term infants without systemic associations. In children aged 2–5 years, Coats' disease becomes a more common cause of leukocoria and retinal detachment, often mimicking the

appearance of cataracts. Coats' disease is also exclusively unilateral and occurs more often in males. Again, in this age group, familial exudative vitreoretinopathy (FEVR), a developmental retinal vascular anomaly, can be seen as an ocular media opacity resembling cataracts, along with retinal detachment in stages 3 and more advanced stages. In children older than 5 years, ocular toxocariasis should also be considered. It can cause a cataract-like appearance due to vitreous inflammation and retinal lesions [31, 33]. Less commonly, posterior lenticonus and iris melanocytomas can also be considered among the lesions that cause cataracts or a cataract-like appearance [34, 35].

Consequently, accurate diagnosis requires a combination of clinical examination and the use of multimodal imaging techniques to differentiate these conditions and ensure appropriate management. Ocular ultrasonography, computed tomography, or MRI, and anterior segment optical coherence tomography are essential and critical for distinguishing these conditions from cataracts.

3.5 IOL calculation

Intraocular lens (IOL) calculation in pediatric cataract surgery presents unique challenges due to the ongoing growth and refractive changes in children's eyes. Children's eyes are still growing, which affects the accuracy of IOL power calculations. This necessitates age-appropriate adjustments and undercorrection strategies to account for future myopic shifts. In pediatric cataract surgery, performing calculations without planning the patient's age and future emmetropic status may result in serious amblyopia [36, 37]. Pediatric eyes pose unique challenges due to their smaller size, changing axial length, and corneal curvature. Accurate measurements of axial length and keratometry are crucial for precise IOL power calculation. Although much more challenging to perform, immersion techniques are more accurate than contact applanation techniques for measuring axial length [38].

At this point, the most critical decision for selecting the right IOL is to use the correct formulation. In a study comparing 16 methods, including both traditional and novel formulations, the Hoffer Q formula was found to be the most successful in terms of achieving predicted values. In contrast, the SRK/T formulation was the furthest from the expected target. However, it is essential to emphasize that the difference between these two extremes is an average of 0.21 diopters, and no data on long-term outcomes have been presented [39, 40]. A recent systematic review also reported successful results with Barrett Universal II (BUII), Hoffer Q, and SRK/T formulations, emphasizing that the best postoperative values were obtained with BUII [40]. Moreover, a meta-analysis reported the top three formulas to be BUII, SRK/T, and Holladay 1, in respective order [41].

We have summarized the comparison of these four formulas recommended in the studies in the **Table 4**.

The key points in IOL selection can be broken down into two crucial aspects:

Undercorrection strategy: A common approach involves undercorrecting the IOL power to allow for the natural growth of the eye, reducing the risk of myopic shifts. However, age at surgery significantly influences the refractive outcomes. Children below 2 years of age tend to experience more hypermetropia post-surgery, whereas in children ≤ 1 year old, a larger myopic shift, with the mean myopic shift being -6.4 diopters, has been reported [42]. There is no significant difference in the myopic shift or postoperative visual acuity between children who received full correction and those who were undercorrected by 2 diopters or more. This suggests that undercorrection does not adversely affect visual outcomes compared to full correction [43].

Formula	Strengths	Limitations
Hoffer Q	High accuracy in shorter axial lengths, good overall performance	Variability in very young children
SRK/T	Reliable for older children and longer axial lengths	Undercorrection tendency in younger children
Barrett Universal II	High predictive accuracy, suitable for a wide range of axial lengths	Requires careful biometry for best results
Holladay 1	Good performance in average axial lengths	Less effective in very short or very long eyes

Table 4.
IOL calculation formula comparison.

The generally recommended undercorrection method is to aim for 20% undercorrection in children under 2 years of age and 10% undercorrection in children between 2 and 8 years of age, or to achieve a postoperative refraction equivalent of 7 minus the current years of age. As a common point among all these formulations, it can be said that it is reasonable to aim for undercorrection of 1–4 diopters, depending on the surgeon's patient-based preference [44–46].

Formula selection: No single formula is perfect for all pediatric cases. The choice often depends on the child's age, axial length, and specific ocular parameters. Newer formulas like Barrett Universal II and Kane show promise, but traditional formulas like Hoffer Q and SRK/T remain widely used due to their proven track records.

3.6 IOL choice and timing

The standard of care in congenital cataracts, undisputedly, is to operate on unilateral cataracts by 6 weeks old and bilateral cataracts by 10 weeks old. For bilateral aphakia, secondary IOL implantation between the ages of 2 and 6 years can achieve comparable visual outcomes. Early surgery (before 30 days of age) and lack of primary IOL implantation are associated with a higher risk of postoperative glaucoma, and primary IOL implantation can reduce this risk [47–49].

Timing for IOL implantation in pediatric cataracts is a contentious topic among ophthalmic specialists. Current trends increasingly favor primary IOL implantation during cataract extraction, particularly for children over 6 months old, as they have been associated with better visual outcomes compared to secondary implantation [50, 51]. A longitudinal study involving a Swedish pediatric cataract registry demonstrated that 71.6% of children underwent primary IOL implantation [51]. However, there remain concerns regarding potential complications associated with primary IOL implantation, particularly in very young patients. For instance, some studies have shown a higher rate of reoperations in infants under 7 months old who received primary IOLs [52]. Thus, decisions must consider individual patient factors, such as ocular health, systemic conditions, and the potential for inflammation, especially in cases with uveitis [53]. In contrast, secondary IOL implantation can reduce the risk of complications, including secondary glaucoma, particularly in complex cases. A retrospective analysis indicated that while there is a general trend toward primary IOL implantation, many pediatric patients remain aphakic for extended periods, with only 24% receiving a secondary IOL within 5 years after lensectomy due to parental

preferences or anticipated lack of benefit [54]. The planning of cataract surgery and IOL implantation in pediatric cataract cases is summarized as a flowchart in **Figure 2**.

The choice of IOL type is equally significant in pediatric cataract management, with factors such as material compatibility, risk of posterior capsule opacification (PCO), and economic considerations playing vital roles. Hydrophobic acrylic IOLs are

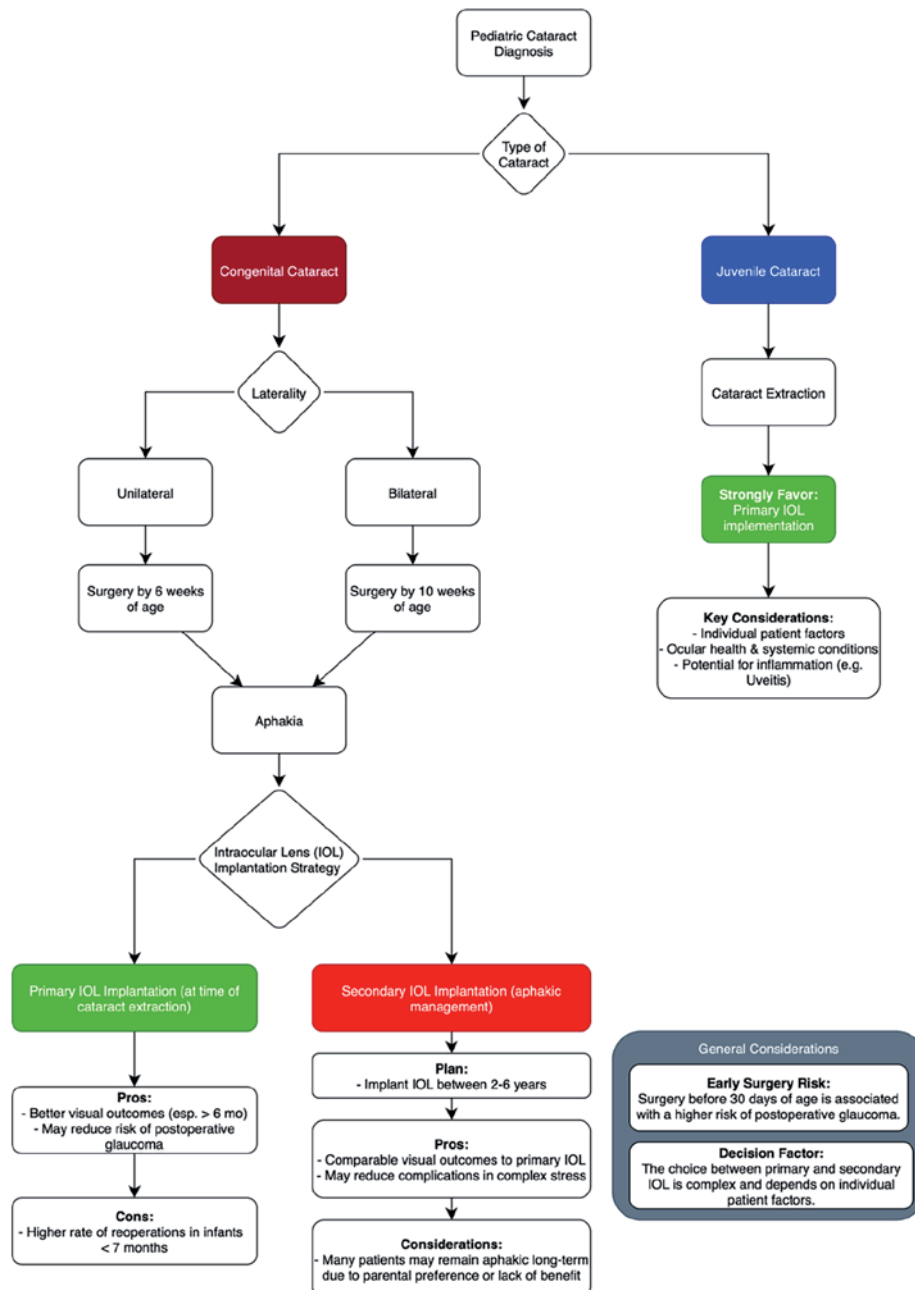


Figure 2.
Basic flow chart for approaching pediatric cataract cases.

often favored for their lower rates of PCO compared to hydrophilic lenses. Studies have indicated that hydrophobic IOLs, particularly those with specific edge designs, outperform their hydrophilic counterparts in preventing PCO, making them a preferable choice in many pediatric cases [55]. Additionally, the implantation technique is pivotal. Primary in-the-bag implantation remains the gold standard (**Figure 3**), particularly when sufficient capsular support is maintained. However, the use of sulcus fixation has been shown to reduce risks in cases where capsular integrity is compromised [56].

Another current and controversial topic is multifocal IOL implantation in pediatric cataract cases. It is a complex and evolving area of ophthalmology. These premium IOLs aim to provide multiple focal points, potentially improving both near and distance vision. Studies have shown significant improvements in visual acuity post-implantation. For instance, one study reported that 79% of eyes with bilateral cataracts achieved a best-corrected distance visual acuity of 20/40 or better, and 26% achieved 20/20 [57]. Another study found that 90.91% of patients showed significant improvement in visual acuity in all three (distance-intermediate-near) distances [58]. Improvement in stereopsis and binocularity was also reported in these studies [57–59]. Although multifocal IOL implantation appears to solve many different problems at once, it remains an uncharted zone due to the lack of long-term results and the unknown effects of orthoptic treatment, which is often required, especially in unilateral cases.



Figure 3.
Anterior polar cataract extraction and simultaneous IOL implantation.

Understanding the visual anatomy and requirements of the individual child influences the decision-making process around IOL types based on age-related factors and anticipated long-term outcomes. In summary, IOL implantation timing and choice in pediatric cataracts must be tailored to the child's individual clinical scenario while weighing the benefits of early correction against potential complications.

4. Conclusion

A comprehensive history and careful clinical examination are essential to address questions regarding the cause of the cataract, whether to operate, when to operate, and how to operate. Preoperative biometry is crucial for determining the specifics of the intraocular lens implant and the postoperative target refraction. Pediatric cataracts can be associated with various systemic conditions, including genetic syndromes, metabolic disorders, and infections. Early diagnosis and prompt surgical intervention are critical to prevent irreversible amblyopia. The timing of surgery should be carefully considered based on the onset, duration, and morphology of the cataract. Preoperative imaging with tools like OCT can provide valuable information about the lens and capsule, reducing intraoperative risks and surprises. Genetic testing is recommended for unexplained bilateral cataracts, while metabolic and infectious testing should be guided by clinical context. In summary, successful management of pediatric cataracts relies on thorough preoperative evaluation, careful planning, and individualized care. Collaboration with pediatricians and genetic counselors, along with advancements in imaging and surgical techniques, can significantly improve outcomes for children with cataracts.

Author details

Ata Baytaroglu
Department of Ophthalmology, Hacettepe University, Ankara, Turkey

*Address all correspondence to: abaytaroglu@hacettepe.edu.tr

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Pediatric Cataract in Type 1 Diabetes Mellitus: Clinical Challenges and Surgical

Shimin Wu and Xiaoqin Yan

Abstract

This chapter systematically examines the distinct pathophysiological mechanisms underlying cataract development in children with Type 1 Diabetes Mellitus (T1DM), while establishing evidence-based protocols for preoperative evaluation and optimized perioperative glycemic management. Special focus is given to surgical challenges unique to diabetic pediatric populations, including compromised corneal endothelial cell density and heightened risks of vitreous liquefaction, with comparative analysis of biocompatibility profiles for various intraocular lens materials. Clinically validated approaches are presented regarding: (1) Adjusted phacoemulsification parameters for diabetic lenses (2) Modified primary posterior continuous curvilinear capsulorhexis (PCCC) techniques (3) Targeted postoperative anti-inflammatory regimens The chapter culminates in proposing a multidisciplinary collaborative framework (endocrinology, ophthalmology, pediatric) for personalized postoperative surveillance, emphasizing dynamic monitoring of diabetic retinopathy progression and refractive status evolution.

Keywords: pediatric, type 1 diabetes mellitus (T1DM), cataract, cataract surgery, long-term management

1. Introduction

Cataracts in pediatric patients with type 1 diabetes mellitus (T1DM) can be categorized into early and late onset [1]. Early-onset cataracts in children with T1DM represent a particularly rare complication, especially when they manifest within the initial 6 months following the onset of diabetes [2, 3]. The incidence of this condition is influenced by a multitude of factors, including age, gender, geographic region, and race, yet comprehensive data remain unavailable [4–6]. Various studies have examined the prevalence and incidence of pediatric cataracts in T1DM, utilizing data from extensive pediatric cohorts and registries. The prevalence of early diabetic cataracts in this population ranges from 0.7 to 3.4% among children and adolescents with T1DM [3]. In contrast, late-onset cataracts are recognized as a long-term complication, typically emerging a decade after the initial diabetes diagnosis, akin to patterns observed in adult diabetes [7].

The pathophysiological mechanisms underlying early diabetic cataracts remain incompletely elucidated [2]. Nonetheless, several hypotheses have been proposed regarding their etiology, including osmotic damage, the polyol pathway, and oxidative stress [8–10]. The development of cataracts in children with T1DM continues to be an area of active investigation. Hyperglycemia, a hallmark of diabetes, plays a significant role in the pathogenesis of diabetic cataracts. During hyperglycemia, the altered metabolism of excess glucose leads to localized disruptions to fiber cell morphology and cell swelling in the outer cortex of the lens. This damage is thought to result from

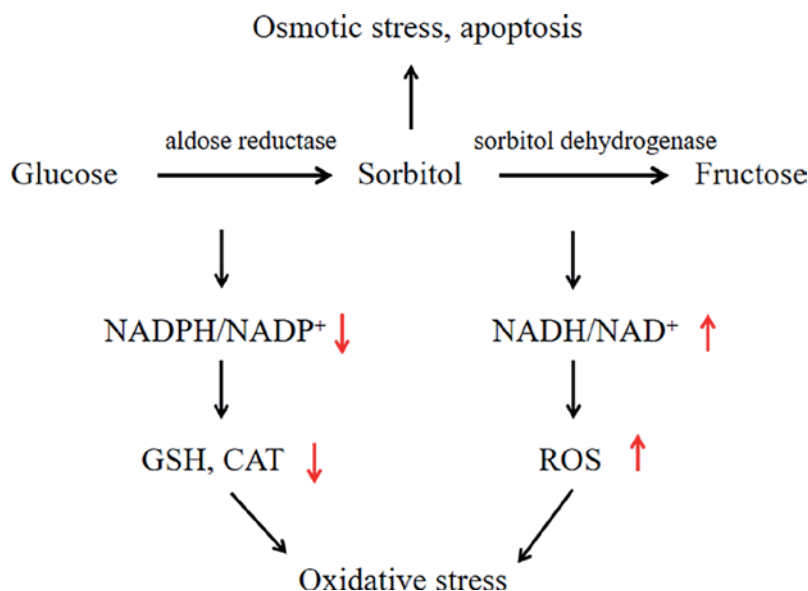


Figure 1.
Schematic diagram of polyol pathway and oxidative stress [11].

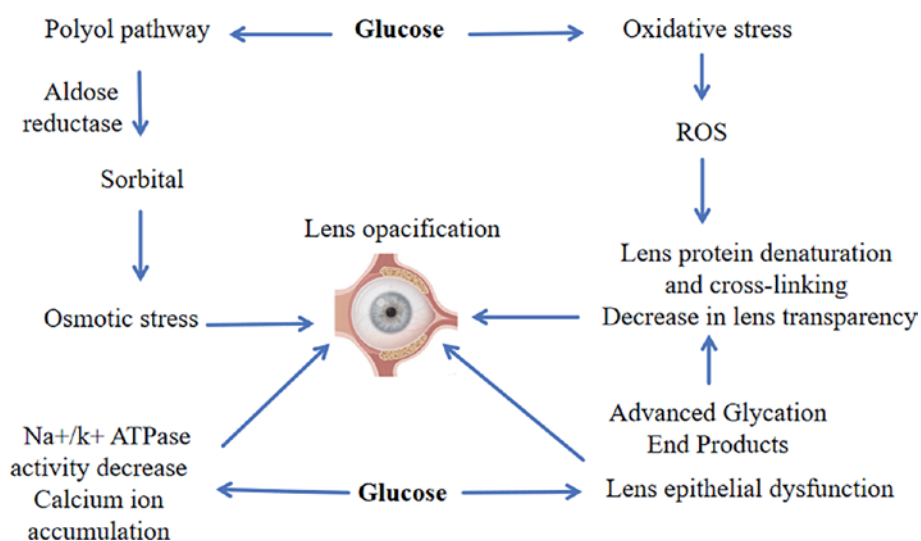


Figure 2.
Schematic diagram of the pathogenesis of diabetic cataract.

osmotic stress and oxidative stress due to the accumulation of intracellular sorbitol, the depletion of NADPH, and the generation of fructose metabolites *via* the polyol pathway (**Figures 1** and **2**) [11–13]. In children with type 1 diabetes, the rate of cataract development shows a peak at diabetes onset and declines with longer diabetes duration. This suggests that hyperglycemia-induced osmotic damage to lens fibers at the onset of diabetes might be the main pathomechanism [3].

2. Clinical manifestations

In pediatric patients with T1DM, cataracts can be categorized into early-onset and late-onset types. The development of diabetic cataracts in this population often serves as an initial indicator of T1DM or manifests within 6 months following the diagnosis. The primary clinical manifestations include diminished visual acuity and alterations in the lens structure. Typically, early-onset cataracts are bilateral and characterized by snowflake-like opacities in the posterior subcapsular region. These cataracts are generally diagnosed concurrently with T1DM or within the first 6 months post-diagnosis. Their rapid and frequently irreversible progression, which persists despite optimal glycemic management through contemporary insulin therapies, implies that lens fiber damage may occur due to undetected hyperglycemia prior to the formal diagnosis of diabetes. Additionally, some patients experience cataracts that can advance and mature swiftly, occasionally within days, particularly during adolescence. A preceding event may include the abrupt onset of myopia, attributed to alterations in the lens's optical density. In examining the morphology of early diabetic cataracts, various forms have been identified, including posterior subcapsular, lamellar, cortical, snowflake, and milky white types. However, most other researchers recognize fewer types, with posterior subcapsular cataracts being the most frequently reported form in pediatric diabetic patients.

Clinical and individual characteristics indicate that female gender, adolescence, a prolonged history of hyperglycemic symptoms, and elevated HbA1c levels at the time of diabetes diagnosis are significant risk factors for cataract development. Conversely, the incidence of ketoacidosis at diabetes onset appears to be lower in these patients [3]. The youngest patients documented in the literature with early diabetic cataracts are as young as 5 years old, although the majority are adolescents [14–16]. Iafusco et al. noted an equal gender distribution in the pediatric population with type 1 diabetes mellitus (T1DM) and early diabetic cataracts, whereas other studies have reported a predominance of female patients [14, 16, 17]. This group of authors also observed the occurrence of ketoacidosis as an indicator of decompensated T1DM in all patients, aligning with the findings of most earlier studies [16]. Recent studies have intriguingly indicated a reduced incidence of ketoacidosis [9, 18]. Additionally, there exists considerable variability in hemoglobin A1c (HbA1c) levels both at the time of diabetes diagnosis and at the onset of early diabetic cataracts [2, 15].

Late cataracts, akin to diabetic cataracts observed in adults, represent a long-term complication, sharing similar clinical manifestations and typically emerging approximately 10 years following the diagnosis of type 1 diabetes [7].

3. Differential diagnosis

Cataracts in children can arise from various causes, including type 1 diabetes, which is associated with endocrine and metabolic disorders such as hypocalcemia, hypoglycemia, and other conditions like atopic dermatitis and corticosteroid use [19].

3.1 Metabolic disorders

Metabolic disorders are significant contributors to cataract formation, particularly those affecting carbohydrate, amino acid, calcium, and copper metabolism. In infants, galactosemia, specifically galactose-1-phosphate uridyl transferase deficiency, is a critical consideration. This condition typically results in zonular cataracts, characterized by haziness or opacification of the perinuclear lens layers and sometimes the nucleus. Early-stage cataracts may exhibit an oil droplet appearance, detectable with a fully dilated pupil, and can progress to complete lens opacification within weeks. However, early intervention with a galactose-free diet can potentially reverse these lens changes. In cases of galactokinase deficiency, cataracts represent the primary clinical manifestation. These cataracts are typically zonular and can manifest within the first few months or years of life, or later during childhood.

Neonatal hypoglycemia is also linked to the early onset of cataracts, and ketotic hypoglycemia has been associated with cataract formation as well. There is a well-established association between cataracts and hypocalcemia. Patients with hypoparathyroidism may exhibit various types of lens opacities.

The oculocerebral renal syndrome of Lowe is characterized by the presence of cataracts in infants, with affected male children often presenting with dense bilateral cataracts at birth, frequently accompanied by glaucoma and miotic pupils. Heterozygous females commonly exhibit punctate lens opacities.

The characteristic sunflower cataract associated with Wilson disease is infrequently observed in children. Additionally, various lens opacities can occur in children with certain sphingolipidoses, mucopolysaccharidoses, and mucopolysaccharidoses, particularly in conditions such as Niemann-Pick disease, mucopolysaccharidoses, Fabry disease, and aspartylglycosaminuria.

3.2 Drugs, toxic agents, and trauma

Among the various pharmacological and toxic agents capable of inducing cataracts, corticosteroids hold significant importance within the pediatric population. Steroid-induced cataracts are typically characterized by posterior subcapsular lens opacities, with variability in both incidence and severity. The relative contributions of factors such as dosage, mode of administration, treatment duration, and individual susceptibility remain subjects of debate, and the pathogenesis of steroid-induced cataracts has yet to be fully elucidated. The impact on visual acuity is contingent upon the extent and density of the lens opacity, with many cases resulting in only minimal to moderate impairment. Notably, there is potential for reversibility in some instances of steroid-induced cataracts. It is imperative that children undergoing prolonged steroid therapy undergo regular ophthalmic evaluations.

Ocular trauma is another significant etiological factor for cataracts in children, with lens opacification potentially arising from either blunt or penetrating injuries. Furthermore, cataracts may serve as a critical indicator of child abuse.

Cataract formation following exposure to therapeutic radiation is contingent upon both the dose and duration of exposure, with adult studies indicating a 50% incidence rate at a lens dose of 15 Gy. A delayed onset is typically observed in these cases.

4. Treatment

Surgical intervention for cataracts in pediatric patients with T1DM requires a meticulous and individualized approach. Early surgical intervention is essential to prevent amblyopia and optimize visual outcomes. Compared to the general population, diabetic patients face increased risks associated with cataract surgery [20]. Therefore, it is critical for ophthalmologists to conduct a comprehensive preoperative assessment, taking into account the timing and selection of intraocular lenses, as well as addressing any pre-existing diabetic ocular conditions. Intraoperatively, particular attention must be paid to achieving adequate pupillary dilation and considering the potential need for adjunctive surgical procedures [20]. Postoperative care should involve vigilant monitoring for complications such as pseudophakic cystoid macular edema, diabetic macular edema, and posterior capsular opacification. Surgical techniques and postoperative management strategies are continually evolving, integrating both conventional practices and innovative advancements derived from adult cataract surgery. Currently, there is no unified set of indications for surgical treatment. For further details, please consult “the Chinese Expert Consensus on the Perioperative Management of Cataracts in Children (2022)”, “Update on pediatric cataract surgery”, and so on. [21–23].

For children unable to cooperate with vision tests, dense nuclear cataracts are present, characterized by turbidity along the visual axis with a diameter exceeding 3 mm. This lens opacity impedes both fundus and refractive examinations and is often associated with strabismus, amblyopia, and nystagmus, resulting in an inability to maintain a fixed gaze. In contrast, children who can cooperate with vision tests exhibit a best corrected visual acuity of less than 0.4 due to lens abnormalities for those with type 1 diabetic cataracts, elective surgical intervention is advised once blood sugar levels are stably controlled.

Cataract surgery is generally conducted *via* small, self-sealing corneal incisions, thereby obviating the necessity for sutures. Contemporary cataract surgery employs phacoemulsification, a technique that utilizes ultrasonic waves delivered through a handheld probe to disintegrate the opacified lens into smaller fragments *via* a circular anterior capsulotomy [23, 24]. The procedure can be primarily divided into the following stages: (1) Corneal Incision; (2) Capsulorhexis; (3) Phacoemulsification; and (4) Intraocular Lens (IOL) Implantation (**Figure 3**).

The management of cataracts that substantially impair vision encompasses: (1) surgical extraction of the lens material to restore an optically clear visual axis; (2) correction of the resultant aphakic refractive error using spectacles, contact lenses, or intraocular lens implantation; and (3) treatment of any concurrent sensory deprivation amblyopia.

In pediatric patients undergoing cataract removal, the use of spectacles may be impractical, rendering contact lenses a medical necessity for visual rehabilitation. Intraocular lens implantation has become a standard approach for visual rehabilitation in children aged 2 years and older [25]. Two multicenter trials [2, 26] have investigated the visual outcomes in very young children treated with either contact lenses or intraocular lens implants. One year post-treatment, children assigned to the intraocular lens implant group experienced a higher incidence of intraoperative complications, adverse events, and required additional intraocular surgeries. Although the median visual acuity was superior in the contact lens group, the difference was not statistically significant. The treatment of amblyopia remains the most challenging

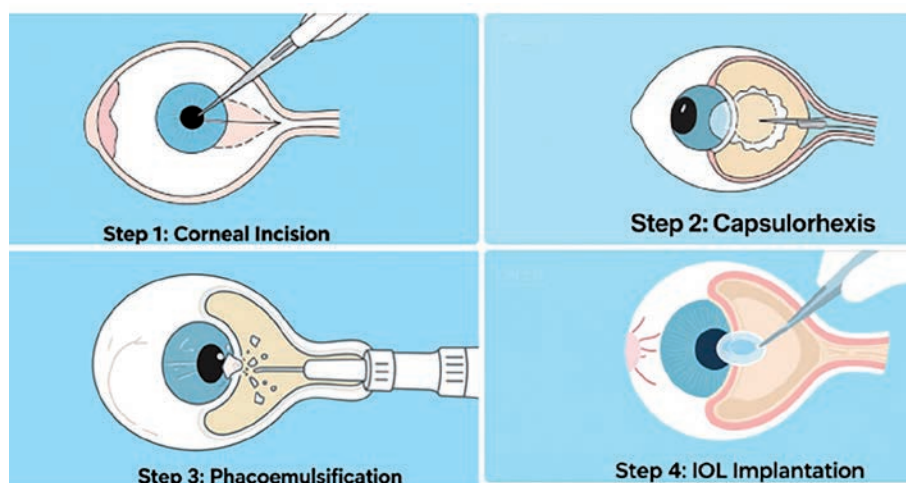


Figure 3.
Simulation diagram for pediatric cataract surgical procedure.

and demanding aspect of visual rehabilitation in infants and children with cataracts. Ophthalmic surgery remains the main treatment and is potentially beneficial for patients with diabetic cataracts, particularly after rapid and effective glycemic control (**Figure 4**) [27]. It is important to note that not all cataracts necessitate surgical intervention [28]. Cataracts that do not significantly impair vision should be regularly monitored for changes, and the child should be assessed for the development of amblyopia (**Table 1**).

5. Prognosis

The prognosis is influenced by various factors, including the characteristics of the cataract, the underlying disease, the age at onset, the age at which intervention occurs, the duration and severity of any accompanying amblyopia, and the presence of associated ocular abnormalities such as microphthalmia, retinal lesions, optic atrophy, glaucoma, nystagmus, and strabismus. Nevertheless, cataract surgery is not devoid of complications, necessitating careful consideration of the long-term risks associated with T1DM and its impact on the growth and development of the anterior eye segment [29]. The most prevalent complications following cataract surgery include posterior capsular opacification (PCO), secondary glaucoma, retinal detachment, amblyopia, and acute complications such as incision leakage, increased intraocular pressure, edema, and uveitis [30, 31]. Management of PCO differs between younger and older children, as PCO is more frequently observed in younger children. Persistent amblyopia remains the leading cause of suboptimal visual recovery post-cataract surgery in pediatric patients. In pediatric patients who have undergone cataract surgery, the development of secondary conditions and complications is possible. These may include inflammatory sequelae, secondary membrane formation, glaucoma, retinal detachment, and alterations in the axial length of the eye. It is imperative that these potential outcomes are taken into account when planning treatment strategies.

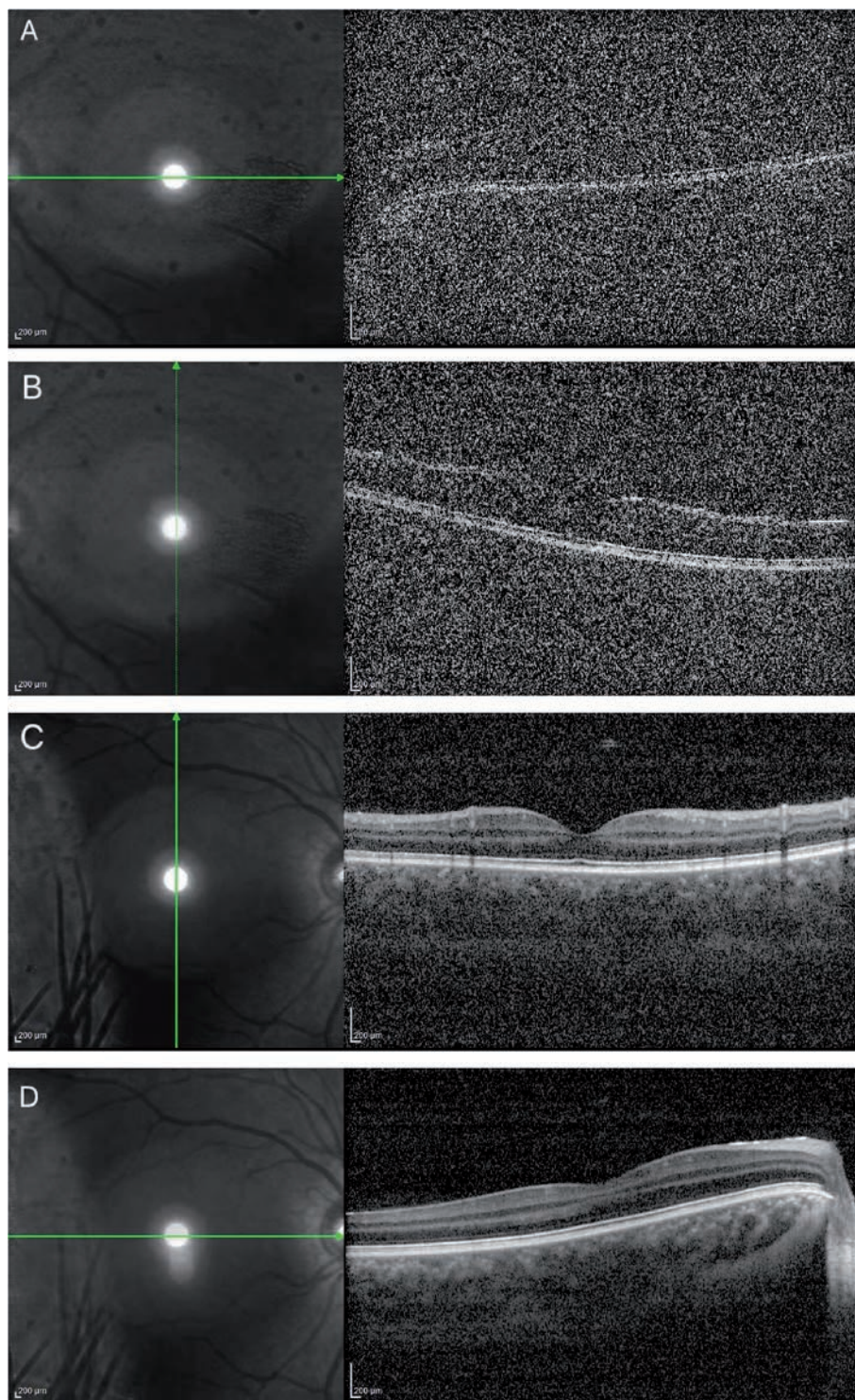


Figure 4.
Preoperative OCT of the patient with diabetic cataract.

<i>Developmental Variants</i>
Prematurity (Y-suture vacuoles) with or without retinopathy of prematurity
Mittendorf dot (remnant of the hyaloid artery)
Persistent pupillary membrane (remnant of embryonic lens vasculature)
<i>Genetic Disorders</i>
Simple Mendelian Inheritance
Autosomal dominant (most common)
Autosomal recessive
X-linked
Major Chromosomal Defects
Trisomy disorders (13, 15, 18, 21)
Turner syndrome (45X) and so on.
<i>Endocrinopathies</i>
Albright hereditary osteodystrophy
Hypocalcemia (hypoparathyroidism)
Hypoglycemia
Diabetes mellitus
<i>Congenital Infections</i>
Toxoplasmosis
Cytomegalovirus infection
Syphilis
Rubella
Perinatal herpes simplex infection
Measles (rubeola)
Poliomyelitis
Influenza
Varicella-zoster
<i>Ocular Anomalies</i>
Peters anomaly (corneal opacifications with iris-corneal dysgenesis)
Rieger syndrome (iris dysplasia, myotonic dystrophy)
Microphthalmia
Coloboma
Aniridia
Mesodermal dysgenesis
Norrie disease
Persistent pupillary membrane
Posterior lenticonus
Persistent fetal vasculature
Primitive hyaloid vascular system
Retinitis pigmentosa
<i>Miscellaneous Disorders</i>

Atopic dermatitis
Drugs (corticosteroids)
Radiation
Trauma
Juvenile idiopathic arthritis
Retinopathy of prematurity
<i>Spherocytosis</i>

Table 1.
Differential diagnosis of cataracts [19].

6. Future directions and emerging therapies

Emerging therapies and future research directions for pediatric cataract associated with T1DM are multifaceted, emphasizing both the enhancement of existing treatments and the development of innovative strategies. Advances in pediatric cataract surgery have integrated techniques and technologies derived from adult cataract management; however, it is recognized that pediatric cataracts necessitate distinct approaches [32]. Significant progress has been made in understanding diabetic retinopathy, a complication closely linked to cataracts. This progress includes the utilization of retinal imaging and functional analysis for the early detection of pathologies, as well as the development of therapies targeting both the neural and vascular components of the disease [33]. Future research is likely to concentrate on optimizing the timing and techniques of cataract surgery in children with type 1 diabetes and exploring the potential benefits of emerging diabetes treatments on cataract development and surgical outcomes [34]. Interdisciplinary collaboration, encompassing fields such as ophthalmology, endocrinology, and biomedical engineering, is essential for the advancement of these research domains and the translation of findings into clinical practice.

7. Conclusion

In summary, the epidemiology of pediatric cataracts in individuals with T1DM is shaped by a multitude of factors. The clinical complexities associated with managing pediatric cataracts in this patient population include the repercussions on glycemic control, the distinct characteristics inherent to pediatric cataracts, and the psychological ramifications of these conditions. These elements underscore the need for a comprehensive and individualized management strategy. The surgical treatment of cataracts in pediatric patients with T1DM demands an approach that thoroughly addresses the specific challenges faced by this demographic, with a pronounced focus on early intervention, meticulous surgical techniques, and rigorous postoperative care.

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Conflict of interest

The authors declare no conflict of interest.

Author details

Shimin Wu^{1*} and Xiaoqin Yan²

1 Department of Pediatrics, Tongji Hospital, Tongji Medical College, Huazhong University of Science and Technology, Wuhan, China

2 Department of Ophthalmology, Tongji Hospital, Tongji Medical College, Huazhong University of Science and Technology, Wuhan, China

*Address all correspondence to: wushiminw123@sina.com

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Section 2

Refractive Cataract Surgery with Advanced Technology

Refractive Lens Exchange Indications

Arañó Ferrer Jerónimo

Abstract

Refractive lens exchange (RLE) is a refractive procedure that has been used more frequently during recent years. With the improvement in technology and outcomes in cataract surgery, the possibility to offer a solution for presbyopic patients has become a great option and even patients come to clinics seeking these surgeries. In this chapter, we will review the indications of refractive lens exchange, and when is not recommended. We will review the importance of an adequate preoperative evaluation of the patient, and the studies needed to make the most accurate IOL calculation so that the patient can have the best outcome. Finally, we discuss the contraindications and when is appropriate to do surgery and when it is not.

Keywords: refractive surgery, multifocal IOL, cataract surgery, intraocular lens exchange, EDOF IOL

1. Introduction

Phacoemulsification surgery with intraocular lens (IOL) implantation is one of the most commonly performed procedure for the treatment of cataracts, aimed at improving patients' vision. Today, people seek better visual outcomes after cataract surgery, not only for distance vision but also for improved functional vision that allows them to perform daily activities more independently and without the need for spectacles. As individuals now work for more years and increasingly rely on digital devices such as computers, smartphones, and tablets, intermediate and near vision has become critically important. This shift has transformed phacoemulsification from a procedure solely for cataract treatment into a refractive surgery as well, where delivering the best possible visual outcome is essential for achieving patient satisfaction. Refractive lens exchange (RLE) has become a viable alternative for patients who are not suitable candidate for corneal refractive procedures or phakic intraocular lenses.

In 1967, Dr. Charles D. Kelman introduced phacoemulsification surgery as a less invasive, faster, and more effective method for treating cataracts [1]. Since then, the evolution of phacoemulsification has extended to new purposes.

Refractive lens exchange is defined as the removal of a clear lens for refractive purposes, with the objective to give patients more spectacle independence, either for far, near, or both visions. RLE provides a solution by replacing the clear crystalline

lens with a monofocal, multifocal, or extended depth-of-focus intraocular lens to correct each refractive error. The fast diffusion of new phacoemulsification machines and better outcomes in the surgery has led to earlier RLE surgery, as many patients have higher expectations of their visual capacity [2]. The sudden increase in this procedure in recent years can raise the ethical question of its boundaries. This chapter will explore the benefits of this procedure, the adequate patient selection, and the contraindications.

2. Patient selection and evaluation

The success of RLE depends mostly on an appropriate patient selection. The main indications for a patient that wants an IOL implantation for better vision can be summarized in these main points [2, 3]:

- Moderate to high hyperopia ($> + 3.00$ D).
- High Myopia in patients who are not candidates for a corneal refractive procedure or Phakic IOL.
- Significant presbyopia with a desire for spectacle independence.
- Significant corneal astigmatism.

These are the first thing to consider, but most important is the patient's age. It is considered that patients should be at least 45 years of age or older to go through a RLE [2]. This will vary depending mostly in the refractive problem of each patient and the condition of the eye. It is important to consider that RLE is an elective procedure that is performed more often in younger patients that are more active and have more visual expectations after the surgery.

2.1 Preoperative evaluation

These patients need a baseline set of studies such as those patients that are having cataract surgery. It is important to know the patient's overall health to determine whether they are an optimal candidate for surgery and how existing comorbidities may affect both surgical performance and visual outcomes. Visual acuity with Snellen chart should be performed in all patients, follow by refraction of the eye [4]. The use of questionnaires is helpful to understand the patients' unconformities with its vision; there are many validated questionnaires for measuring vision-specific measures (Visual Activities Questionnaire, The Activities of Daily Vision Scale and other) [4].

Full slit lamp evaluation of the patient's eye undilated and dilated for complete examination of the retina is the next step. A complete examination of the retina and its periphery is fundamental, even more in patients with high myopia to discard any retinal lesions that can increase the risk of retinal detachment (RD). It is important to search for clinical signs of glaucoma, macular disease, pseudoexfoliation syndrome, and poorly dilating pupils that can affect the outcomes of the surgery [5].

Preoperative assessment includes biometry that can be performed using optical laser interferometry biometry, ultrasound A-scan, or optical coherence tomography [4, 5]. It is important to obtain keratometry values with either automated devices or

manually [4, 5]. Corneal topography is helpful to decide if a toric IOL is indicated [5]. The use of aberrometry is essential if a multifocal or extended depth of focus IOL is being considered [5]. Retinal optical coherence tomography (OCT) should be performed in all patients to discard any macular pathologies and to understand vitreous adherence to the macula for any possible signs of traction or macular holes [5].

The decision for continuing with the RLE should be done after carefully examining all of the studies mention above and individualizing the IOL selection for each patient depending on what was found in the studies.

2.2 IOL selection and IOL calculation

The IOL selection should be individualized for each patient. In patients with high myopia the availability of minus, zero or low plus power lenses has made possible the option to always implant and IOL, which mitigates the development of posterior capsular opacification (PCO) and reduces the risk of retinal detachment [6]. Aspherical IOLs can compensate for the positive spherical aberration of the cornea to provide better outcomes; this type of IOLs is widely used because of this characteristic [7]; it is important to know the spherical aberration (SA) of the IOL for patients who have different corneal spherical aberration so that the IOL can help compensate this; it is recommended to leave a residual spherical aberration between 0.07 and 0.10 μm [7, 8].

New designs in optics in IOLs have developed rapidly in this last years; presbyopia correcting IOL designs using different refractive methods has led to have a variety of options for each individual case. Most of these IOLs use a diffractive design to achieve good near and far vision. Currently, new designs of IOLs use a refractive segmented varifocal optic; there are also trifocal diffractive IOL that have a better intermediate vision compared to those that are purely diffractive. The extended depth of focus (EDOF) IOLs achieves an elongated focus of vision by inducing negative aberration of the IOL or by the use of a pinhole principle [7].

In **Table 1** is a summary of different IOL options with its spherical aberration.

IOL calculation should be assessed for each individual case. In a systematic review by Stopyra et al. [15], Barret Universal II was the most precise vergence formula;

IOL (Model)	Type	SA Zernike (~6 mm)
Tecnis ZCB00	Monofocal Aspheric (SA -)	-0.27 μm
Tecnis Symphony ZXR00	EDOF Hybrid (SA -)	~ -0.27 μm
Tecnis ZMB00	Multifocal Diffractive (SA -)	~ -0.27 μm
AcrySof IQ SN60WF	Monofocal Aspheric (SA -)	-0.20 μm
Clareon SY60WF	Monofocal Aspheric (SA -)	-0.20 μm
Akreos Adapt AO	Monofocal Neutral SA	0.00 μm
EnVista MX60	Monofocal Neutral SA	0.00 μm
Rayner C-flex 570C	Monofocal Spherical (SA +)	+0.10 to +0.20 μm
Mini WELL Ready	EDOF Zonal SA	SA Positive/Negative Zones
LuxSmart	EDOF Zonal SA	SA Modulated

Table 1.
 Different IOLs with their optical type and Spherical Aberration [9–14].

Kane and PEARL-DGS were the most accurate among the artificial intelligence-based formulas. In patients with short eyes, PEARL-DGS formula demonstrated the highest accuracy in artificial intelligence-based formulas [16]. For patients with long eyes (>26 mm), Barret Universal II showed the most accurate results [17]. In patients with previous refractive corneal surgery, Barret True-K showed the best results in patients with previous myopic and hyperopic laser refractive surgery [18, 19].

Aside of the importance of the IOL selection and IOL calculations, there are some fundamental technical principles to be conscious during RLE: during the surgery, it is important to have minimal intraoperative manipulation with microincisions, inducing the least possible surgical astigmatism; incisions should be placed over the steepest corneal meridian if possible. The surgeon should be conscious and cause minimal damage to intraocular structures and a correct IOL implantation in the capsular bag is crucial. The surgeon should have all the precautions to reduce the risk of posterior capsule opacification [6].

3. Considerations and outcomes

3.1 Myopia

Refractive lens exchange has been widely used for correcting myopia in patients who are not suitable for corneal refractive surgery [20]. This helps in having a better overview of myopic patients undergoing RLE. RLE should be considered for patients with high myopia (> -6.00 D or axial length > 26 mm) who are not candidates for corneal refractive procedure or phakic IOLs [21]. It is important to consider the age of the patients in this group.

Studies have shown that the younger the patient is, the risk of retinal detachment increases [21]. High myopia eyes have an increased risk of RD compared to non-myopic eyes; some studies report a prevalence of RD in high myopes between 0.71% and 3.2% [21]. This prevalence increases in patients with high myopia that underwent RLE, being a total prevalence between 1.5 and 8.1% [2]. The group at higher risk is patients with an axial length more than 28 mm and below the age of 50.

The increased risk of RD in myopic patients is considered to be because of a higher incidence of predisposing retinal lesions and vitreous changes after the procedure [22]. Therefore, the importance of a thoughtful retina examination prior to the surgery.

It is important to talk about this risk with the patient before the surgery and emphasize the importance of continuous retina examinations throughout the patient's life, to be able to prevent an RD. Higher risk of choroidal neovascularization has also been described in patients with high myopia that underwent cataract surgery [23]. Even though it has been described the increased risk of RD in this group undergoing RLE, a large 2024 meta-analysis found that the incidence of RD after RLE in general was of 0.023%, compared to 0.012% in standard cataract surgery with at least a 24 month follow-up, considered to be an uncommon complication, even though it was almost twice the incidence [24]. These numbers reflect low risk, but the increase is clinically significant, especially when evaluation of surgical options for younger myopic patients. An important consideration is that postoperative YAG laser capsulotomy may further increase the risk of RD; therefore, selecting an IOL with a lower likelihood of posterior capsule opacification is crucial, like an hydrophobic sharp edge IOL [2].

RLE is an effective option to correct myopia and high myopia; with the correct evaluation of each patient, it can significantly improve quality of life and achieve optimal

visual acuity outcomes [25]. RLE is indicated in patients with axial length < 26 mm who are over 50 years old, in the absence of other contraindications; patients between 45 and 50 years old can be considered for RLE if no primary refractive procedure is possible, as far as posterior vitreous detachment is demonstrated. RLE is not recommended in patients under the age of 45 and in eyes with axial length of 26 mm or more. In the presence of retinal risk factors, including extensive lattice degeneration, lacquer cracks or neovascular membrane is present in the fellow eye; surgery is contraindicated [2].

3.2 Hyperopia

Patients with hyperopia are more suitable for RLE mainly because hyperopic eyes typically have shorter axial lengths and shallower anterior chambers; this can make corneal refractive surgery or phakic IOL implantation less safe or technically unfeasible. Patients with hyperopia older than 45 years of age are good candidates for RLE; it offers a safe and effective alternative to correct both distance and near vision while preventing the onset of age-related cataracts.

With the advancement of multifocal, trifocal, and EDOF IOLs, hyperopic patients are suitable candidates for premium IOLs. These technologies offer an extended range of vision and are particularly optimal in presbyopic hyperopes who seek spectacle independence. Some recent studies have shown great patient satisfaction and quality of life following bilateral implantation of multifocal IOLs in hyperopic patients, with over 85% of patients with complete spectacle independence [26].

Another benefit is that hyperopic eyes, due to their shorter axial length and less vitreoretinal degeneration, have shown almost no incidence of RD after RLE [27]. Additionally, some hyperopic patients may have angle closure risk due to shallow anterior chamber; RLE can help deepen the anterior chamber and eliminate the potential risk of pupillary block or acute angle-closure glaucoma [28].

3.3 Astigmatism

Different approaches can be made for correcting astigmatism during RLE. Clear corneal incision in the steepest meridian is an effective way in low astigmatisms < 1.00 D [29]. Another approach is to use single or paired peripheral corneal relaxing incisions that can correct astigmatisms up to 3.00 D. Nowadays, the use of toric IOLs is an effective way to correct astigmatism up to 12.00 D. Most of premium IOLs can have toricity to correct symmetric astigmatism. This helps patients to have great visual outcomes after surgery.

It is important to address astigmatism in patients with premium IOLs, because residual astigmatism can lower visual acuity and increase optical aberrations that can impact patient satisfaction and quality of vision. This reduction in quality vision is mainly due to reduced contrast sensitivity and increase in halos and glare [29, 30].

During surgery, it is critical to align the toric lens in the correct orientation for astigmatic correction, because for every 3 degrees of rotation, around 10% of the astigmatic correction is lost [7].

3.4 Presbyopia

Nowadays, presbyopia is the most common refractive error. With the increase in life expectancy, most people will live many years of their lives with presbyopia, with

increasing dependence on their intermediate and near vision. Many patients that go through an RLE might be seeking more spectacle independence. RLE with premium IOLs (multifocal, trifocal, or EDOF) is one of the most common procedures for the correction of presbyopia.

When considering RLE in a patient who wants to correct presbyopia, it is important to consider their other refractive errors to address them as mention above. Patients who seek RLE for presbyopia correction and have low degrees of other refractive errors or even emmetropia with great distance vision should be address carefully about their expectations. This group of patients can have worse contrast sensitivity and more corneal aberrations after surgery that may impact their satisfaction and be very demanding on their new vision [29]. Presbyopia RLE in emmetropic patients should only be considered in the presence of advanced presbyopia [2].

4. Conclusion

Refractive lens exchange has gained more popularity among refractive procedures. It is a valid and proven method to correct refractive problems. It is important to remember that this is an elective procedure, and many of these patients can have great vision with the use of glasses or contact lenses. As physician is important to always seek for the better benefit of the patient.

In this chapter, we reviewed the importance of doing a thoughtful examination before considering an RLE. Is important to consider that all surgeries can have complications and always protecting the integrity of the person is the most ethical thing to do. RLE should be done after a good physical and ophthalmological examination, the correct analysis of the required studies performed to the patient, and, last but not the least important, after a well-informed talk with the patient.

RLE in myopic eyes is not recommended in patients under 45 years of age with axial length > 26 mm. In patients between 45 and 50 years, it should be done after ruling out any retinal comorbidities. In patients with hyperopia, it is recommended to do an RLE in those with moderate to high hyperopia, and it is not recommended in patients under 45 years of age. Finally, in patients with presbyopia and emmetropia, it should be carefully addressed and done in the presence of advanced presbyopia in an unsatisfied patient [2].

Conflict of interest

The author declares no conflict of interest.

Author details

Arañó Ferrer Jerónimo
Asociación para Evitar la Ceguera en México, Mexico City, Mexico

*Address all correspondence to: jeronimoaranof@gmail.com

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Advanced Techniques in Refractive Cataract Surgery (RCS): Achieving Spectacle Independence with Precision Technology

Amr Saad and Detlev R.H. Breyer

Abstract

This chapter explores the latest advancements in refractive cataract surgery (RCS), with a focus on techniques and technologies that increase spectacle independence and enhance the patient's quality of life. It provides a deep analysis of premium intraocular lenses (IOLs), including multifocal and extended depth of focus (EDOF) designs. It details their optical principles, clinical outcomes, and patient suitability. The chapter also examines the roles of corneal surgery and femtosecond laser-assisted cataract surgery (FLACS) in achieving surgical precision and optimizing refractive outcomes. These include corneal touch-up procedures such as keratorefractive lenticule extraction (KLEx, including SMILE-Pro), laser *in situ* keratomileusis (LASIK), and photorefractive keratectomy (PRK) for correcting residual refractive errors. Additionally, the chapter addresses postoperative challenges, such as dysphotopsia, reduced contrast sensitivity, light distribution, and neuroadaptation. It also highlights emerging trends, including enhanced monofocal, spiral, and pinhole IOLs. By integrating evidence-based insights with nearly two decades of practical experience in a private, premium clinical setting with scientific work and international speaking, this chapter provides ophthalmic and refractive surgeons with the knowledge necessary to optimize the patient outcomes in modern cataract surgery on an individual basis.

Keywords: refractive cataract surgery, RCS, intraocular lenses, IOL, multifocal IOL, MIOL, EDOF, extended depth of focus IOL, femtosecond laser-assisted cataract surgery, FLACS, patient selection, preoperative assessment, postoperative management, dysphotopsia, neuroadaptation

1. Introduction

Modern refractive cataract surgery has advanced significantly, expanding beyond the restoration of basic visual function to a technologically sophisticated approach that manages cloudy lens changes and addresses the entire range of refractive errors simultaneously [1]. This transformation from classic cataract surgery, which resulted in patients needing glasses after surgery, to refractive cataract surgery (RCS), which

results patients being able to see without glasses, represents a fundamental reevaluation of surgical objectives. This aligns with patient lifestyle demands and is associated with the aging of the global population and the rise in patient demands [2]. In this modern era, ophthalmic surgeons must navigate a multifaceted landscape, characterized by sophisticated diagnostic modalities, diverse surgical options and devices, and complex preoperative and postoperative management strategies to achieve the optimal outcomes for each individual patient [3].

This chapter provides ophthalmologists and ophthalmic surgeons with a foundational understanding of the latest evidence-based strategies for effectively navigating this complex and rapidly evolving field. Key topics include patient selection, various intraocular lens (IOL) technologies, femtosecond laser-assisted cataract surgery (FLACS), postoperative management, and emerging trends. Supported by recent scientific literature and two decades of practical clinical experience, pioneering work, and key opinion leadership in the field of minimally invasive cataract surgery, advanced technology IOLs, and laser surgery, these topics are presented by Detlev R.H. Breyer.

1.1 Evolution of RCS

Cataract surgery has undergone a remarkable transformation, progressing from basic interventions aimed at achieving light perception to sophisticated refractive procedures designed to optimize visual performance across multiple distances. This evolution demonstrates the continuous refinement of surgical techniques and a better understanding of visual physiology, resulting in today's personalized precision-driven approach of RCS [2].

The earliest documented cases of cataract interventions date back to the fifth century BC, when couching techniques were used to displace the clouded lens into the vitreous cavity [4, 5]. These interventions were associated with severe complications, including permanent blindness. The true cataract extraction procedure was then initiated by Jacques Daviel in 1747 when he performed the first successful extracapsular cataract extraction (ECCE). This was then followed by Samuel Sharp's subsequent development of intracapsular cataract extraction (ICCE) in 1753.

The introduction of intraocular lenses (IOLs) by Sir Harold Ridley in 1949 marked the beginning of the modern era of cataract surgery and laid the foundation for refractive enhancement [6]. Ridley observed that Royal Air Force pilots could tolerate acrylic fragments in their eyes after being injured by aircraft canopies. This led him develop polymethylmethacrylate (PMMA) IOLs, which addressed the fundamental problem of aphakia and established the concept of lens replacement rather than simple removal [7]. The revolutionary implementation of ultrasonic energy-based phacoemulsification, pioneered by Charles Kelman in 1967, enabled the fragmentation of the crystalline lens through small incisions of 3 millimeters or less [8]. This approach significantly reduced surgically induced astigmatism (SIA) and accelerated visual recovery. The later development of foldable IOL materials, including silicone IOLs, was a pivotal advancement in enhancing the predictability of refractive outcomes [9].

The twenty-first century brought further advancements in surgical precision and IOL technology, transforming cataract surgery into a refractive procedure capable of addressing the entire spectrum of ametropia. The introduction of FLACS in 2008 represented a paradigm shift toward more automated and predictable surgical precision. FLACS enables reproducible capsulotomies, precise lens fragmentation, and accurate corneal incisions [10]. Trifocal or multifocal IOLs (MIOLs) can provide functional vision at near, intermediate, and distance ranges, whereas extended depth of focus (EDOF) lenses use

novel optical designs to extend the range of clear vision while minimizing the optical phenomena associated with traditional MIOL designs [11, 12]. Recent advancements include light-adjustable, spiral, and accommodative IOLs [13].

1.2 Today's paradigm shift

The modern transformation of RCS encompasses technological advancements and patient-centered approaches. Historically, the rationale for cataract surgery has been limited to cases of visually significant cataracts. The efficacy of this surgical intervention has predominantly been assessed based on enhancing distance visual acuity (VA) and reducing glare. The timing of surgery was typically based on cataract density and its impact on daily activities.

Modern RCS takes a proactive and comprehensive approach to intervention, considering lens replacement as an opportunity for visual enhancement rather than simply cataract treatment. This requires modified, comprehensive patient selection criteria that include multifactorial assessment protocols extending beyond traditional clinical parameters to encompass lifestyle demands, visual requirements, and psychosocial factors (see Chapter 2.2).

The integration of advanced diagnostic and surgical technologies has enabled unprecedented precision in surgical interventions and customized treatment protocols. Artificial intelligence (AI) algorithms that enhance the accuracy of intraocular lens (IOL) power calculations, such as the Hill-RBF and Pearl-DGS methods, are continuously refined based on real-world outcome data [14, 15]. These algorithms are particularly beneficial for eyes with atypical dimensions or a history of refractive surgery, where accurately calculating the IOL power is challenging.

1.3 Core principles of RCS

Successful RCS is founded on three interconnected pillars that collectively determine surgical outcomes: precise preoperative assessment and planning with the most up-to-date diagnostics and an experienced team, careful intraoperative execution by an experienced, high-volume surgeon, and comprehensive postoperative management including touch-up surgery in 5–10% of cases. It is important to understand that RCS operates within significantly narrower tolerance margins compared to conventional cataract surgery. Even minor deviations in planning or execution can substantially impact final refractive outcomes and patient satisfaction, so it should only be performed by experienced, high-volume surgeons in a premium setting.

2. Patient selection and preoperative assessment

2.1 Preoperative evaluation of potential RCS candidates

A comprehensive preoperative evaluation is essential for achieving successful outcomes in RCS. This process integrates multimodal diagnostics to evaluate the ocular surface, corneal structure, biometric parameters, posterior segment health, and systemic factors to minimize refractive surprises and optimize patient satisfaction [3].

A thorough medical history is the cornerstone of the preoperative assessment in RCS. It helps identify potential risk factors and contraindications, thereby decreasing the

likelihood of complications [3]. Key elements include a review of current medications. For example, alpha-1 adrenergic blockers (e.g., tamsulosin) increase the risk of intraoperative floppy iris syndrome (IFIS) [16]. Hereditary eye conditions, such as keratoconus (KC) or glaucoma, could also lead to poor RCS outcomes [17, 18]. The ocular history should include any prior surgeries, such as photorefractive keratectomy, as well as any history of trauma or maculopathies. These factors can increase higher-order aberrations (HOAs) and limit visual outcomes with MIOLs [19]. A thorough systemic history is essential to identifying comorbidities that could impair healing or outcomes. For example, diabetes mellitus increases the risk of postoperative cystoid macular edema (CME) [20]. Lifestyle and daily activities (e.g., hobbies, night driving, screen-based work) should be explored in depth to tailor IOL selection to the patient's functional demands [21]. Patients who frequently drive at night are better candidates for EDOF IOLs rather than diffractive MIOLs because the latter can worsen photopsias like halos and glare in low-light (mesopic) conditions, which can lead to reduced vision [22].

The clinical examination is a multifaceted process that aims to comprehensively evaluate ocular health and identify pathologies that could compromise surgical success [3]. Beginning with the anterior segment, slit-lamp biomicroscopy is essential for evaluating corneal clarity and excluding corneal degenerations and dystrophies, including epithelial or stromal opacities, and endothelial guttata, which may indicate Fuchs' endothelial corneal dystrophy, which holds the risk of postoperative corneal decompensation. Assessing pupil size under mesopic (dim light) and photopic (bright light) conditions is crucial especially for MIOL candidates. Small pupils in mesopic settings can impair near vision in pupil-dependent MIOL designs, while large pupils in photopic settings can exacerbate halos and glare [23]. Angle kappa (κ) measurements are critical because values exceeding 0.5 mm have been associated with an increased risk of dysphotopsia and reduced VA in MIOL patients, although the evidence is mixed [24, 25]. Determining ocular dominance, typically done *via* the hole-in-card test, is vital for allocating the motoric dominant eye to distance correction in blended vision approaches and accelerating postoperative neuroadaptation [26]. Another valuable test for determining the dominant eye is to blur the vision with a + 1.0 diopter (D) lens and ask the patient which eye is more distracting. Never forget to ask the patient which eye he uses to shoot a rifle. Due to its high prevalence, which is often exacerbated by age-related meibomian gland dysfunction (MGD), assessing dry eye disease (DED) assessment is essential [27]. Using the Ocular Surface Disease Index (OSDI) questionnaire to quantify symptoms can inform preoperative management decisions, including intense pulsed light therapy with meibomian gland expression (IPL-MGX) or thermal pulsation systems (e.g., LipiFlow) [28]. A dilated fundus examination is essential for identifying retinal pathologies, such as age-related macular degeneration (AMD), epiretinal membranes (ERM), and peripheral degenerations predisposing to retinal detachment (RD), particularly in myopic eyes. A detached vitreous should be documented. Although retinal diseases are often considered relative contraindications for Advanced Technology (AT) IOLs, recent evolving analyses suggest that mild, stable conditions may not preclude AT-IOL use. Objective (autorefractor) and subjective (phoropter) refractions, along with distance and near VA and contrast sensitivity testing, establish fundamental baseline RCS metrics.

Finally, biometry and high-resolution imaging form the technical foundation of the preoperative evaluation in RCS [3]. These technologies are used to precisely calculate and select the IOL power and to identify subtle anatomical variations that could significantly influence outcomes. Prior to these assessments, patients must stop wearing contact lenses (CL) for at least 14 days to avoid lens-induced corneal distortion and inaccurate IOL calculations [29]. Aberrometry is essential

for measuring HOAs, such as spherical aberration (SA). High corneal HOA values often contraindicate MIOL implantation and guide surgeons toward monofocal or EDOF alternatives. Precise axial length (AL) measurement *via* optical biometry (e.g., IOLMaster or Lenstar) is critical for IOL power calculations. Eyes with high myopia (AL >26 mm) require caution due to an increased risk of RD post-operatively, so patients need thorough education. Scheimpflug tomography (e.g., Pentacam), combined with biomechanical analysis *via* Corvis ST, assesses corneal hysteresis and resistance. This helps to exclude subclinical KC through parameters such as the tomographic-biomechanical index (TBI). Corneal pachymetry can map central and peripheral thickness. Thin corneas pose a heightened risk of ectasia in potential touch-up procedures like LASIK and should be excluded [30]. Additionally, endothelial cell density measured by specular microscopy is essential for evaluating decompensation risk [31]. Irregular astigmatism patterns, such as skewed axes or asymmetry, as measured by keratometry and topography, contraindicate MIOL implantation due to the reduced predictability. In general, targeting postoperative astigmatism of less than 0.75 D is key for AT-IOL efficacy. Lastly, retinal OCT imaging can rule out pathologies such as epiretinal membranes or early CME precursors and optic nerve damage.

2.2 Patient selection and preoperative counseling in RCS

Ideal candidates for RCS are generally healthy individuals with active lifestyles who are motivated to achieve independence from glasses and have realistic expectations about surgical outcomes. Accurate IOL power calculations and predictable outcomes depend on refractive stability. Ideal candidates should demonstrate this stability over at least 2 years. Age is also a key factor, as optimal candidates are typically 40 years or older to balance the need for presbyopia correction with the elevated risk of retinal detachment in younger patients [32]. We do not recommend clear lens exchange solely for optical reasons and only perform lens surgery on cloudy crystalline lenses. Otherwise, we prefer corneal or ICL surgery to avoid the higher complication rate inherent to IOL surgery.

Success in RCS depends on aligning patient expectations with the achievable outcomes. Candidates must understand potential trade-offs, such as glare or halos with MIOLs, and accept that they may need glasses for certain activities. Completely eliminating the need for glasses is (currently) unrealistic and technically impossible. It is crucial to explicitly address visual expectations, including the desire for spectacle independence, as unrealistic expectations significantly contribute to IOL explanations. The difference should be explained to the patient as achievable spectacle independence versus unrealistic freedom from spectacles. In this context, screening for personality traits such as perfectionism, anxiety, and depression is essential. Tools like the Five Factor Inventory (FFI) scale can assess these traits, which are linked to an increased risk of dissatisfaction, even following technically successful surgery [33]. A history of nonadherence to postoperative care regimens signals unsuitability because diligence in follow-up care is nonnegotiable.

The efficacy of RCS procedures depends heavily on comprehensive patient education and counseling. This counseling should include translating complex optical principles into the understandable concepts [34, 35]. Nowadays, patients have a growing number of options for independent education before undergoing refractive surgery, which makes overcoming prejudiced opinions more challenging. RCS is based on shared decision-making, a collaborative approach that enables patients to actively participate in selecting an IOL and surgical plan that align to their unique visual needs and lifestyle preferences [36]. The informed consent process must

explicitly outline these factors to ensure that patients understand the full scope of the procedure, including the potential need for additional interventions to refine their vision. To enhance comprehension, clinicians may use visual aids or IOL simulators to illustrate how different IOLs might affect postoperative vision and to preview potential visual outcomes with multifocal or EDOF IOLs and anticipate phenomena like glare or halos [37]. Transparency regarding the financial and legal aspects of RCS is critical for making an informed decision. Patients should receive a clear explanation of the differences between standard cataract surgery, which is usually covered by insurance, and RCS options, which often require additional out-of-pocket payments.

Regardless of patient suitability, it is important to note that integrating RCS into conventional ophthalmological practice requires considering surgical training requirements, capital expenditures on specialized equipment, and workflow modifications (e.g., increased counseling time). Therefore, it may not be applicable to all practices or clinics.

3. Multifocal intraocular lenses (MIOLs)

3.1 Optical principles and design

Multifocal intraocular lenses (MIOLs) represent a significant advancement in presbyopia-correcting IOL technology. Diffractive MIOLs enable functional vision across far, intermediate, and near distances by simultaneously projecting multiple focal points onto the retina [38]. Unlike monofocal IOLs, which provide a single focal point and typically require additional correction for near or intermediate vision, diffractive MIOLs distribute incoming light to generate overlapping depth-of-focus (DOF) zones. However, this optical strategy introduces inherent trade-offs, including reduced contrast sensitivity and photopic phenomena such as halos and glare. These phenomena arise from unfocused light rays and neural processing challenges [39].

The foundational principle of MIOLs is the manipulation of light through refraction, diffraction, or hybrid mechanisms [40]. First refractive MIOLs use variations in lens curvature or zonal power to bend light rays differently across the optic surface. Early designs, introduced in the 1990s, featured concentric or annular zones with distinct refractive powers and often incorporated a near addition of +3.0 to +4.0 diopters (D) [41]. For example, the central zones were optimized for distance vision, and the peripheral zones focused light for near tasks. This zonal refraction created discrete foci but was highly dependent on the pupil size. Optimal visual performance required a mesopic pupil diameter of approximately 3–4 mm to evenly distribute light distribution evenly between zones. However, the abrupt transitions between zones led to light scattering and edge effects, resulting in halos and glare. This limited their widespread adoption despite their ability to provide good near and far vision [42].

To address these limitations, diffractive optics emerged. First introduced in 1987 with models like the 815E/815X (3 M, now discontinued), these lenses use microscopic echelettes, or step-like gratings etched onto the lens surface, to split incoming light into multiple diffraction orders [43]. The zeroth order typically directs light to the distance focus, while the first order creates the near focus [44]. Trifocal diffractive designs, such as the AcrySof IQ PanOptix (Alcon) and the AT LISA tri (Carl Zeiss Meditec), introduce an intermediate focus, with an effective add power ranging from +1.66 to +2.17 D [45]. This elongates the DOF for seamless vision from approximately 40 cm to infinity. Apodization further improves this performance by gradually reducing the

height of the echelettes from the center to the periphery. This directs more light to the distance focus under photopic conditions and mitigates photopic phenomena [46].

Segmental refractive designs are an alternative to concentric zoning, reducing pupil dependency and photic effects. The Lentis Mplus series (Teleon), for example, incorporates an asymmetrical inferior sector with a near addition ranging from +1.5 to +3.0 D. This design distributes light unevenly between near and distance vision [47]. While this minimizes edge-induced scatter and enhances contrast sensitivity, slight anisometropia can be induced in bilateral implantation.

Hybrid MIOLs combine the refractive and diffractive elements to leverage the strengths of both. For example the TECNIS Synergy (Johnson & Johnson Vision) that uses diffractive echelettes for multifocality and refractive asphericity to increase the DOF, resulting in high light efficiency and reduced halos [48]. Similarly, the FineVision Triumf (PhysIOL) uses a trifocal diffractive pattern with variable step heights to optimize intermediate vision and counteract corneal SA [49]. Aspheric surfaces often correct $-0.20\text{ }\mu\text{m}$ of SA, which neutralizes the cornea's inherent positive SA ($+0.27\text{ }\mu\text{m}$ on average). This improves contrast sensitivity and reduces coma-like aberrations.

3.2 Clinical outcomes

Recent meta-analyses consistently show that diffractive MIOLs outperform monofocal lenses in achieving uncorrected near and intermediate visual acuity. Diffractive trifocal designs have high spectacle independence rates, though they slightly reduce contrast sensitivity and increase dysphotopsia in some patients [50, 51]. These outcomes vary by optical design. Refractive MIOLs often prioritize distance and intermediate vision, while diffractive models excel in near VA [52]. Neuroadaptation, which typically resolves within 3 to 6 months, plays a critical role in subjective satisfaction [53].

Bifocal refractive MIOLs have demonstrated reliable distance VA (typically 20/20 or better uncorrected) and functional near vision in clinical trials. However, intermediate performance remains a limitation [54]. Segmental variants, such as the Lentis Mplus (Teleon), deliver better results, providing high VA at all working distances and offering spectacle independence for daily activities in up to 100% of patients [55, 56]. Patient satisfaction scores average 9/10 and are attributed to lower photic phenomena and preserved contrast sensitivity. However, slight anisometropia in bilateral implantation can necessitate a longer period of adaptation [55].

Diffractive bifocal MIOLs provide superior near VA, but at the expense of intermediate vision and visual quality. For example, the TECNIS ZMB00 (Johnson & Johnson Vision) yields an uncorrected near visual acuity of 0.10 logMAR in clinical trials. Defocus curves show a bimodal peak, and the lens provides complete spectacle independence in approximately 80% of patients [57, 58]. However, studies have highlighted a reduction in contrast sensitivity loss and the incidence of photic disturbances, which often partially resolve through neuroadaptation [59, 60]. Comparative studies against refractive bifocals indicate that diffractive models offer similar near and distance performance with high overall satisfaction rates of 9/10 [61, 62].

Trifocal diffractive MIOLs address the intermediate vision limitations of bifocals by providing smoother defocus curves from 40 cm to infinity and comparable or higher levels of spectacle independence [63]. For instance, clinical data indicate that the AcrySof IQ PanOptix (Alcon) provides UDVA of 0.01 logMAR, intermediate VA at 60 cm of 0.06 logMAR, and near VA at 40 cm of 0.04 logMAR. Over 90% of patients achieve spectacle independence, and satisfaction scores exceed 90% [64, 65]. Photopic phenomena occur more often with trifocals than with EDOF IOLs but are potentially

milder than in bifocals due to optimized light distribution. Contrast sensitivity usually also dips slightly in mesopic conditions. Similarly, the AT LISA tri 839MP (Carl Zeiss Meditec) shows comparable results with an UNVA of approximately 0.16 logRAD, around 88% spectacle-free rates, and high satisfaction (over 90%). Defocus curves reveal minimal intermediate dips [66, 67]. Head-to-head comparisons with bifocal diffractive lenses confirm trifocals' superiority in intermediate VA and overall visual range, though photopsia rates are similar [57, 63].

Hybrid MIOLs, which integrate refractive and diffractive elements, often yield the highest patient-reported metrics [68, 69]. The TECNIS Synergy (Johnson & Johnson Vision) stands out in this regard, with clinical evaluations demonstrating UDVA, UIVA, and UNVA ranging from 0.00 to 0.03 logMAR. Ninety percent of patients are spectacle-independent, and satisfaction rates exceed 90% [68–70]. Photic phenomena affect less than 5% of patients, which is lower than with pure diffractive designs due to refractive smoothing. The spiral MIOL mentioned in Chapter 5.3 seems to reduce the induction of photopic phenomena even further and does not cause light loss.

4. Extended Depth of Focus (EDOF) IOLs

4.1 Optical principles and design

Extended Depth of Focus (EDOF) IOLs offer a balanced solution that addresses the limitations of both monofocal and multifocal IOL designs [71, 72]. While diffractive MIOLs achieve spectacle independence at multiple distances through discrete focal points, this is often at the expense of reduced contrast sensitivity and increased photic phenomena, such as halos and glare. Clinically, patients realize the light distribution of diffractive MIOLs in different foci, like far (60%), intermediate (30%), and near (10%) and may experience difficulty reading in mesopic conditions. In contrast, EDOF IOLs extend the focal range, enhancing intermediate and sometimes functional near vision without the significant optical compromises of traditional diffractive multifocality.

The basic optical concept behind EDOF IOLs is to adjust the incoming light to create a wider DOF than the single focal plane typical of monofocal IOLs [71]. DOF refers to the range of distances at which an image remains acceptably sharp without accommodation. These IOLs typically extend DOF by 1.5 to 2.5 D without splitting light into multiple discrete foci. This elongation reduces defocus blur and dysphotopsia, which are key challenges in presbyopia correction. EDOF IOLs provide functional vision from distance to intermediate ranges (typically 60–80 cm) and sometimes extend to near tasks (around 40–50 cm), depending on the specific IOL design [73]. EDOF IOLs use various optical strategies to achieve this DOF. They often incorporate negative aspheric surfaces to neutralize corneal SA, which typically ranges from -0.1 to $-0.27\ \mu\text{m}$ [74]. These strategies fall under three categories: refractive, diffractive, and minimally diffractive.

Refractive EDOF IOLs create zonal variations in power and distribute light asymmetrically and progressively across the lens optic [71, 75]. Segmental or progressive zonal optics incorporate low-add segments, typically +1.5 D, which provide intermediate vision while blending seamlessly with the distance zone. This asymmetry extends the focal range by inducing controlled defocus gradients, thereby achieving high light efficiency and reducing pupil dependency [75]. The result is an elongated focus that supports activities such as computer work or driving with minimal energy loss to HOAs.

In contrast, diffractive EDOF designs use subtle microstructural patterns, such as echelettes (low-profile diffractive gratings), to extend focus through controlled light

interference [71, 76]. Unlike traditional diffractive MIOLs, which have pronounced rings that split light and lead to significant energy loss, EDOF designs aim to cause minimal diffraction. This limits light scattering and directs most energy into an elongated primary focus. This “stretched” focal zone, rather than discrete points, improves intermediate vision while reducing unwanted diffraction orders that may cause photopic phenomena. Further improvement can be achieved through aspheric integration, which modulates wavefront curvature.

Damien Gatinel coined the term minimal diffractive IOL designs, which eliminate the need for severe gratings. Instead, they use wavefront shaping or small-aperture optics to extend DOF [77–79]. Wavefront extension uses surface modifications to elongate the focal point with few diffractive elements. This further minimizes dysphotopsia while preserving contrast sensitivity. Small-aperture designs, such as the pinhole principle, use an embedded mask with a small aperture (e.g., 1.36 mm) to block peripheral rays [80]. This enhances the DOF by increasing the f-stop equivalent, similar to camera optics. However, this approach may slightly reduce light transmission and requires careful patient selection to prevent unwanted dimming in low-light conditions. Therefore, minimal diffractive EDOF IOLs are an interesting compromise between refractive and diffractive EDOF IOLs. For this reason, Detlev Breyer no longer uses diffractive EDOF IOLs but prefers refractive, segmental, and minimally diffractive EDOF IOLs.

4.2 Clinical outcomes

EDOF IOLs generally demonstrate superior intermediate VA compared to monofocal designs. Their functional near vision surpasses monofocals, though it falls short to trifocal MIOLs. EDOF IOLs present a reasonable dysphotopsia profile, comparable to monofocals [72, 81, 82]. Overall, EDOF IOLs achieve high patient satisfaction rates and high spectacle independence for intermediate tasks. However, reading glasses are commonly needed for fine near work in these patient populations [83].

On the one hand, refractive EDOF IOLs, such as the Lentis Comfort (Teleon Surgical), which integrates a + 1.5D low-add sector, have shown robust clinical results in multiple studies [84–86]. A prospective multicenter trial involving 120 eyes reported a mean binocular uncorrected intermediate VA (UIVA) of 0.1 logMAR at 70 cm. Distance VA (UDVA) was 0.00 logMAR, and near VA (UNVA) was 0.48 logMAR at 30 cm. These results indicate functional, but not full, spectacle independence for close tasks [84]. Defocus curves revealed a broad plateau from 0.00 to –1.50 D, with a VA of 20/25 or better across this range. Contrast sensitivity remained comparable to that of monofocal IOLs under the photopic conditions [85]. Dysphotopsia rates were low, with only a small percentage of patients experiencing halos and glare as also experienced with monofocal IOL, and no severe symptoms. This contributed to the satisfaction scores above 90%. The LuxSmart IOL (Bausch and Lomb) is a non-diffractive, hydrophobic acrylic EDOF lens that uses Pure Refractive Optics (PRO) technology to provide a continuous range of vision. It emphasizes intermediate distances while maintaining high contrast sensitivity and low dysphotopsia rates. Its aberration-neutral design balances the distance and intermediate VA, and clinical studies have demonstrated its superior uncorrected intermediate VA compared to monofocal lenses and its reduced halos compared to the diffractive MIOLs [87]. When used in mini-monovision (with a target of –0.50 D in the non-dominant eye), near visual acuity extends to 0.12 logMAR at 40 cm [88].

On the other hand, large-scale trials have evaluated diffractive EDOF IOLs, such as the TECNIS Symphony (Johnson & Johnson Vision), a diffractive IOL model. These trials include the Concerto study, which examined 411 eyes. The mean UDVA was –0.02

logMAR, the UIVA was 0.1 logMAR at 70 cm, and the UNVA was 0.16 logMAR at 40 cm [89]. Binocular defocus curves showed a continuous range from 0.00 to -1.50 D with VA of 0.02 logMAR or better. This performance surpassed that of monofocal IOLs in the intermediate vision range [73]. Contrast sensitivity was slightly reduced compared to aspheric monofocal IOLs, and photic phenomena were moderate [90]. A meta-analysis of five studies (466 eyes) confirmed 90% spectacle independence for daily activities and improvements in quality of life (QoL) *via* validated questionnaires like the VF-14 [91]. Another diffractive EDOF with chromatic aberration correction, the AT LARA 829MP (Carl Zeiss Meditec), mirrored these results in a comparative trial of 211 patients, achieving UIVA of 0.07 logMAR and a defocus range of to -1.5 D [92]. However, near VA lagged, necessitating glasses for reading in some patients, though dysphotopsia was low due to smoother echelette transitions.

There is strong evidence from clinical studies supporting minimally diffractive EDOF IOLs, such as the AcrySof IQ Vivity (Alcon), which employs wavefront-shaping technology for wavefront extension. These studies report UDVA of approximately 0.04 logMAR, UIVA of 0.06 logMAR at 66 cm, and UNVA of 0.21 logMAR at 40 cm [93, 94]. Defocus curves exhibited a plateau from 0.00 to -1.5 D, with binocular summation enhancing intermediate performance. Contrast sensitivity levels matched those of monofocal lenses (1.6–1.9 logCS photopically), and dysphotopsia was minimal. These results led to high patient satisfaction and 94% spectacle independence for daily activities. One study compared the Vivity IOL to trifocal MIOs and found equivalent intermediate VA but superior contrast sensitivity and fewer visual disturbances [95]. The IC-8 Aphera (Bausch + Lomb) is a small-aperture, non-diffractive design with a 3.23 mm optic and a 1.36 mm mask. It extends the DOF *via* the pinhole effect and yields UDVA of -0.01 logMAR, UIVA of 0.05 logMAR, and functional near VA of 0.19 logMAR with the bilateral implantation [96].

4.3 EDOF blended vision: The Duesseldorf formula

In 2010, Detlev Breyer published his initial findings on the implantation of this IOL in a blended vision mode, targeting the far dominant eye for distance (emmetropia) and the non-dominant eye for -1.5 D [97]. This approach yielded excellent distance vision, very good intermediate vision, and sufficient near vision for reading print in book and newspapers [83, 98]. He also demonstrated that, after a neuroadaptation period of 1 to 3 months, 3D stereopsis returned. In the following years, he demonstrated that blended vision is an interesting option for patients seeking independence from glasses and wanting to avoid the disadvantages of diffractive MIOs, such as photopic phenomena and reduced contrast sensitivity. Note that the Duesseldorf Formula only works with refractive and minimal diffractive EDOF IOLs, as diffractive EDOF IOLs cause too much photopic phenomena and blurry vision when defocused to -1.5 D [39].

5. Emerging trends and innovations

5.1 Enhanced monofocal IOLs

Enhanced monofocal IOLs represent a hybrid approach that extends the DOF beyond that of traditional monofocal designs while preserving high contrast sensitivity and minimizing dysphotopsia [99, 100]. These lenses provide the modest extension of focus, typically improving intermediate vision at distances of around 66 cm. The

Tecnis Eyhance (Johnson & Johnson Vision), for example, has a higher-order aspheric surface that creates a continuous power progression from the center to the periphery of the optic, shifting the focal point slightly anteriorly and extending the DOF by 0.5–1.0 D compared to standard monofocal IOLs [101, 102]. This enables better uncorrected intermediate VA while maintaining distance VA [103]. The RayOne EMV (Rayner) uses a patented non-diffractive optic with positive SA to extend the DOF by up to 1.5D [104–107]. These IOLs are ideal for individuals who rely on good intermediate vision for activities such as computer work and who are wary of MIOL-related optical side effects [106]. However, the challenges of such optics include limited near distance VA, which often necessitates reading glasses for fine print, as well as variability in outcomes based on individual corneal aberrations. Detlev Breyer uses the Rayner One EMV IOL as an EDOF IOL with the Duesseldorf Formula in a blended vision mode, as the monocular and binocular defocus curves reflect typical EDOF defocus curves.

5.2 Accommodative IOLs

Accommodative IOLs aim to replicate the natural lens' ability to change focus through ciliary muscle contraction to overcome the fixed focal point principle of MIOLs or EDOF IOLs [108, 109]. These designs are usually based on shape-changing optics or anterior-posterior optic shifts. For instance, the FluidVision (Alcon, in development) uses fluid redistribution within the IOL haptics to alter the optic curvature. The Juvene (LensGen) uses a modular, fluid-filled system that can theoretically provide functional accommodation [110, 111]. However, the long-term efficacy of these IOL designs is limited and many may only provide pseudoaccommodation (e.g., *via* miosis or residual astigmatism), rather than true dynamic focus [108]. Additionally, accommodation amplitudes typically decrease over time due to capsular fibrosis or haptic fatigue.

The AkkoLens Lumina is one of the most promising accommodating IOLs, which is a sulcus-based accommodative IOL and uses the Alvarez principle and two optical elements that shift laterally during ciliary muscle contraction [112–114]. This shift alters the IOL's refractive power dynamically, providing true accommodation. Unlike capsular bag-dependent IOLs, its sulcus placement minimizes fibrosis-related complications and enhances long-term stability. A one-year, multicenter, phase III clinical trial demonstrated stable visual outcomes, including a mean uncorrected distance visual acuity (VA) of -0.01 logMAR, preserved contrast sensitivity, and an accommodative performance of -0.65 D.

5.3 Spiral IOLs

The spiral Galaxy MIOL by Rayner is an innovative presbyopia-correcting IOL that uses unconventional optic geometries to achieve DOF while minimizing common drawbacks like dysphotopsia [115]. These IOLs create progressive focus elongation through a helical refractive profile, providing smoother visual transitions across distances [116]. The RayOne Galaxy IOL (Rayner), which uses proprietary AI algorithms trained on extensive patient outcome data, was launched in Europe in 2024. It is a non-diffractive IOL with a patented spiral optic that provides a full, continuous range of vision, without the light energy loss typical of diffractive trifocal IOLs. Initial patient satisfaction metrics suggest the high levels of spectacle independence for daily activities [117].

From October 2024 to August 2025, Detlev Breyer implanted over 200 IOLs of this type. His first clinical results showed binocular defocus curves that closely resembled the Duesseldorf Formula blended vision EDOF IOL concept, offering excellent far and intermediate vision, as well as the ability to easily read book and newspaper

print. Both approaches demonstrate significantly reduced photopic phenomena compared to diffractive MIOs, with less light loss and better contrast sensitivity. The Duesseldorf Formula concept seems to be slightly more advantageous for patients who rely on excellent distance vision, such as hunters and snipers.

5.4 Further IOL innovations

Light-adjustable IOLs, such as the RxSight LAL, allow for postoperative UV light adjustments of up to $\pm 2.0\text{D}$ of sphere and up to -2.0D of cylinder in multiple sessions [118]. These adjustments achieve a residual refractive error $\pm 1.00\text{ D}$ in 100% of eyes in a retrospective case series. However, they require patient compliance with light exposure restrictions [119, 120]. Modular IOL systems, like the Harmoni (ClarVista), enable optic exchange without the need for full IOL removal [121]. This could be promising for younger patients or those at risk of future retinal issues. New hydrogel materials and drug-eluting coatings could reduce posterior capsule opacification (PCO) rates and aim to extend IOL longevity [122, 123].

6. Laser surgery, refractive enhancements, and neuroadaptation

6.1 Femtosecond laser-assisted cataract surgery (FLACS)

In modern cataract extraction, femtosecond laser-assisted cataract surgery (FLACS) has emerged as a transformative advancement [10]. First introduced clinically in 2009 with the LenSx platform (Alcon Laboratories), FLACS uses femtosecond lasers that deliver pulses in the range of 10^{-15} sec, to create tissue photodisruption with minimal collateral thermal damage, achieving submicron accuracy [124]. In 2009, Detlev Breyer began using the same system but switched to the LENSAR FLACS system 1 year later because the Scheimpflug technology in the LENSAR system created free-floating buttons in a more reliable manner.

This technology is nowadays available on platforms such as the Catalys (Johnson & Johnson Vision), the Victus (Bausch + Lomb), and the Femto LDV Z8 (Ziemer Ophthalmic Systems), and it allows for optimal IOL positioning and astigmatic control [125]. The automated steps include corneal incisions, capsulotomy, and lens fragmentation. These systems improve reproducibility by reducing surgeon variability. However, its adoption remains selective due to cost issues.

In 2024, Detlev Breyer began using the newest LENSAR ALLY FLACS system, which uses innovative computer systems and multiple Scheimpflug cameras to significantly improve precision, individual settings, and speed. With this laser system, creation of the clear corneal incision (CCI) takes only 1 second, and the overall laser time can be reduced to less than 1 minute, further improving the safety and patient comfort of FLACS.

FLACS uses real-time imaging *via* integrated OCT or Scheimpflug systems to customize procedure planning based on lens density and corneal thickness [126, 127]. The primary steps include creating CCIs, performing an anterior capsulotomy, and fragmenting the lens. CCIs can be tailored in length, width, and architecture (e.g., triplanar or biplanar) and positioned limbus-parallel or temporally to induce minimal SIA [128, 129]. Next is capsulotomy, which produces a perfectly circular, centered opening with 360-degree overlap to ensure IOL stability and reduce the risk of future

tilt and decentration [130, 131]. Next, lens fragmentation involves customizable patterns that pre-soften the nucleus, decrease cumulative dissipated energy, and preserve the corneal endothelium [132].

Clinical evidence underscores the advantages of FLACS in terms of precision and safety, especially in challenging cases [133]. A meta-analysis of over 14,000 cases reports superior capsulotomy circularity and reduced phacoemulsification time, which correlates with better preservation of the corneal endothelium. For toric IOLs, FLACS-integrated digital marking may reduce misalignment, though it is not significantly better than standard phacoemulsification [134]. Limitations of FLACS include the equivocal long-term visual outcomes compared to manual techniques in uncomplicated cases, as well as anterior chamber gas bubbles that impede subsequent phacoemulsification [135].

6.2 Postoperative touch-up procedures

Despite advanced preoperative diagnostics and the integration of sophisticated IOL power calculation formulas, residual refractive errors persist in approximately 6–20% of cataract surgery cases, depending on the threshold error [1]. These discrepancies often stem from unpredictable factors, including SIA or deviations in effective lens position (ELP) due to postoperative capsular bag contraction [1, 136]. Such errors typically manifest as residual spherical or astigmatic ametropia or HOAs, which can compromise patient satisfaction. These “errors” are particularly pronounced in RCS patients, who usually have very high demands and expectations.

Touch-up procedures are generally postponed for at least 3 to 6 months after initial cataract surgery to allow for refractive stability and sufficient neuroadaptation [137]. During this time, conservative management should be prioritized to address reversible causes of dissatisfaction. This includes spectacle correction for ametropia and optimization of ocular surface disease with lubricants and anti-inflammatory agents. After careful consideration, posterior capsule opacification treatment with Nd:YAG laser can be an effective option in some cases.

Femtosecond (FS)-LASIK is the preferred touch-up method in most cases because of its rapid visual recovery, high predictability, and safety profile [138, 139]. This procedure involves creating a corneal flap with a femtosecond laser, followed by excimer laser ablation to reshape the corneal stroma bed. Wavefront-guided or topography-guided ablation profiles can further mitigate HOAs, enhancing outcomes, especially in eyes with irregular astigmatism. Studies on post-cataract LASIK demonstrate its efficacy. Uncorrected distance visual acuity (UDVA) of 20/40 or better is achieved in over 90% of patients, and refractive predictability is within ± 0.50 D in over 80% [139, 140]. Detlev Breyer completely abandoned microkeratome LASIK due to its higher inherent risk of complications.

In contrast, PRK is a viable alternative for patients who are not suitable candidates for LASIK, including those with thin corneas (central thickness less than 500 μm) [141]. In PRK, the corneal epithelium is removed mechanically, with alcohol, or the excimer laser itself (transepithelially). This is followed by stromal ablation. In many cases, outcomes may be similar to LASIK for low-to-moderate corrections, although studies on post-cataract enhancement show better predictability with LASIK [142]. To counteract the subepithelial haze, mitomycin C (0.02%) is routinely applied intraoperatively [143]. However, PRK may demonstrate superiority to LASIK in cases of high myopia or irregular astigmatism. It is worth noting that PRK recovery is prolonged, involving 3 to 7 days of sometimes severe discomfort and pain, necessitating careful

patient education and selection. Visual recovery may last up to 6 weeks, and corneal scarring occurs more frequently than with FS-LASIK. Therefore, FS-LASIK should be preferred in all cases, even in cases involving thin corneas or medical conditions such as Map-Dot-Fingerprint (MDF) Dystrophy.

SMILE Pro is an advanced lenticule extraction procedure based on the FS-laser technology using the VISUMAX 800 (Zeiss) [144]. It is a flapless alternative for correcting residual refractive errors in patients who have undergone cataract surgery. The procedure involves using a femtosecond laser to create an intrastromal lenticule that is then manually extracted through a small incision [145]. Although clinical evidence has proven the procedure to be an effective treatment for residual refractive errors after cataract surgery, it is limited to cases of moderate errors (-1.5 to $+3.0$ D) [146].

Add-on IOLs provide a reversible approach to correct residual spherical errors, because they are implanted in the ciliary sulcus, anterior to the primary IOL. Lenses such as the Sulcoflex (Rayner) and the Add-On (HumanOptics) are ideal for spherical corrections due to their simplicity and minimal invasiveness, which avoids corneal alterations [147–149]. However, toric add-on IOLs are not commonly used for astigmatism correction due to a higher risk of rotation. This risk is attributed to sulcus placement and ciliary muscle dynamics, so these lenses should be reserved for exceptional cases (off-label use).

6.3 Neuroadaptation

Neuroadaptation, the brain's capacity to reorganize visual processing pathways in response to the novel optical environment created by the implanted IOLs, is a critical and important postoperative process in RCS [53, 150]. Unlike monofocal IOLs, which provide a single clear focal point and require minimal neural adaptation, AT-IOLs distribute incoming light across multiple focal zones and often cause in initial optical artifacts, such as blurriness, halos, glare, and diminished contrast sensitivity. This process requires significant neural plasticity, whereby the visual cortex learns to prioritize relevant images while suppressing extraneous ones. This is similar to the interocular blur suppression observed in monovision corrections [151].

The timeline for neuroadaptation varies from person to person, but it generally unfolds over 3 to 6 months. Complete stabilization is possible within 12 months in some cases [150, 152]. One study examined the correlation between Mini-Mental State Examination (MMSE) completion times and adaptation speed, revealing that patients with strong baseline cognitive abilities tend to adapt more quickly following MIOL implantation [153]. Similarly, another study demonstrated that structured neuroadaptation training reduced adaptation time in MIOL recipients, highlighting the potential for targeted interventions to improve the outcomes in certain cases [154].

Despite its effectiveness for most patients, neuroadaptation sometimes fails, resulting in persistent dissatisfaction that impairs daily activities [155, 156]. The failure rate is higher with MIOLs than with EDOF IOLs because the former have a greater propensity for photopic phenomena. Important risk factors include having unrealistically high preoperative expectations and having personality traits such as perfectionism. Effective management begins clinically with thorough preoperative counseling to set realistic expectations about the adaptation period. This is the most effective strategy to mitigate these challenges. Neuroadaptation also plays a key role in stereopsis in the Duesseldorf Formula. A preoperative assessment of orthoptic status

is also essential because it influences neuroadaptation and a preoperative contact lens trial may be recommended on an individual basis.

7. Conclusion

Advancements in IOL technology, preoperative diagnostics, laser-assisted surgery, personalized strategies, and touch-up procedures have transformed cataract extraction into refractive cataract surgery (RCS), which aims to correct vision and achieve spectacle independence after IOL surgery. Ophthalmologists can achieve optimal individualized outcomes by adhering to core principles, leveraging evidence-based techniques, and embracing innovations. Touch-up procedures play an essential role in RCS, as 5–20% of cases rely on them to achieve the highest degree of spectacle independence. The only disadvantage is the high cost of high-end diagnostics, continuous employee education, surgical devices, and surgeon skills. Not to mention the costs of premium ambiance and customer relations management for demanding patients.

Financial disclosure

The authors have no conflicts of interest to declare that are relevant to the content of this chapter.

A. Appendix

(See **Figures A1–A3**, Video 1, https://drive.google.com/file/d/1uDDFBeHD4mwSl4RZ9VgoCv2jxxFY6q0Z/view?usp=drive_link).



Figure A1.
Visual chart showing four different intensity levels of photopic phenomena (halos and glare) for patient counseling.

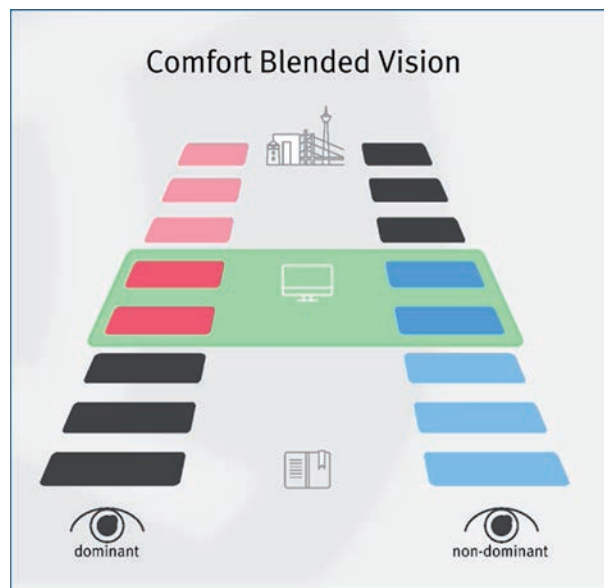


Figure A2.
Graphic illustration of “The Duesseldorf Formula”, a blended vision approach.

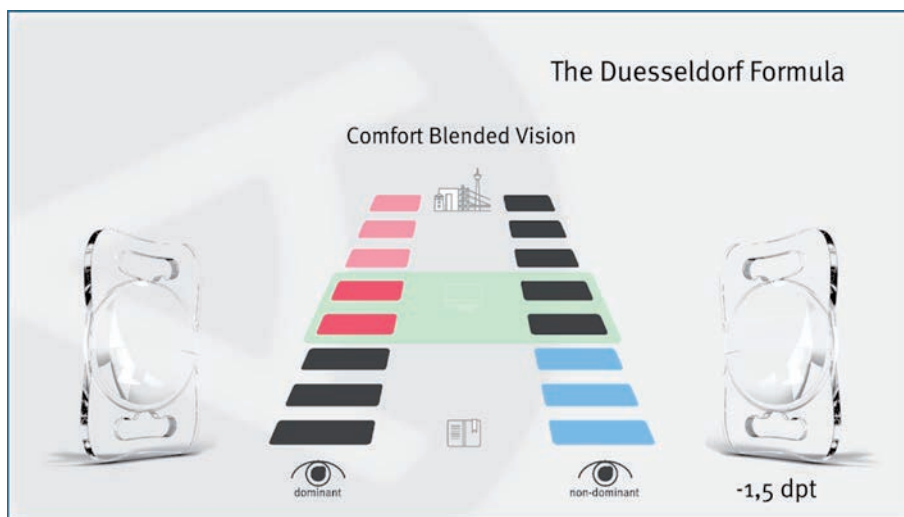


Figure A3.
Düsseldorf Formula explanation video (screenshot).

(See **Figure A4**, Video 2, https://drive.google.com/file/d/1fH0EsJpwzlj90hB1F7gta5lw7FGOAcEf/view?usp=drive_link).



Figure A4.
LensAR femtosecond laser system.

(See **Figures A5–A13**, Video 3, https://drive.google.com/file/d/1Xf3hx5MlgsOlj3bnNEhkZhX6plDsQpWo/view?usp=drive_link).

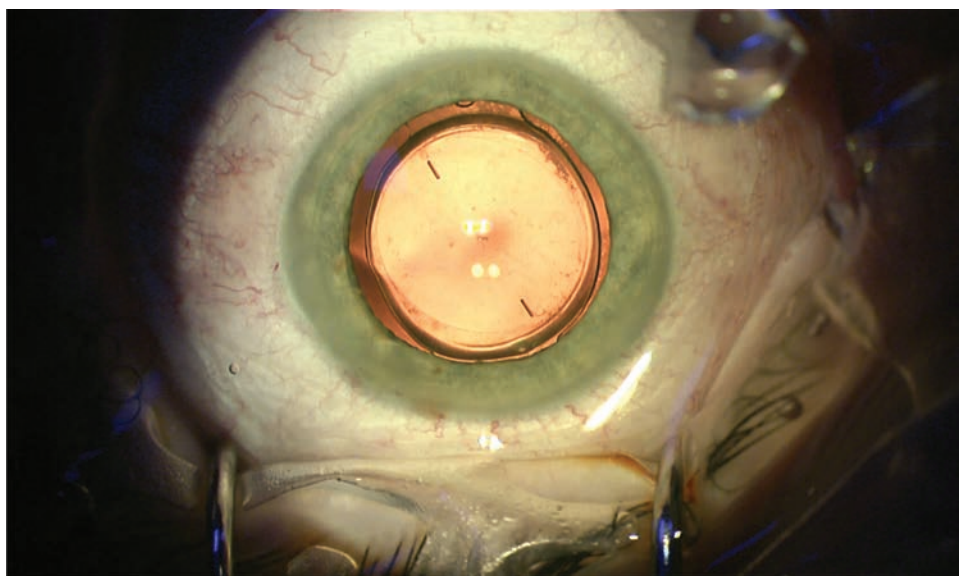


Figure A5.
Alignment of toric IOL using capsular markings in FLACS.

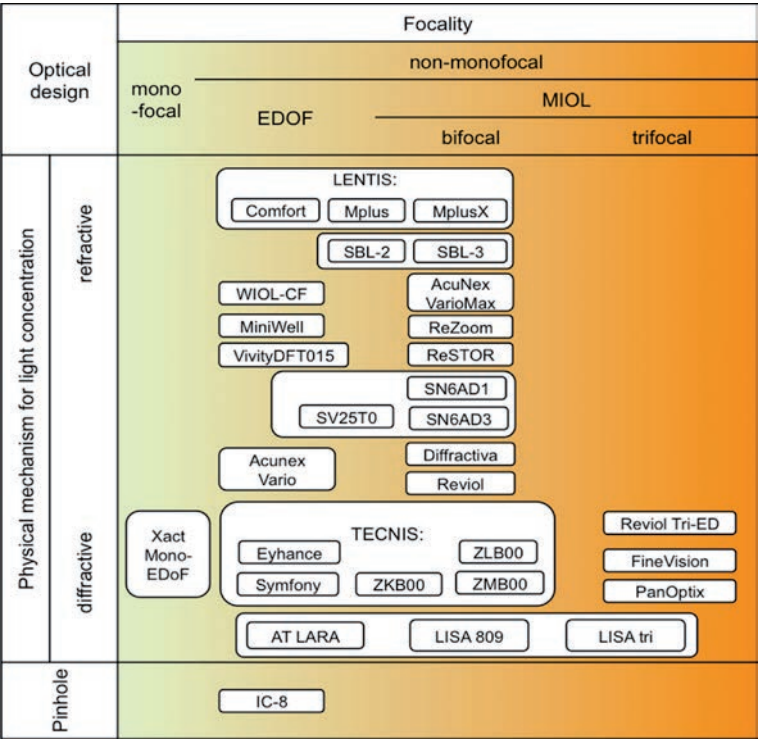


Figure A6.
A comprehensive diagram showing most of the AT-IOL currently available, categorized by focality and mechanism for light concentration.

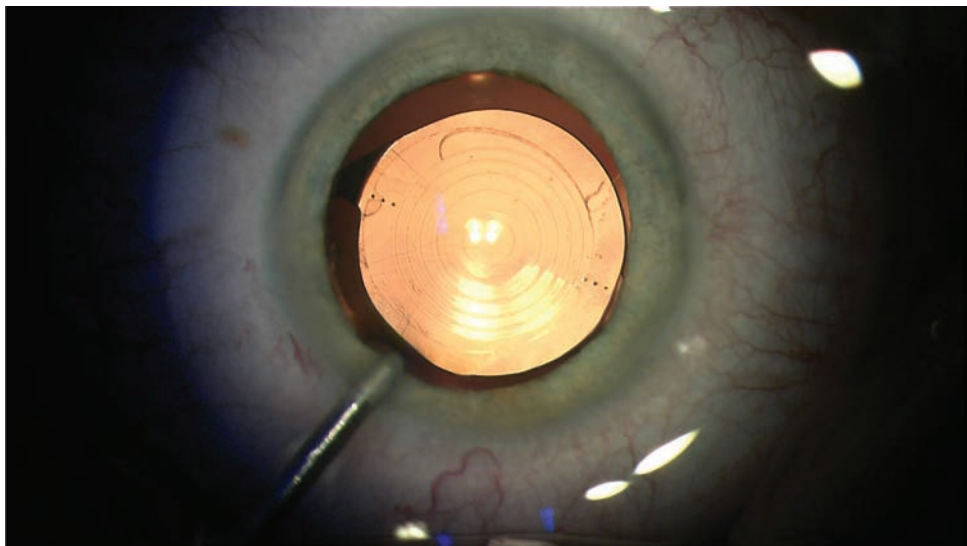


Figure A7.
Intraoperative image after PanOptix toric IOL implantation. The alignment of the IOL and FLACS markings is clearly visible.

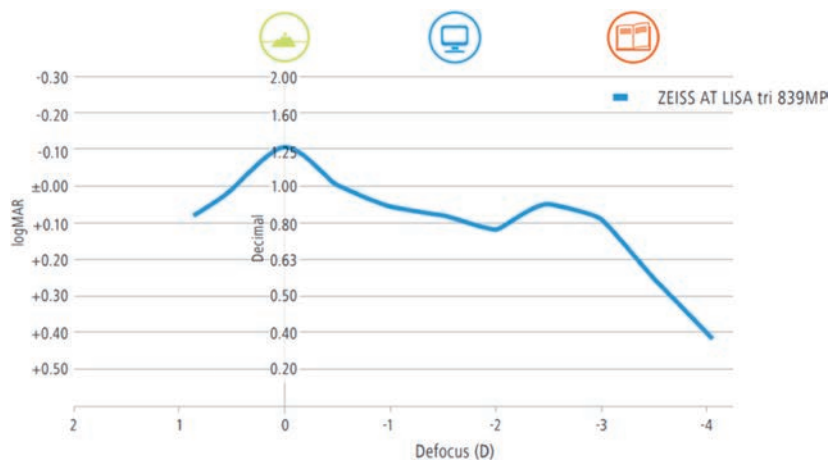


Figure A8.
Defocus curve of the LISA trifocal 839 MP [65].

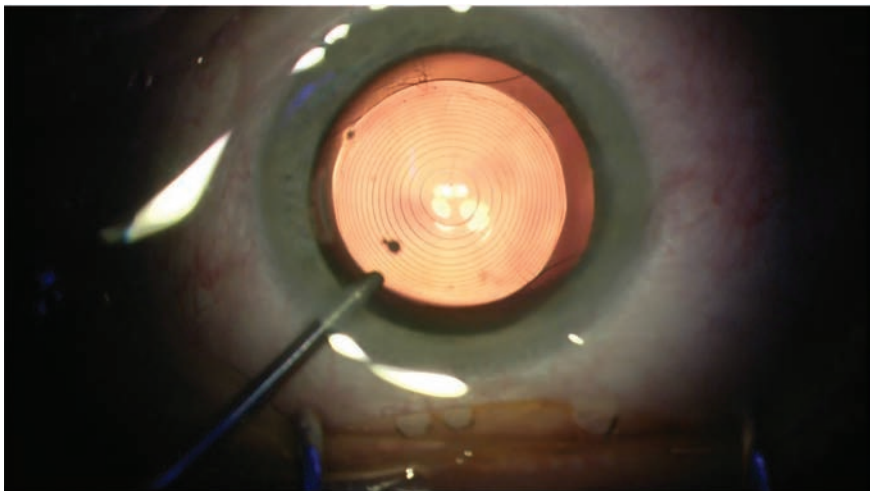


Figure A9.
Intraoperative image after LISA trifocal IOL implantation.

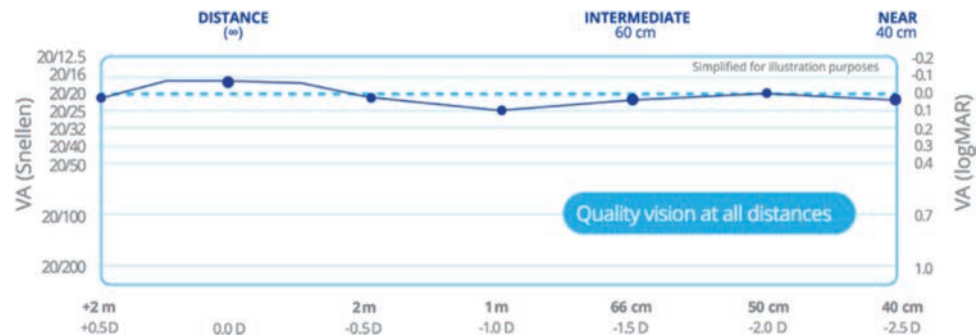


Figure A10.
Defocus curve of the PanOptix MIOL [65].

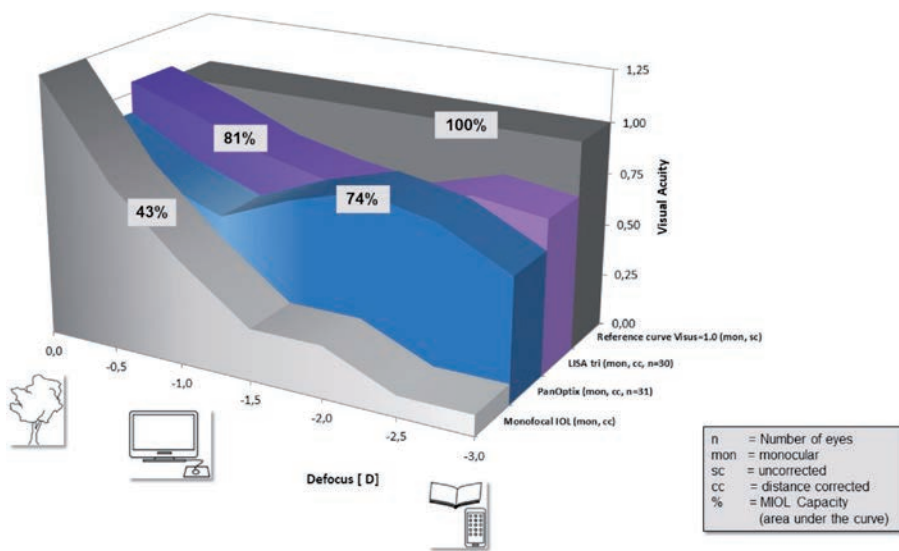


Figure A11.

Following defocus curves are presented: Reference curve (dark gray), LISA trifocal MIOL (purple), PanOptix MIOL (blue), monofocal IOL (light gray).

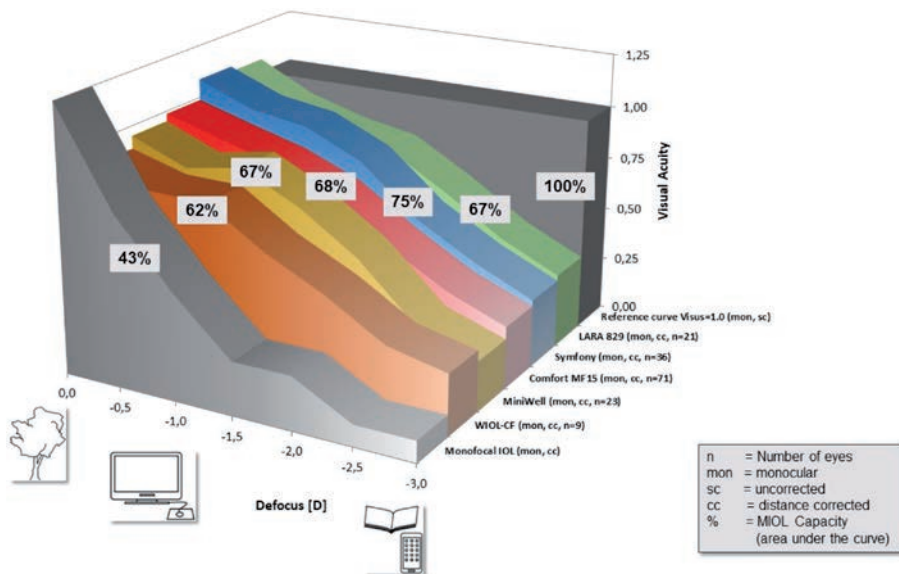


Figure A12.

Following defocus curves are presented: Reference curve (dark gray), LARA 829MP EDOF IOL (green), Tecnis Symphony EDOF IOL (blue), Lentis Comfort MF15 IOL (red), MiniWell (yellow), WIOL-CF (orange), and monofocal IOL (light grey).

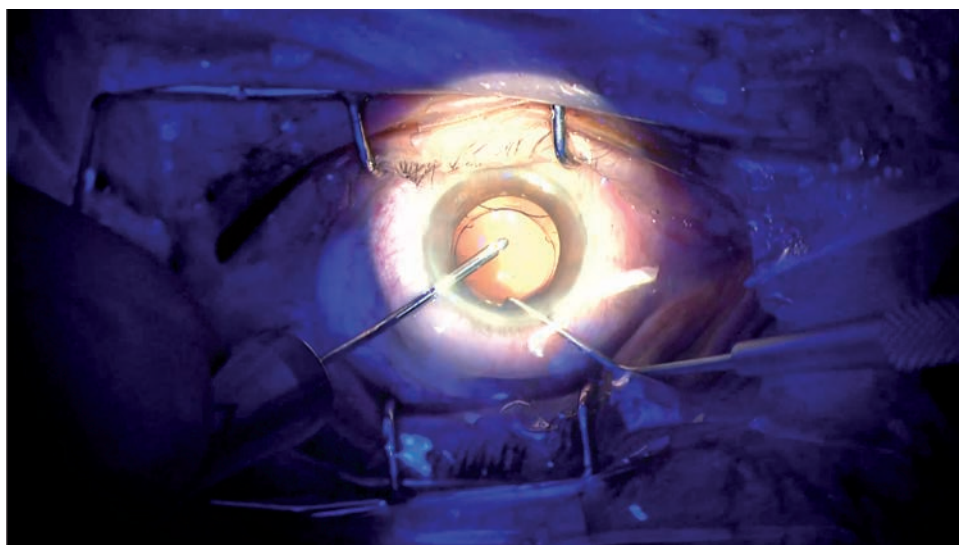


Figure A13.
 Implantation of Lentis Comfort MF15 IOL.

(See **Figures A14–A22**).

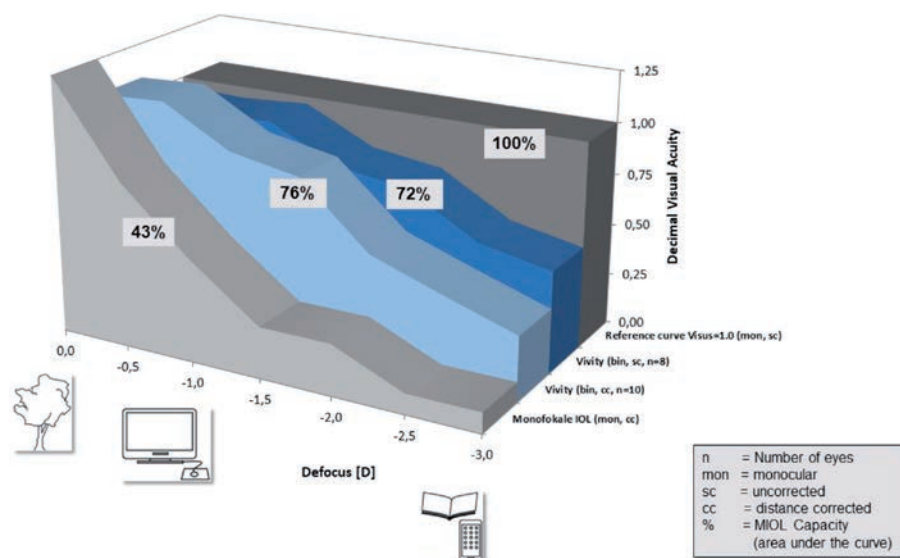


Figure A14.
 Following defocus curves are presented: Reference curve (dark gray), uncorrected AcrySof IQ Vivity EDOF IOL (dark blue), corrected AcrySof IQ Vivity EDOF IOL (light blue), monofocal IOL (light gray).

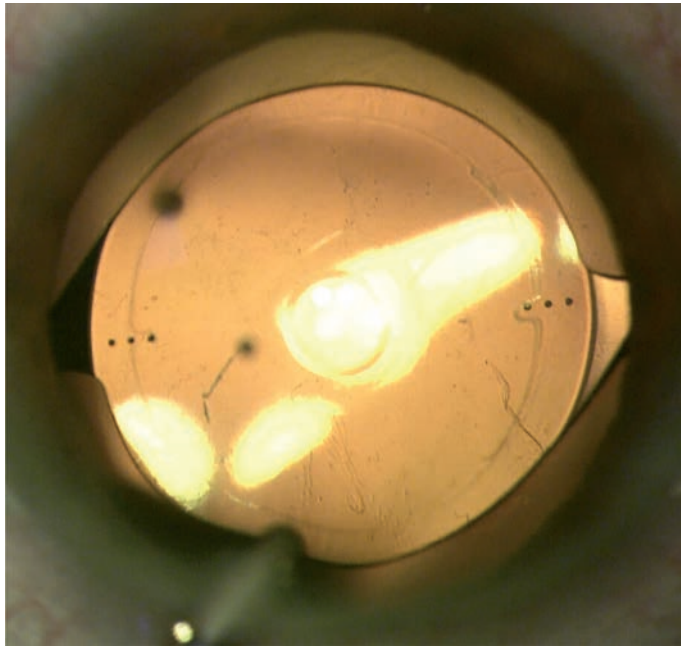


Figure A15.
Intraoperative image after Vivity EDOF toric IOL implantation. The alignment of the IOL and FLACS markings is clearly visible.

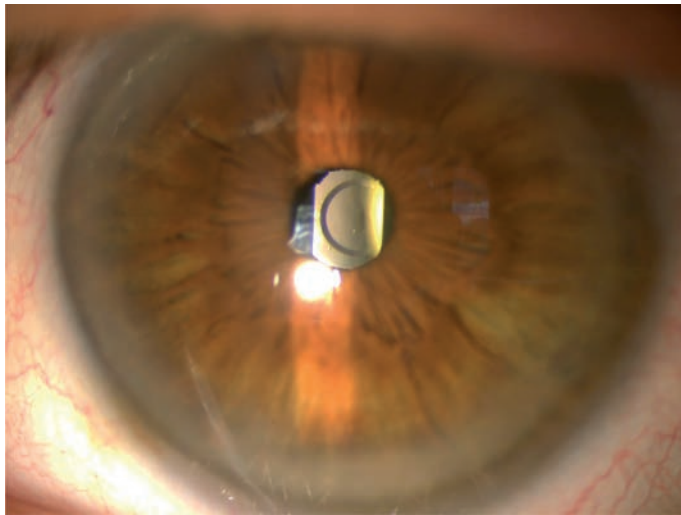


Figure A16.
Slit lamp image after Vivity EDOF toric IOL implantation.

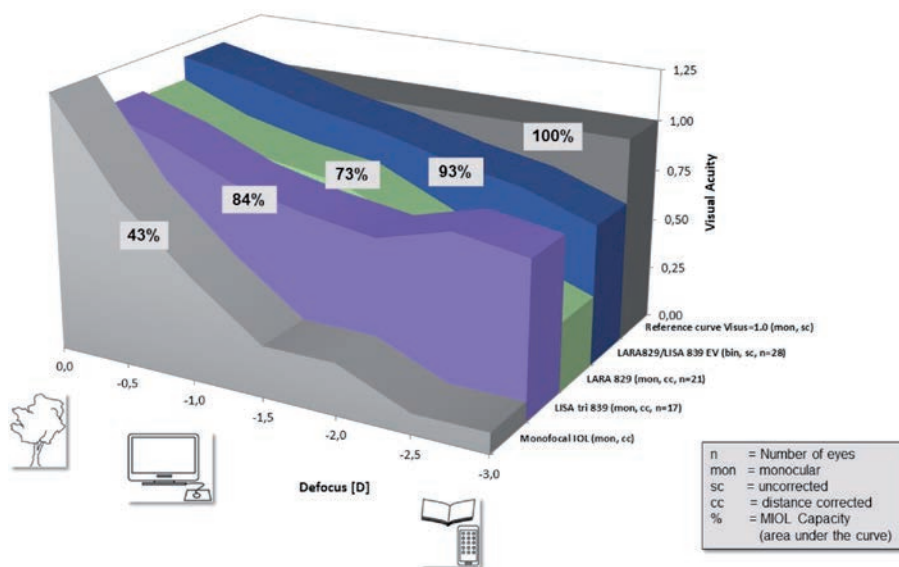


Figure A17.

Following defocus curves are presented: Reference curve (dark gray), combined LARA 829 and LISA 839 IOL (blue), LARA EDOF IOL (green), LISA trifocal MIOL (purple), monofocal IOL (light gray).



Figure A18.

The Small-Aperture IC-8 IOL [93, 94].

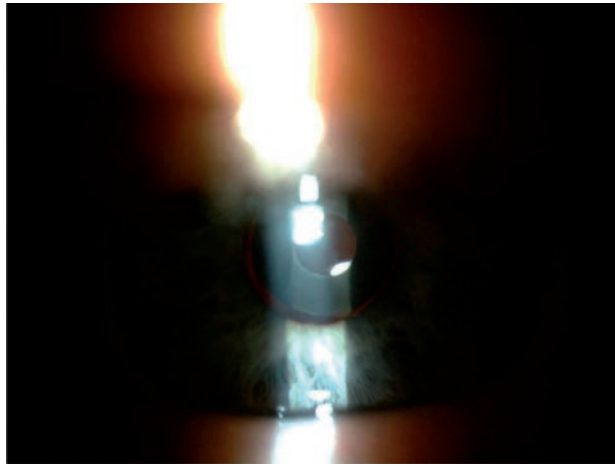


Figure A19.
Slit lamp image of the implanted IC-8 in an eye with corneal degeneration (1/2).

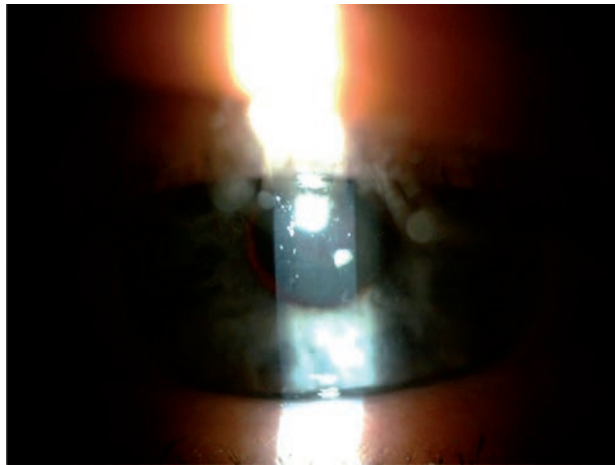


Figure A20.
Slit lamp image of the implanted IC-8 in an eye with corneal degeneration (2/2).



Figure A21.
The Rayner supplementary Sulcoflex aspheric IOL.



Figure A22.
A QR code providing access to lectures and in-depth resources on advanced refractive cataract surgery techniques.

Author details

Amr Saad^{1,2,3,4*} and Detlev R.H. Breyer^{1,2}

1 Breyer, Kaymak, Klabe Eye Surgery and Premium Eyes Düsseldorf, Germany

2 Institution for International Innovative Ophthalmic Surgery, Düsseldorf, Germany

3 Department of Ophthalmology, Stadtsptal Zürich, Zurich, Switzerland

4 Spross Research Institute, Stadtsptal Zürich, Zurich, Switzerland

*Address all correspondence to: a.saad@augenchirurgie.clinic

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Optical Coherence Tomography in Cataract Surgery

Adel Ebraheem

Abstract

Utilizing optical coherence tomography (OCT) before and after cataract surgery is critical for optimal outcomes. Complications following cataract surgery are frequently observed, including conditions such as Irvine Gass syndrome, uveitis, elevated intraocular pressure and several others. Additionally, ophthalmologists may carry out cataract surgery on patients who have other eye conditions, including wet age-related macular degeneration, macular holes, epiretinal membrane, glaucoma and several other ocular diseases. Utilizing anterior and posterior segment OCT enables the surgeon to manage complications efficiently and provide the patient with an accurate prognosis and follow up management plan. Additionally, intraoperative OCT can be employed during cataract surgery to address specific situations, including those arising from ocular trauma complicated by intraocular foreign bodies and membrane peeling.

Keywords: ocular coherence tomography, cataract, anterior segment, intraocular lens, intraocular lens power formulas

1. Introduction

Optical Coherence Tomography (OCT) is a non-invasive diagnostic technique that produces cross-sectional images of the retina. It uses the principle of interferometry to create detailed images of the retinal structure, achieving a precision of at least 10–15 microns.

In the early stages, OCT image acquisition was performed using a time-domain technology achieving a speed of approximately 400 A-scans per second, distributed across six radial slices, each separated by 30 degrees. Spectral-domain technology, in contrast, performs scans at a rate of approximately 20,000–40,000 A-scans per second.

A higher frequency and greater volume of scans reduce the likelihood of motion artifacts, enhance image resolution, and increase the probability of identifying lesions. The application of spectral domain technology, through enhanced depth imaging (EDI), enables a more detailed visualization of the choroid and the underlying layers.

The implementation of swept-source technology has primarily driven the latest developments in optical coherence tomography. This technology utilizes a wavelength-sweeping laser, along with a dual-balanced photodetector. This technology

results in a remarkable enhancement in acquisition speeds, allowing for the collection of 100,000–400,000 A-scans per second. The improved axial resolution and accelerated scanning rates contribute to superior image averaging, thus enhancing image quality and enabling a more thorough investigation of deeper structures.

Swept-source optical coherence tomography (SS-OCT) has been employed to produce non-invasive, dye-free OCT angiography. In conclusion, OCT angiography leverages motion contrast by assessing the decorrelation signal between several B-scans obtained at each retinal cross-section to identify blood flow.

To ensure a successful cataract surgery outcome, the OCT is currently used in pre-operative assessment, intraoperative guidance, and postoperative follow-up to detect any potential complications. The OCT allows detailed visualization of the anterior chamber structure and retinal layers.

The objective of contemporary cataract surgery includes the correction of refractive errors and the optimization of optical quality by decreasing high-order aberrations. Recently, a proposal has been made to tailor the design of intraocular lenses to the unique anatomical parameters of each patient [1]. Yet, the accuracy of intraocular lens (IOL) power selection is limited by the precision of pre-operative ocular biometry and the approximations that are applied in the IOL calculation formulas [2].

In general, theoretical calculations for IOL power, including the SRK-T method, adopt a thin lens framework and apply different approximations for the cornea and lens, usually within the paraxial domain.

To utilize these formulas, it is essential to have preoperative data related to axial length and corneal power, along with an estimation of the postoperative anterior chamber depth (ACD), commonly referred to as Estimated Lens Position (ELP).

The precise ray tracing method can be utilized, which requires positional and geometrical data related to the cornea and crystalline lens [3].

Higher-order aberrations in pseudophakic eyes can be predicted using individualized computer simulations that factor in the position of intraocular pressure (IOP), corneal topography, and the depth of the anterior chamber [4].

Furthermore, acquiring three-dimensional data on the crystalline lens and the anatomy of the anterior chamber is crucial for improving the accuracy of the estimated postoperative effective lens position. Currently, there is no device available that offers an exhaustive and complete optical analysis of the anterior segment, which is imperative for the effective planning of cataract surgery.

Spectral OCT equips surgeons with unparalleled lateral and axial resolution three-dimensional imaging of the anterior segment. This advanced technology enhances precision and confidence in surgical procedures, ultimately fostering better patient outcomes.

2. Corneal architecture and pathology

The curvature of the cornea contributes to about 72 percent of the total eye power. A significant limitation of using keratometry in the evaluation of cataract surgery is that it fails to offer enough data on corneal topography outside the central 3 mm. Computerized videokeratography is the most reliable device that provides standardized corneal topography results [5].

A review of over 260,000 eyes found that fewer than 1% of cataract surgeons achieved an accuracy of ± 0.50 D at or above 92%. Moreover, most surgeons had an

accuracy level around 78% [6]. It is indisputable that disorders of the cornea and diseases impacting the ocular surface considerably influence visual acuity results.

The likelihood of corneal healing complications and decompensation after cataract surgery increases when corneal thickness is above 640 microns and in the presence of corneal dystrophy.

Izatt et al. first described anterior segment optical coherence tomography (ASOCT) imaging in 1994, utilizing the same wavelength of light as that used in retinal OCT, which is 830 nm [7]. This wavelength does not provide an optimal visualization of the anterior chamber angle because of its restricted penetration through the scleral tissue. Subsequently, a longer wavelength of 1310 nm presents improved penetration and the ability for real-time imaging at a rate of 8 frames per second [8].

The most superficial, thin, hyperreflective layer identified by AS-OCT is the tear film. A number of researchers utilized AS-OCT to examine the corneal endothelium and tear film in patients diagnosed with systemic lupus erythematosus; their findings indicated that these patients exhibited a reduced tear meniscus and a decrease in central corneal thickness. Moreover, the scientist discovered that patients with systemic lupus had a decreased tear meniscus thickness even without exhibiting dry eye clinical features [9].

With AS-OCT, practitioners can accurately map clear and opacified corneas, facilitating the precise delineation of the various corneal layers. A variety of corneal disorders, such as infectious, inflammatory, or ectatic conditions, can be evaluated with greater precision through the use of AS-OCT. The measurement tool aids in the assessment of the advancement or resolution of subepithelial infiltrates, corneal scars, or edema (**Figure 1**) [10].

Pachymetry, corneal topography, and Scheimpflug imaging are employed in the diagnosis of ectatic conditions. The advent of AS-OCT allows specialists to observe and monitor the distinct characteristics of keratoconus across the different layers of the cornea. Recent research has underscored the pivotal role of Bowman's membrane and epithelial thickness maps at the apex of the cone in effectively differentiating non-diseased eyes from those affected by manifest, subclinical, and forme fruste keratoconus.

The cataract surgeon should create a clear cornea incision (CCI) architecture to ensure successful phacoemulsification. The ophthalmologist strives to prevent various complications, such as wound leakage and Descemet's membrane detachment, resulting from misconstruction of CCIs. The AS-OCT can be used for further evaluation of CCI parameters such as incision angle, location, and length, along with associated factors, including posterior wound gap and wound retraction during the initial postoperative period [11].



Figure 1.
Anterior segment ocular coherence tomography shows corneal scar.

Several research surgeons found that AS-OCT revealed various types of Descemet's membrane detachment, including planar and nonplanar, as well as local and extensive [12].

The literature features anecdotal reports on the use of OCT-assisted Descemetopexy during surgery for non-resolving Descemet's membrane detachments [12]. Furthermore, this device is beneficial for selecting the right treatment options and for evaluating treatment outcomes when corneal edema is identified. The OCT serves to guide cataract surgeons in choosing the right instruments for corneal incisions and the relevant surgical techniques, especially when they should endeavor to avoid making corneal incisions in vascularized regions, if possible. The cataract surgeon is required to document the placement of radial or astigmatic incisions, as well as any evident issues with the healing process [13].

The ray tracing equation utilizes a specific technique, like the Oslen formula, which follows the path of refracted light from the surfaces of the cornea and lens. By implementing this approach, one can account for high-order aberrations to achieve enhanced accuracy [14].

The AS-OCT is used in evaluating the anatomical stability of the implanted keratoprosthesis, as it visualizes the interface between the cornea and the anterior keratoprosthesis [15].

3. Anterior angle, crystalline lens, and its anterior capsule and zonules

Through the evaluation of AS-OCT images, the scleral spur is recognized as an inwardly directed projection of the sclera at the point where the inner curvature of the sclera intersects with the curvature of the cornea. The apposition of the iris to the inner corneo-scleral wall is utilized as a qualitative means for detecting angle closure; however, it is imperative to note that the level of apposition can vary and does not directly correlate with angle closure as defined by gonioscopy [16].

The AS-OCT software built in is capable of quantitatively assessing the anterior chamber angle, which requires identification of the scleral spur. A variety of quantitative assessment metrics are available for the anterior angle

1. Angle opening distance (in mm): Defined as the perpendicular distance between a point that is 500 μm (AOD 500) or 750 μm (AOD 750) anterior to the scleral spur and the iris on the opposite side.
2. Angle recess area (in mm^2): The triangular section (ARA 500 or 750) enclosed by the AOD 500 or 750, the front surface of the iris, and the inner corneo-scleral wall
3. The area of the trabecular space (measured in mm^2) is defined as the trapezoidal area (TISA 500 or 750) enclosed by the AOD 500 or 750, the anterior surface of the iris, the inner wall of the corneoscleral region, and the perpendicular distance from the scleral spur to the opposing iris (**Figure 2**)

Due to corneal abnormalities or a lack of cooperation from the patient, ASOCT serves as a substitute of gonioscopy in clinical glaucoma practice. OCT's non-contact nature enhances patient comfort while providing accurate assessments of the angle. The OCT offers better visualization of the anterior angle than gonioscopy, especially in low illumination due to physiological mydriasis. The Ultrasound microscopy

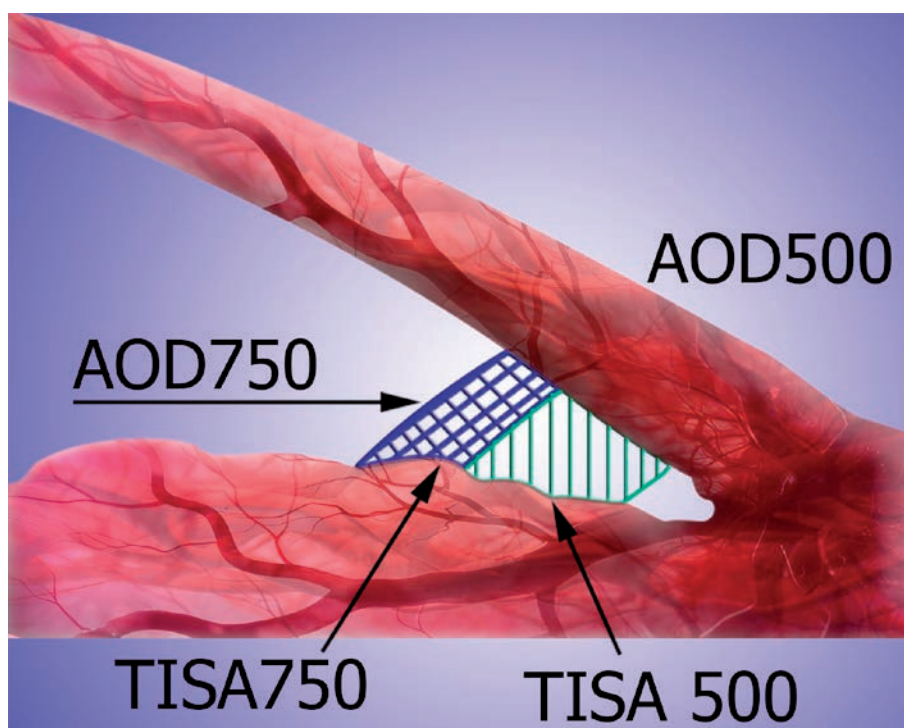


Figure 2.
 Anterior chamber angle anatomical landmarks and measurement of AOD, and TISA in an optical coherence tomography line scan image.

is superior to AS_OCT in the diagnosis of conditions such as iridociliary lesion or plateau iris that are associated with angle closure.

Primary angle closure suspect (PACS) is characterized by a narrow angle that is at risk of angle closure. Trabecular obstruction as a result of angle closure is the hallmark of primary angle closure (PAC). If optic neuropathy is the result of PAC, the condition is called primary angle closure glaucoma (PACG). The majority of ophthalmologists choose phacoemulsification and IOL implantation as the primary intervention for PACG.

Cataract surgeons recommend using capsular rings or scleral-fixed IOL in case of lens zonule instability or weakness, which are often associated with primary angle closure [17].

The preliminary signs of lens subluxation due to partial zonular dehiscence include iridodonesis, phacodonesis, the visibility of the lens equator, and an asymmetric ACD. It is challenging to determine zonular instability through slit-lamp, gonioscopy, or ocular B-mode ultrasound in the case of PAC, as malposition of the crystalline lens is not always apparent in eyes with shallow ACD.

The AS-OCT showed the ability to identify zonular instability post-acute angle closure attack. The eyes with zonular instability are characterized by diminished hyperopic spherical equivalent, longer axial length, shallower anterior chamber depth, and increased lens vault [18].

Pei and others observed that the crystalline lens is characterized by steeper anterior curvature, increased thickness in the anterior portion, and elevated ratio of anterior-to-posterior portion thickness in patient with PAC diseases [19].

Sometimes the AS-OCT is used intraoperatively during cataract surgery accompanied by glaucoma surgery [20].

There are presently three microscope-integrated commercial intraoperative OCT (iOCT) platforms that have been approved by the US Food and Drug Administration (FDA)—these include the Haag-Streit iOCT system, the Zeiss Rescan 700, and the Leica EnFocus system [21].

In patients with pseudoexfoliation, the high-resolution OCT enables the identification of increased thickness of the anterior capsule compared to normal individuals [22]. Additionally, the OCT is significant in evaluating the probability of IOL tilting after cataract surgery and in the analysis of toric IOL power calculations [23].

AS-OCT-assisted Descemet stripping automated endothelial keratoplasty was applied in managing the anterior chamber fibrous ingrowth. A surgical operation assisted by AS OCT was conducted on a 61-year-old woman suffering from corneal edema and chronic angle-closure glaucoma, which arose due to fibrous ingrowth after two glaucoma shunt device implantations. The procedure involved the dissection and removal of the fibrous ingrowth in the anterior chamber, in addition to DSAEK. The recovery period post-surgery was uncomplicated, resulting in a positive outcome [24].

4. Posterior capsule

The lens capsule is a smooth, transparent basement membrane that varies in thickness between 2 and 28 microns, surrounding the entire crystalline lens. The lens capsule is made of type IV collagen and glycosaminoglycans.

One of the possible complications during cataract surgery is posterior capsule rupture, which requires careful evaluation of the capsule. Some surgeons use AS-OCT in evaluating the integrity of the posterior capsular bag. It was found that the sensitivity and specificity of AS-OCT in identifying posterior capsule dehiscence were 100% and 94.92%, respectively [25]. A different study revealed that AS-OCT achieved approximately 94% accuracy in assessing the morphological features of cataracts. Additionally, the OCT identified fibrosis and ruptures in both the anterior and posterior capsules with an accuracy exceeding 95% [26].

A group of researchers at the Vienna Institute for Research in Ocular Surgery observed that employing the AS-OCT intraoperatively for lens capsule measurement improves the predictability of IOL position post-surgery rather than relying on preoperative ACD measurements [27].

One of the rare complications of post-cataract surgery is capsular block syndrome (CBS), which is characterized by a collection between the capsular bag and the IOL. Fluid retention between the IOP and posterior capsule is the result of impairment of aqueous humor exchange between the anterior chamber and the capsular bag. Researchers observed that persistent capsulorhexis and adhesion of the anterior capsule to the IOL are the leading causes of capsular block syndrome. A range of manifestations associated with CBS has been documented, such as reduced visual clarity, increased ocular pressure, closed-angle glaucoma, and posterior capsule rupture.

The evolution of ophthalmic imaging technology allows for a definitive diagnosis through Scheimpflug-based photography, AS-OCT, or anterior segment UBM. While Scheimpflug-based photography offers valuable anterior chamber insights, spectral domain AS-OCT delivers superior detail about the intraocular lens (IOL) and any fluid between the IOL and the posterior capsular bag, leading to improved assessments and patient outcomes [28].

5. Vitreous and retina

The presence of occult macular pathologies that remain undetected through biomicroscopic fundus examination is significant in assessing the final visual acuity of patients post-cataract surgery. The OCT serves as a crucial imaging technique for diagnosing and monitoring both clinical and subclinical macular lesions. This highlights the critical role OCT plays in preoperative evaluations, as 13.7% of patients were found to have undetected macular issues that could influence their postoperative visual outcomes [29].

Velthoven et al. observed that the presence of cataract compromised the quality of the OCT image, and macular thickness was increased after cataract surgery [30].

Recognizing retinal pathology promptly yields three crucial benefits: (1) It equips the patient with a solid prognosis prior to surgery. (2) Specific retinal disorders, including macular oedema, must be managed before cataract surgery. (3) The presence of serious macular or optic nerve diseases can result in the cancellation of cataract surgery.

Studies that tracked the frequency of macular pathology also provided descriptions of the types of pathology that were observed. These pathologies were broadly categorized into five groups: interface abnormalities, macular degeneration, oedema, macular hole, and miscellaneous.

One of the most common retinal interface irregularities is associated with the epiretinal membrane (ERM). It is a notable challenge to diagnose fine ERM without OCT screening [31]. The existence of ERM entails a heightened risk for the development of cystoid macular edema subsequent to intraocular surgery [32]. Cystoid macular edema is regarded as one of the most prevalent complications that hinder recovery, extend the duration of treatment, and necessitate more intensive therapeutic interventions [33].

Following the enrollment of 614 patients for pre-cataract surgery assessment, the OCT identified retinal pathology in approximately 7% of individuals who exhibited a normal fundoscopic examination. Among these, 5% were diagnosed with ERM, age-related macular degeneration was observed in 7 eyes, an intraretinal cyst was found in less than 1%, a lamellar hole was present in 4 patients, and a full-thickness hole was noted in one eye [34].

In a large-scale cohort study from China, OCT detected macular pathologies in 25% of the assessed eyes. While AMD, central serous chorioretinopathy, and polypoidal choroidal vasculopathy were the least frequently reported conditions, the three most common macular pathologies found were ERM, myopic atrophy, and dome-shaped macula associated with pathological myopia [31].

Kowallick et al. documented the presence of drusen bodies in four out of 162 eyes, as well as retinal pigment epithelial atrophy in one eye, during their examination of the patients' OCT scans. They hypothesized that the low prevalence could be attributed to the significant cataract densities observed in the patients involved in their study (**Figure 3**) [35].

In patients with macular pathologies, multifocal or trifocal intraocular lenses may fail to deliver optimal visual outcomes, potentially leading to a decrease in contrast sensitivity [36].

Swept source OCT is superior to SD-OCT by utilizing longer wavelengths and a faster scanning speed [37]. Theoretically, The SS-OCT provides higher-resolution images compared to SD-OCT, which might reveal subtle macular pathologies [38]. In contrast, the fovea scan produced by SS-OCT exhibits a flatter profile when

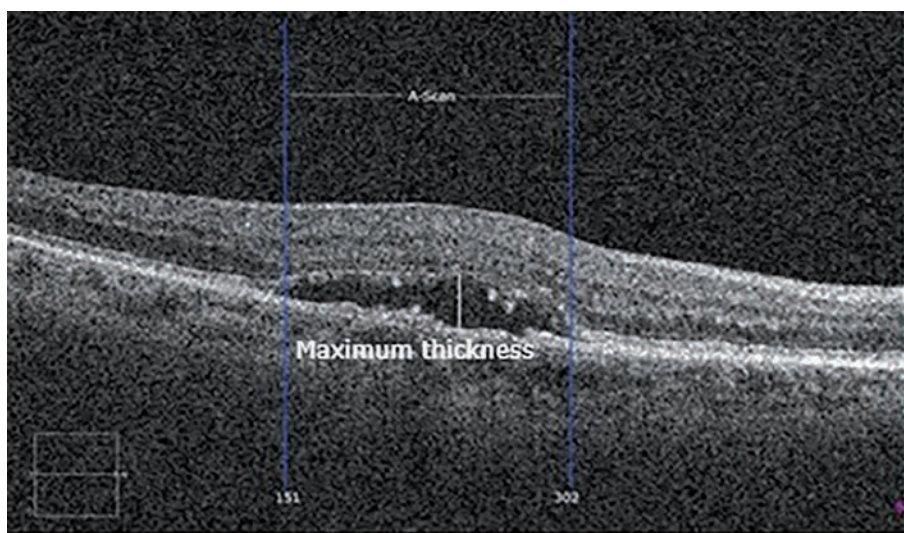


Figure 3.
Ocular coherence tomography shows subretinal fluid with intraretinal hyperintensity foci.

compared to that of SD-OCT, resulting in a reduced scan area of 1 mm. Consequently, the sensitivity of macular screening may not be equivalent to that of SD-OCT [38]. In their study, Hirnschall et al. found that the SS-OCT biometer had a moderate sensitivity of 0.48 to 0.62 when compared to SD-OCT, identifying macular pathology in about 58.5% of eyes that SD-OCT revealed macular pathology [39]. The subsequent research carried out by Tognetto et al. clearly demonstrated that the SS-OCT biometer attained a mean sensitivity of 0.81 when compared to SD-OCT. It successfully identified pathology in 81% of eyes that were deemed abnormal based on SD-OCT findings [40].

It was demonstrated that the SS-OCT is just as effective as the SD-OCT in identifying macular holes and intraretinal fluid by a study conducted by Hirnschall et al. However, the SS-OCT scan was not effective in detecting geographic atrophy and epiretinal membranes (ERM). The authors proposed that widening the SS-OCT scan to a diameter of 1 mm may result in an improvement in image sensitivity [39].

6. Intraocular lens power calculation

An accurate assessment of ocular dimensions is crucial for surgical intervention, especially cataract and refractive surgeries. Axial length measurement is critical for the calculation of IOL power following cataract surgery. The assessment of axial length through non-contact biometry devices outperforms the traditional ultrasound method by effectively resolving issues related to variability and ocular indentation.

To significantly reduce refractive prediction errors, it is imperative to accurately predict postoperative optical biometry using preoperative data. Research by Norrby and colleagues illustrates that predicting the position of the IOL prior to surgery can result in notable inaccuracies in determining the appropriate IOL power [41]. The calculation of IOL power relies heavily on the postoperative ACD, known as ELP, which varies depending on the specific formula applied. Unfortunately, this approach often fails to capture the true postoperative ACD from an anatomical perspective.

This limitation is especially pronounced in third-generation IOL power calculation, specifically, Hoffer Q7 [42], Holladay 1 [43], and SRK/T [44].

Ray tracing software can determine the IOL power with more accuracy through a precise estimation of postoperative ACD. The methodology proposed by Goto et al. focuses on predicting postoperative ACD, utilizing the angle-to-angle (ATA) depth derived from AS-OCT [45]. Enriquez et al. introduced a technique that facilitates precise estimation and quantification of the complete shape of the crystalline lens obtained from OCT data. They emphasized that the preoperative anterior segment parameters are vital for accurately estimating the IOL position [46].

A research conducted by Satou et al. aimed at creating a novel formula utilizing paraxial ray tracing for IOL power calculations, incorporating postoperative IOL placements, and assessing the precision of this newly formulated equation.

The enrolled patients were organized into training and validating subgroups. The alignment of the implanted IOLs in the training dataset was rigorously evaluated through multiple linear regression analyses, conducted one month after the surgical procedures. The validation dataset successfully computed postoperative refractive values using paraxial ray tracing of both the cornea and lens. This methodology was based on assumptions regarding finite structural thicknesses and unique surface curvatures. The new formula demonstrated a percentage error of around 84%, which falls within ± 0.50 diopters. The formula improved predictions of postoperative refraction and may be useful for eyes with abnormal characteristics, such as unusual corneal curvatures and varying axial lengths [47].

A group of researchers investigated the application of OCT for evaluating corneal power and improving the selection of IOL power during cataract surgeries after refractive surgery. A comprehensive analysis of 46 patients demonstrated that all underwent uncomplicated cataract surgery with the successful implantation of monofocal IOLs. The mean arithmetic prediction error for postoperative refraction was recorded as 0.05 ± 0.65 D for the OCT formula, 0.14 ± 0.83 D for the Haigis-L formula, and 0.24 ± 0.82 D for the Shammas-PL formula in cases with no prior history. In eyes that have had laser vision correction, OCT-based IOL power calculation demonstrated greater predictive accuracy compared to the Haigis-L and Shammas-PL formulas [48].

Savini et al. focused on evaluating the results of IOL power calculations, employing data gathered through a SS-OCT optical biometer. They concluded that the SS-OCT optical biometer's measurements contribute to the precise calculation of IOL power, as all formulas yielded a prediction error within 0.50 D in at least 80% of patients [49].

7. Cost-effectiveness and the future of OCT in cataract surgery

Several surgeons advocate for the OCT screening in patients being assessed for cataract surgery, especially those considering premium IOLs. This approach aims to refine patient selection criteria and ultimately improve postoperative satisfaction outcomes. The OCT screening reimbursement is not guaranteed unless the patient has a reasonable medical diagnosis according to Medicare and Medicaid Services guidelines.

In individuals exhibiting normal OCT results, the direct medical expenses and lost opportunity costs may be incurred by the physician or the medical institution. Given the current uncertainty regarding the cost-effectiveness of a preoperative OCT

in cataract surgery, it is likely that patients who pay out-of-pocket for multifocal IOLs represent the subgroup most affected by and most dissatisfied with undiagnosed retinal pathologies.

For individuals evaluating cataract surgery, the performance of optical coherence tomography with an IOL before the operation may raise the overall costs. However, it may also help uncover other macular conditions and improve life quality. The cost of an OCT that is reimbursable by Medicare was \$41.81, with all associated costs and benefits adjusted for inflation to reflect 2019 U.S. dollars, discounted at a rate of 3% per year over 16 years. In the fundamental scenario, an adjunctive preoperative OCT proved to be cost-effective from both a third-party payer and societal viewpoint in the United States. The study indicated that 64.4% of patients would likely accept the extra cost of an OCT prior to cataract surgery, considering a willingness-to-pay standard of \$50,000 for each quality-adjusted life year [50].

Many cataract surgeons will use OCT intraoperatively in patients who have an underlying anterior segment condition to achieve optimal visual outcomes.

Author details

Adel Ebraheem

Ophthalmology and Visual Sciences Department, University of Maryland—School of Medicine, USA

*Address all correspondence to: dr.adel.ebraheem@gmail.com

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Cataract surgery has recently become the backbone of ophthalmic surgery. It aims for a clear visual axis, a perfect optical system, visual improvement, amblyopia management, and a spectacle-free life at all distances. There are certain tender spots in dealing with a pediatric cataract case, where developmental stages are not yet completed, and in using the best of current technology for refractive lens exchange. This book covers important aspects of preoperative evaluation, surgical tips and techniques, and postoperative care for both pediatric and refractive cataract surgeries.

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