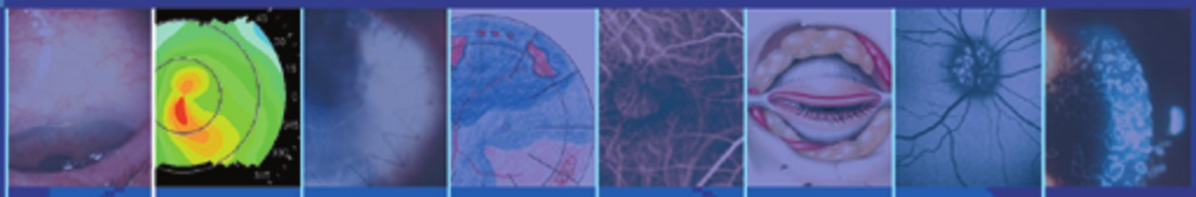
ESSENTIALS IN OPHTHALMOLOGY

G. K. KRIEGLSTEIN · R. N. WEINREB

Series Editors



Glaucoma | **Cataract and Refractive Surgery** | Uveitis and Immunological Disorders | Vitreo-retinal Surgery | Medical Retina | Oculoplastics and Orbit | Paediatric Ophthalmology, Neuro-ophthalmology, Genetics | Cornea and External Eye Disease

Cataract and Refractive Surgery

Edited by

T. KOHNEN

D. D. KOCH

Springer

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Cataract and Refractive Surgery

With 75 Figures, Mostly in Colour
and 22 Tables

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Series Editors

Günter K. Krieglstein, MD
Professor and Chairman
Department of Ophthalmology
University of Cologne
Kerpener Straße 62
50924 Cologne
Germany

Robert N. Weinreb, MD
Professor and Director
Hamilton Glaucoma Center
Department of Ophthalmology
University of California at San Diego
9500 Gilman Drive
La Jolla, CA 92093-0946
USA

Volume Editors

Thomas Kohnen, Prof. Dr.
Augenklinik der Johann Wolfgang
Goethe-Universität
Theodor-Stern-Kai 7
60590 Frankfurt
Germany

Douglas D. Koch, MD, Prof.
Department of Opthalmology
6565 Fannin, NC 205
Houston, TX 77030
USA

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Foreword

The series *Essentials in Ophthalmology* was initiated two years ago to expedite the timely transfer of new information in vision science and evidence-based medicine into clinical practice. We thought that this prospicient idea would be moved and guided by a resolute commitment to excellence. It is reasonable to now update our readers with what has been achieved.

The immediate goal was to transfer information through a high quality quarterly publication in which ophthalmology would be represented by eight subspecialties. In this regard, each issue has had a subspecialty theme and has been overseen by two internationally recognized volume editors, who in turn have invited a bevy of experts to discuss clinically relevant and appropriate topics. Summaries of clinically relevant information have been provided throughout each chapter.

Each subspecialty area now has been covered once, and the response to the first eight volumes in the series has been enthusiastically positive. With the start of the second cycle of subspecialty coverage, the dissemination of practical information will be continued as we learn more about the emerging advances in various ophthalmic subspecialties that can be applied to obtain the best possible care of our patients. Moreover, we will continue to highlight clinically relevant information and maintain our commitment to excellence.

G. K. Krieglstein
R. N. Weinreb
Series Editors

Preface

In a field that changes as rapidly as ophthalmology, why do clinicians continue to buy books? There are probably several reasons, but a primary one is that a well-written book provides comprehensive, evidence-based, clinically relevant overviews that cannot be obtained elsewhere. The challenge is to provide this material to readers in a timely fashion, in a format that facilitates easy reference and clinical use, and in sufficient detail that basic science and theoretical aspects are provided. We hope that this volume accomplishes these goals.

This second edition of *Cataract and Refractive Surgery* includes topics that complement those in the first edition and represent new areas of clinical importance in cataract and refractive surgery. The cataract section emphasizes the management of complex cases, intraocular lens selection and power calculations. In the refractive surgery section, topics include both corneal and lenticular approaches, particularly new technologies in both realms.

We hope that the readers will find this edition to be of intellectual interest and substantial clinical value. We owe a great deal of gratitude to the authors who have worked so hard to mine their own and others' experiences and data to write these chapters.

T. Kohnen
D. D. Koch
Volume Editors

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Contributors

Jorge L. Alió y Sanz, MD, Prof.
Medical Director
VISSUM, Instituto Oftalmologico de Alicante
Avda. de Denia, s/n
03016 Alicante
Spain

Ehud I. Assia, MD, Prof.
Department of Ophthalmology
Meir Medical Center
Tsharnihovski Street
Kfar-Saba 44281
Israel

Hiroko Bissen-Miyajima, MD, Prof.
Department of Ophthalmology
Tokyo Dental College Suidobashi Hospital
2-9-18 Misaki-cho, Chiyoda-ku
Tokyo 101-0061
Japan

Anne Bottros, MD
Department of Ophthalmology
Boston Medical Center
85 East Concord Street
Boston, MA 02118
USA

Victor Chang, MD
Department of Ophthalmology
Baylor College of Medicine
6565 Fannin, NC 205
Houston, TX 77030
USA

Robert J. Cionni, MD
Cincinnati Eye Institute
10494 Montgomery Road
Cincinnati, OH 45242-5214
USA

Alan S. Crandall, MD
Department of Ophthalmology
University of Utah
75 North Medical Drive
Salt Lake City, UT 84132-0001
USA

H. Burkhard Dick, Prof. Dr.
Direktor der Universitäts-Augenklinik
In der Schornau 23-25
44892 Bochum

John P. Fang, MD
Department of Ophthalmology
Baylor College of Medicine
6565 Fannin, NC 205
Houston, TX 77030
USA

I. Howard Fine, MD
1550 Oak Street, Suite 5
Eugene, OR 97401-7700
USA

Warren E. Hill, MD
East Valley Ophthalmology
Mesa, AZ 85206-1438
USA

Richard S. Hoffman, MD
1550 Oak Street, Suite 5
Eugene, OR 97401-7700
USA

Andrea Huber, Dr.
Augenklinik Klinikum Rechts der Isar
Technische Universität
Ismaninger Strasse 22
81675 München
Germany

Thomas Kasper, Dr.
Augenklinik der Johann Wolfgang
Goethe-Universität
Theodor-Stern-Kai 7
60590 Frankfurt
Germany

Douglas D. Koch, MD, Prof.
Department of Ophthalmology
Baylor College of Medicine
6565 Fannin, NC205
Houston, TX 77030
USA

Thomas Kohnen, Prof. Dr.
Augenklinik der Johann Wolfgang
Goethe-Universität
Theodor-Stern-Kai 7
60590 Frankfurt
Germany

Chris P. Lohmann, Prof. Dr. Dr.
Augenklinik Klinikum Rechts der Isar
Technische Universität
Ismaninger Strasse 22
81675 München
Germany

Scott M. MacRae, MD, Prof.
University of Rochester
StrongVision
100 Meridian Center 125
Rochester, NY
USA

Mark Packer, MD
1550 Oak Street, Suite 5
Eugene, OR 97401-7700
USA

Emanuel Rosen, MD
Rosen Eye Associates
Harbour City
Salford, Manchester M3 4DY
UK

Mohamed Helmy Shabayek, MD
Instituto Oftalmológico de Alicante
Avda. Denia, s/n, (Edificio VISSUM)
03016 Alicante
Spain

Manoj Subbaram, PhD
Department of Ophthalmology and
Center for Visual Science
University of Rochester
100 Meridian Center Blvd, Suite 125
Rochester, NY 14618
USA

Li Wang, MD, PhD
Department of Ophthalmology
Baylor College of Medicine
6565 Fannin, NC 205
Houston, TX 77030
USA

Mitchell P. Weikert, MD, Prof.
Department of Ophthalmology
Baylor College of Medicine
6565 Fannin, NC205
Houston, Texas 77030
USA

Christoph Winkler von Mohrenfels, Dr.
Augenklinik Klinikum Rechts der Isar
Technische Universität
Ismaninger Strasse 22
81675 München
Germany

Cataract Surgery

Chapter 1

Intraocular Lenses to Restore and Preserve Vision Following Cataract Surgery

1

Robert J. Cionni

Core Messages

- Our ability to restore vision lost to cataracts has improved tremendously over the last few decades.
- More focus on maintaining vision is essential, especially for patients with macular degeneration.
- Blue light has been shown to be potentially damaging to the retina.
- The normal human crystalline lens filters out much blue wavelength light. Removal of this lens and placing a colorless UV-blocking intraocular lens (IOL) leaves the retina exposed to higher levels of blue light.
- IOLs are now available that can filter out blue light similar to the normal human lens.
- These blue filtering IOLs have been shown to have no negative effect on vision in terms of visual acuity, contrast sensitivity, color perception, and night vision.

1.1 Introduction

Although cataract surgery has been performed for many centuries, technological advances now provide us with the opportunity to afford our patients vision more similar to the pre-cataract state than ever before. Advanced instrumentation and surgical techniques allow our patients to expect excellent uncorrected vision within 24 h of surgery. In addition, newer multifocal and accommodating intraocular lens (IOLs) offer the possibility of distance, near, and intermediate vision without glasses [2, 23, 32]. With these IOLs we can not only restore vision to the pre-cataract level, but also to the pre-presbyopia state, thereby reducing spectacle dependency. Unfortunately, many of our cataract patients suffer from age-related macular degeneration (ARMD) as well and are concerned about progressive vision loss following cataract surgery. Despite our success in restoring vision for our cataract patients, we have not gained much ground in preserving vision for those patients with macular degenerative disease. Over the last few decades more and more literature has surfaced suggesting that blue light may be one factor in the progression of ARMD [8]. The normal human crystalline lens filters not only ultraviolet light, but also much of the high frequency blue wavelength light. When we remove the crystalline lens, we remove the eye's natural blue light filter. If we replace the crystalline lens with an IOL that does not filter this blue wavelength light, we must wonder if we are increasing the risk of worsening ARMD. In recent years, blue-light filtering IOLs have been released by two IOL manufacturers. In this chapter we will look at the rationale for implanting blue-light filtering IOLs in an effort to not only restore our patients' vision, but also to preserve that vision.

1.2 Why Filter Blue Light?

It is well known that pseudophakic eyes are more susceptible to retinal damage from near ultraviolet light sources [11, 15]. Pollack et al. followed 47 patients with bilateral early ARMD after they underwent extracapsular cataract extraction and

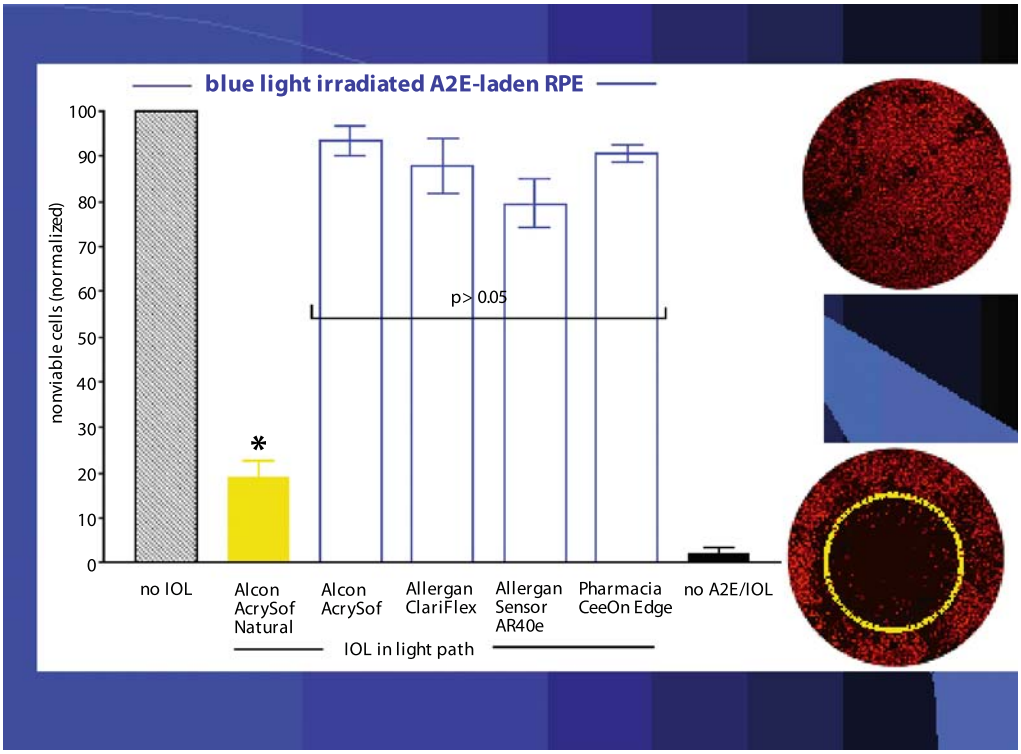

Fig. 1.1 Cultured human retinal pigment epithelial (RPE) cells laden with A2E exposed to blue wavelength light. Cell death is significant when UV blocking colorless intraocular lenses (IOLs) are placed in the path of the light, yet markedly reduce when the AcrySof Natural IOL is placed in the light path

implantation of a UV-blocking IOL in one eye, with the fellow eye as a phakic control [25]. Neovascular ARMD developed in 9 of the pseudophakic eyes versus 2 of the control eyes, which the authors suggested might be due to the loss of the "yellow barrier" provided by the natural crystalline lens.

Data from the Age-Related Eye Disease Study (AREDS), however, suggest a heightened risk of central geographic retinal atrophy in pseudophakic eyes [1]. The retina appears to be susceptible to chronic repetitive exposure to low-radiance light as well as brief exposure to higher-radiance light [17, 18, 31, 34]. Chronic, low-level exposure (Class 1) injury occurs at the level of the photoreceptors and is caused by the absorption of photons by certain visual pigments with subsequent destabilization of photoreceptor cell membranes. Sparrow and coworkers have demonstrated that a component of lipofuscin, known as A2E, is integral in blue light-induced retinal pigment epithelium (RPE) damage [3, 14, 29] and although the retina has inherent mechanisms from Class 1 photochemical damage, the aging retina is less able to provide sufficient protection [27, 37].

Several epidemiological studies have concluded that cataract surgery or increased exposure of blue wavelength light may be associated with progression of macular degeneration [5, 35]. However, other epidemiologic studies have failed to come to this conclusion [6, 7, 19]. Such conflicting epidemiological results are not unexpected since age-related macular disease is felt to be a multifactorial biologic process. Therefore, many of the studies concerning the effects of blue light on the retina have been conducted in animals and in vitro [13, 16, 17, 21, 24, 26]. Numerous of these laboratory studies demonstrate a susceptibility of the RPE to damage when exposed to blue light [28, 29].

If blue light can potentially induce retinal injury, what is felt to be the etiology of the damage? It is well known that lipofuscin accumulates in the RPE cells as we age. One component of lipofuscin is a compound known as A2E and it is this compound that is believed to be the culprit in RPE cell death. A2E has an excitation maximum in the blue wavelength region (441 nm) and when excited by blue light, A2E generates oxygen free radicals, which can lead to RPE cell damage and death. At Columbia University, Sparrow and colleagues exposed cultured human RPE cells laden with A2E to blue light and observed extensive cell death. They then placed different UV blocking IOLs or a UV blocking and blue light filtering IOL in the path of the blue light to see if any of the IOLs provided a protective effect. The results of this study demonstrated that cell death was extensive with all UV blocking colorless IOLs, but significantly diminished with the UV and blue light filtering IOL (Fig. 1.1) [30]. These experiments were conducted in vitro and therefore cannot take into account any natural protective mechanisms that might be present in vivo. Additionally, the light exposure employed was more representative of high-level short-term exposure rather than low-level chronic exposure. Still, this work demonstrates clearly that blue light-filtering IOLs can help A2E-laden RPE cells to survive the phototoxic insult of the blue light.

Summary for the Clinician

- A growing body of literature suggests that blue light exposure may be one factor in the progression of macular degeneration.

1.3 Why is the Consideration of Blue Light Important to Our Cataract and Refractive Lens Exchange Patients?

The human crystalline lens normally filters ultraviolet light and much of the light in the blue wavelength spectrum [12]. When the lens is removed during cataract or refractive lens exchange (RLE) surgery, this blue-wavelength light can now reach the retina, thereby exposing the RPE cells to much higher levels of blue light than they have ever known. If a *colorless* UV blocking IOL is implanted, the RPE cells remain exposed to this increased level of potentially damaging blue light ever after. At the time of writing, two manufacturers have developed IOLs that filter blue light in addition to UV light.

The AcrySof Natural (Alconlabs, Fort Worth, TX, USA) is a hydrophobic acrylic foldable IOL that incorporates a yellow chromophore cross-linked to the acrylic molecules. This yellow chromophore allows the IOL to filter not only UV light, but also specific levels of light in the blue wavelength region. Aging studies have shown that the chromophore will not leach out or discolor (unpublished, Alconlabs). The AcrySof Natural IOL was approved for use in Europe in 2002 and in the USA in 2003. Evaluation of its light transmission curve demonstrates that this IOL approximates the transmission spectrum of the normal human crystalline lens in the blue light spectrum (Fig. 1.2). Therefore, in addition to benefiting from less retina blue light exposure, color perception should seem more natural to these patients as opposed to the increased blue hues seen by patients who have received colorless UV blocking IOLs [39]. Hoya brought blue-light filtering IOLs to Japan in 1991 (three-piece PMMA Model HOYA UVCY) and in1994 (single-piece PMMA Model HOYA UVCY-1P). The blue-light filtering characteristics of the Hoya and the AcrySof Natural differ slightly (Fig. 1.3). Clinical studies of some of these blue light-filtering IOLs have been carried out in Japan. One study found that pseudophakic color vision with a yellow-tinted IOL approximated the vision of 20-year-old control subjects in the blue light range [9]. Another study found some improvement in photopic and mesopic contrast sensitivity, as well as a decrease in the effects of central glare on contrast sensitivity, in pseudophakic eyes with a tinted IOL versus a standard lens with UV blocker only [22].

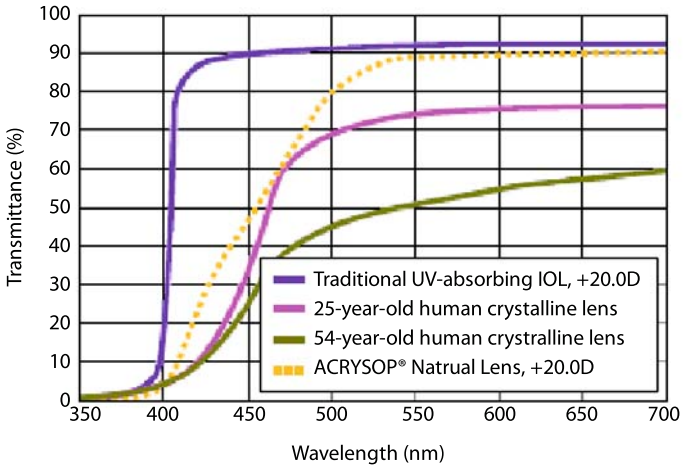

Fig. 1.2 Light transmission spectrum of the AcrySof Natural IOL compared with those of a 25-year-old and a 54-year-old human crystalline lens and a 20-diopter colorless UV-blocking IOL [12]

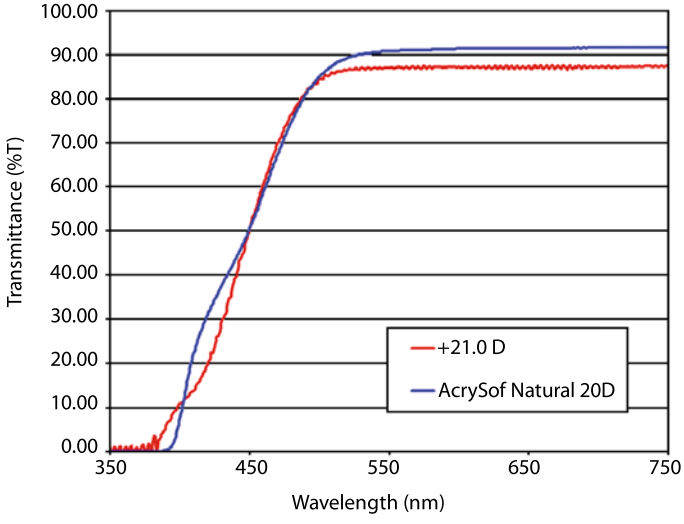

Fig. 1.3 UV/visible transmission spectra for AcrySof Natural and Hoya AF-1 blue light-filtering IOLs obtained using the same instrument under identical conditions (unpublished, Alconlabs)

Summary for the Clinician

- Removing the cataractous or noncataractous human lens removes the eye's natural blue light filter and exposes the retina to higher levels of blue light than ever before. IOLs are now available that can filter out much of that blue wavelength light similar to the normal noncataractous human lens.

1.4 Quality of Vision with Blue-Light Filtering IOLs

A multi-centered, randomized prospective FDA evaluation of the AcrySof Natural IOL was carried out before the lens gained approval for use in the USA. Three hundred patients were randomized to bilateral implantation of the AcrySof Natural IOL or the clear AcrySof Single-Piece IOL. All patients were screened to ascertain normal preoperative color vision before being deemed eligible for the study. Postoperative parameters measured included visual acuity, photopic and mesopic contrast sensitivity, and color percep-

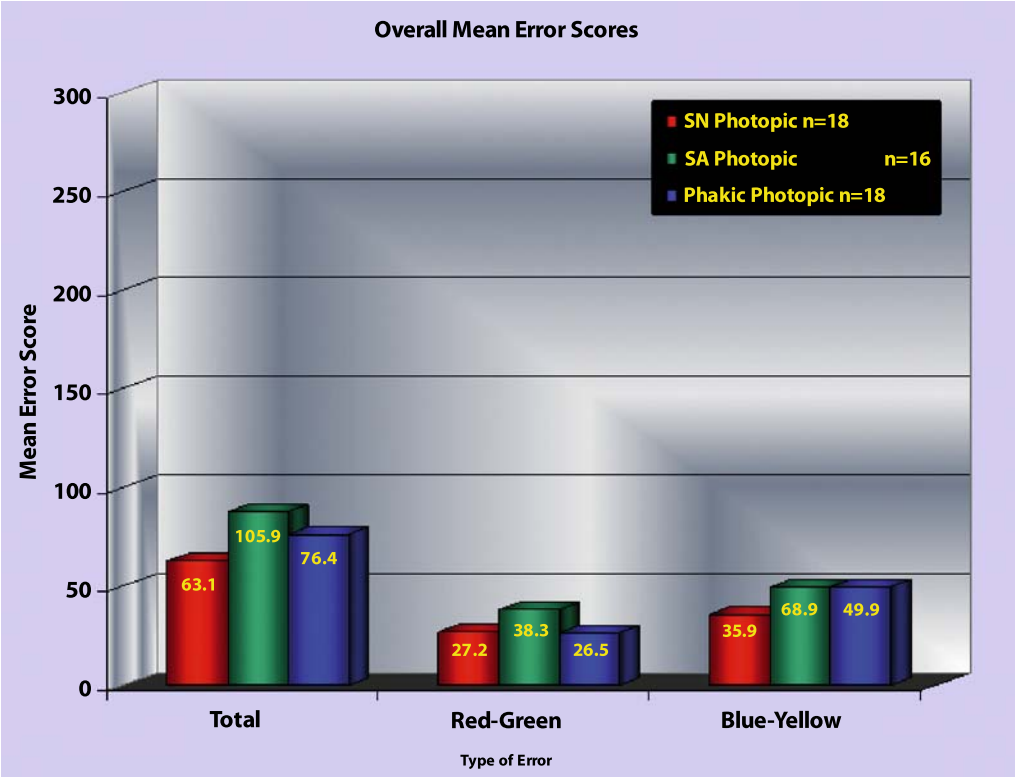

Fig. 1.4 FM 100 Hue results comparing AcrySof Natural IOL with the Single-Piece AcrySof colorless IOL and noncataractous phakic controls [4, 36]

tion using the Farnsworth D-15 test. Results demonstrated no difference between the AcrySof Natural IOL and the clear AcrySof IOL in any of these parameters (unpublished, Alconlabs). More substantial color perception testing using the Farnsworth-Munsel 100 Hue Test has also demonstrated no difference in color perception between the AcrySof Natural IOL and the clear AcrySof IOL [4] (Fig. 1.4).

Although the contrast sensitivity tests performed under mesopic conditions in the FDA trials demonstrated that the AcrySof Natural IOL does not negatively affect mesopic vision, some have raised concerns about mesopic and scotopic vision in patients with blue light filtering IOLs since blue light is imperative for night vision. Mesopic vision begins at approximately 0.001 cd/m² and extends up to 5 cd/m² for a centrally fixated target 3O in diameter [38]. The upper range could extend up to 15 cd/m² for a target 25° in diameter; however, 3 cd/m² is the upper limit for mesopic vision that is most often cited. One can liken this to the low-light conditions on a cloudless night with a full moon. Scotopic refers to light levels below the mesopic range, which can be likened to a moonless, starry night.

Certainly, if all blue light were blocked, one might expect some decrease in scotopic vision. However, neither the HOYA nor the AcrySof Natural IOL blocks all blue light. It is well recognized that the most important wavelengths for scotopic vision are at and around 507 nm [33]. The AcrySof Natural IOL allows transmission of approximately 85% of light at 507 nm. In comparison, a UV blocking colorless IOL transmits only 4% more light at this wavelength. It is also important to note that the normal human crystalline lens at any age transmits significantly *less*

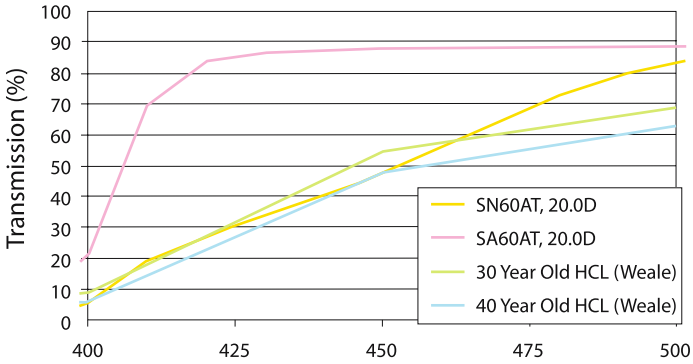

Fig. 1.5 Blue light transmission spectrum showing low transmission of 441 nm light and high transmission of 507 nm light with the AcrySof Natural IOL. *HCL* hard contact lenses

light at and near 507 nm than the AcrySof Natural IOL and, therefore, patients implanted with the AcrySof Natural IOL should have *enhanced* scotopic vision. It would be counterintuitive to believe that scotopic vision would be diminished instead of enhanced (Fig. 1.5).

A recent study presented at the ASCRS Annual Meeting in 2005 evaluated detection thresholds for a Goldmann size V target at wavelengths of 410 nm, 450 nm, and 500 nm using a modified Humphrey Field Analyzer in patients with and without yellow clips that approximated the filtering ability of the AcrySof Natural IOL [10]. Each test was carried out with a single wavelength of light present. The results showed a decreased ability to perceive objects when only 410 nm or 450 nm light was present but no significant decrease in perception ability at 500 nm. This decrease was more significant in patients with ARMD. The results are exactly what would be expected based on the light transmission spectrum of these IOLs. However, the study fails to provide insight into mesopic or scotopic vision as it does not represent mesopic or scotopic conditions. In all real-life environments there is always a spectrum of light present, not just one wavelength. This is also true of mesopic and scotopic conditions, where there is more 500 nm and longer wavelength light than 410 nm or 450 nm wavelength light (Fig. 1.6).

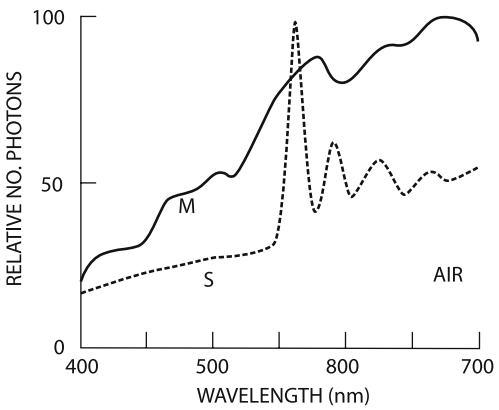

Fig. 1.6 Spectral light distribution in air under mesopic (*M*) and scotopic (*S*) conditions [20]

Summary for the Clinician

- Clinical studies demonstrate no difference between colorless, UV-blocking IOLs and blue light-filtering IOLs in terms of visual acuity, contrast sensitivity, color vision or night vision.

1.5 Clinical Experience

Having implanted several thousand AcrySof Natural IOLs, I have had the opportunity to gain insight into the quality of vision provided by this unique IOL. The visual results in my patients have been excellent, with no complaints regarding color perception or night vision problems. I have implanted a blue light filtering IOL in the fellow eye of many patients previously implanted with colorless UV-filtering IOLs. When asked

to compare the color of white tissue paper, 70% do not see a difference between the two eyes. Of the 30% who could tell a difference, none perceived the difference before I checked and none felt the difference was bothersome. With more than 1,000,000 AcrySof Natural IOLs implanted worldwide at the time of writing, there are no confirmed reports of color perception or night vision problems.

Summary for the Clinician

- Clinical experience with blue light filtering IOLs shows no difficulty with color perception or night vision.

1.6 Unresolved Issues and Future Considerations

Laboratory studies have demonstrated the protective benefit filtering blue light provides for cultured RPE cells. However, the clinical benefits of blue light filtering IOLs in preventing the development or worsening of macular degeneration have not been proven. A large, multicenter, prospective clinical study will be necessary to determine if these IOLs truly provide a protective effect. Additionally, there may be a role for different levels of blue light-filtering capabilities in these in an effort to maximize retinal protection while minimizing any possible compromise to the quality of vision.

1.7 Conclusion

New technology provides us with the opportunity to improve vision following cataract or RLE surgery more substantially and predictably than ever before. We now need to make efforts to maintain that vision long-term. Given the growing body of evidence implicating blue light as a potential factor in the worsening of ARMD and the positive collective clinical experience with blue-light filtering IOLs, it makes sense to implant these protective IOLs when possible. I firmly believe that blue light-filtering IOLs will eventually become the gold standard of care in cataract and RLE surgery.

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Chapter 2

Cataract Surgery in Eyes with Loose Zonules

2

Ehud I. Assia

Core Messages

- Lens subluxation is often associated with accompanying ocular pathologies.
- To reduce zonular stress during surgery always pull *toward*, not away from, weakened zonules.
- Zonular stress is minimal when lens material is separated from the capsule. Complete hydrodissection is essential.
- A capsule tension ring inserted prior to lens removal facilitates phacoemulsifications, but complicates cortex aspiration.
- A capsular tension ring alone is not sufficient if the zonular defect is larger than 5 h.
- Capsular PC-IOL may subluxate/dislocate years after surgery. In-the-bag fixation is not always advantageous.

2.1 Introduction

The stability of the crystalline lens depends entirely on the integrity of the zonular apparatus. Loosening of the zonular fibers is manifested clinically as phacodonesis (or pseudophacodonesis), anterior or posterior displacement of the lens, subluxation, and decentration. In addition to the optical impairment, the malpositioned lens may cause shallowing of the anterior chamber (AC) and narrowing of the angle with a subsequent increase in intraocular pressure (IOP). Lens removal may thus be indicated when the lens opacifies (cataract), or is misplaced anteriorly (high IOP), posteriorly (optical aberration) or laterally (decentration). Zonular weakness may progress to zonular dehiscence, which may eventually involve the entire zonular apparatus and result in complete lens or IOL luxation into the vitreous body.

There are numerous causes of weakening of the zonules, the most common of which is pseudoexfoliation (PXF) of the lens [8]. Other common causes include high myopia and hereditary conditions such as Marfan syndrome, homocystinuria, and Weill–Marchesani syndrome. Rare causes include sulfite oxidase deficiency, scleroderma, porphyria and hyperlysinemia. Zonular weakness or rupture may also result from ocular trauma, usually a blunt trauma.

Lens subluxation can present as an isolated ocular pathology (primary ectopia lentis), usually as a hereditary bilateral disease. However, zonular weakness related to most of the other causes is often accompanied by other ocular pathologies that may complicate surgery. Pseudoexfoliation is associated with a small pupil, increased fragility of the zonular fibers, impaired blood–ocular barrier and a tendency toward increased inflammatory reaction and bleeding [8]. PXF glaucoma may present either before or after lens removal. Marfan syndrome is frequently associated with high myopia, retinal breaks, and glaucoma. In addition, these patients may suffer significant morbidity related to cardiac valve diseases and skeletal anomalies. Patients with homocystinuria are at high risk of developing thromboembolic events. Ocular trauma may present as lens subluxation; however, in many cases the initial presentation does not reveal the full spectrum of the ocular damage. The extent of zonular breaks may be far larger than previously estimated, the anterior hyaloid may rupture, and vitreous prolapse is not rare. Intraocular pressure may increase via several mechanisms, including lens displacement and angle closure, angle recession,

lens particle glaucoma, or intraocular bleeding. Traumatic rupture of the lens capsule and dialysis of the zonules, iris or even the retina may be evident only during surgery. Thus, surgery after significant ocular trauma should be done with extreme caution, not only because of the technical challenge of removing the lens in the presence of loose zonules, but also because of the potential risks of additional hidden ocular pathologies. Preoperative evaluation should always include, in addition to routine biomicroscopy and pressure measurement, gonioscopy, detailed retinal examination, and, if necessary, ultrasonography.

Summary for the Clinician

- Weakening of the zonules may occur spontaneously with age or may be associated with other diseases, the most common of which are pseudoexfoliation and trauma.
- Thorough clinical investigation is required to reveal the extent of zonular dialysis and accompanying pathologies.

2.2 Surgical Approach

A basic rule of surgery in cases of loose or torn zonules is to minimize the tension over the diseased zonular fibers. The instinct of the beginner surgeon is to work away from the affected area and pull the lens material toward the opposite side. This may stretch the weakened zonules or further unzip the remaining fibers. Therefore, lens material should first be carefully separated from the lens capsule, and only then removed with minimal tension.

2.3 Weakened Zonules

Capsulorhexis is a challenge in eyes with significant phacodonesis or posterior displacement. It is often difficult even to penetrate the anterior lens capsule with a regular cystotome. A very sharp needle, a slit knife or a stiletto knife should be used for the initial cut. The anterior chamber should preferably be filled with a highly viscous Ophthalmic Viscoelastic Device (OVD) and the capsulectomy is completed using capsule forceps by pulling the capsule anteriorly, thus reducing the tension on the zonular fibers. Needle capsulectomy can be performed in mild cases; however, the forces are then directed posteriorly and the lens may further dislocate or fall backward. When the lens is decentered it might be very difficult to create a central capsulorhexis of a desired diameter (5.0–5.5 mm), since some of the capsule is then hidden behind the iris. A relatively small pupil, as often occurs in PXF, may further complicate capsulorhexis. A large volume of OVD may assist pupil dilation; however, in some cases other means of dilating the pupil might be needed, such as iris hooks. If the initial anterior continuous curvilinear capsulorhexis (CCC) is not wide enough, it can be enlarged later, after lens removal or even at the end of the procedure after IOL implantation.

Hydrodissection should be done carefully, by repeated injection of a small amount of fluid. Even though it might be quite difficult to achieve a satisfactory hydrodissection when the lens is unstable, this procedure should be done persistently and never bypassed. This is probably the most critical part of surgery since separation of the lens material from the capsule allows manipulation of even the hardest lens with minimal trauma to the zonular fibers. Injection of fluid at various locations, seeing that the nucleus moves anteriorly, followed by gentle pushing of the nucleus backwards, indicate that the nucleus is freed from the capsule and can be safely rotated using two instruments.

Lens removal is usually carried out in a routine, yet very careful, manner. The initial groove should be made with minimal pressure, to create the first nucleus splitting, followed by chopping and emulsifying of the remaining nucleus. In cases of severe zonular weakness, or a very hard nucleus, making the initial groove might be difficult since the phaco tip pushes the lens posteriorly. Some surgeons prefer to use in these cases Nagahara's original chopping technique, i.e., penetrating the nucleus using high vacuum and breaking it into segments by chopping, without making the initial groove. Since the lens is then always pulled, and not pushed away, the tension

over the zonules in minimized; however, this technique requires experience and skills. High vacuum also assists lens removal by utilizing low ultrasonic energy; however, since the capsular diaphragm is loose it can be easily sucked into the phaco tip. A capsular tension ring (CTR) inserted prior to phacoemulsification may help maintain a taut capsule throughout the procedure. The CTR does not usually interfere with enlargement of the anterior CCC or even formation of the posterior CCC. Lens removal in the presence of severe phacodonesis can be facilitated by temporary suspension of the capsule using iris hooks [14, 20]. The hooks are first used to dilate the pupil and perform a proper sized anterior CCC. Then the hooks are repositioned to engage the capsulorhexis margin and stabilize the capsular bag during phacoemulsification and IOL implantation.

Implantation of a posterior chamber lens should preferably be done using a cohesive OVD. The viscous OVD not only inflates the capsular bag and maintains a deep chamber, but also permits a slow and smooth release of the IOL from the injector, especially silicone lenses, which tend to open up fast. The insertion of the trailing loop can be assisted by holding the capsulorhexis with a second instrument such as an iris hook or lens manipulator.

The preferred location of the implanted lens is still controversial. Whereas most surgeons prefer in-the-bag fixation, in some cases the loose fibers may eventually break, even many years later, and the entire IOL capsule complex may subluxate or dislocate. Sulcus fixation using a lens with a large haptic diameter may be more stable since the haptic is supported by both the ciliary process and the capsular diaphragm [8]. The preferred direction of the lens axis, relative to the area of missing zonules, is also controversial. Some surgeons prefer to place the lens axis in the direction of the dialysis so that the IOL haptic will push away the capsular equator. Others advocate placing the haptic perpendicular to the missing zonules to achieve maximal lens support; however, the IOL may then be slightly decentered. Using a capsular tension ring evenly distributes the forces around the capsular equator, making the IOL position less significant; however, it also adds weight to the compromised capsular bag.

The debate on IOL implantation in the pediatric age is still ongoing; however, in cases of zonular dehiscence and lens subluxation most surgeons prefer complete lens removal (ICCE), usually combined with an anterior vitrectomy, and fitting of contact lenses. Conventional angle supported anterior chamber IOLs resulted in an unacceptable high rate of complications; however, reports in the last decade have documented that the Artisan iris-supported lenses were also safe and effective in children [12].

2.4 Zonular Dialysis

The surgical technique in broken zonules is basically similar to that of weakened zonules, i.e. careful forceps assisted capsulorhexis using viscous OVD, a complete hydrodissection, and emulsification of the hard lens material only after it is completely separated from the lens capsule. The forces should always be directed towards the area of the missing zonules. Pulling the capsule in the other direction may unzip the surviving zonules and enlarge the defect.

Summary for the Clinician

- The basic surgical rule in the presence of zonular dialysis is to minimize the tension over the remaining zonules.
- Careful hydrodissection allows the lens to be manipulated without exerting forces on the capsule–zonules complex.
- Pulling maneuvers are usually safer than pushing.
- Highly viscous OVDs are essential tools to stabilize the lens. Do not overfill the AC.

2.5 Capsule Tension Rings

The introduction of CTRs in 1993 revolutionized cataract removal and IOL implantation in eyes with loose zonules. The CTR helps not only to support the IOL postoperatively, but is also used as an important surgical tool to allow safe removal

of the crystalline lens [11, 13, 19]. A large zonular defect, especially in the inferior half, may make phacoemulsification a very complex procedure as the loose capsular equator tends to be sucked into the phaco tip at any attempt to aspirate the lens material. The posterior capsule is pushed forward by fluid accumulated behind the posterior capsule and vitreous prolapse is not uncommon. Insertion of a CTR after hydrodissection, before phacoemulsification, stabilizes the lens equator and maintains the posterior capsular diaphragm in a taut and backward position.

A rule of thumb commonly practiced is:

1. Dialysis of 2–3 h (<90°)—CTR is an option, not a necessity.
2. Dialysis of 3–5 h (90–150°)—CTR is required to assure capsular stability and IOL centration.
3. Dialysis of 5–7 h (150–210°)—CTR can be used, but may not be sufficient. The lens or the ring should also sutured to adjacent structures.
4. Dialysis of more than 7 h usually requires complete lens removal and implantation of an AC-IOL (angle or iris supported) or PC-IOL sutured to the sclera and/or iris.

There are several models and sizes of CTRs ranging between 12–14 mm in the open configuration and 10–12 mm when the ring is compressed. The CTR can be inserted manually by using forceps and lens hooks or be injected using an injector. If inserted manually it is safer and easier to insert the ring through the side port paracentesis, rather than through the main 3-mm incision, as the narrow paracentesis eliminates the

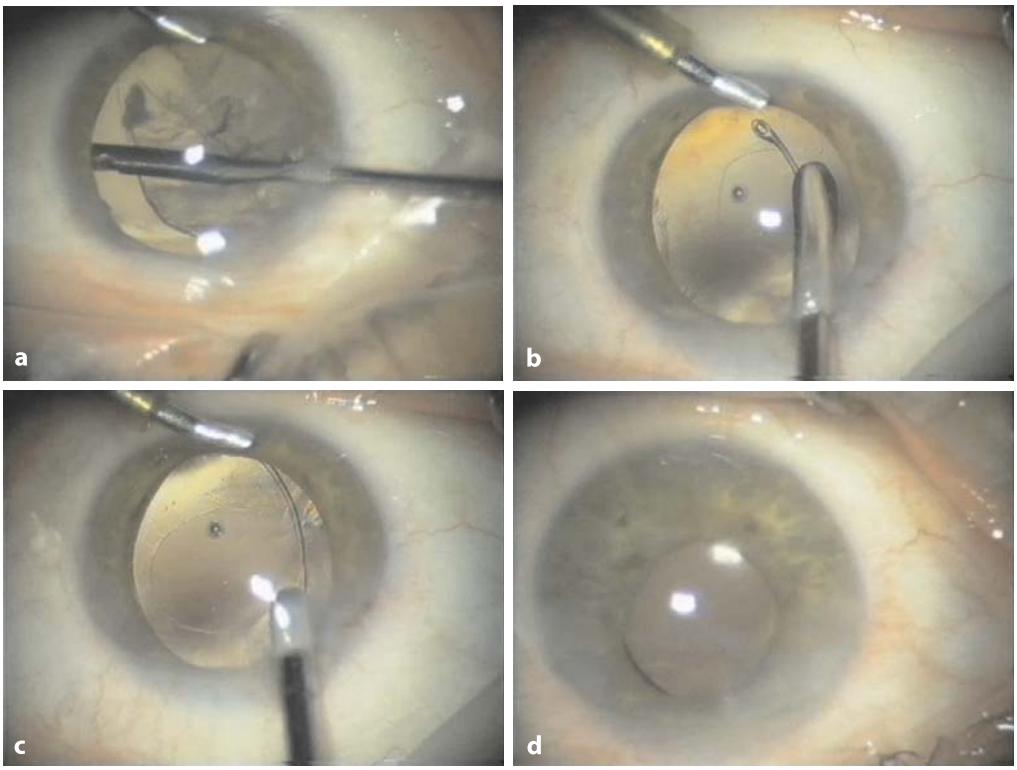

Fig. 2.1 Insertion of a capsular tension ring (CTR). **a** A large (~5 h) zonular dialysis in an eye with high myopia. Anterior vitrectomy is performed after lens removal. **b** Since the zonules are missing on the left side, the CTR is inserted in a counter-clockwise fashion. **c** The trailing edge is released under the anterior capsule. Note the central position of the capsulorhexis. **d** The posterior chamber lens is stable and well centered

side-to-side movements of the ring and allows a smoother insertion. A CTR with an additional positioning hole in the center may further assist ring manipulation and direction. An easier and safer technique is to utilize a spring-loaded injector. The injector is introduced through the main incision (the paracentesis is too small) and the ring is slowly inserted in a controlled manner and released only when its correct position has been established (Fig. 2.1). If the ring is misplaced during implantation the CTR can be easily retracted into the barrel in a reverse motion and reinjected in the proper direction [1].

Even though the presence of the CTR in the bag significantly assists lens removal by phacoemulsification, many surgeons are reluctant to use it for the following reasons:

1. Insertion itself may enlarge the capsular defect.
2. The peripheral cortical fibers are trapped between the CTR and the lens equator, making their removal a risky and complex maneuver.
3. If the capsule ruptures or the zonular dehiscence is enlarged and stability of the lens is no longer established, the surgeon now needs to deal also with removal of the CTR. This can be a complicated procedure, especially if the ring escapes the capsular bag and is hidden in the ciliary body, obscured by the iris.

In a large multicenter study, enlargement of zonular dialysis occurred in only 1 out of 255 eyes (0.39%) following insertion of a CTR compared with 12.8% in historical data without using the rings [19]. Jacob reported extension of zonular dialysis in 2 out of 21 eyes (9.5%) [11].

The loading of the ring determines the direction of insertion. Using the "left" eyelet would load the ring in a counter-clockwise direction, thus releasing it into the eye in a clockwise direction. The opposite occurs when the "right" eyelet is used. The ring should first be directed toward the areas of the loose or missing zonules to minimize the stress on the fibers adjacent to the defect. Since the capsular equator is loose in this area, entanglement of the leading eyelet in the capsule may push the capsule rather than advance the ring. The ring should then be slightly redrawn into the injector and redirected after the bag is refilled with a highly viscous OVD. Before releasing of the second eyelet it should be assured that the ring edge is posterior and lateral to the edge of the anterior CCC, otherwise the loop might be released into the anterior chamber, over the iris. Retrieval and redirecting the ring into the capsular bag is then a risky maneuver that may damage the angle and cause bleeding.

Trapping of cortical fibers between the ring and the capsule often occurs when the CTR is inserted prior to lens removal. A thorough cortical cleavage hydrodissection performed prior to CTR insertion may facilitate cortical fiber aspiration. Removal of the fibers should not be done by pulling them in the regular manner toward the center, as this may inflict stress on the remaining zonules. Preferably, the cortical fibers should be pulled side-to-side in a circumferential manner until they are liberated (Fig. 2.2).

Removal of a CTR may be indicated in cases of capsule rupture or extension of the zonular defect. A technique to safely remove the ring has been suggested: threading a 10-0 suture through the CTR eyelet prior to its insertion [13, 17]. The concept is similar to the safety sutures suggested for safe insertion of an IOL in challenging situations [2]. The suture is externalized through the main incision and does not interfere with phacoemulsification and IOL implantation. The preplaced safety suture may also assist insertion of the CTR. If capsule entanglement occurs, the leading edge is slightly pulled and viscoelastic substance is injected to inflate and smooth the capsular equator [13]. If CTR removal is required, pulling of the safety sutures exposes and attracts the CTR end. The CTR is then gently removed through the surgical opening, pulling the safety suture alone or by using a hook or forceps [17]. If the posterior capsule ruptures after a CTR has been implanted (without a safety suture), it is controversial whether attempts should be made to remove the CTR from the eye. Even though there is always the risk of dislocating into the vitreous cavity, attempts at "blind" fishing of the CTR may be much more dangerous to the eye than leaving it alone. The CTR often stabilizes at the ciliary sulcus and only rarely falls posteriorly. Moreover, if a PC-IOL is sutured to the sulcus, the sutures or the IOL haptic may further hold

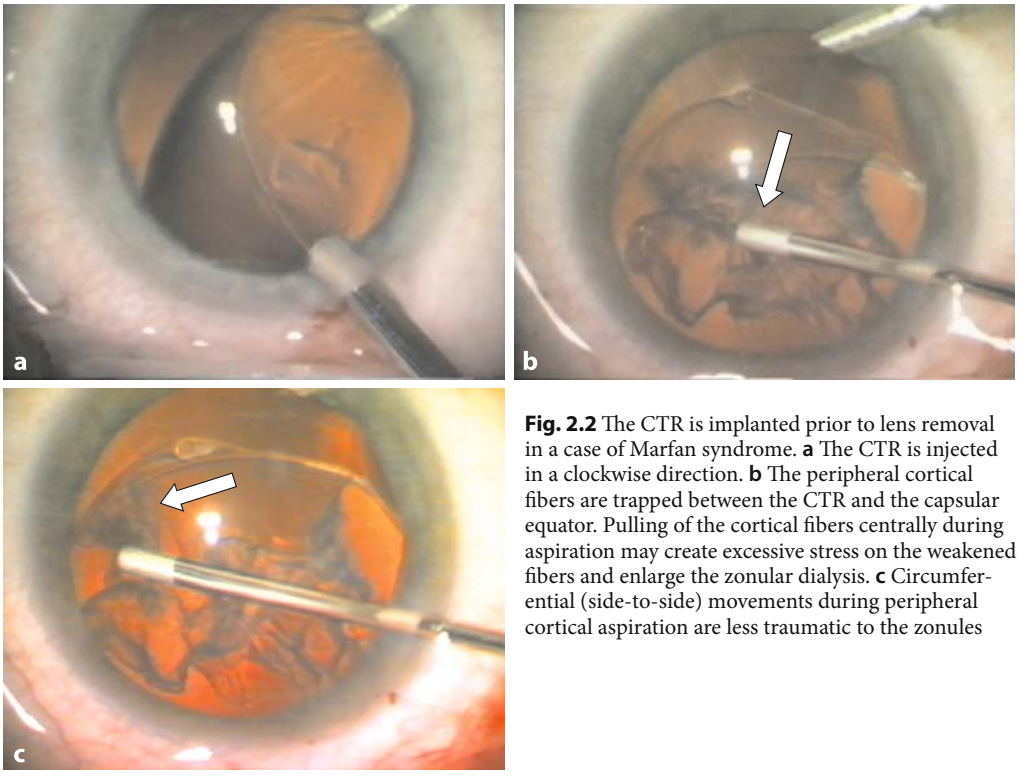

Fig. 2.2 The CTR is implanted prior to lens removal in a case of Marfan syndrome. **a** The CTR is injected in a clockwise direction. **b** The peripheral cortical fibers are trapped between the CTR and the capsular equator. Pulling of the cortical fibers centrally during aspiration may create excessive stress on the weakened fibers and enlarge the zonular dialysis. **c** Circumferential (side-to-side) movements during peripheral cortical aspiration are less traumatic to the zonules

the CTR in place. My experience is that unless an element of the ring is clearly visible (with mild indentation), it might better to leave it untouched. If the CTR does dislocate into the vitreous cavity, removal should be done via a three-port pars plana vitrectomy [1].

The CTR may alternatively be inserted after removal all of the lens material, prior to IOL implantation, or even after IOL implantation. The CTR distributes the force of the intact zonules to support the entire capsular equator. The CTR increases somewhat the weight of the unstable capsular bag; however, the weight addition is apparently negligible compared with its obvious advantages. Another advantage of the CTR is prevention of capsular phimosis seen postoperatively, usually with silicone lenses or in cases of pseudoexfoliation [13, 19].

Summary for the Clinician

- Using an injector is easier and safer than manual insertion.
- An intact capsular bag and a continuous capsulorhexis are prerequisites for using a CTR.
- A safety-suture may assist secure insertion and removal of the CTR.
- Modified CTRs are used to fixate the lens to the scleral wall without jeopardizing the integrity of the capsular bag.

2.6 Other Types of CTRs

The most commonly used CTRs are 12.0/10.0 mm or 13.0/11.0 mm rings. CTRs were made in various sizes and configurations to fit small (hypermetropic, pediatric) and large (myopic) eyes (14.0/12.0 mm).

Capsular tension rings assist stability and centration of PC-IOLs in cases of small to moderate zonular dialysis; however, in the presence of large zonular defects (>5 clock hours) CTRs may not be sufficient. Logically, if the crystalline lens was decentered prior to surgery, one may expect that an artificial lens, placed within the same bag, will also be displaced. Suture fixation of the CTR to the scleral wall may provide the necessary lateral support for the bag. Osher presented in 1997 the "synthetic zonule" (Video Journal of Cataract Implant Surgery 8 [8]) and Assia developed a technique to suture a CTR through the capsule in a relatively closed system (ASCRS meeting 1996, Seattle, WA, USA). However, the sharp needle and the thin suture may "cheese wire" the posterior capsule and the break may extend posteriorly and jeopardize IOL fixation. CTRs designed for scleral fixation were later developed by Cionni and Osher and include an additional hook that arises perpendicular to the plain of the CTR and bends around the capsulorhexis to approach the scleral wall. The eyelet at the end of the hook is used for trans-scleral fixation of the ring without damaging the lens capsule (Fig. 2.3) [6, 7]. For cases of very large zonular defects modified versions of Cionni rings with two hooks were designed. Alternatively, the surgeon may use two one-hook Cionni rings in the same eye. Implantation of the Cionni ring is quite challenging and not without complications. Insertion and the ring position are cumbersome and the zonular defect may enlarge, the anterior CCC may tear, or corectopia may occur [16]. Nevertheless, clinical results are encouraging and this ring broadened the ability to preserve the capsular bag in cases with zonular defects larger than

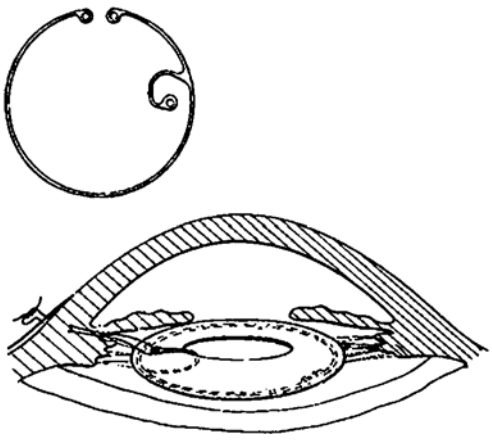

Fig. 2.3 Schematic illustration of Cionni's ring

4–5 h [13]. The Cionni ring was further modified by Ahmed with ring segments that are easier to implant and manipulate.

We have recently developed a new model of anchoring device, independent of an equator ring or segment, to fixate the subluxated capsular bag to the scleral wall. The one-plane, single-piece PMMA capsular "anchor" (Hanita lenses, Kibbutz Hanita, Israel) is inserted after an intact capsulorhexis has been performed, to grasp the anterior lens capsule. The device acts like a paper clip, pressing the anterior lens capsule between its horizontal bars. The capsular "anchor" is fixated to the scleral wall using a 9-0 or 10-0 polypropylene suture. A safety suture can also be used to facilitate implantation and ensure that the device will not fall backward through the zonular defect (Fig. 2.4). A CTR can also be inserted, either be-

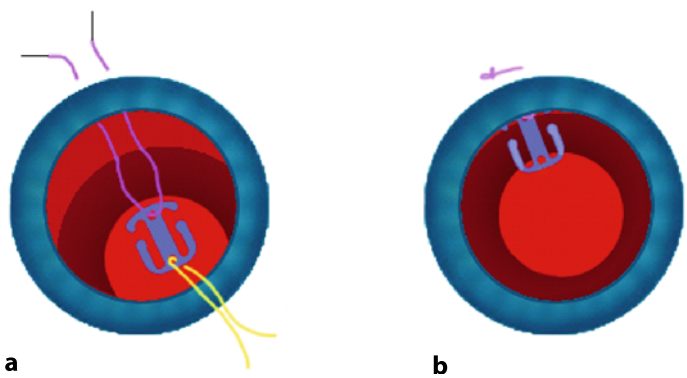

Fig. 2.4 Schematic illustration of the capsular "anchor". **a** The 9-0 or 10-0 polypropylene scleral suture (*purple*) is threaded through the hole in the base of the single-plane device. A safety suture (*yellow*) can be used to prevent dislocation through the large zonular defect. **b** The two lateral arms of the device are inserted underneath the capsulorhexis to grasp the anterior capsule. The scleral suture is tied when the capsulorhexis is centralized and the knot is buried in the sclera

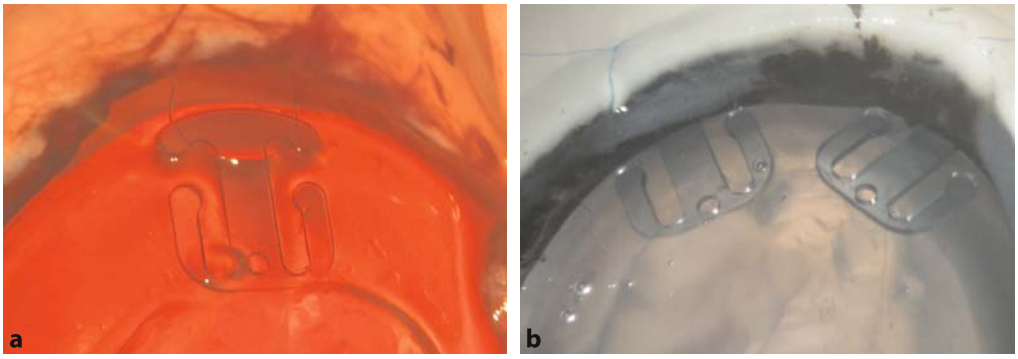

Fig. 2.5 The capsular "anchor" in experimental animal models. **a** A living rabbit eye. In this model the scleral suture is wrapped around the base of the device. **b** Two capsular clips in a porcine model after fixation to the scleral wall

fore or after placing the capsular anchor, or not used at all. In the case of large zonular defects, two or more clips can be used. Preliminary studies were carried out in dead porcine and live rabbit eyes after cutting a large portion of the zonular fibers. The capsular anchor was found to be quite easy to implant and very effective in the animal studies. Clinical studies are now underway.

Dick et al. recently presented a closed foldable capsular ring (CFCR) composed of alternate flexible (hydrophilic) and solid (hydrophobic) segments that can be injected or manually inserted through the surgical opening [9]. This ring, however, cannot be inserted prior to lens removal to stabilize the lens equator. Also, the final diameter of a closed ring configuration is predetermined; thus, various sizes may be required to fit the large variety of capsular dimensions.

Endocapsular rings were developed not only to provide support to the capsular equator in eyes with compromised zonules. CTRs with tinted segments are used to treat partial or complete iridal defects (traumatic, surgical or colobomatous) and alleviate symptoms such as glare and monocular diplopia [11, 13]. The contact of CTR elements on the lens equator, at the location of the epithelial germinal cells, may potentially reduce cell proliferation and posterior capsular opacification (PCO). In 1997–1998 we experimented on flexible latex rings in rabbit eyes and demonstrated that wide square-edged equator rings can indeed reduce PCO rate in this animal model [3]. Menapace et al. designed a broad, square-edged capsular bending ring (CBR) to reduce PCO by two mechanisms: prevention of cell migration by the ring bending effect and separation of the anterior and posterior capsule by the broad profile of the CBR [13].

2.7 Dislocation of Capsular PC-IOL

Intraocular lense dislocation has been reported in 0.2–2.8% of eyes undergoing a cataract operation, even many years after surgery [10]. An IOL placed within the capsular bag may subluxate laterally or dislocate posteriorly while still in the bag, most commonly in eyes with pseudoexfoliation. The degenerative process of PXF progresses with age, the surgical maneuvers weaken the zonules and late capsular contraction further imposes tension on the compromised zonular fibers. A minor, often unnoticed, trauma may end up causing lens dislocation and acute loss of vision. Most surgeons usually prefer to remove the dislocated IOL and replace it with another lens, either an anterior chamber lens or a sutured posterior chamber IOL. In recent years, a large variety of surgical techniques were reported to refixate the same IOL to either the scleral wall or to the iris diaphragm [10, 15, 18]. The main advantage of this approach is avoiding the large corneal or scleral opening required to remove the IOL while still in the capsular bag. Most of these techniques are based on externalizing an element of the haptic in order to tie the suture [15]. In the last 13 years we have used a technique to reposition and suture misplaced IOLs, either within or

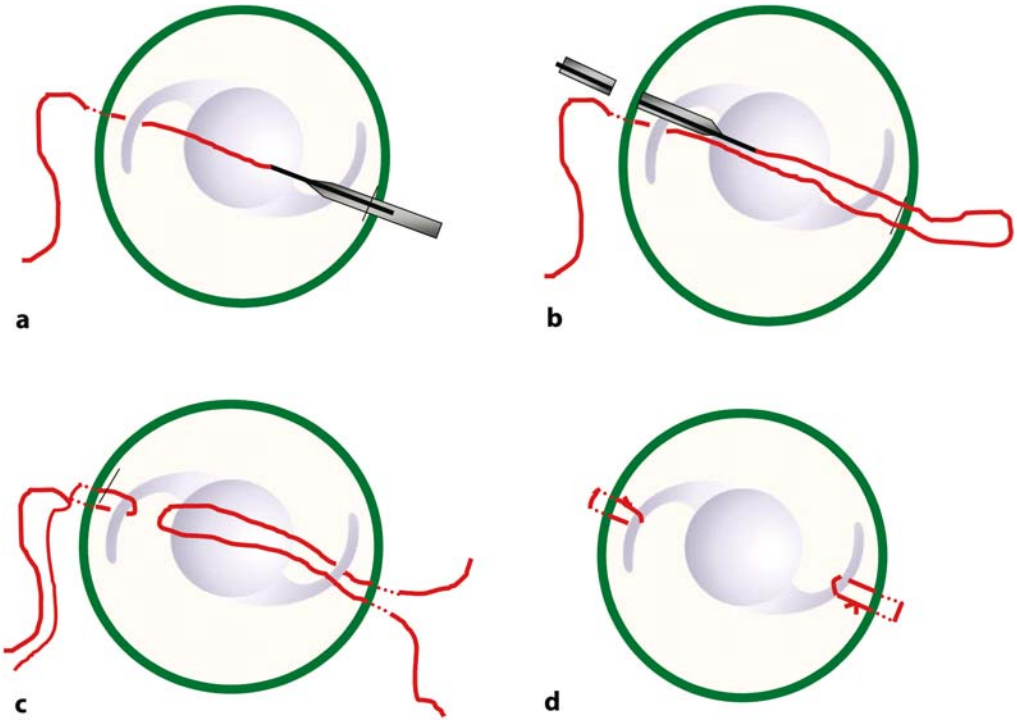

Fig. 2.6 The "closed system scleral fixation" technique. **a** The 9-0 or 10-0 prolene suture with a long (16 mm) needle is inserted 0.5–1.0 mm posterior to the limbus *behind* the IOL loop. A 27G needle is inserted through a paracentesis on the opposite side to guide the suture needle through the incision. **b** The suture needle is rotated 180° and reinserted through the same paracentesis. The 27G needle is inserted through the scleral wall to pass *in front* of the IOL loop. **c** A ring suture is created around the IOL haptic. A similar procedure is carried out on the opposite side. **d** Final position of the IOL. The knots are buried and no scleral flaps are needed. The entire procedure was performed through two paracenteses and four needle holes

outside the capsular bag [5]. The "closed system scleral fixation technique" is performed through external incisions no bigger than two paracenteses and four needle holes (Fig. 2.6). We have used this technique in tens of cases including solid and soft IOLs, one-piece or three-piece looped lenses, and even plate haptic IOLs, in which the needle was threaded through the large hole in the haptic. This technique is especially effective in eyes with a CTR since the location of the sutures is, than, less critical.

Scleral and iris suturing are effective for both primary and secondary fixation of PC-IOLs; however, stability of the lenses then depends entirely on two 10-0 sutures, made of a biodegradable material. There are numerous reports on recurrent lens dislocation following scleral fixation because of suture breakage [4]. Therefore, it is now our policy to secure each haptic with at least two separate sutures, preferably one to the iris and one to the sclera. Also, a 9-0 prolene suture is probably superior to a 10-0 suture because of its significantly higher tensile strength. Hopefully, stronger non-degradable sutures will soon be introduced onto the market, such as Gortex sutures, to provide safer long-term fixation.

Summary for the Clinician

- Dislocated IOLs can be repositioned and fixated to the scleral wall and/or the iris diaphragm in a relatively closed system.

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Chapter 3

Management of the Small Pupil for Cataract Surgery

3

Alan S. Crandall

Core Messages

- While there are various causes of small pupils, adequate pupil size is imperative for safe cataract removal.
- Instruments to produce three- or four-point stretches with one hand have been designed. However, if the procedure is done too quickly the tears will be longer.
- The pupil should only be opened enough to complete phacoemulsification safely. There are diamond-shaped hooks to make sub-incisional insertion easier and decrease iris damage.
- The silicone expander has been revised recently to make insertion and removal easier.
- Devices designed to expand the pupils made of PMMA are placed manually.
- Several equally spaced mini-sphincterotomies can benefit patients with very small pupils.
- Flomax has led to intraoperative floppy iris syndrome. Not only does the floppy iris billow with the flow in the anterior chamber, it will also prolapse into the phaco and side port incisions.
- There are different strategies available to reduce posterior capsule tears during surgery.

3.1 Introduction

A small pupil is a relatively common problem experienced during cataract surgery [5]. The definition of a small pupil will differ with each surgeon, but is generally defined as a pupil less than 4 mm in diameter. It has been shown that about 1.6% of cases will fall into this category [4]. Furthermore, the presence of a small pupil is a significant risk factor for the development of complications during cataract surgery [7, 9]. A small pupil also makes it more difficult to complete each step of the surgery including the capsulorrhexis, the phacoemulsification itself, and the irrigation/aspiration procedure. Lens insertion can be more difficult and visualization of the hepatics and the IOL position difficult to evaluate.

3.2 Surgical Management of the Small Pupil

Preoperatively identify patients that are likely to have a small pupil and consider starting a nonsteroidal anti-inflammatory agent prior to surgery. If the patient is on miotics, stop them, if possible, 2 weeks before surgery. Be prepared to handle the iris (see below) with a variety of techniques [1, 4, 11].

The type of anesthesia is surgeon-dependent, but topical anesthesia provides acceptable comfort levels for the patient. After the paracentesis, 0.4–0.6 cc of unpreserved lidocaine (1%) with 1:100,000 unpreserved epinephrine will often help. Injection of viscoelastic to maintain the chamber is followed by inspection of the iris with an instrument such as a Kuglen hook, which helps to identify synechia. If adhesions or a thin, veneer-like membrane are present these should be removed by nonsharp forceps (Fig. 3.1).

There are many causes of small pupils. Previous use of miotics in patients with glaucoma, synechia from anterior uveitis, and previous

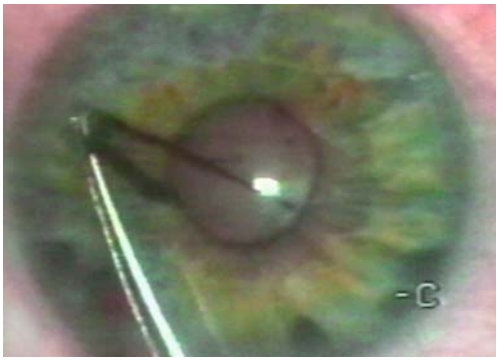

Fig. 3.1 Stripping of posterior synechia

trauma may cause iris damage as well as posterior synechia. Some older patients do not dilate well for obvious reasons. The most common cause of a small surgical pupil is the pseudoexfoliation syndrome with or without glaucoma [9]. Patients with pseudoexfoliation syndrome may also have weak zonules and fragile capsules, further complicating the surgery, and making management of the pupil imperative.

In managing the pupil we have two goals. Primarily, we need to achieve adequate pupil size to perform safe cataract removal, but we also want to maintain pupillary function and good cosmoses.

3.2.1 Two-Instrument Iris Stretch

There are a variety of techniques available to aid the surgeon with the management of small pupils. The simplest is the two-instrument iris stretch [1, 3]. After the chamber is deepened with viscoelastic, two hooks (Kuglen or Y-hooks) are utilized. One is placed through the paracentesis and one through the phaco incision. Once the iris is hooked, the two instruments are slowly moved toward the limbus 180° apart (Fig. 3.2). If necessary this can be repeated 90° apart.

3.2.2 Iris Stretch: Beehler Device

Another technique for iris stretching is the use of instruments that have been designed to produce a three- or four-point stretch with one hand.

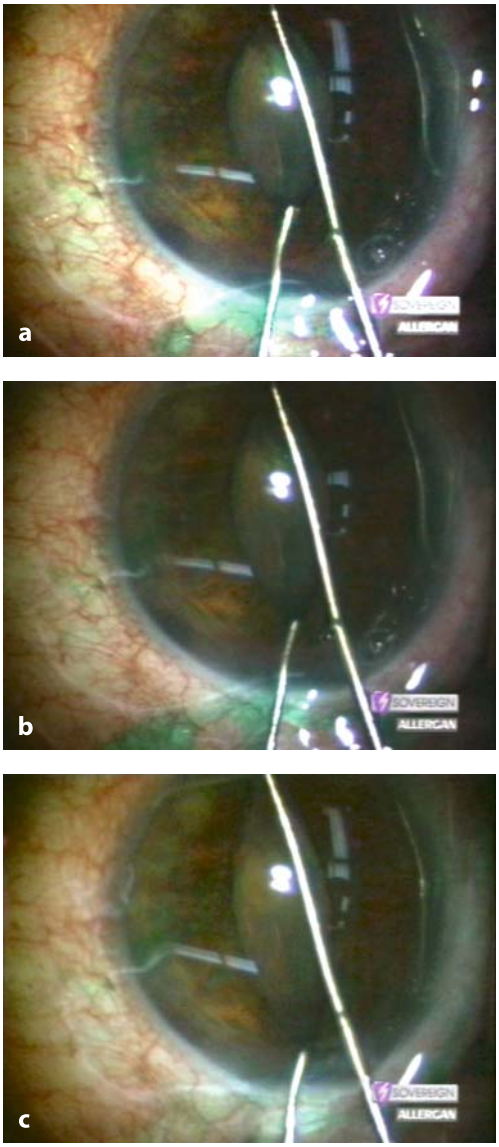

Fig. 3.2 Two-instrument iris stretch

The Moria Company (#18032) in association with Beehler makes a four-point unit (with three prongs) that requires a 3.0-mm incision (Fig. 3.3) while ASICO (AE-2225) and Katena (K-3-4950) have made three-point devices (with two prongs) that can go through smaller incisions (Fig. 3.4).

Once the anterior chamber has been filled with a viscoelastic material the instrument is

Fig. 3.3 Beehler 3-pronged instrument

Fig. 3.4 Beehler 2-pronged instrument

inserted through the incision turned sideways to allow the hook to pass into the chamber. The hook is then rotated downward and the sub-incisional iris engaged. The splines are extended and manipulated to engage the pupil margin and then slowly the instrument is gently pulled toward the incision to stretch the iris in the three or four directions. The splines are then retracted and the instrument is moved centrally to release the sub-incisional iris, the hook is rotated, and the instrument is removed (Fig. 3.5). Like the two-instrument stretch, this will cause multiple tears in the iris and may leave the iris flaccid. Care during the phaco is important to avoid further damage to the iris (Fig. 3.5).

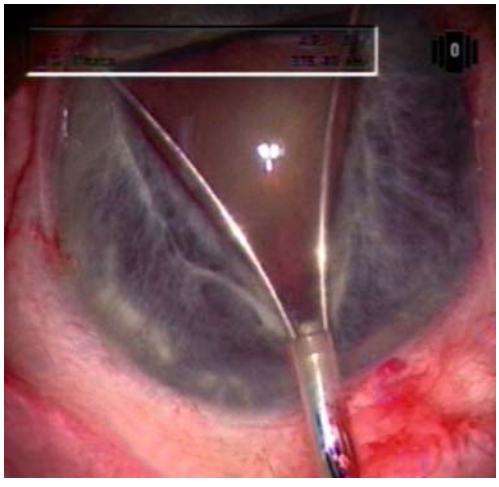

Fig. 3.5 Beehler instrument in use

It has been shown that stretching can cause micro-sphincter tears and if the procedure is done too quickly the tears will be longer and may lead to permanent mydriasis.

Summary for the Clinician

- There are three-point devices that can go through smaller incisions.
- This can cause multiple tears and may leave the iris floppy.

3.2.3 Iris Stretch/Iris Retractors

There are both nylon and titanium iris retractors available to dilate the pupil. The titanium instruments are reusable. Both the nylon and titanium retractors use silicone cinches to adjust the iris position. It is important to place the paracentesis correctly. If they are too anterior this will pull the iris up and result in difficulty in insertion of the phaco tip and problems with flow.

It is not necessary to enlarge the pupil maximally. This can lead to postoperative pupil irregularity and dysfunction due to permanent damage to the iris. The pupil should therefore be opened only to the point that is comfortable for the surgeon to complete safe phacoemulsification (Fig. 3.6). To make the sub-incisional phaco insertion easier and decrease the likelihood of iris damage, Oetting designed a diamond-shaped configuration of the iris hooks (Figs. 3.6, 3.8d).

Summary for the Clinician

- Both nylon and titanium retractors use silicone cinches, but the titanium instruments are reusable.
- If the paracentesis is too anterior the iris will be pulled up and insertion of the phaco tip will be difficult, also resulting in problems with flow.
- Permanent damage to the iris may result if the pupil is distended maximally, leading to postoperative pupil irregularity.

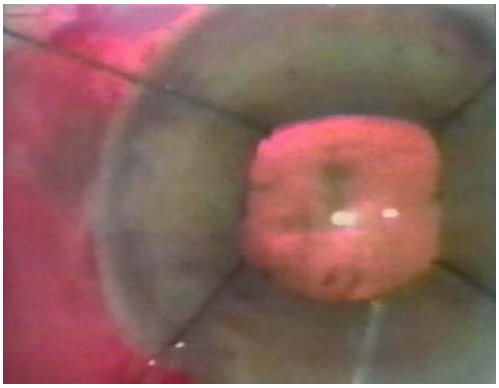

Fig. 3.6 Nylon iris hooks

3.2.4 Silicone Pupil Expander

John Graether developed a silicone expander, which has been recently revised to make its insertion easier (Fig. 3.7). It is made of silicone and comes in different diameters. Once the chamber is deepened with viscoelastic, a small sleeve is used to retract the iris sub-incisionally. The sleeve is placed across the anterior chamber and seated on the iris. It is released by an injector. After IOL insertion it can easily be removed.

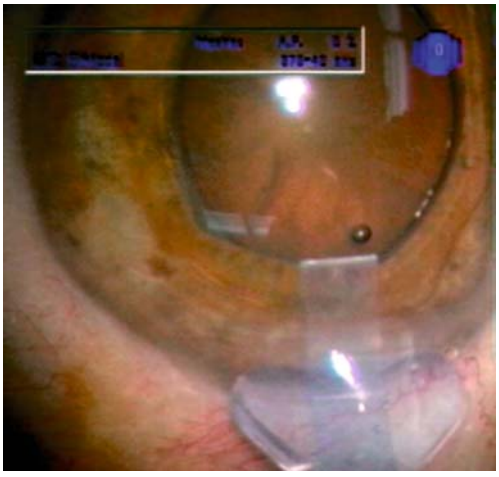

Fig. 3.7 Graether silicone iris expander

Summary for the Clinician

- Made of silicone, this expander comes in various diameters.
- The iris is retracted sub-incisionally using a small sleeve once the chamber is deepened with viscoelastic. It is released by an injector.

3.2.5 PMMA Pupil Expanders

Morcher, a company from Germany, has designed a clever device to expand the pupil (Fig. 3.8b). It can be injected with a device from Moria or placed manually with forceps. It leaves an open area toward the incision to allow phaco unhindered and removal is fairly easy.

The Perfect Pupil is also made of PMMA. It is inserted manually and requires the incision to be enlarged slightly. Removal is a little difficult.

Summary for the Clinician

- Both expanders are inserted manually, but the expander from Morcher can also be injected.
- The Perfect Pupil requires a slightly larger incision.

3.2.6 Multiple Sphincterotomies

In patients with very small pupils, or fibrotic irides, it is sometime advantageous to use a tech-

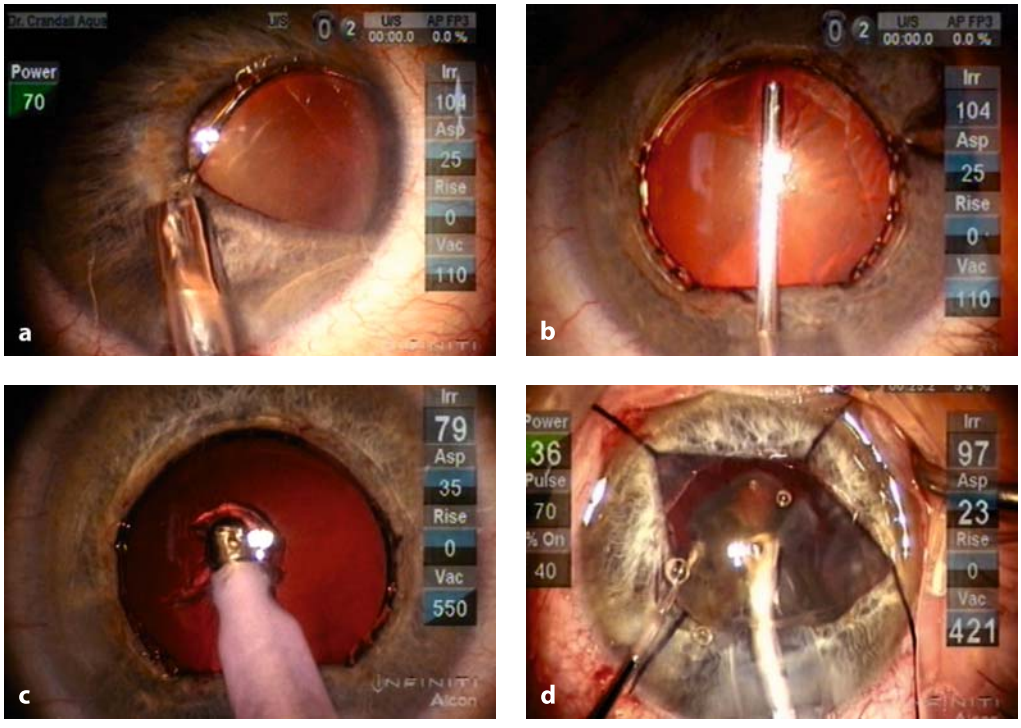

Fig. 3.8 Morcher iris diaphragm

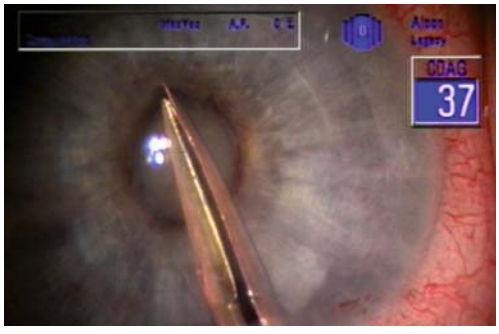

Fig. 3.9 Fine mini-sphincterotomies

nique devised by Fine [4]. After the chamber is filled with viscoelastic, six to eight equally spaced mini-sphincterotomies are performed. The incisions are made 0.5 mm into the pupillary sphincter, and then the pupil can be stretched using any of the above techniques. The small incisions will allow the sphincter to remain functional and reduce the tears in these small pupils (Fig. 3.9).

Summary for the Clinician

- By performing these multiple small incisions, the sphincter remains useful and the tears are decreased.
- Six to eight equally spaced mini-sphincterotomies are performed after the chamber is filled.

3.2.7 Special Circumstances: Systemic Alpha 1 Blockers

There are several medications available for the treatment of benign prostatic hypertrophy. These medications are alpha 1 blockers and they improve the urinary outflow by relaxing the smooth muscle in the bladder neck and the bladder. Tamsulosin (Flomax) is favored by urologists because it has fewer systemic side effects than others such as doxazosin (Cardura), terazosin (Hytrin) or alfuzosin (Uroxatral). Flomax has a high affinity

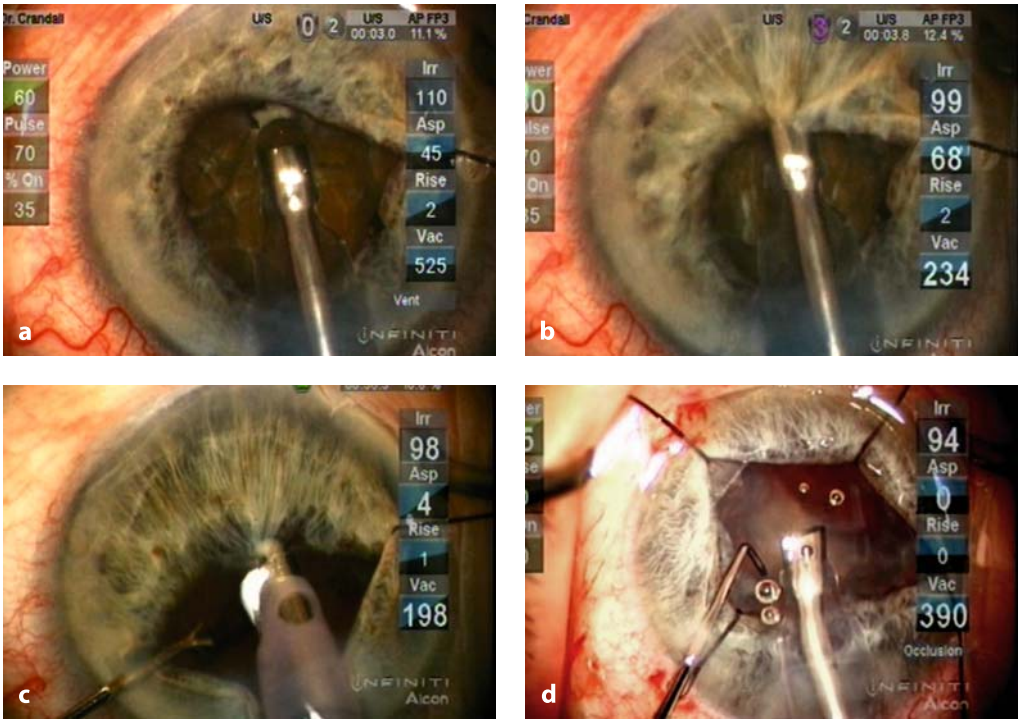

Fig. 3.10 Intraoperative floppy iris syndrome

and specificity for the alpha 1-A receptor subtype, which is the predominant receptor in the prostate and the bladder.

It has been shown that the alpha 1-A receptor is in the iris dilator muscle [10]. The use of Flomax has led to a condition called intraoperative floppy iris syndrome (IFIS) recently described by Chang and Campbell (Fig. 3.10) [2].

The syndrome involves a triad of findings. First, the iris is floppy and tends to billow with the normal flow in the anterior chamber. Second, the iris tends to prolapse into the phaco and side port incisions. Finally, and most concerning, is the tendency toward progressive pupil constriction during surgery. This combination can lead to difficult surgery and in the original communication the authors had a 12.5% capsule rupture rate.

Different strategies are available for the operative management of IFIS to reduce the problem of posterior capsule tears. It is important to understand that pupil stretching is detrimental and that it is necessary to change your machine parameters to low flow techniques. The bottle height should be lowered to around 70 cm, the aspiration flow rate to below 25 cc/min, and the vacuum to less than 250 mmHg.

The iris itself can be effectively handled by a variety of methods. The use of iris hooks to hold the iris is effective especially in the diamond configuration as described by Oetting and Omphroy [8]. Other mechanical devices, such as the Morcher iris diaphragm, the Graether pupil expander (Eagle Vision), or the Perfect Pupil (BD Medical Systems) are also helpful. However, in most cases the iris can be maintained by the use of Healon V (AMO). The Healon will remain in the chamber with the low flow parameters as described by Osher et al. [6] and can be re-added to the anterior chamber if the iris comes down, as described by Koch.

Summary for the Clinician

- Pupil stretching is detrimental and it is very important that the following measures be taken seriously:
- The machine parameters should be changed to low flow techniques;
- The bottle height should be lowered to around 70 cm;
- The aspiration flow rate should be lowered to below 25 cc/min;
- The vacuum should be lowered to less than 250 mmHg.

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Chapter 4

Advanced Intraocular Lens Power Calculations

4

John P. Fang, Warren Hill, Li Wang, Victor Chang, Douglas D. Koch

Core Messages

- Accurate IOL power calculations are a crucial element for meeting the ever increasing expectations of patients undergoing cataract surgery.
- Although ultrasound biometry is a well-established method for measuring axial length optical coherence biometry has been shown to be significantly more accurate and reproducible.
- The power adjustment necessary between the capsular bag and the ciliary sulcus will depend on the power of the intraocular lens.
- When the patient has undergone prior corneal refractive surgery, or corneal transplantation, standard keratometric and topographic values cannot be used.
- Several methods have been proposed to improve the accuracy of IOL power calculation in eyes following corneal refractive surgery; these can be divided into those that require preoperative data and those that do not.
- Because it is impossible to accurately predict the postoperative central power of the donor graft, there is presently no reliable method for calculating IOL power for eyes undergoing combined corneal transplantation and cataract removal with intraocular lens implantation.
- The presence of silicone oil in the eye complicates intraocular lens power measurements and calculations.

4.1 Introduction

Accurate intraocular lens (IOL) power calculations are a crucial element for meeting the ever increasing expectations of patients undergoing cataract surgery. As a direct result of technological advances, both our patients and our peers have come to view cataract surgery as not only a rehabilitative procedure, but a refractive procedure as well. The precision of IOL power calculations depends on more than just accurate biometry, or the correct formula, but in reality is a collection of interconnected nuances. If one item is inaccurate, the final outcome will be less than optimal.

4.2 Axial Length Measurement

By A-scan biometry, errors in axial length measurement account for 54% of IOL power error when using two-variable formulas [23]. Because of this, much research has been dedicated to achieving more accurate and reproducible axial lengths. Although ultrasound biometry is a well-established method for measuring ocular distances, optical coherence biometry has been shown to be significantly more accurate and reproducible and is rapidly becoming the prevalent methodology for the measurement of axial length.

4.2.1 Ultrasound

Axial length has traditionally been measured using ultrasound biometry. When sound waves encounter an interface of differing densities, a fraction of the signal echoes back. Greater dif-

ferences in density produce a greater echo. By measuring the time required for a portion of the sound beam to return to the ultrasound probe, the distance can be calculated ($d = v \times t)/2$. Because the human eye is composed of structures of varying densities (cornea, aqueous, lens, vitreous, retina, choroid, scleral, and orbital fat), the axial length of each structure can be indirectly measured using ultrasound. Clinically, applanation and immersion techniques have been most commonly used.

4.2.1.1 Applanation Technique

With the applanation technique, the ultrasound probe is placed in direct contact with the cornea. After the sound waves exit the transducer, they encounter each acoustic interface within the eye and produce a series of echoes that are received by the probe. Based on the timing of the echo and the assumed speed of the sound wave through the various structures of the eye, the biometer software is able to construct a corresponding echogram. In the phakic eye, the echogram has six peaks (Fig. 4.1), each representing the interfaces of:

1. Probe tip/cornea,
2. Aqueous fluid/anterior lens,
3. Posterior lens/vitreous,
4. Vitreous/retina,
5. Retina/sclera,
6. Sclera/orbital fat.

The axial length is the summation of the anterior chamber depth, the lens thickness, and the vitreous cavity.

The y-axis shows peaks (known as spikes) representing the magnitude of each echo returned to the ultrasound probe. The magnitude or height of each peak depends on two factors. The first is the difference in densities at the acoustic interface; greater differences produce higher echoes. The second is the angle of incidence at this interface. The height of a spike will be at its maximum when the ultrasound beam is perpendicular to the acoustic interface it strikes. The height of each spike is a good way to judge axiality and, hence, alignment of the echogram.

Because the applanation technique requires direct contact with the cornea, compression will typically cause the axial length to be falsely shortened. During applanation biometry, the compression of the cornea has been shown to range

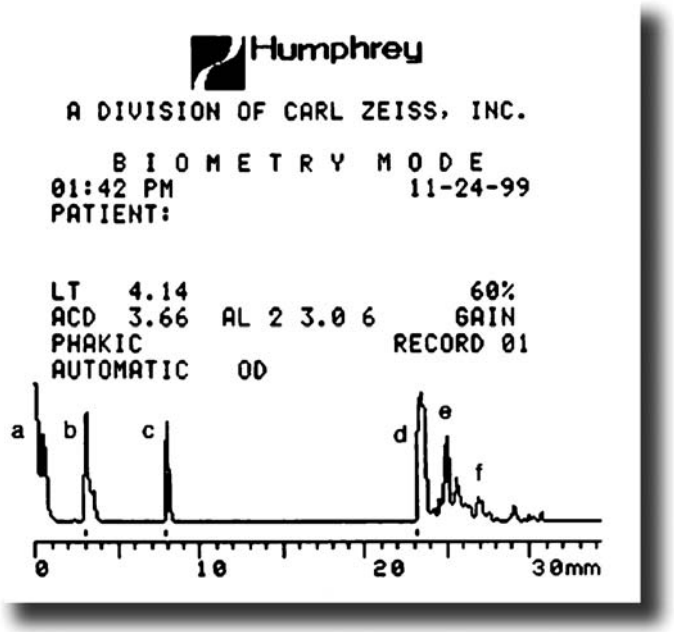

Fig. 4.1 Phakic axial length measurement using the applanation technique. **a** Initial spike (probe tip and cornea), **b** anterior lens capsule, **c** posterior lens capsule, **d** retina, **e** sclera, **f** orbital fat

from 0.14 to 0.33 mm [24, 29, 30]. At normal axial lengths, compression by 0.1 mm results in a postoperative refractive error toward myopia of roughly 0.25 D. Additionally, this method of ultrasound biometry is highly operator-dependent. Because of the extent of the error produced by direct corneal contact, applanation biometry has given way to noncontact methods, which have been shown to be more reproducible.

4.2.1.2 Immersion Technique

The currently preferred A-scan method is the immersion technique, which, if properly performed, eliminates compression of the globe. Although the principles of immersion biometry are the same as with applanation biometry, the technique is slightly different. The patient lies supine with a clear plastic scleral shell placed over the cornea and between the eyelids. The shell is filled with coupling fluid through which the probe emits sound waves. Unlike the applanation echogram, the immersion technique produces an additional spike corresponding to the probe tip (Fig. 4.2). This spike is produced from the tip of the probe within the coupling fluid.

Although the immersion technique has been shown to be more reproducible than the applanation technique, both require mindfulness of the properties of ultrasound. Axial length is calculated from the measured time and the assumed average speed that sound waves travel through the eye. Because the speed of ultrasound varies in different media, the operator must account for prior surgical procedures involving the eye such as IOL placement, aphakia, or the presence of silicone oil in the vitreous cavity (Table 4.1). Length correction can be performed simply using the following formula:

True length = [corrected velocity/measured velocity] × measured length

However, using a single velocity for axial length measurements in eyes with prior surgery is much less accurate than correcting each segment of the eye individually and adding together the respective corrected length measurements. For example, in an eye with silicone oil, the anterior chamber depth would be measured at a velocity of 1,532 m/s, the crystalline lens thickness at 1,641 m/s, and the vitreous cavity at either 980 m/s or 1,040 m/s depending on the

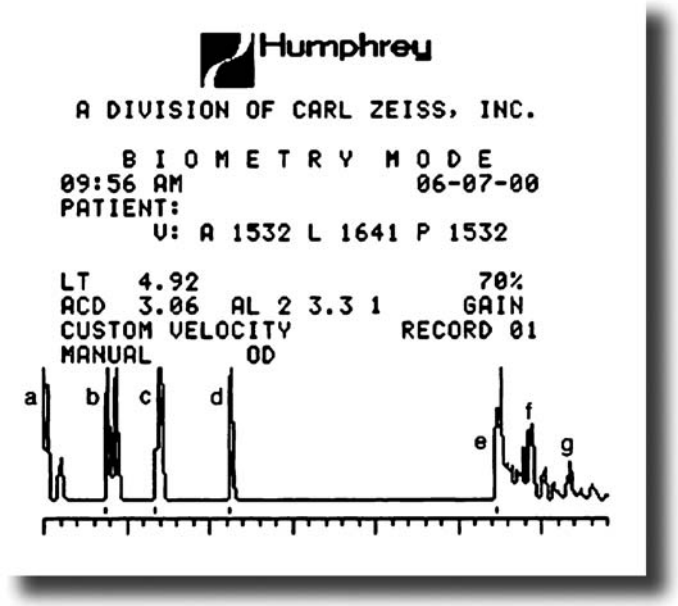

Fig. 4.2 Phakic axial length measurements using the immersion technique. **a** Probe tip—echo from tip of probe, has now moved away from the cornea and becomes visible; **b** cornea—double-peaked echo will show both the anterior and posterior surfaces; **c** anterior lens capsule; **d** posterior lens capsule; **e** retina; **f** sclera; **g** orbital fat

Table 4.1 Average velocities under various conditions for average eye length [16]. *PMMA:* polymethyl methacrylate

Condition	Velocity (m/s)
Phakic eye	1,555
Aphakic eye	1,532
PMMA pseudophakic	1,556
Silicone pseudophakic	1,476
Acrylic pseudophakic	1,549
Phakic silicone oil	1,139
Aphakic silicone oil	1,052
Phakic gas	534

density of the silicone oil (1,000 centistokes vs. 5,000 cSt). The three corrected lengths are then added together to obtain the true axial length. Sect. 4.8 describes in greater detail IOL calculations in eyes with silicone oil.

For pseudophakia, using a single instrument setting may also lead to significant errors because IOL implants vary in sound velocity and thickness (Table 4.2). By using an IOL material-specific conversion factor (CF), a corrected axial length factor (CALF) can be determined using:

$$CF = 1 - (VE/VIOL)$$
$$CALF = CF \times T$$

where VE = sound velocity being used (such as 1,532 m/s),
VIOL = sound velocity of the IOL material being measured,
T = IOL central thickness.

By adding the CALF to or subtracting it from the measured axial length, the true axial length is obtained.

Another source of axial length error is that the ultrasound beam has a larger diameter than the fovea. If most of the beam reflects off a raised parafoveal area and not the fovea itself, this will result in an erroneously short axial length reading. The parafoveal area may be 0.10–0.16 mm thicker than the fovea.

In addition to compression and beam width, an off-axis reading may also result in a falsely shortened axial length. As mentioned before, the probe should be positioned so that the magnitude of the peaks is greatest. If the last two spikes are not present (sclera and orbital fat), the beam may be directed to the optic nerve instead of the fovea.

In the setting of high to extreme axial myopia, the presence of a posterior staphyloma should be considered, especially if there is difficulty obtaining a distinct retinal spike during A-scan ultrasonography. The incidence of posterior staphyloma increases with increasing axial length, and it is likely that nearly all eyes with pathologic myopia have some form of posterior staphyloma. Staphylomata can have a major impact on axial length measurements, as the most posterior portion of the globe (the anatomic axial length) may not correspond with the center of the macula (the refractive axial length). When the fovea is situated on the sloping wall of the staphyloma, it may only be possible to display a high-quality retinal spike when the sound beam is directed eccentric to the fovea, toward the rounded bottom of the staphyloma. This will result in an erroneously long axial length reading. Paradoxically, if the

PMMA	2,713 m/s (Alcon MC60BM)
Acrylic	2,078 m/s (Alcon MA60BM)
First generation silicone	990 m/s (AMO SI25NB)
Second generation silicone	1,090 m/s (AMO SI40NB)
Another second generation silicone	1,049 m/s (Staar AQ2101V)
Hydrogel	2,000 m/s (B&L Hydroview)
HEMA	2,120 m/s (Memory lens)
Collamer	1,740 m/s (Staar CQ2005V)

Table 4.2 Velocities for individual intraocular lens materials [13]. *HEMA:* hydroxyethyl methylmethacrylate

sound beam is correctly aligned with the refractive axis, measuring to the fovea will often result in a poor-quality retinal spike and inconsistent axial length measurements.

Holladay has described an immersion A/B-scan approach to axial length measurement in the setting of a posterior staphyloma [4, 33]. Using a horizontal axial B-scan, an immersion echogram through the posterior fundus is obtained with the cornea and lens echoes centered while simultaneously displaying void of the optic nerve. The A-scan vector is then adjusted to pass through the middle of the cornea as well as the middle of the anterior and posterior lens echoes to assure that the vector will intersect the retina in the region of the fovea. Alternatively, as described by Hoffer, if it is possible to visually identify the center of the macula with a direct ophthalmoscope, the cross hair reticule can be used to measure the distance from the center of the macula to the margin of the optic nerve head. The A-scan is then positioned so that measured distance is through the center of the cornea, the center of the lens, and just temporal to the void of the optic nerve on simultaneous B-scan.

Summary for the Clinician

- Because the applanation technique requires direct contact with the cornea, compression will typically cause the axial length to be falsely shortened.
- The speed of ultrasound varies in different media. To account for this, the operator must alter ultrasound speed settings for eyes that are pseudophakic or aphakic or that contain silicone oil in the vitreous cavity.
- In the setting of high to extreme axial myopia, the presence of a posterior staphyloma should be considered.

4.2.2 Optical Coherence Biometry

Introduced in 2000, optical coherence biometry has proved to be an exceptionally accurate and reliable method of measuring axial length. Through noncontact means, the IOL Master (Carl Zeiss Meditec, Jena, Germany) emits an infrared laser beam that is reflected back to the instrument from the retinal pigment epithelium. The patient is asked to fixate on an internal light source to ensure axiality with the fovea. When the reflected light is received by the instrument, the axial length is calculated using a modified Michelson interferometer. There are several advantages of optical coherence biometry:

1. Unlike A-scan biometry, the optical coherence biometry can measure pseudophakic, aphakic, and phakic IOL eyes. It can also measure through silicone oil without the need for use of the velocity cenversion equation.
2. Because optical coherence biometry uses a partially coherent light source of a much shorter wavelength than ultrasound, axial length can be more accurately obtained. Optical coherence biometry has been shown to reproducibly measure axial length with an accuracy of 0.01 mm.
3. It permits accurate measurements when posterior staphylomata are present. Since the patient fixates along the direction of the measuring beam, the instrument is more likely to display an accurate axial length to the center of the macula.
4. The IOL Master also provides measurements of corneal power and anterior chamber depth, enabling the device to perform IOL calculations using newer generation formulas, such as Haigis and Holladay 2.

The primary limitation of optical biometry is its inability to measure through dense cataracts and other media opacities that obscure the macula; due to such opacities or fixation difficulties, approximately 10% of eyes cannot be accurately measured using the IOL Master [21].

When both optical and noncontact ultrasound biometry are available, the authors rely on the former unless an adequate measurement cannot be obtained. Both the IOL Master and immersion ultrasound biometry have been shown to produce a postoperative refractive error close to targeted values. However, the IOL Master is faster and more operator and patient-friendly.

Though mostly operator-independent, some degree of interpretation is still necessary for op-

timal refractive outcomes. During axial length measurements it is important for the patient to look directly at the small red fixation light. In this way, axial length measurements will be made to the center of the macula. For eyes with high to extreme myopia and a posterior staphyloma, being able to measure to the fovea is an enormous advantage over conventional A-scan ultrasonography. The characteristics of an ideal axial length display by optical coherence biometry are the following (Fig. 4.3):

1. Signal-to-noise ratio (SNR) greater than 2.0.
2. Tall, narrow primary maxima, with a thin, well-centered termination.
3. At least one set of secondary maxima. However, if the ocular media is poor, secondary maxima may be lost within a noisy baseline and not displayed.
4. At least 4 of the 20 measurements taken should be within 0.02 mm of one another and show the characteristics of a good axial length display.
5. If given a choice between a high SNR and an ideal axial length display with a lower SNR, the quality of the axial length display should always be the determining factor for measurement accuracy.

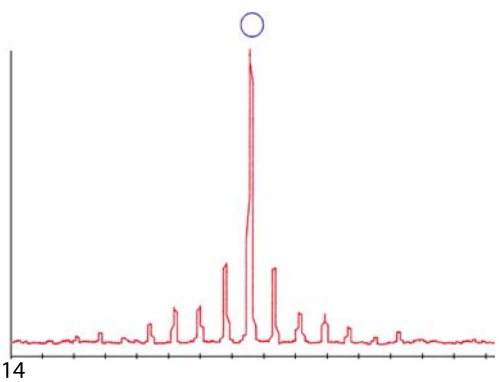

Fig. 4.3 An ideal axial length display by ocular coherence biometry in clear ocular media [12]

Summary for the Clinician

- Optical coherence biometry has proved to be an exceptionally accurate and reliable method of measuring axial length.
- The primary limitation of optical biometry is its inability to measure through dense cataracts and other media opacities that obscure the macula.

4.3 Keratometry

Errors in corneal power measurement can be an equally important source of IOL power calculation error, as a 0.50 D error in keratometry will result in a 0.50 D postoperative error at the spectacle plane. A variety of technologies are available, including manual keratometry, automated keratometry, and corneal topography. These devices measure the radius of curvature and provide the corneal power in the form of keratometric diopters using an assumed index of refraction of 1.3375. The obtained values should be compared with the patient's manifest refraction, looking for large inconsistencies in the magnitude or meridian of the astigmatism that should prompt further evaluation of the accuracy of the corneal readings.

Important sources of error are corneal scars or dystrophies that create an irregular anterior corneal surface. While these lesions can often be seen with slit lamp biomicroscopy, their impact on corneal power measurements can best be assessed by examining keratometric or topographic mires. The latter in particular give an excellent qualitative estimate of corneal surface irregularity (Fig. 4.4). In our experience, if the irregularity is considered to be clinically important, we try to correct it whenever feasible before proceeding with cataract surgery. Examples would include epithelial debridement in corneas with epithelial basement disease, and superficial keratectomy in eyes with Salzmann's nodular degeneration.

When the patient has undergone prior corneal refractive surgery, or corneal transplantation, standard keratometric and topographic values cannot be used. This topic will be further discussed in Sect. 4.6.

4.4 Anterior Chamber Depth Measurement

A-scan biometers and the IOL Master calculate anterior chamber depth as the distance from the anterior surface of the cornea to the anterior surface of the crystalline lens. In some IOL calculation formulas, the measured anterior chamber depth is used to aid in the prediction of the final postoperative position of the IOL (known as the effective lens position, or the ELP).

4.5 IOL Calculation Formulas

There are two major types of IOL formulas. One is theoretical, derived from a mathematical consideration of the optics of the eye, while the other is empirically derived from linear regression analysis of a large number of cases.

The first IOL power formula was published by Fyodorov and Kolonko in 1967 and was based on schematic eyes [7]. Subsequent formulas from Colenbrander, Hoffer, and Binkhorst incorporated ultrasound data [3, 5, 14]. In 1978, a regression formula was developed by Gills, followed by Retzlaff, then Sanders and Kraff, based on analysis of their previous IOL cases [8, 26, 28]. This work was amalgamated in 1980 to yield the SRK I formula [27]. All of these formulas depended on a single constant for each IOL that represented the predicted IOL position. In the 1980s, further refinement of IOL formulas occurred with the incorporation of relationships between the position of an IOL and the axial length as well as the central power of the cornea.

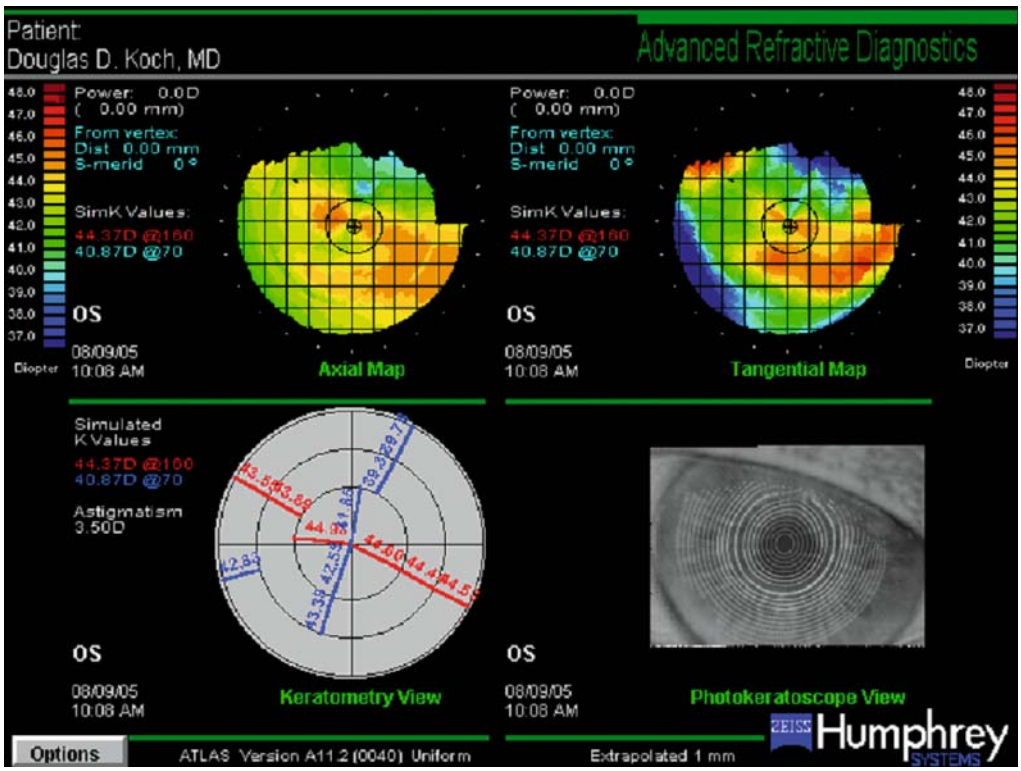

Fig. 4.4 Corneal surface irregularity shown on the Humphrey topographic map of an eye with epithelial basement disease

4.5.1 The Second and Third Generation of IOL Formulas

The IOL constants in the second and third generation of IOL formulas work by simply moving up or down the position of an IOL power prediction curve for the utilized formula. The shape of this power prediction curve is mostly fixed for each formula and, other than the lens constant, these formulas treat all IOLs the same and make a number of broad assumptions for all eyes regardless of individual differences.

For example, two hyperopic eyes with the same axial length and the same keratometry may require different IOL powers. This is due to two additional variables: of more importance, the actual distance from the cornea that the IOL will sit in the pseudophakic state (i.e., ELP) and to a lesser degree, the individual geometry of each lens model. Commonly used lens constants do not take both of these variations into account. These include:

SRK/T formula—uses an "A-constant,"

Holladay 1 formula—uses a "Surgeon Factor,"

Hoffer Q formula—uses a "Pseudophakic Anterior Chamber Depth" (pACD).

These standard IOL constants are mostly interchangeable—knowing one, it is possible to estimate another. In this way, surgeons can move from one formula to another for the same intraocular lens implant. However, the shape of the power prediction curve generated by each formula remains the same no matter which IOL is being used.

Variations in keratometers, ultrasound machine settings, and surgical techniques (such as the creation of the capsulorrhexis) can impact the refractive outcome as independent variables. "Personalizing" the lens constant for a given IOL and formula can be used to make global adjustments for a variety of practice-specific variables.

Popular third generation two-variable formulas (SRK/T, Hoffer Q and Holladay 1) also assume that the distance from the principal plane of the cornea to the thin lens equivalent of the IOL is, in part, related to the axial length. That is to say, short eyes may have a shallower anterior chamber and long eyes may have a deeper anterior chamber. In reality, this assumption may be invalid. Short eyes and many long eyes typically have perfectly normal anterior chamber anatomy with normal anterior chamber depth. The error in this assumption accounts for the characteristic limited axial length range of accuracy of each third generation two-variable formula. The Holladay 1 formula, for example, works well for eyes of normal to moderately long axial lengths, while the Hoffer Q has been reported to be better suited to normal and shorter axial lengths [15].

4.5.2 The Fourth Generation of IOL Formulas

A recent exception to all of this is the Haigis formula [9]. Rather than moving a fixed formula-specific IOL power prediction curve up or down, the Haigis formula instead uses three constants (a_0, a_1, and a_2) to set both the position and the shape of a power prediction curve:

$$d = a_0 + (a_1 * ACD) + (a_2 * AL)$$

where d is the effective lens position, ACD is the measured anterior chamber depth of the eye (corneal vertex to the anterior lens capsule), and AL is the axial length of the eye (the distance from the cornea vertex to the vitreoretinal interface). The a_0 constant basically moves the power prediction curve up, or down, in much the same way that the A-constant, Surgeon Factor, or pACD does for the SRK/T, Holladay 1, and Hoffer Q formulas. The a_1 constant is tied to the measured anterior chamber depth, and the a_2 constant is tied to the measured axial length. In this way, the value for d is determined by three constants, rather than a single number.

The a_0, a_1, and a_2 constants are derived by regression analysis from a sample of at least 200 cases and generate a surgeon and IOL-specific outcome for a wide range of axial lengths and anterior chamber depths. The resulting constants more closely match actual observed results for a specific surgeon and the individual geometry of an IOL implant. This means that a portion of the mathematics of the Haigis formula is individually adjusted for each surgeon/IOL combination.

The Holladay 2 formula uses another innovative approach, which is to use measurements of corneal power, corneal diameter, ACD, lens

thickness, refractive error, and axial length to further refine the ELP calculation. The Holladay 2 formula is based on previous observations from a 35.000 patient data set and has been shown to be advantageous in both long and short eyes.

Summary for the Clinician

- The shape of the power prediction curve is mostly fixed for each second and third generation formula.
- Popular third generation two-variable formulas may also assume that the distance from the corneal vertex to the thin lens equivalent of the IOL is, in part, related to the axial length and/or central corneal power.
- The fourth generation IOL power formulas address these issues.

4.5.3 Capsular Bag to Ciliary Sulcus IOL Power Conversion

Intraocular lens power formulas typically calculate the power of the intraocular lens to be positioned within the capsular bag. Occasionally, this is not possible, as with an unanticipated intraoperative tear in the posterior lens capsule. In order to achieve a similar postoperative refractive result with an IOL placed at the plane of the ciliary sulcus, a reduction in IOL power is typically required.

The power adjustment necessary between the capsular bag and the ciliary sulcus will depend on the power of the capsular bag IOL (Table 4.3). The important concept is that for stronger intraocular lenses, the reduction in power must be greater. For very low IOL powers, no reduction in IOL power is required. Table 4.3 will provide good results for most, modern posterior chamber IOLs.

Table 4.3 Intraocular lens (IOL) power correction for unanticipated sulcus implantation [13]

Capsular bag IOL power	Ciliary sulcus power adjustment
+35.00 D to +27.50 D	−1.50 D
+27.00 D to +17.50 D	−1.00 D
+17.00 D to +9.50 D	−0.50 D
+9.00 D to -5.00 D	No change

4.6 Determining IOL Power Following Corneal Refractive Surgery

The true corneal power following corneal refractive surgery is difficult to obtain by any form of direct measurement. This is because keratometry and topography measure the anterior corneal radius and convert it to total corneal power by assuming a normal relationship between the anterior and posterior corneal curvatures. However, unlike incisional corneal refractive surgery for myopia, which flattens both the anterior and the posterior corneal radius, ablative corneal refractive surgery for myopia primarily alters anterior corneal curvature. Additionally, standard keratometry measures a paracentral region and assumes that this accurately reflects central corneal power. For these reasons, keratometry and simulated keratometry by topography typically under-estimate central corneal power following ablative corneal surgery for myopia and overestimate it for corneas that have undergone hyperopic ablation.

There is a second and less commonly recognized source of unanticipated postoperative refractive error. As a general rule, IOL power calculations following all forms of corneal refractive surgery should not be run using an uncorrected two-variable, third-generation formula because they assume that the effective lens position is, in part, related to central corneal power. By using axial length and keratometric corneal power to estimate the postoperative location of the IOL, or the ELP, the artifact of very flat Ks following myopic corneal refractive surgery will cause these formulas to assume a falsely shallow postoperative ELP and recommend less IOL power than required. To avoid this potential pitfall, the double K feature of the Holladay 2 formula allows direct entry of two corneal power values by

checking the box "Previous RK, PRK…"; if the corneal power value before refractive surgery is unknown, the formula will use 43.86 D as the default preoperative corneal value. Another option is to apply Aramberri's "double K method" correction to the Holladay 1, Hoffer Q or SRK/T formulas [1] or refer to the IOL power adjustment nomograms published by Koch and Wang [19].

Several methods have been proposed to improve the accuracy of IOL power calculation in eyes following corneal refractive surgery; these can be divided into those that require preoperative data and those that do not.

4.6.1 Methods Requiring Historical Data

4.6.1.1 Clinical History Method

The clinical history method [18] for corneal power estimation requires accurate historical data and was first described by Holladay as:

Kp + SEp - SEa = Ka

where Kp = the average keratometry power before corneal refractive surgery,
SEp = the spherical equivalent before corneal refractive surgery,
SEa = the stable spherical equivalent after corneal refractive surgery,
Ka = the estimate of the central corneal power after corneal refractive surgery.

4.6.1.2 Feiz-Mannis IOL Power Adjustment Method

Another method that is helpful to use when good historical data are available is the IOL power adjustment method of Feiz and Mannis et al. [6]. Using this technique, the IOL power is first calculated using the pre-LASIK (laser-assisted in situ keratomileusis) corneal power as though the patient had not undergone keratorefractive surgery. This pre-LASIK IOL power is then increased by the amount of refractive change at the spectacle plane divided by 0.7. This approach is outlined as follows:

IOLpre + (ΔD / 0.7) = IOLpost
where IOLpre = the power of the IOL as if no LASIK had been performed,
ΔD = the refractive change after LASIK at the spectacle plane,
IOLpost = the estimated power of the IOL to be implanted following LASIK.

4.6.1.3 Masket IOL Power Adjustment Method

Masket [22] has developed another method that adjusts the IOL power based on the amount of refractive laser correction. Instead of calculating IOL power with pre-LASIK data as above, this method modifies the predicted IOL power obtained using the patient's post-laser correction readings by using the following formula:

IOLpost + (ΔD × 0.326) + 0.101 = IOLadj

where IOLpost = the calculated IOL power following ablative corneal refractive surgery,
ΔD = the refractive change after corneal refractive surgery at the spectacle plane,
IOLadj = the adjusted power of the IOL to be implanted.

4.6.1.4 Topographic Corneal Power Adjustment Method

There are several approaches to modifying post-LASIK corneal power measurements:

1. To adjust the effective refractive power (EffRP) of the Holladay Diagnostic Summary of the EyeSys Corneal Analysis System by using the following formulas after myopic or hyperopic surgery respectively [11, 31]:

EffRP – (ΔD × 0.15) – 0.05 = post-myopic LASIK adjusted EffRP
EffRP + (ΔD × 0.16) – 0.28 = post-hyperopic LASIK adjusted EffRP

where ΔD = the refractive change after LASIK at the corneal plane.

2. To average the corneal curvatures of the center and the 1-mm, 2-mm, and 3-mm annular rings of the Numerical View of the Zeiss Humphrey Atlas topographer (AnnCP) and modify the result using the following formula [31]:

AnnCP + (ΔD × 0.19) – 0.4 = post-hyperopic LASIK adjusted AnnCP

3. To modify keratometry (K) values as follows [11]:

K – (ΔD × 0.24) + 0.15 = post-myopic LASIK adjusted K

This latter approach is not as accurate as the two above-mentioned topography-based methods.

4.6.2 Methods Requiring No Historical Data

4.6.2.1 Hard Contact Lens Method

This method does not require pre-LASIK data, but can only be used if the visual acuity is better than around 20/80 [34]:

Bc + Pc + SEc – SEs = Ka

where Bc = base curve of contact lens in diopters,
Pc = refractive power of contact lens in diopters,
SEc = spherical equivalent with contact lens in place,
SEs = spherical equivalent without contact lens,
Ka = estimated corneal power following refractive surgery.

Unfortunately, the literature now suggests that the hard contact lens method may be less accurate than originally thought following all forms of ablative corneal refractive surgery [2, 10, 17, 32]. Better results may require the use of contact lens designs with posterior curvatures that better fit the surgically modified corneal surface.

4.6.2.2 Modified Maloney Method

Another very useful method of post-LASIK corneal power estimation is one that was originally described by Robert Maloney and subsequently modified by Li Wang and Douglas Koch et al. [32]. Using this technique, the central corneal power is obtained by placing the cursor at the exact center of the Axial Map of the Zeiss Humphrey Atlas topographer. This value is then converted back to the anterior corneal power by multiplying this value by 376.0/337.5, or 1.114. An assumed posterior corneal power of 6.1 D is then subtracted from this product:

(CCP × 1.114) – 6.1 D = post-LASIK adjusted corneal power

where CCP = the corneal power with the cursor in the center of the topographic map.

The advantage of this method is that it requires no historical data and has a low variance when used with either the Holladay 2 formula or a modern third generation two-variable formula combined with the "double K method" correction nomogram published by Koch and Wang [19].

4.6.3 Hyperopic Corneal Refractive Surgery

For eyes that have undergone hyperopic LASIK, it is easier to estimate central corneal power than for myopic LASIK. This is presumably because the ablation takes place outside the central cornea. The average of the 1-mm, and 2-mm annular power rings of the Numerical View of the Zeiss Humphrey Atlas topographer can serve as an estimate of central corneal power following hyperopic LASIK. As an alternative, the adjusted EffRP of the EyeSys Corneal Analysis System proposed by Drs. Wang, Jackson, and Koch also works well (see Sect. 4.6.1.4) [31].

Remember that some form of a "double K method" is still required for IOL power calculations following hyperopic LASIK in order to avoid an inaccurate estimation of ELP.

Summary for the Clinician

- In eyes that have undergone ablative corneal surgery, IOL calculations are more complex due to difficulty in calculating true corneal refractive power and potential errors in estimating the effective lens position.
- A variety of approaches can be used to calculate corneal power (see Table 4.4).

4.6.4 Radial Keratotomy

Unlike the ablative forms of corneal refractive surgery (LASIK and PRK) in which only the anterior radius is changed, eyes that have previously undergone radial keratotomy experience flattening of both the anterior and posterior radii. This approximate preservation of the ratio between the anterior and posterior radii allows for a direct measurement of the central corneal power. Thus, any map that provides some average of anterior corneal power over the central 2–3 mm gives an accurate estimation of corneal refractive power. Examples include averaging the 0-mm, 1-mm, and 2-mm annular power rings of the Numerical View of the Zeiss Humphrey Atlas topographer and the EffRP from the Holladay Diagnostic Summary of the EyeSys Corneal Analysis System. It is important to remember that one still needs to compensate for potential errors in ELP by using the Holladay 2 formula or the double-K approach with third-generation formulas described in Sect. 4.6.

Patients with previous radial keratometry will also commonly show variable amounts of transient hyperopia in the immediate postoperative period following cataract surgery [20]. This is felt to be due to stromal edema around the radial incisions, which flattens the central cornea. Although usually transient, it may be as high as +6.00 D. It may be more likely to occur in eyes with eight or more incisions, an optical zone of less than 2.0 mm, or incisions that extend to the limbus. The hyperopia may take 8–12 weeks to resolve. Thus, we recommend following up these patients with refractions and topographic maps obtained at 2-week intervals, deferring surgical correction (IOL exchange or a piggyback IOL) until two reasonably stable refractions and topographies are obtained at the same time of the day.

Because of both the relative inaccuracy of IOL calculations in RK eyes and their tendency to experience a long-term hyperopic drift, we usually target IOL power calculations for –1.00 D. A detailed discussion with the patient regarding these issues is required. Finally, if more than 6 months passes before cataract surgery is required for the fellow eye, the corneal measurements should be repeated due to the fact that additional corneal flattening frequently occurs over time following radial keratotomy.

Summary for the Clinician

- Eyes that have previously undergone radial keratotomy experience flattening of both the anterior and posterior radii; this allows for a direct "averaging" measurement of the central corneal power.
- Patients with previous radial keratometry will commonly show variable amounts of transient hyperopia in the immediate postoperative period following cataract surgery.

4.6.5 Accuracy and Patient Expectations

It is important to explain to patients in that intraocular lens power calculations following all forms of corneal refractive surgery are, at best, problematic. In spite of our best efforts, the final refractive result may still end up more hyperopic or more myopic than expected. In addition, astig-

Table 4.4 Example of post-corneal refractive surgery intraocular lens calculation: a 50 year-old male underwent cataract extraction and posterior chamber IOL implantation in both eyes 5 years after myopic laser-assisted in situ keratomileusis (LASIK). The following data is from his left eye. *EffRP:* effective refractive power

Pre-cataract surgery data:

Pre-LASIK data:

- Pre-LASIK refraction: -8.50 D
- Pre-LASIK mean keratometry: 44.06 D

Post-LASIK data:

- Post-LASIK refraction: -0.50 D
- EffRP: 38.82 D
- Central topographic power (Humphrey Atlas): 39.00 D
- Contact lens over-refraction data: refraction without contact lens: -0.50 D, contact lens base curve: 37.75 D, contact lens power: +1.75 D, refraction with contact lens: -2.00 D

Post-cataract surgery data:

- An Alcon SA60AT lens with power of 23.5 D was implanted in this eye, and the manifest refraction after cataract surgery was +0.125 D

Corneal refractive power estimation:

Clinical history method:

- Pre-LASIK refraction at corneal plane (vertex distance: 12.5 mm): (-8.50)/{1-[0.0125*(-8.50)]} = -7.68 D
- Post-LASIK refraction at corneal plane: (-0.50)/{1-[0.0125*(-0.50)]} = -0.50 D
- Corneal power = 44.06 + (-7.68) - (-0.50) = 36.88 D

Hard contact lens method:

- Corneal power = 37.75 + 1.75 + [(-2.00) - (-0.50)] = 38.00 D

Adjusted EffRP:

- Adjusted EffRP = 38.82 - 0.15 * [(-0.50 - (-7.68)] - 0.05 = 37.69 D

Modified Maloney Method:

- Corneal power = 39.00 * (376/337.5) - 6.1 = 37.35 D

IOL power calculation (aiming at refraction of +0.125 D):

Clinical history method:

- IOL power using corneal power obtained from the clinical history method: 24.42 D

Hard contact lens method:

- IOL power using corneal power obtained from the hard contact lens method: 23.01 D

Adjusted EffRP:

- IOL power using Adjusted EffRP: 23.54 D

Modified Maloney method:

- IOL power using corneal power obtained from the Modified Maloney method: 23.94 D

Feiz-Mannis IOL power adjustment method:

- IOL power using pre-LASIK K: 14.55 D
- IOL power after LASIK: 14.55 + 7.18/0.7 = 24.81 D

Masket IOL power adjustment method

- IOL power using post-LASIK K (EffRP in this case): 20.19 D
- IOL power after LASIK: 20.19 + [-0.50 - (-7.68)] * 0.326 + 0.101 = 22.63 D

IOL power prediction error using different methods (Implanted – Predicted):

- Double-K clinical historical method: -0.92 D
- Double-K CL over-refraction: +0.49 D
- Double-K Adjusted EffRP: -0.04 D
- Double-K Modified Maloney method: -0.44 D
- Feiz-Mannis IOL power adjustment method: -1.31 D
- Masket IOL power adjustment method: +0.87 D

matism may be present and may not respond as expected to corneal relaxing incisions.

The higher order optical aberrations and multifocality that often accompany the various forms of corneal refractive surgery also remain unchanged following cataract surgery. For example, third- and fourth-order higher order aberrations produced by radial keratotomy can be as much as 35 times normal values. Elevated higher order aberrations are also seen following PRK and LASIK, particularly decentered ablations or older treatments with small central optical zones. Although the positive spherical aberration induced by myopic procedures may be partially ameliorated by implanting an IOL with negative asphericity, moderate to high amounts of positive spherical aberration usually remain. The visual consequence of these aberrations is loss of best-corrected acuity and contrast sensitivity and, understandably, some patients mistakenly expect that cataract surgery will alleviate these symptoms. Thus, it is important to discuss this prior to surgery so that their expectations will be realistic.

The active use of so many different methods of IOL calculation following corneal refractive surgery is eloquent testimony to how far we still have to go in this area. To minimize the risk of unexpected postoperative hyperopia, we generally recommend a refractive target of around –0.75 D, depending on the refractive status of the fellow eye.

See Table 4.4 for an example of an intraocular lens calculation following corneal refractive surgery.

4.7 Corneal Transplantation

There is presently no reliable method for calculating IOL power for eyes undergoing combined corneal transplantation and cataract removal with IOL implantation. This is because it is impossible to accurately predict the central power of the donor graft. There are several options:

1. Use a mean corneal power, based on evaluation of prior grafts, as a "best guess" of postoperative corneal power and proceed with IOL implantation. In eyes with an acceptable postoperative refractive error, additional lens surgery will not be required. For eyes with unacceptably high ametropia, options include IOL exchange, a piggyback IOL, or corneal refractive surgery.
2. Defer cataract surgery until the graft has stabilized, preferably after suture removal. Although more accurate, there would be a delay in visual rehabilitation and the second procedure may cause surgical trauma to the donor cornea.
3. Perform cataract extraction alone without IOL implantation in conjunction with the corneal graft. With this approach, there is minimal risk of trauma to the graft with the second procedure. However, it essentially eliminates the chance of implanting the IOL in the capsular bag.

Summary for the Clinician

- Because it is impossible to accurately predict postoperative central power of the donor graft, there is presently no reliable method for calculating IOL power for eyes undergoing combined corneal transplantation and cataract removal with IOL implantation.

4.8 Silicone Oil

For eyes containing silicone oil, A-scan axial length measurements are best carried out with the patient seated as upright as possible, especially if the vitreous cavity is partially filled with silicone oil. In the upright position, it is more likely that the silicone oil will remain in contact with the retina. In the recumbent position, the less dense silicone oil will shift away from the retina, toward the anterior segment. This can lead to confusion as to the correct interpretation of the position of the retinal spike.

The refractive index of silicone oil is also higher than that of the vitreous, requiring an adjustment to IOL power. To prevent the silicone oil from altering the refractive power of the posterior surface of the IOL, it is preferable to implant polymethyl methacrylate (PMMA) convex-plano lenses, with the plano side oriented toward the vitreous cavity and preferably over an intact posterior capsule. The additional power that

must be added to the original IOL calculation for a convex-plano IOL (with the plano side facing toward the vitreous cavity) is determined by the following relationship, as described in 1995 by Patel [25]:

((Ns – Nv)/(AL – ACD)) × 1,000 = additional IOL power (diopters)
where Ns = refractive index of silicone oil (1.4034),
Nv = refractive index of vitreous (1.336),
AL = axial length in mm,
ACD = anterior chamber depth in mm.

For an eye of average dimensions, and with the vitreous cavity filled with silicone oil, the additional power needed for a convex-plano PMMA IOL is typically between +3.0 D and +3.5 D. However, if the silicone oil will not be left in the eye indefinitely, then it might be preferable to use an IOL that will provide the optimal refractive error after the oil has been removed.

As an alternative, if the length of time that the silicone oil will remain in place is uncertain, a low-power single-piece PMMA can be placed in the ciliary sulcus to correct for the additional power required while the silicone oil is in place. At the time the silicone oil is removed, this "temporary" piggyback IOL can then be removed, restoring the eye to its former refractive power.

For patients who may possibly undergo a silicone oil procedure at some point in the future, it is recommended that bilateral baseline axial length measurements be carried out. This would include any patient with a prior retinal detachment, high axial myopia, proliferative vitreoretinopathy, proliferative diabetic retinopathy, acquired immune deficiency syndrome, giant retinal tear, or a history of perforating ocular injury.

Summary for the Clinician

- The presence of silicone oil in the eye complicates IOL power measurements and calculations.
- The refractive index of silicone oil is higher than that of the vitreous, requiring an adjustment to IOL power.

4.9 Conclusion

The methodology for accurately calculating IOL power in normal and complex eyes has improved dramatically in recent years. Future advances are needed in all areas, including methods of measuring corneal power, predicting effective lens position, and perhaps even measuring axial length. The ultimate solution may be an IOL whose spherical and astigmatic power and higher order aberrations can be modified postoperatively. Ideally, such an IOL could be modified multiple times to adapt to the patient's changing visual needs and to compensate for aging changes of the cornea.

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Refractive Surgery

Chapter 5

Customized Corneal Treatments for Refractive Errors

5

Scott M. MacRae, Manoj V. Subbaram

Core Messages

- The ultimate goal of custom corneal treatments is to satisfy patient's visual needs and can be achieved through anatomical, optical, and functional optimization.
- After establishing the safety of custom corneal treatment, the focus is now to reduce the incidence of postoperative "outliers," which results in decreased visual performance.
- Visual and refractive outcome following custom corneal treatment is influenced by many variables, which include wavefront measurement, and laser, surgical, biomechanical, and environmental factors.
- Significant improvement in the predictability of postoperative visual and refractive outcome can be achieved using nomogram adjustments and understanding the role of the epithelium in the corneal healing process.

5.1 Introduction

Laser refractive surgery has advanced rapidly, since the inception of excimer laser ablation in 1985 and LASIK (laser-assisted in situ keratomileusis) in 1990, and millions of patients worldwide have benefited from its use. Advancements such as scanning spot lasers to create smoother and subtler ablations, and eye movement tracking to precisely deliver treatment, have considerably refined laser refractive surgery. These refinements have improved the delivery system of excimer ablation, but the basic diagnostic and treatment input driving the ablation process has remained relatively unchanged. The treatment patterns have been driven by the manifest and cycloplegic subjective refractions that relied on the patient's subjective assessment.

The incorporation of wavefront technology into refractive surgery has signaled an important transition to the use of objective methods of measuring and treating refractive error vision correction. This chapter provides a brief practical overview of wavefront-guided refractive surgical ablation.

5.2 Some Basics of Customized Laser Refractive Surgery

A comprehensive review of laser refractive surgery is beyond the scope of this chapter. The reader is directed to numerous excellent overviews of this field [24, 32]. The chapter will focus on the basic requirements and some of the challenges encountered with the refinement of customized refractive surgery techniques.

Simple myopia treatment is performed by removal of cornea tissue, more central than peripheral, to effect central corneal flattening. There is one transition point per semi meridian, which is at the juncture of the ablation and the untreated cornea as shown in Fig. 5.1A. Astigmatic treatment is possible by removing a cylindrical mass of tissue, which flattens one meridian more than the meridian 90° away (Fig. 5.1B). There is one transition point per semi meridian in the steep meridian and two transition points per semi meridian in the flat meridian, one at the outer edge

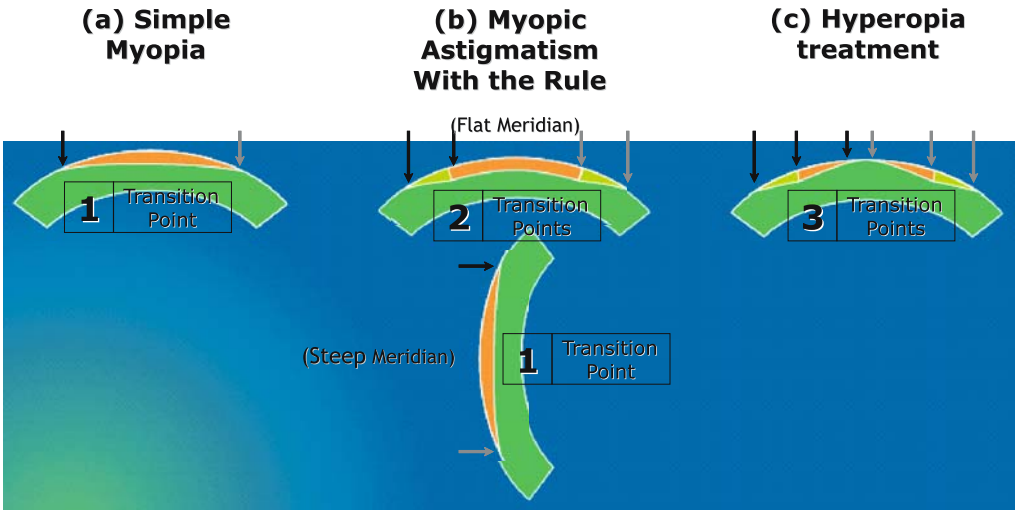

Fig. 5.1 Excimer ablation optical zone and transition zone profiles are shown in *green* for **a** myopic, **b** myopic-astigmatic, and **c** hyperopic or hyperopic-astigmatic treatments. **a** A simple myopic treatment involves more tissue removal from the central cornea than the peripheral cornea. **b** Myopic astigmatic treatment involves tissue removal of uniform thickness in the flatter meridian. This causes no change in power in the flat meridian. The steep meridian, shown below, has a convex shape, which is removed to flatten the steep meridian. **c** In hyperopic treatments, a donut-shaped ablation is performed to remove more tissue in the peripheral portion of the ablation optical zone than in the central cornea. This treatment steepens the central cornea. Hyperopic astigmatism simply applies this same pattern to steepen the flat meridian, while the steep meridian is untreated

of the ablation optical zone and one at the outer edge of the transition zone. Hyperopic treatment removes more corneal tissue in the mid-periphery of the cornea leaving the central cornea with less treatment (Fig. 5.1C). A doughnut-like mass of tissue is removed, which steepens the central cornea. There are three transition points per semi meridian with hyperopic correction, one at the central cornea, one at the deepest part of the trough, and one at the outer edge of the transition zone.

In the early years of refractive surgery, patients were treated with broad beam excimer lasers, 6 mm in diameter, and the optical zones were often even smaller, sometimes as small as 4.0–5.0 mm, which tended to cause night glare and halos when the pupil dilated beyond 6 mm, making driving at night problematic. Although these patients had symptoms because of their small optical zone, the photorefractive keratectomy (PRK) refractive correction has remained relatively stable based on 12 years of follow-up as noted by Rajan and coworkers [52].

Current excimer laser systems are more sophisticated and use small spot treating systems with fast eye tracking systems, which minimize decentrations. The use of larger optical zones and limiting the treatment to less than 12 D has reduced the likelihood of patients having problems postoperatively. Now, many patients receiving customized excimer laser eye treatment experience fewer night driving symptoms than they noted before the surgery. Patients with larger amounts of myopic refractive error often undergo correction with phakic intraocular lenses [22, 47].

Wavefront sensors were initially utilized for research in ophthalmology and visual sciences. Liang, Grimm, Goelz, and Bille [26] introduced the Shack–Hartmann wavefront sensor in 1994 into ophthalmology and subsequently in 1997, Liang, Williams, and Miller [27] used a Shack–Hartmann system and coupled it with an adaptive optics deformable mirror to improve in vivo retinal imaging and demonstrate marked improvement in visual performance with higher

Table 5.1 Summary of customized laser-assisted in situ keratomileusis (LASIK) results from industry-sponsored FDA studies. *BCVA* best corrected visual acuity testing

Customized platform	Vision without glasses ≥20/20 at 6 months postoperatively (%)	Prescription within ±0.50 D of intended correction (%)	Loss of ≥2 lines BCVA postoperatively (%)
Alcon LadarVision[a]	85.8	80.2	0
Bausch and Lomb Technolas 217z[b]	91.5	90.9	0.6
Visx Star S4 and WaveScan[c]	93.9	90.3	0
Visx Star S4 and WaveScan for hyperopia	61.8	64.9	0

Source documents available at: www.fda.gov/cdrh/LASIK/lasers.htm

[a]Autonomous LadarVision data on myopic eyes collected with 4,000-Hz eye tracker.

[b]B+L Technolas data collected on myopic eyes with 217z model with a 120-Hz eye tracker

[c]Does not include 12 myopic eyes that were retreated within the first 6 months of surgery

Table 5.2 Summary of myopic conventional LASIK results from industry-sponsored FDA studies

Customized platform	Vision without glasses ≥20/20 at 6 months postoperatively (%)	Prescription within ±0.50 D of intended correction (%)	Loss of ≥2 lines BCVA postoperatively (%)
Alcon LadarVision	65.2	82	1.9
Bausch and Lomb Technolas 217a	87.3	87.6	0.4
Visx Star S3 and WaveScan	54.1	72.5	0
Wavelight Allegreto[a]	87.7	85.3	0.7
Nidek	47.4	60.3	1.2

Source documents available at: www.fda.gov/cdrh/LASIK/lasers.htm

[a]Wavefront optimized procedure; does not include 10 eyes that were retreated before 6 months after surgery

order aberration correction. In 2000, Seiler [59] coupled the Tscherning diagnostic wavefront sensor with a flying spot excimer laser to treat patients with customized ablation. Pallikaris et al. [43] were also able to couple a Shack–Hartmann wavefront sensor with another flying spot laser later that year and perform wavefront-driven customized ablation as well. By 2003, three wavefront driven excimer laser systems were approved by the US FDA (Federal Drug Administration) and even more were being utilized worldwide. The results of the clinical trials (Table 5.1) indicate improved visual and refractive outcome compared with the equivalent conventional treatment platforms for myopia (Table 5.2) and hyperopia (Table 5.3). The exciting field of wavefront technology and ocular higher order aberration correction had been established, but

Table 5.3 Summary of hyperopic conventional LASIK results from industry-sponsored FDA studies

Customized platform	Vision without glasses ≥20/20 at 6 months postoperatively (%)	Prescription within ±0.50 D of intended correction (%)	Loss of ≥2 lines BCVA postoperatively (%)
Alcon LadarVision	48.8	65	1.4
Bausch and Lomb Technolas 217a	61.4	66.5	2.8
Visx Star S3 and WaveScan	48.1	76.4	3.8
Wavelight Allegreto	67.5	72.3	0.8

Source documents available at: www.fda.gov/cdrh/LASIK/lasers.htm

there were and remain many important challenges.

5.3 Forms of Customization

The ultimate goal of customized ablation is to optimize the treatment to help satisfy a patient's visual needs. This goal is best achieved by performing three forms of customization [33]:

1. Optical,
2. Anatomical,
3. Functional.

5.3.1 Optical Customization

Optical customization involves treating refractive error by measuring and treating the second (lower) order aberrations of sphere, either myopia or hyperopia, and astigmatism and higher order (third and above) aberrations. This includes third order aberrations like coma and trefoil as well as positive spherical aberrations (fourth order), which are also found in the normal population. The wavefront sensor measures the ocular aberrations and a treatment file developed to treat the aberrations using 193 nm argon fluoride excimer laser.

Various commercial wavefront sensors allow optical customization by measuring the ocular aberrations based on techniques that include Shack–Hartmann [26], Tscherning [40], and the Scanning Slit, a subjective system [57] using spatially resolved refractometry. The most popular of the systems is the Shack–Hartmann technique, which is used by at least four of the laser refractive surgical eye companies offering customized ablation. Each system has relative strengths and weaknesses and there are trade-offs. Some wavefront sensors have greater dynamic range, but may sacrifice accuracy or vice versa. A more detailed discussion is included elsewhere and is beyond the scope of this chapter [24].

5.3.2 Anatomical Customization

This form of customization involves careful measurement of the corneal curvature using corneal topography, the corneal thickness [29] using ultrasonic pachymetry [35, 62], and the pupil size [35, 38] under low light (mesopic) conditions. These measurements are critical in helping to design an optimal ablation pattern, which gives an adequate ablation optical zone diameter [14, 30], while avoiding treating with too deep an ablation. The larger the optical zone the deeper the tissue removal [30].

The normal cornea is about 500–540 μ. LASIK creates a flap that is usually between 90–180 μm, and laser ablation is performed to remove tissue either over the central cornea for myopia correction, or in the corneal mid-periphery for hy-

peropia treatment. The laser ablation can be anywhere between 10 and 160 μm depending on the amount of myopia or hyperopia and the diameter of the optical zone. Most surgeons prefer not to ablate deeper than the posterior or remaining 250 μm of the cornea (to avoid corneal ectasia). The thickness of the flap has an indirect influence on the surgeon's options in optical zone sizes since a thick flap may limit the amount of ablation the surgeon can apply before ablating deeper than the posterior 250 μm. If there is not enough room to treat with an adequate optical zone, the surgeon may opt for "surface ablation," which has the advantage of conserving tissue with surgery.

There are three common surface ablations, PRK or LASEK (laser-assisted epithelial keratoplasty). In PRK the superficial layer of the cornea, the corneal epithelium, is removed and the laser treatment applied. LASEK is a variant of PRK where the superficial layer, the corneal epithelium, is peeled back (like an apron), the laser treatment is applied, then the epithelial layer is floated back over the treated cornea, and a bandage soft contact lens is applied over the cornea for comfort. PRK and LASEK have longer recovery periods than LASIK, usually 2–4 days, and there may be more discomfort because the surface layer of the cornea is disrupted [33]. Epi LASIK is a variant of LASEK where a mechanical microkeratome with a dulled blade is used to remove the epithelium in a single sheet without the use of dilute alcohol and may have the advantage of less tissue damage to the epithelium than LASEK, but this remains to be demonstrated [45].

Interestingly, the outcomes for LASIK, PRK, and LASEK are similar in the few studies that have compared the treatments in the same patients in paired eye studies [12, 31]. LASIK is used for the typical patient while PRK or LASEK are used more commonly in patients who have thin corneas that are not deep enough for LASIK [2]. Surface ablation is also used preferentially in patients who have a tendency toward dry eyes since it tends not to increase dryness symptoms in patients who have dry eyes [4]. The popularization of Intralase, which uses a femtosecond laser to create the flap with LASIK, has further encouraged surgeons to use thinner flaps and strive for lower standard deviation when making LASIK flaps. One study has shown that thinner flaps (<100 μm), are associated with better efficacy, predictability, and contrast sensitivity suggesting that better control of flap thickness may improve outcomes [8]. The optimal anatomical approach is still being clarified, although we have become much more sophisticated in our approach to anatomical customization in recent years.

5.3.3 Functional Customization

Functional customization requires an understanding of the visual needs of the patient and factors such as age, occupation, hobbies, and the patient's expectations. Myopic (nearsighted) individuals see poorly at distance, but often can take off their glasses and see well close up. These patients need to be alerted that their ability to read may be reduced, but they will probably get a dramatic improvement in their distance vision. A number of studies have shown that elderly myopes, over 45 years of age, are more susceptible to hyperopic overcorrection [13, 17]. Furthermore, treating younger myopes more aggressively and hyperopes less aggressively result in greater patient satisfaction. Young myopes have large accommodative amplitudes and hence tolerate a slight hyperopic overcorrection postoperatively. Conversely, older patients prefer emmetropic or slight myopia postoperatively to compensate for reduced accommodative amplitudes. An overcorrection or hyperopic outcome would blur both distance and near vision and is highly undesirable. Presbyopic patients may be treated with monovision where one eye is fully corrected for distance and one eye is intentionally left with a moderate amount of nearsightedness, or monovision (an intentional correction to make one eye −1.25 to 1.50 D myopic) or mini monovision (one eye made −0.25 to −0.75 D myopic). This gives the patient a greater dynamic working range when using both eyes together and allows the presbyopic patient more independence from reading glasses. Most patients who need to see well with both eyes at distance prefer being treated by aiming for optimal distance vision in both eyes. The use of a soft contact

lens trial to allow the patient to simulate mono or mini monovision is also helpful in making a decision whether or not this is a viable option for the patient [9]. The use of multifocal or aspheric ablations is being advocated to correct presbyopic patients, but the long-term viability remains to be established [6, 63].

5

Summary for the Clinician

- Customized correction involves consideration of anatomical, functional, and optical factors that would provide optimal visual performance based on the patient's requirements.
- Correction of preoperative higher order aberrations could provide greater visual benefit through improvement in uncorrected visual acuity and contrast sensitivity.

5.4 Technological Requirements for Customized Refractive Surgery

Laser refractive surgery has evolved rapidly from the first treatments, which were carried out in blind eyes by Seiler in 1985 [58] and then on sighted eyes in 1987 using PRK [25]. In 1990, Pallikaris combined the lamellar splitting of the corneal stroma with treatment using an excimer laser, which formed the basis of modern-day LASIK surgery [42]. Since the advent of LASIK, several technological advancements have revolutionized the treatment procedure. These include physical properties of the laser, eye movement tracking, wavefront measurement, and laser–wavefront interface.

5.4.1 Physical Properties of the Laser

In order to correct the complex nature of the higher order aberrations, the laser system must be precise to make the eye near diffraction limited. When the ablation depth is small, the ablation depth per pulse limits the precision of the laser system. Current excimer lasers have an ablation depth per pulse of about 0.30 μm, which is sufficient for such a level of precision treatment [18].

A smaller spot size such as a <1 mm spot can treat finer aberrations, but larger spot sizes (>2 mm) can treat a sphere or cylinder. The trend over recent years has been to use smaller spot sizes and faster laser repetition rates from 50 to 500 Hz. These faster Hertz rates for lasers are preferable since they reduce treatment time, which reduces variability due to the dehydration of the cornea that occurs with longer treatment times. Thus, shorter treatment times allow for more uniform and predictable ablations. The excimer laser spot sizes for customized correction have decreased, sometimes to less than 1.0 mm and rapidity of the treatment has increased from 10 Hz to sometimes as fast as 500 Hz. Guirao and coworkers [16], as well as Huang and Arif [19], have noted that a spot size of 0.5–1.0 mm is capable of reducing lower and higher order aberrations. A study by Bueeler and Mrochen (cited in [23, 24]) comparing ablation depths of 0.25 and 1.0 μ with laser spot diameters of 0.25 and 1.0 mm and tracker latencies of 0, 4, 32, and 96 ms as well as no eye tracking, and looking at the simulated efficacy of a scanning spot correction of a higher order aberration of 0.6 mm vertical coma with a 5.7 mm pupil diameter. They found that the shallower ablation depth of 0.25 μm combined with a larger spot size of 1.0 mm is more stable and less dependent on tracker latency, but less capable of treating very finely detailed aberrations. A shorter latency is advantageous since it reduces the time the target has to move before the laser mirrors react to the movement [23, 24].

5.4.2 Eye Movement Tracking

The eye makes frequent saccades during fixation that could reduce the effectiveness of customized vision correction. A laser ablation driven by a robust eye tracking system, which can follow such rapid eye movements, can allow effective customized vision correction. Eye tracking has been incorporated into treatments using video-based

and laser radar tracking, with tracking rates varying between 60 and 4,000 Hz. Porter, Yoon, and coworkers indicate that over 90–95% of eye movement during laser refractive surgery could be captured by a 1- to 2-Hz closed loop tracking system [50]. In addition, these studies indicated that the most critical component of eye tracking was the accuracy of the centering of the tracker over the pupil center at the time the tracker was activated. Small decentrations of 200–400 μm were not uncommon in the above study, even with meticulous centering by the surgeon, suggesting that greater magnification and a more automated system may be advantageous.

Small eye movements do occur during ablation as noted above as well as static decentration errors, which occur when attempting to center the tracker over the pupil. Guirao and coworkers found that a translation of 0.3–0.4 mm or a rotation of 8–10° could still correct up to 50% of the higher order aberrations in a normal eye [15]. The corollary of this is that 50% of the benefit of the correction of a higher order aberration would be lost with such translation or rotation, stressing the importance of proper centration and an adequate tracking system.

5.4.3 Wavefront Measurement and Wavefront–Laser Interface

More recently, clinicians have begun using wavefront sensing to measure and treat the subtle aberrations of the eye in addition to sphere and cylinder. Different types of wavefront sensors exist, including Tscherning and subjective wavefront sensors, but the most popular used by the laser companies is the Shack–Hartman system. The latter system is an objective technique that measures the slope of the wavefront exiting the pupil using a Shack–Hartman lenslet array. The wavefront image provides an image of the lower and higher order aberrations that patients have.

In order to obtain optimal results, a very reproducible and accurate map needs to be created. This is achieved through multiple captures, comparisons, and often combining (or averaging) information to generate a composite wavefront map based on 3–5 wavefront scans. The wavefront error can be documented and then transferred to the excimer laser via a floppy disc. The corneal ablation pattern is then formulated, which is the reverse of the wavefront error to correct the wavefront aberrations. When implementing this step, the diameter of the measured wavefront needs to be at least the scotopic or low mesopic pupil diameter if possible [24]. To achieve a large pupil diameter, pharmacological dilating agents such as 2.5% neosynephrine or tropicamide may be used. Recently, we have demonstrated that the use of a nonpharmacologically dilated pupil in 90 eyes achieves equivalent results to 155 eyes dilated with a mild noncycloplegic dilating agent such as 2.5% neosynephrine. In those studies, 93.4% and 94.6% of eyes obtained an uncorrected visual acuity of 20/20 or better in the above respective groups. The final step in this process is the design of a laser shot pattern, which is determined by the laser characteristics described above and the treatment of the optic zone diameter.

This strategy did not take into account the biomechanics of the cornea, which resulted in patients developing positive spherical aberration after myopic treatment and negative spherical aberration with the treatment of hyperopia. The laser companies have incorporated correction factors in an attempt to minimize the induced positive or negative spherical aberration created by the ablation with refractive surgery.

Summary for the Clinician

- Wavefront sensors deduce ocular aberrations based on the measured slope of the wavefront error at a discrete set of points. Pupil size and wavefront aperture diameter have a profound effect on the magnitude of the higher order aberrations measured.
- A 2-mm laser spot diameter is adequate for correcting defocus and astigmatism and a 1-mm spot size for correction up to fourth order Zernike modes.
- Greater laser frequencies reduce treatment time and thereby minimize corneal dehydration time.

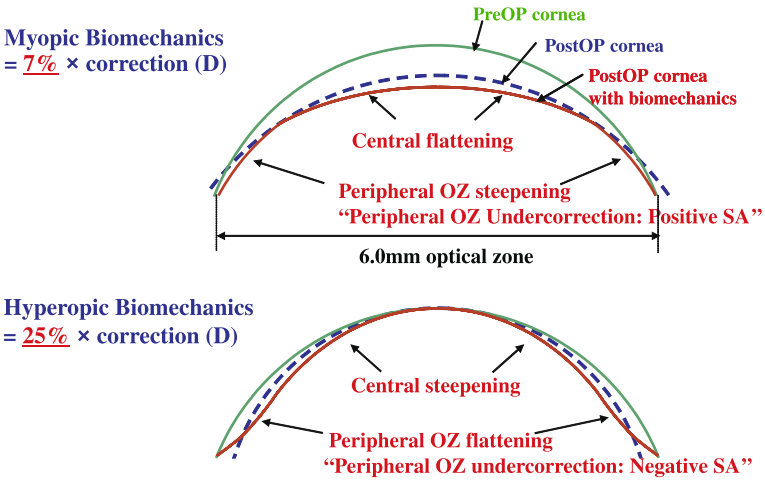

Fig. 5.2 A hypothesis by Yoon et al. [43] of the biomechanical response of the cornea to excimer laser refractive surgery after a **a** myopic and **b** hyperopic procedure. Preoperative corneal shape, postoperative corneal shape, and postoperative corneal shape including biomechanical effects are denoted using *solid gray*, *dashed black* and *solid black* lines, respectively. **a** In myopic laser correction, the central cornea is flattened while the peripheral portion of the optical zoned steepens (causing peripheral optical zone undercorrection) and flattens, causing positive spherical aberration. **b** In hyperopia, the central cornea and ablation optical zone steepens, but the peripheral part of the ablation optical zone flattens (resulting in peripheral optical zone undercorrection), causing negative spherical aberration. (Figure is courtesy of Dr. Geunyoung Yoon)

5.5 Biomechanics of Refractive Surgery

The biomechanical effects on the cornea have direct relevance to optimizing customized ablation because the biomechanical changes caused by creating a flap or carrying out an ablation may induce higher order aberrations. The biomechanics of refractive surgery is a complicated subject, but there are several empiric observations that help clarify the cornea's response to refractive laser eye treatment. The most prominent change that occurs with myopic excimer laser surgery is an increase in positive spherical aberration, while hyperopic treatment tends to cause an increase in negative spherical aberration [5, 37]. Normally, most individuals in the population have a slight positive spherical aberration, which means that the central light rays would fall directly on the macula in an emmetropic individual, but the peripheral light rays coming in closer to the edge of the pupil would be focused in front of the retina. Roberts has shown that the cornea actually steepens and thickens slightly in the mid-periphery after myopic excimer laser treatment, which accounts for the positive spherical aberration noted after myopic ablation with either LASIK PRK [10, 21, 54].

Huang et al. [20] developed a mathematical model of corneal smoothing to explain regression and induction of postoperative higher order aberrations observed clinically. Mrochen and Seiler postulated that the ablation in the central cornea is more effective than the more peripheral cornea [39], while Dupps and Roberts [10] and Roberts [54, 55, 56] proposed that the corneal shape or curvature change is caused by the biomechanical response of the cornea. Yoon et al. [66] have modeled the cornea calculating the variable ablation rate as one moves to the periphery of the optical zone and the effect of biomechanics and wound healing. In this model, the variable ablation rate in which the efficacy of the laser pulses decreases as one moves to the peripheral part of the optical zone accounts for up to a maximum 8% decrease in efficacy when one reaches the peripheral part of a 6.0-mm diameter optical zone. In the same model noted above, the biomechanical/biologic healing would increase positive spherical aberration by 7% of the spherical value of myopia being

treated and negative spherical aberration by 25% of the spherical value in hyperopia treatment (see Fig. 5.2).

5.5.1 LASIK Flap

Potgieter et al. [51] followed corneal topography and ocular wavefront changes after a lamellar flap creation. They observed that statistically significant changes in wavefront data that showed significant change in four Zernike modes—90/180° astigmatism, vertical coma, horizontal coma, and spherical aberration. The topography data indicated that the corneal biomechanical response was significantly predicted by stromal bed thickness in the early follow-up period and by total corneal pachymetry and flap diameter in a two-parameter statistical model in the late follow-up period. They concluded that uncomplicated lamellar flap creation was responsible for changes in corneal topography and induction of higher-order optical aberrations. Predictors of this response include stromal bed thickness, flap diameter, and total corneal pachymetry.

Further studies by Porter, MacRae, and coworkers [49] noted that the increase in positive spherical aberrations with LASIK is primarily related to the excimer laser ablation and not the cutting of peripheral collagen fibers caused by the microkeratome incision. The microkeratome or laser incision to create the corneal flap generally cuts a flap approximately 100–180 μm deep. This study involved making a superior hinged microkeratome flap with a Hansatome (Bausch and Lomb) and observing the flap-induced aberrations for 2 months. In one group the flap was lifted and a sham ablation was performed using a microkeratome, which created a flap with a superior hinge. In another group the flap was not lifted and the eye was simply observed for 2 months. In the group where the flap was lifted, there was a 0.19 μm (50%) increase in higher order root mean square (RMS) wavefront error, while a negligible increase was measured in the group with no flap lift. Horizontal trefoil was the only higher aberration that consistently increased. After 2 months, the flap was lifted and the cornea ablated with the excimer laser to treat myopia. With the ablation, we found an increase in positive spherical aberration. The increase in positive spherical aberration was proportional to the amount of myopia treated with greater amounts of myopic treatment causing larger amounts of positive spherical aberration. Overall, we noted that most of the increase in higher order aberration was induced by the ablation with conventional LASIK [61]. We were impressed that flap manipulation also contributed significantly to an increase in higher order aberrations and recommend that clinicians minimize flap hydration and meticulously reposition the flap after ablation.

Pallikaris and coworkers noted an increase in horizontal coma and spherical aberration when they made a microkeratome flap using a nasal hinged microkeratome and observed the effects of the flap cut alone for several months [44]. Waheed and coworkers have also created a flap using a Moria 2 and an SKBM microkeratome and noted a mild hyperopic shift of 0.5 D, but they did not observe this shift in the SKBM group [65].

Interestingly, they noted that post-flap aberrations accounted for less than one-quarter of the increase in post-laser aberrations suggesting that the ablation contributes significantly to the post-LASIK higher order aberration increase with conventional LASIK treatments. This finding is also similar to those noted by our group as reported above by Porter et al. [49].

In a contralateral study comparing the Bausch and Lomb Hansatome with the Intralase, Tran et al. found in eight paired eyes a significant increase in higher order aberration 10 weeks post-flap creation in the microkeratome group, which was driven mainly by trefoil and quadrafoil [64]. The difference in higher order aberration between the microkeratome eye and Intralase was subtle and even though they found a statistically significant difference, the change in higher order aberrations (microkeratome with a 0.055-μm RMS (32%) increase vs. Intralase, with a 0.03-μm RMS (20%) increase, 6.0-mm pupil) is of equivocal clinical significance. Further paired-eye studies are warranted to clarify the differences in mechanical vs. Laser-created flaps and the clinical meaning of any differences noted. Control of hydration and flap thickness may also be helpful in such studies. As noted previously, Cobo Soriano et al. reported that thinner flaps of less than 100 μm tend

to achieve better uncorrected visual acuity and contrast sensitivity results than eyes that have thicker flaps [8]. Thus, further studies comparing varying flap creation techniques need to attempt to use flaps of similar thickness and diameters to make comparisons more meaningful.

We have also noted that we can improve on results in eyes that averaged a spherical equivalent of almost –5.00 D and had more higher order aberration than the normal myopic population using the Rochester Nomogram, a nomogram that modifies the spherical correction based on the amount of preoperative higher order aberration, as we will discuss later.

Thus, in myopic laser treatment, there is a tendency for the central cornea to flatten more, but the cornea in the periphery optical zone steepens and thickens causing an unanticipated positive spherical aberration. This causes the peripheral light rays to be focused more anteriorly than the central light rays. In hyperopic corneal laser surgery, the tendency is for the central cornea to steepen, but the peripheral optical zone cornea tends to flatten slightly causing unanticipated negative spherical aberration. In this case the central light rays are focused on the retina with emmetropia, but the mid-peripheral lights rays passing through the pupil are focused behind the retina.

One strategy to minimize spherical aberration is to use an aspheric curvature to compensate for the spherical aberration, which is induced by conventional refractive surgery. This strategy uses an aspheric constant for a given amount of correction, which is based on the average amount of aspheric change induced in a previously treated group of eyes. Most eyes have a small amount of positive spherical aberration in the normal population of people who have never had refractive surgery [36].

The advantage of this technique is that it helps minimize the amount of spherical aberration induced for the average eye [48]. One disadvantage of this approach is that a moderate number of eyes in the normal preoperative population are not close to the population average; some eyes actually have negative spherical aberration and may actually experience an increase in spherical aberration, while some eyes have much larger amounts of positive spherical aberration and would benefit more from a larger amount of aspheric adjustment to reduce their preoperative spherical aberration. The second disadvantage is that it is not a customized ablation and would not be suitable for eyes that had even modest amounts of higher order aberration. These eyes with mild and greater amounts of higher order aberrations do benefit from treatment with customized ablation, which improves contrast sensitivity under photopic and mesopic conditions [61]. These strategies are being employed to treat eyes with minimal amounts of higher order aberration and are currently being used by Nidek, Bausch, and Lomb as well as Wavelight (Wavelight's results are noted in Table 5.2).

Summary for the Clinician

- Postoperative higher order aberrations are induced by flap creation, magnitude of treatment, loss of ablation depth per pulse, and the corneal healing response.
- Among myopes, postoperative regression and increased positive spherical aberration results from unanticipated steepening of the midperipheral cornea.
- Among hyperopes, the midperipheral cornea flattens postoperatively, resulting in unanticipated negative spherical aberration.

5.6 Clinical Results of Customized Excimer Laser Ablation

Laser companies have performed a number of large, well-controlled clinical trials to provide evidence of the relative success, and to establish the safety and efficacy of customized excimer laser treatment. Several reports have been published to establish the safety and efficacy of the customized LASIK treatment for myopia using the Bausch and Lomb Zyopitx system [1, 34], the Alcon CustomCornea platform [3, 46], the VISX Wavescan system [28], the Carl Zeiss Meditec platform [53], the Allegretto Wavelight [41], and the Nidek NAVEX platform [7].

Tables 5.1 and 5.2 provide information on the visual outcome of the customized LASIK procedure compared with that following conventional

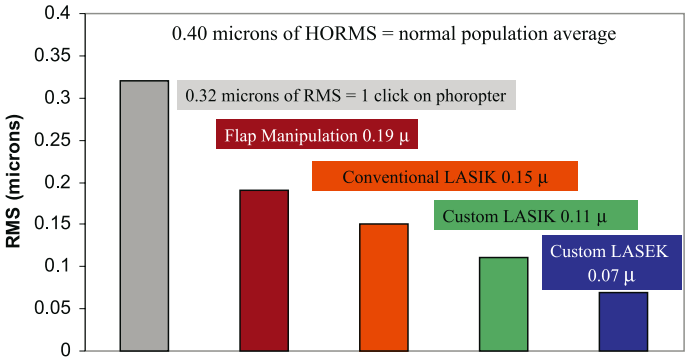

Fig. 5.3 Summary of higher order aberration induction with several different refractive surgery interventions. Flap manipulation associated with lifting the flap caused the greatest amount of higher order aberration increase due to flap swelling and less meticulous attention to symmetric lying down of the flap

LASIK treatment for myopia. In the conventionally treated myopic eye groups the data suggest that 20/20 or better uncorrected vision (vision without spectacles or contacts) ranges between 40 and 90% depending on the preoperative myopia and the laser used. The eyes treated with customized or wavefront-guided ablation range between a 60 and 95% likelihood of obtaining 20/20 or better uncorrected visual acuity under high contrast conditions (Table 5.1). The conventional hyperopic eyes have about a 40–88% chance of achieving 20/20 or better uncorrected vision as noted in Table 5.3.

Most treatments with customized LASIK or customized surface treatments do introduce slight increases in higher order aberration. We have carried out other studies [31] comparing the use of the Customized LASEK with the Bausch and Lomb Zyoptix System and compared that with conventional (noncustomized) LASIK using the same Bausch and Lomb Planoscan system. In a paired study of 24 patients where one eye was treated with customized LASEK and the contralateral eye treated with conventional LASIK, we found a 0.07-µm increase (6.0-mm aperture) in higher order aberration in the customized LASIK eyes compared with a 0.15-µm increase with conventional LASIK. We compared these results with those of an equivalent group of 340 eyes in the US FDA Bausch and Lomb Zyoptix clinical trial where there was a 0.11-µ increase in higher order aberration (6.0-mm aperture). The amount of increase in higher order aberration is relatively trivial when one compares this with the amount of wavefront error (0.32 µm RMS—6.0-mm aperture) introduced with 0.25 D of spherical refractive error (one click on the phoropter). Thus, the amount of higher order aberrations introduced with customized ablation is equivalent to about one half of a click of a sphere on a phoropter. These results are summarized in Fig. 5.3.

We also found that with customized ablation, eyes with greater amounts of preoperative higher aberration obtained greater benefit with customized ablation. This is similar to what we have noted in eyes with astigmatism. If patients have more astigmatism, it is more worthwhile to treat these eyes with an astigmatism treatment. In our FDA study evaluating the Bausch and Lomb Zyoptix customized ablation in 340 eyes, we found that eyes with greater amounts of preoperative higher order aberration (>0.35 µm of RMS; 6.0-mm pupil) wavefront error were more likely to experience an improvement in contrast sensitivity of one to two patches than eyes with lower amounts of preoperative higher order aberrations and eyes were five times as likely to gain one patch of contrast sensitivity than lose one patch of contrast in the study. Two percent of eyes had a two-patch contrast sensitivity loss compared with 24% of eyes that had a two-patch gain in mesopic contrast sensitivity and that gain in contrast was related to a reduced increase in higher order aberration compared with the eyes that lost mesopic contrast. In the study, mesopic contrast sensitivity gains were ten times more likely than losses and the gains in contrast were related to a decrease or minimal increase in higher order aberration, while those eyes that lost contrast had a higher increase in higher order aberration than the eyes that gained contrast [61]. The greatest gain in vision with customized ablation is under low light conditions when the pu-

pil is more dilated and not in visual acuity. Thus, measurements of contrast sensitivity changes are more helpful at articulating the visual gains using customized ablation than high-contrast visual acuity changes. In the future, we will carry out more studies that evaluate the visual benefit of customized ablation by evaluating the changes in contrast sensitivity under normal and low lighting conditions.

Treatment using a customized correction method may need an adjustment of sphere when treating higher order aberrations. Durrie and coworkers noted a tendency of hyperopic overcorrection in LASIK retreatment eyes, particularly in eyes with larger amounts of spherical aberration and cautioned users to reduce myopic sphere in customized retreatments. They also cautioned the user to sometimes plan for a second retreatment to treat the residual hyperopia when retreating myopic eyes with larger amounts of spherical aberration using the Alcon Ladarwave System [11]. Recent studies by our group have also demonstrated that the treatment of preoperative higher order aberration using the Bausch and Lomb Zyoptix may secondarily affect sphere and cylinder [61]. We noted in the 340-eye US FDA trial that eyes with larger amounts of preoperative coma, trefoil, or spherical aberration were more likely to result in hyperopic overcorrection. We noted that 21.8% of eyes were likely to have a mild overcorrection of 0.5 D or more, while only 2% of eyes were likely to be undercorrected. The overcorrections were strongly associated with preoperative coma, trefoil, and spherical aberrations. We also noted that the postoperative cylinder is also more likely with eyes that had preoperative coma. Since this study, we have improved our results using a nomogram (the Rochester Nomogram), which modifies the treatment sphere based on the amount of preoperative higher order aberration and the preoperatively manifest sphere and cylinder.

Using the Rochester Nomogram, we subsequently treated 175 eyes that were more myopic and had more higher order aberration than in the FDA study and yet we achieved better results than in the FDA study. Using this nomogram, 160 out of 175 eyes (91.5%) were within ±0.5 D, or less, and all eyes (100%) were within ±1 D of the target refraction. Five out of 175 eyes (2.8%) had an overcorrection or residual hyperopia (>0.5 D), while 10 other eyes (5.7%) had undercorrection or residual myopia (>-0.5 D) demonstrating that the tendency toward hyperopic overcorrection with higher order aberration treatment was minimized.

In comparison, if we used a simple theoretical linear regression that only uses the preoperative wavefront sphere to optimize the postoperative sphere, our results would not have been as good. The simple theoretic linear regression recommended we use 93% of the Zywave wavefront sensor's preoperative Predicted Phoropter Refraction. If we had used the theoretic 93% nomogram, which does not take into account the effect of preoperative higher order aberration and manifest refraction, only 121 of the 175 eyes (69.1%) would have been within ±0.5 D or less of the target spherical equivalent (compared with 91.5% with the Rochester Nomogram). Thirty-nine of the 175 eyes (22.3%; compared with 2.8% with the Rochester Nomogram) would have been overcorrected and would have obtained residual hyperopia >0.5 D. In addition, 15 out of 175 eyes (8.6%) would have been undercorrected and would have had myopia (>–0.5 D) postoperatively (compared with 5.7% with the Rochester Nomogram). Note that the tendency toward greater accuracy and the reduced rate of postoperative hyperopic overcorrection with the Rochester Nomogram, which takes into account the amount of preoperative higher order aberration and manifest refraction compared with the theoretical 93% of the preoperative Zywave sphere, which only considers the relationship between the preoperative wavefront sphere and the postoperatively manifest sphere. We believe this approach of considering the effect of the preoperative manifest sphere and cylinder as well as the preoperative higher order aberrations on postoperative sphere and cylinder may have some merit and may warrant further studies by other groups using different laser platforms. We are currently working on clarifying the effect of third-order terms, coma, and trefoil on astigmatism.

5.7 Summary

The field of refractive surgery has been revolutionized by the use of wavefront sensing, which has helped us understand how effective our at-

tempts were in reducing or minimizing an increase in ocular aberrations. With this understanding, we have been able to correct our patients' refractive errors, minimizing the increase in higher order aberration. Customized refractive surgery provides very good outcomes among normal eyes, but a better understanding of the role of biomechanics and tissue healing as well as how correction of preoperative higher order aberrations effects the correction of the sphere and cylinder is warranted [11, 60, 61]. The knowledge gained from such understanding will allow significant enhancements to outcomes and provide insights into customized treatment of eyes with increased higher order aberrations such as transplant eyes, post-refractive surgery, irregular astigmatism, etc. This exciting field has been led by the synergy between basic scientists and clinicians who have worked together to allow us to apply space age technology to improve patients' quality of vision.

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Chapter 6

EpiLASIK

6

Chris P. Lohmann, Christoph Winkler von Mohrenfels, Andrea Huber

Core Messages

- EpiLASIK is a new technique for the correction of ametropia using the excimer laser.
- The epithelium is separated mechanically with a microkeratome and the laser ablation is carried out on the stromal surface.
- The separation is between the lamina lucida of the basal lamina and Bowman's membrane.
- 92% of all patients are within ±0.5 D of the intended correction (myopia <8 D; hyperopia <3 D, astigmatism <5 D).
- Refractive results are equal to those for LASEK and LASIK (safety, stability, efficacy).
- Less pain and faster visual recovery compared with PRK.
- More standardized epithelial flaps and no ethanol toxicity compared with LASEK.
- Fewer dry eye problems and flap complications compared with LASIK, but slightly longer visual recovery.
- Wavefront-guided and wavefront-optimized laser profiles have similar refractive wavefront results.
- Re-EpiLASIK is possible with good safety and stability.

6.1 Introduction

Excimer lasers were introduced for the correction of refractive errors in 1983. Since then, the techniques, algorithms, and laser systems have continuously improved. The techniques are divided into surface ablation (photorefractive keratectomy [PRK]; laser subepithelial keratomileusis [LASEK], and EpiLASIK) and deep stromal ablation (laser in situ keratomileusis [LASIK]).

Photorefractive keratectomy (PRK) was the first technique to be used in the early 1990s and has proved to be a predictable and safe method for the treatment of low to moderate refractive errors [5, 26]. The main disadvantages of PRK were the postoperative pain and long visual recovery. Therefore, surgeons were seeking a painless method with a faster visual recovery.

In LASIK a stromal flap is created and the laser ablation is carried out in the deeper corneal stroma [17]. LASIK is currently the most common type of laser refractive surgery. The main reason is that the patients have almost no pain and a fast visual rehabilitation. But there are also some typical complications after LASIK, such as epithelial ingrowth, diffuse lamellar keratitis, infections, dry eye, cutting problems, and biomechanical problems like iatrogenic keratectasia [16, 18]. All of these complications are mainly flap-related.

To incorporate the advantages of PRK (long term stability, no flap-associated risks, less dry eye) and LASIK (minimal pain, fast visual recovery) advanced surface ablation techniques (ASAt) have been developed.

One of these ASAt is laser-assisted subepithelial keratectomy (LASEK), which was introduced by Massimo Camellin in 1999 (M. Cimberle, "LASEK May Offer the Advantages of Both LASIK and PRK," Ocular Surgery News, International Edition, March 1999, page 28). It involves the creation of an epithelial flap that is repositioned after laser ablation of Bowman's membrane and the anterior stroma. The epithelial flap is repositioned on the cornea after the ablation to act as a therapeutic contact lens [14]. Various concentrations of alcohol (e.g., 18% and 20%) [1, 12, 14, 27] have been used for different amounts of time (from 15 s to 2 min) to loosen

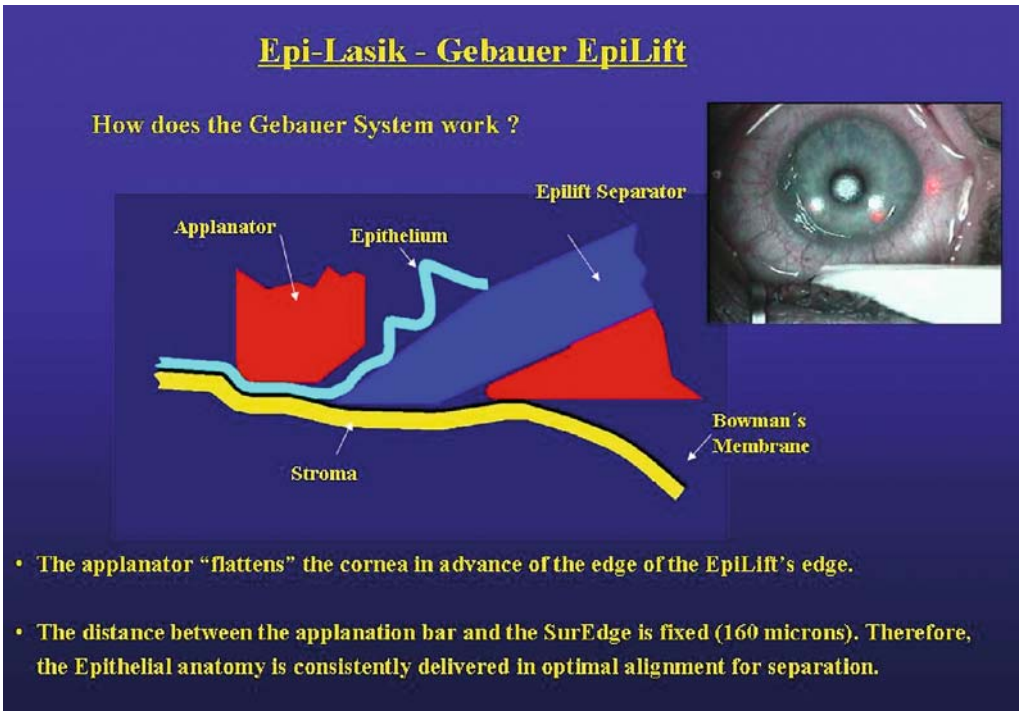

Fig. 6.1 Schematic picture of EpiLASIK using the Gebauer/CooperVision EpiVision microkeratome

the epithelial layer. Gabler et al. showed that most of the epithelial cells are viable directly after the flap creation [8]. Scerrati found that LASEK was superior to LASIK regarding the uniformity of corneal topography, best corrected visual acuity, and contrast sensitivity 6 months postoperatively [25].

Although the clinical results of LASEK are very encouraging, there is still concern about the probable toxic effect of alcohol on the epithelium and underlying corneal stroma [11, 13]. Retrospective studies of LASEK-treated eyes report good refractive and visual results, but suggest the need for a different way of creating the epithelial flap without using alcohol [3, 28].

An alternative for alcohol separation is a mechanical, microkeratome-based method. Pallikaris et al. developed such a technique. Since *epipolis* in Greek means *superficial*, this technique has been named *epi-LASIK* [19].

6.2 EpiLASIK Microkeratomes

The first microkeratome was the Centurion SES Epikeratome from CIBA Vision and later from Norwood Abbey. Shortly after the introduction of the Centurion the EpiVision keratome from Gebauer/CooperVision appeared. Other microkeratomes on the market are the Mori EpiK from Moria and the Amadeus II microkeratome from AMO, which has been modified for EpiLASIK. All have CE and FDA approval. The beauty of the Gebauer/CooperVision and the AMO devices is that with both microkeratomes EpiLASIK and LASIK can be performed just by changing the head.

Figure 6.1 shows how the EpiVision microkeratome of Gebauer/CooperVision works. An applanator flattens the cornea in advance of the edge of the separator, which is in this case a blunt metal blade. The distance between the applanation bar and the edge of the separator (blade) is fixed at 160 µm. Therefore, the epithelial archi-

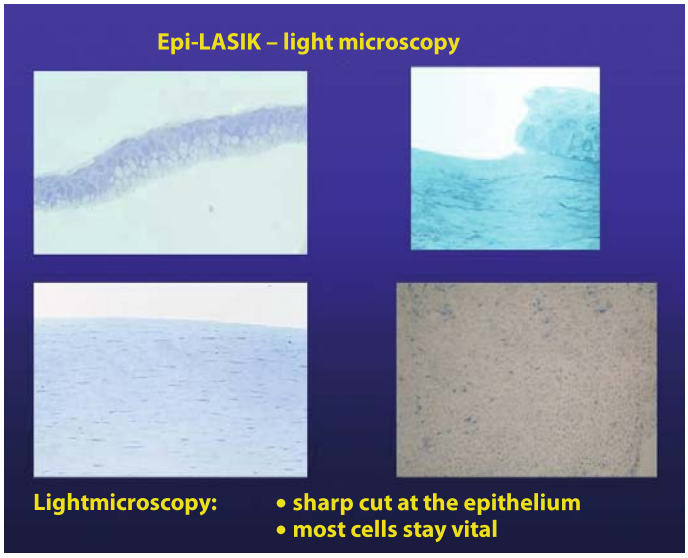

Fig. 6.2 Histology after EpiLASIK: light microscopy

tecture is consistently delivered in an optimal alignment for separation.

6.3 Histology of the EpiLASIK Cut

For the evaluation of the cleavage plane of EpiLASIK human corneas that were not suitable for transplantation were obtained from the Bristol eye bank. The corneo-scleral buttons were placed in an artificial anterior chamber. EpiLASIK cuts were performed on these human corneas with the EpiVision microkeratome (Gebauer/CooperVision). In 5 eyes the epithelium and the stromal beds were embedded for light and electron microscopy in paraformaldehyde. In 5 corneas the epithelium was used to test for cell viability with Trypan blue.

6.3.1 Light Microscopy

For light microscopic examinations the epithelial flaps were embedded immediately after the separation. The epithelial flap showed that the epithelium was uniformly thick along its entire length. The epithelial layer retained its typical stratification and integrity. There was no disruption of the basal membrane in any of the specimens. The stromal bed appeared to be very smooth with smooth cutting edges (Fig. 6.2).

6.3.2 Transmission Electron Microscopy

The epithelial flap and the stromal bed for transmission electron microscopy were embedded in glutaraldehyde. The flap demonstrated that the epithelial layer was separated beneath the level of the basement membrane (between the lamina lucida and Bowman's membrane. The epithelium consisted of healthy-looking cells with intact basal membrane. The intracellular organelles and intercellular desmosomal connections looked very healthy and there are no evident morphological abnormalities. Basal epithelial cells rested on the prominent basal lamina, which consisted of an apparently structureless lamina lucida and an electron-dense lamina densa with occasional focal disruptions. In some places, the disruptions were associated with the formation of small blebs surrounded by a cell membrane. The basal cells of the epithelial disk had a normal morphology with minimal evidence of trauma or edema (Fig. 6.3).

6.3.3 Scanning Laser Microscopy

Corneas were also embedded for scanning laser microscopy. The wound edges showed a very smooth cut at the edges. The surface is very regular without any disruptions of Bowman's membrane (Fig. 6.3).

6.3.4 Cell Vitality

To maintain the surface of the cornea and induce minimal wound healing reactions after laser ablation, minimal harm to the epithelium should be applied during the separation and the whole surgical period. In LASEK the vitality of the epithelium is dependent on the ethanol concentration and the exposure time. After 0 s of 20% ethanol less than 1% of all epithelial cells are dead, after 15 s 8%, after 30 s 21%, after 45 s 54%, and after 60 s more than 97% of all epithelial cells are dead. Most surgeons use ethanol exposure times of 20–30 s, which result in 10–20% of cell deaths and more cells that are stimulated. In contrast to this, after EpiLASIK, around 95% of all cells are vital directly after the cut. The high amount of vital cells in connection with the intact basal lamina should reduce the wound healing reactions, although more studies to evaluate the wound healing are necessary (Fig. 6.2).

6.4 EpiLASIK: the Surgery

6.4.1 Preoperative Evaluation

As in all keratorefractive techniques all patients have to undergo a full ophthalmic examination before treatment (primary and enhancement surgery). This includes a detailed history and a complete examination with manifest and cycloplegic refractions, slit lamp microscopy, keratometry, corneal topography, applanation tonometry, pachymetry, determination of scotopic pupil size, and dilated fundus examination. The use of contact lenses was discontinued 4 weeks and 2 weeks before examination and surgery for hard and soft lenses respectively.

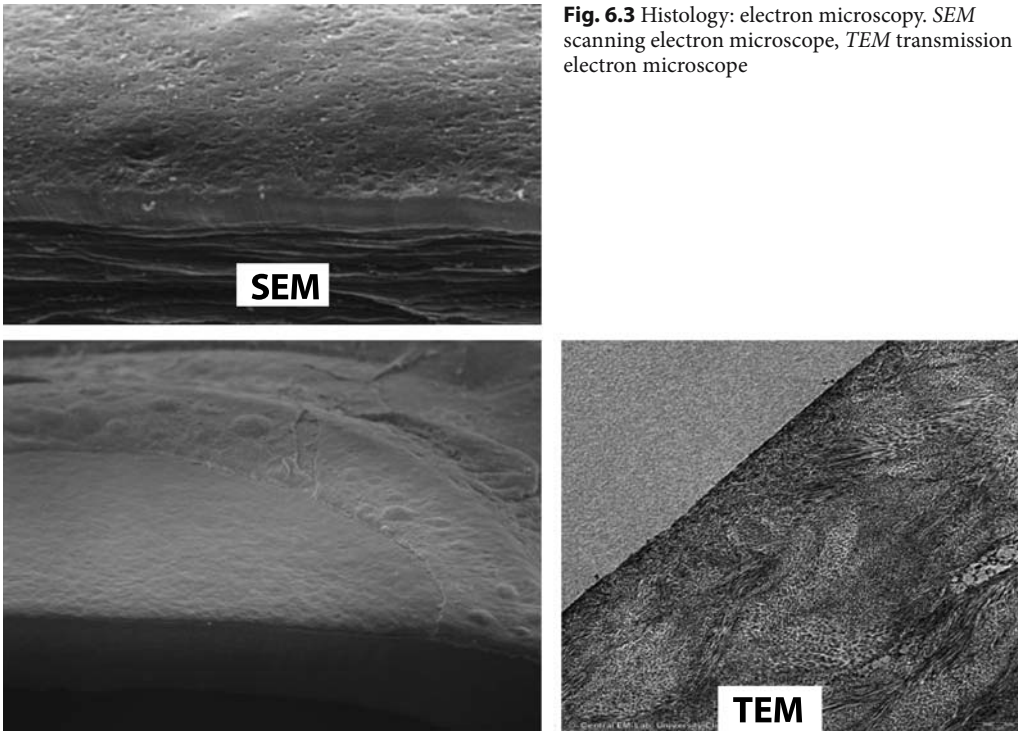

Fig. 6.3 Histology: electron microscopy. *SEM* scanning electron microscope, *TEM* transmission electron microscope

Patients with diabetes mellitus, a rheumatic disease, an autoimmune condition, or a dermatological disease possibly afflicting the eyes (e.g., rosacea) were excluded, as were patients with severe keratoconjunctivitis sicca, a corneal disease (e.g., keratoconus), or another pathological eye condition. A scotopic pupil larger than 7.0 mm was also an exclusion criterion.

6.4.2 Indication for Refraction

- Myopia up to –8.0 D,
- Hyperopia up to +3.0 D,
- Astigmatism up to –5.0 D.

6.4.3 Inclusion Criteria

- Age (at least 18 years old),
- Stable refraction (changes less than 0.5 D within 2 years),
- Signing of informed consent.

6.4.4 Exclusion Criteria

- No stable refraction;
- Refraction outside the indication (see above);
- Corneal disease (e.g., keratoconus, acute inflammation);
- Glaucoma;
- Scotopic pupil larger than the intended ablation zone;
- Patients with systemic disease like diabetes mellitus, rheumatic disease, autoimmune condition, or dermatological disease possibly afflicting the eyes (e.g., rosacea);
- Pregnancy.

6.5 EpiLASIK Technique

Figure 6.4 shows the EpiLASIK technique using the EpiVision by Gebauer/CooperVision. After the application of anesthetic eye drops (e.g., mepivacaine) twice within 1 min, the patient is positioned on the operating table of the laser system. The eyes are disinfected with Octenisoft solution and afterwards draped with a sterile drape. The eye is kept open during surgery with a sterile speculum. For every eye a new blade is used.

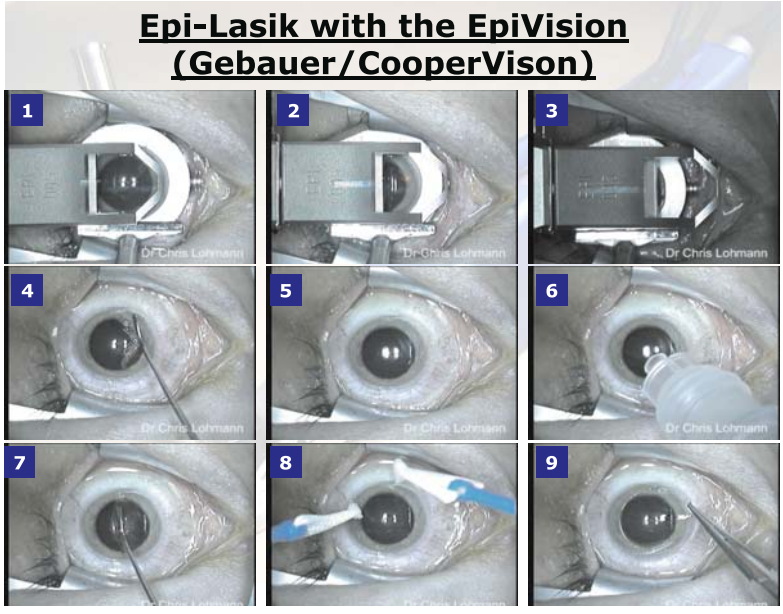

Fig. 6.4 Clinical images

After the microkeratome has been positioned preassembled on the cornea, the suction of the keratome is turned on. One drop of cooled sterile BSS is applied to the cornea and the microkeratome and the separation of the epithelium is made automatically by the microkeratome. After the microkeratome head goes back to its origin, the suction is turned off and the keratome is removed. The separated epithelium is pushed back with a blunt epithelial peeler to its hinge position and the eye is centerd beneath the laser. The laser ablation is carried out, and the wound bed is rinsed thoroughly with BSS. Then the epithelium is replaced carefully, so that the epithelium is adapted well to the wound edge without any wrinkles. After the wound edges have been dried with a sponge a bandage contact lens is applied for the fixation of the epithelium for 3 days.

6.5.1 Surgical Technique: Pearls

- Cut correct angle of hand piece,
- Cut with not too much upward or downward pressure exerted by user,
- No tilting of the microkeratome,
- Use recommended speculum.

After laser treatment:

- Wash wound bed thoroughly with cooled balanced salt solution,
- Completely dry around wound bed especially hinge area,
- Replace Epi-flap,
- Dry surface of flap and surrounding tissue before applying bandage contact lens,
- Using a swab, press gently on the surface of bandage contact lens to ensure all excess fluid is expressed from under the lens.

6.5.2 EpiLASIK Microkeratome Settings Exemplary for the Gebauer/ CooperVision EpiVision

- Flap size 9.0 mm
- Hinge 0.5 mm
- Speed 1.0 mm/s
- Oscillation 10,000 rpm

6.5.3 High Myopia: Mitomycin C

Wound healing reaction is one major problem that occurs after surface ablation. Especially in the case of higher intended corrections the typical subepithelial haze may appear. After EpiLASIK the wound healing reaction is reduced, as a healthy epithelium minimizes the induction of wound healing mediators like growth factors or cytokines. But there is still a higher induction of wound healing reaction in the case of higher intended corrections.

Mitomycin C (MMC) is an alkylating substance. DNA synthesis is inhibited, preformed DNA is degraded, and lysis of nuclei is induced. DNA synthesis inhibition by the cross linking of DNA requires the lowest concentrations of MMC and is the most important mechanism. DNA repair mechanisms do not tend to be influenced.

Mitomycin C has been used for several years in refractive surgery. In the first reports investigators tried to reduce the wound-healing reactions after PRK and LASEK. MMC (0.02%) was applied for 2 min in most studies. The first studies showed a reduction in haze and a slight overcorrection appeared. Therefore, the intended correction was reduced by 10–15%.

In EpiLASIK we use MMC in corrections with ablation depths of more than 100 µm to reduce the wound-healing reaction. The application time was primarily also 2 min with 0.02% MMC. As the clinical trials and wound-healing models showed that a shortened application time is enough, we now use an application time of 30 s. The intended correction is also reduced by an average of 15%. This setting results in almost no haze and also does not influence the visual recovery and time course of the surgery.

6.5.4 Bandage Contact Lens

After the EpiLASIK, the epithelial flap is put back to minimize pain and minimize the wound-healing reaction. As the epithelium is only a very thin layer a bandage contact lens is needed for the fixation of the epithelial flap.

Problems of contact lenses:

- Risk of infections,

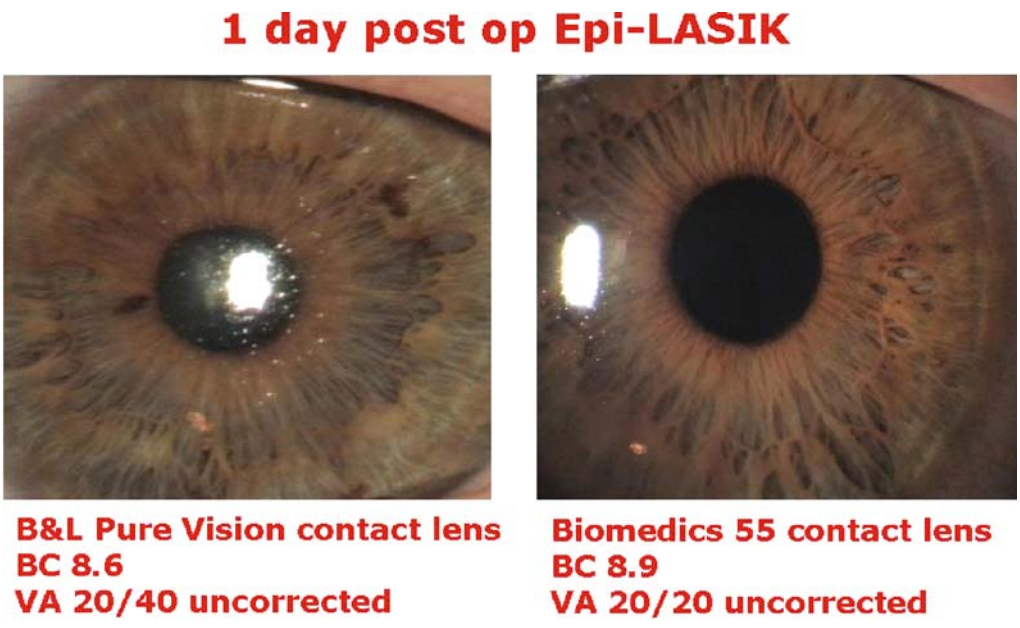

Fig. 6.5 Comparison of two different contact lenses

- Edema,
- Foreign body sensation,
- Pain,
- Reduced visual acuity.

Therefore, it is important to minimize the application time of the contact lens. Many different contact lenses have been evaluated after refractive surgery. The perfect contact lens must have two major features: good oxygen permeability and perfect fitting.

The oxygen permeability of the new generation of soft contact lenses has improved a great deal. The Dk/t value of standard soft contact lenses is between 20 and 40. But these Dk/t values would still result in corneal edema after some days. The new silicone hydrogel contact lenses like the Fokus Night and Day (CIBA Vision) and the Pure Vision (Bausch & Lomb) have much higher Dk/t values (over 100). Therefore, the oxygen permeability to the cornea is better compared with the standard contact lenses. But, even if the oxygen permeability is very good, we noticed cell debris beneath the contact lens in some patients and that they had pain. We compared the immediate postoperative period of a silicon hydrogel contact lens (Pure Vision, base curve 8.6) with a flatter standard contact lens (Biomedics 55, base curve, 8.9, OSI; Fig. 6.5). The higher myopic patients in particular had less pain and a faster visual recovery with the Biomedics contact lens. In myopic excimer laser surgery the cornea is made flatter. If the contact lens is too steep, the epithelial flap can move beneath the contact lens and the cell debris will result in pain. Therefore, a contact lens with a flatter base curve is beneficial. The silicone hydrogel lenses are only available with base curves up to 8.6; therefore, conventional contact lenses with flatter base curves may be superior (8.9 or even 9.1).

6.5.5 Postoperative Examinations and Medication

All patients undergo postoperative examinations 30 min after surgery. The fitting of the contact lens and the underlying epithelial flap should be assessed at the slit lamp. Dislodged flaps should be repositioned during this visit. All patients

are scheduled for routine follow-up visits after 1 and 3 days, after 1 week, and after 1, 3, 6, and 12 months after EpiLASIK. The bandage contact lens was routinely removed on the third postoperative day. In about 85% of all surgeries the epithelial surface was intact with slight irregularities. If the flap was not firmly attached a new contact lens was applied to the eye for a further 2 days. After this time, no further contact lens was necessary in over 98% of all surgeries. The follow-up visits involved a detailed ophthalmologic examination including manifest refraction, slit lamp microscopy, corneal topography, and tonometry.

The postoperative therapy until removal of the bandage contact lens consists of:

- Unpreserved topical antibiotics (e.g., neomycin, polymyxin-B) five times a day,
- Corticosteroids (e.g., dexamethasone 0.1%) five times a day,
- Lubrication (carbomer) six times a day.

Diclofenac eye drops and tablets (50 mg) were handed out to the patient as rescue medication in case of pain.

Therapy after re-movement of the contact lens:

- Lubrication (carbomer) five times daily,
- Corticosteroids (e.g., dexamethasone 0.1%) four times daily for 2 weeks and two times daily for a further 2 weeks.

6.6 Clinical Experiences

EpiLASIK is becoming more and more popular. Up to now several thousand EpiLASIK surgeries have been carried out all over the world using the three available devices. In our clinic we have performed over 600 EpiLASIK procedures within the last 12 months. The average age of the patients was 32.5 years (range: 18–52, 60% women, 40% men). The Gebauer/CooperVision EpiVision microkeratome was used in all cases. The excimer laser employed in this study was the MEL 80 by Carl Zeiss Meditec.

6.6.1 Conventional EpiLASIK

The preoperative refraction was between –1.5 and –8.0 D spherical equivalent (SE; mean –4.75) and the astigmatism was up to 4 D. The preoperative and postoperative refractions are listed in Table 6.1.

All EpiLASIK surgeries were carried out without any intraoperative pain. During the suction of the microkeratome all patients reported blurred vision, but none of the patients reported a "lights out" phenomena, which is common in LASIK. In one eye a free flap appeared. This surgery was converted into a PRK. All other EpiLASIK surgeries were without any intraoperative complications. There were no holes in the epithe-

Table 6.1 Refractive results of EpiLASIK for myopia. *SE* spherical equivalent, *UCVA* uncorrected visual acuity, *BCVA* best corrected visual acuity

EpiLASIK	1day	3 days	1 week	1 month	3 month	6 month	1 year
SE			0.23	–0.11	–0.12	–0.11	–0.10
UCVA	20/30	20/40	20/20	20/18	20/18	20/18	20/18
Haze	0	0	0	0.22	0.19	0.11	0.07
Percentage within ± 0.5 D			0.56	0.86	0.92	0.92	0.91
Percentage within ± 1.0 D			0.93	0.97	0.97	0.98	0.97
Loss of Snellen lines >2 lines (%)			0	0	0	0	0

lial flaps and there were also no incomplete or stromal cuts.

During the postoperative course, no infections, stromal infiltrates or similar interface appearances were visible, as seen after LASIK. Although the epithelial cells were visible under the contact lens after 2 days, after the re-movement of the contact lens no epithelial defect was visible. After the re-movement of the contact lens, in 15% of eyes the flap was a little bit loose, and therefore a new contact lens was given for further 2 days. After this time, the epithelium was stable. No epithelial instability occurred in any of the eyes treated during the entire postoperative time.

6.6.2 Refractive Results

The refractive results were very encouraging. Figure 6.6 shows the comparisons of the intended and the attained correction (SE) after 6 months. After 1 week, 56% of all patients were within ±0.5 D and 93% were within ±1.0 D SE around emmetropia. This increased during the first month to 86% of all patients within ±0.5 D and 97% were within ±1.0 D SE around emmetropia. Twelve months after surgery 91% of all patients were within ±0.5 D and 9% were within ±1.0 D SE around emmetropia (Table 6.1).

Initially a slight hyperopic shift of +0.23 D could be determined after 1 week, which was only temporary. After 1 month the refraction was –0.11 and was stable at the 3-, 6-, and 12-month follow-up visits (Fig. 6.7). One year after EpiLASIK, 93% of all patients had an astigmatism ≤0.5 D and 99% had an astigmatism ≤1.0 D. To evaluate the astigmatic results after EpiLASIK, vector analysis was calculated according to the Alpins method. The surgically induced astigmatism 12 months after EpiLASIK was 1.04 of the intended astigmatism correction. The index of success according to Alpins, which is defined as the quotient of the remaining astigmatism and

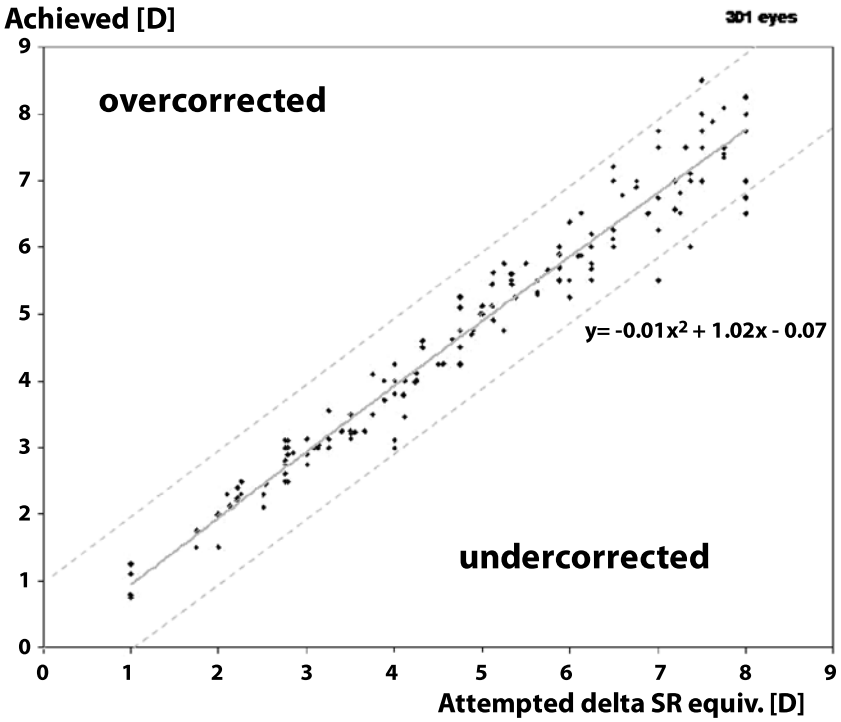

Fig. 6.6 Achieved vs. attempted refraction after EpiLASIK for myopia. One year postoperatively

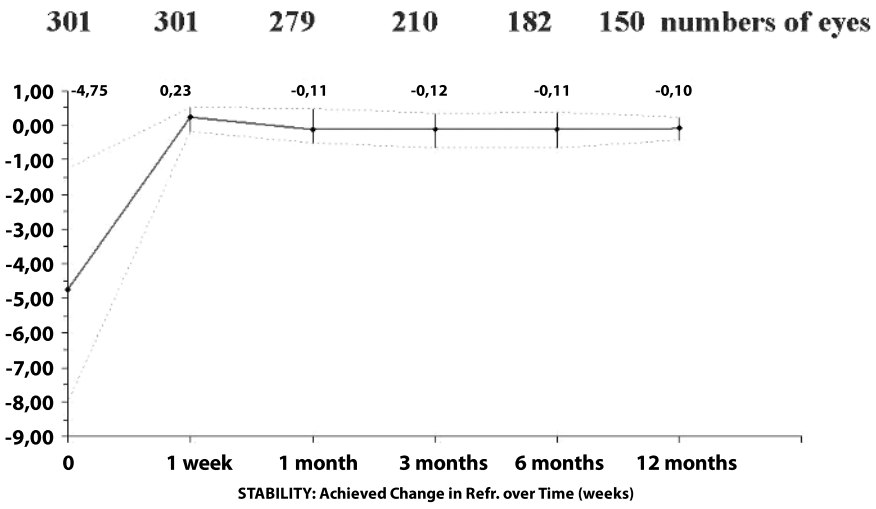

Fig. 6.7 Postoperative refraction after EpiLASIK for myopia

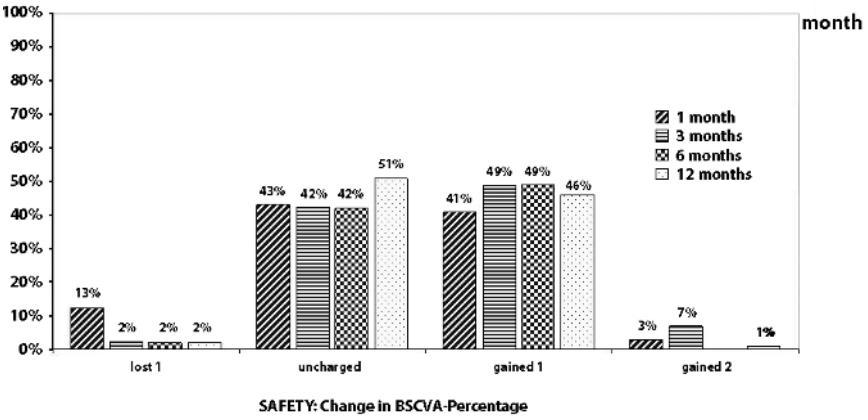

Fig. 6.8 Safety after EpiLASIK for myopia

the intended correction, with an ideal value of 0, had a value of 0.21.

6.6.3 Safety

Safety of a refractive procedure is the changes in postoperative best-corrected visual acuity (BCVA) in comparison to the preoperative BCVA. One week after EpiLASIK 13% of all patients lost one line of Snellen visual acuity, 43% of all patients were unchanged, and 44% gained one or two lines. After 1 month 2% lost one line, 42% were unchanged, and 56% gained one or two lines (Fig. 6.8). None of the patients lost more than two lines of Snellen visual acuity 1 week after EpiLASIK and during the rest of the follow-up.

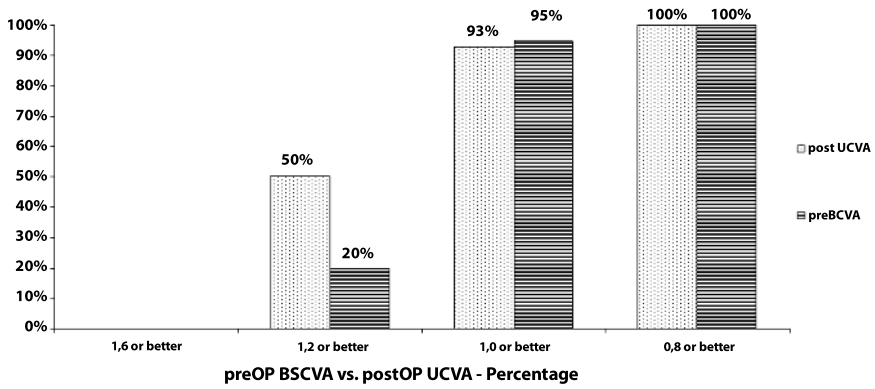

Fig. 6.9 Efficacy after EpiLASIK for myopia

6.6.4 Uncorrected Visual Acuity (UCVA Efficacy)

Ten minutes after EpiLASIK all patients had an UCVA of 20/40 or better. On day 1, the average visual acuity was 20/30 with a range of 20/60 to 20/15. On day 3 the visual acuity dropped slightly, due to edema through the contact lens, to an average visual acuity of 20/40 with a range from 20/80 to 20/15. One week after EpiLASIK most of the patients already had a good visual acuity with an average of 20/20 (range 20/30 to 20/15). This increased continuously. After 1 month all patients had a visual acuity of 20/25 with an average of 20/18).This was stable throughout the whole year (Table 6.1). At 12 months 85% had a visual acuity of 20/20 or better (Fig. 6.9).

6.6.5 Postoperative Pain

Postoperative pain is one of the key issues in refractive surgery. The postoperative pain was evaluated using the visual analog scale. Therefore, the patients were given a scale with ten units, from 0 to 10. The patients quote 0 if they do not have any pain and 10 if they have maximal pain. The patients noted their subjective pain values for the first 14 h and then every 12 h. About 25% of all patients had no pain during the whole follow-up. The other patients ranged from foreign body sensation up to pain. The maximal pain score was on average 3.5 (SD±3.2) and started 3.0 h (SD±3.1) after the surgery. There were two different peaks of the pain values. The first peak was after 3 h, when the pain started, and after 3 days, when the foreign body sensation got worse. Patients noted that above all wearing the contact lens was unpleasant, and that after the removal of the contact lens the pain disappeared.

6.6.6 Corneal Haze

One major problem of the PRK was the wound healing reaction with the development of subepithelial haze, especially in the case of higher intended corrections. This haze formation was reduced with LASEK technique, but still occurred.

The subepithelial corneal haze was classified subjectively using slit lamp examination according to its degree with values between 0 and 4 on the basis of the current scale (Hanna):

0 = No haze, completely clear cornea,
0.5 = Low trace haze, seen only with indirect illumination,
1 = Clouding at the slit-lamp, visible with direct and indirect illumination,
2 = Moderate haze, well visible,
3 = Distinctive haze with clearly reduced intraocular insight,
4 = Very strong haze, iris details not visible on the basis of clouding of the cornea.

The mean maximal haze value was 0.31±0.30 (range 0 to 1). One month after EpiLASIK, the

mean haze value was 0.27±0.31 (range 0 to 1), at 3 months it was 0.19±0.29 (range 0 to 1), and at 6 months it was 0.19±0.21 (range 0 to 0.5). There were no eyes with significant haze (i.e., worse than grade 1) throughout follow-up after retreatment.

6.6.7 Corneal Sensitivity

Dry eye problems after refractive surgery are a common problem. After LASIK this can persist for years. The main reason is that with LASIK the nerve fibers in the stroma are cut with the microkeratome. In EpiLASIK, patients also complain of dry eye symptoms during the first weeks after surgery, as the sub-epithelial nerve fiber bundles and stromal nerves are disrupted during EpiLASIK surgery and the procedure results in a significant reduction in corneal sensation.

Corneal sensation, measured with the Cochet-Bonnet aesthesiometer, is significantly reduced 3 days, 7 days, and 14 days after surgery ($p<0.01$). The loss of corneal sensation is greatest 3 days after surgery and corneal sensation increased during the first month after EpiLASIK. After 1 month, 3 months, and 6 months no significant difference was found between preoperative and postoperative sensation. There was no significant difference in sensation among different areas of the cornea after EpiLASIK.

6.7 Customized Ablation: Wavefront-Guided or Wavefront-Optimized

In a perfect, aberration-free optical system all light rays would focus on one point. This would result in a perfect wavefront. But the human eye is not a perfect optical system. The human cornea is naturally prolate. Conventional laser systems use similar energy to treat both centrally and peripherally resulting in oblate ablations due to less tangential peripheral treatments. The change from prolate to oblate results in higher amounts of spherical aberrations in wavefront measurement. Although most patients are very happy after refractive surgery, some patients have visual problems, especially in ambient light, like glare or halos. The induction of higher order aberrations is the main reason for these symptoms; however, this may be reduced with wavefront-guided ablation.

Another possibility for reducing the induction of spherical aberrations may be the wavefront-adjusted (optimized) ablation profiles. In these profiles more relative energy would be used to treat the peripheral cornea to compensate for the prolate shape. In a prospective study, we compared the visual outcome after wavefront-guided with the results after wavefront-optimized ablation in 60 eyes in 30 patients. The laser used in this study was the Concept 500 from WaveLight Technology. The microkeratome was the EpiVision by Gebauer/CooperVision.

6.7.1 Refractive Results

The SEs before EpiLASIK were –4.13±1.38 D in the wavefront-guided group (range: –2.5 to –6.75 D) and –5.01±1.86 in the wavefront-optimized group (range: –2.5 to –7.63 D). There was no statistically significant difference. One month after EpiLASIK, SE was +0.08 D±0.21 D in the wavefront-guided group and +0.21 D±0.31 D in the wavefront-optimized group, at 3 months 0.13 D±0.25 D and 0.13 D±0.29 D respectively, and at 6 months –0.06 D±0.18 D and –0.03±0.21 D respectively. Six months after LASEK all 30 eyes in both groups were within ±1.0 D of emmetropia, and 90% of all eyes in the wavefront-guided group and 87% of all eyes in the wavefront-optimized group were within ±0.5.

6.7.2 Visual Outcome

Uncorrected visual acuity (UCVA) was improved and reached at least 20/25 in all eyes following EpiLASIK in both groups. It was 20/20 or better in 93% of all eyes after wavefront-guided and 90% of all eyes after wavefront-optimized ablation.

Best corrected visual acuity (BCVA) was 20/20 or better in all 30 eyes in both groups 6 months after treatment. Before surgery, 24% of

all patients had a visual acuity of 20/15 or better in the wavefront-guided and 20% in the wavefront-optimized groups. This increased to 50% after wavefront-guided EpiLASIK and to 48% in the wavefront-optimized group. None of the eyes lost one line of the pre-EpiLASIK BCVA. All patients reported improved visual acuity. Sixty percent of all eyes in the wavefront-guided and 47% in the wavefront-optimized groups had the same postoperative Snellen visual acuity as before and 40% of the wavefront-guided and 53% of the wavefront-optimized groups even gained one line.

The mesoptometer tests stayed nearly the same in both groups. Without a glare source it improved slightly in the wavefront-guided group from an average of grade 6.39 (±1.72) to 6.31 (±1.78) and in the wavefront-optimized group from an average of grade 6.45 (±1.68) to 6.33 (±1.75). With a glare source it improved from 6.22 (±2.51) to 5.94 (±2.65) in the wavefront-guided group and from 6.33 (±2.63) to 6.01 (±2.55) in the wavefront-optimized group. However, none of these differences were statistically significant. Also, the Pelli Robson Chart test improved slightly from 1.425 log contrast sensitivity (±0.093) to 1.524 (±0.915) in the wavefront-guided and from 1.422 (±0.093) to 1.503 (±0.0885) in the wavefront-optimized groups. This was also not statistically significant.

6.7.3 Wavefront Analysis

Preoperatively and 6 months after the EpiLASIK, wavefront was measured with the Wavelight ALLEGRO Analyzer. All wavefront measurements were carried out with at least 7 mm pupil size. Preoperatively, all patients in both groups had low amounts of higher aberrations. There was no statistically significant difference. The higher order aberrations (hoRMS) slightly increased in both groups. In the wavefront-guided group hoRMS increased from 0.26 (±0.12) to 0.31 (±0.14) and in the wave-optimized group hoRMS increased from 0.27 (±0.13) to 0.32 (±0.15). Third order aberrations increased from 0.20 (±0.09) to 0.23 (±0.10) in the wavefront-guided and from 0.19 (±0.08) to 0.22 (±0.13) in the wavefront-optimized groups. Also, all fourth order and fifth order aberrations showed a slight increase.

The spherical aberrations, which had shown the highest increase in former studies, also increased slightly, but there was no statistical significance. Preoperatively, they were 0.18 (±0.16) and increased slightly to 0.23 (±0.18) in the wavefront-guided group. In the wavefront-optimized group there was an increase from 0.16 (±0.08) to 0.21 (±0.11). There was no statistically significant difference. In addition, coma and trefoil were increased slightly in both groups, but there was no statistical significance.

6.7.4 Corneal Haze

Most patients had no visible haze during the whole follow-up. There were no eyes with significant haze (i.e., worse than grade 1) throughout the whole follow-up. In both groups the mean values and the standard deviations were nearly the same (statistically not significant). Three months after wavefront-guided EpiLASIK the mean haze values were 0.21±0.28 (range 0 to 1) and 0.19±0.25 (range 0 to 1) in the wavefront-optimized group and 0.20±0.24 (wavefront-guided) and 0.18±0.20 (wavefront-optimized) at 6 months.

6.8 EpiLASIK Enhancement

Undercorrection and regression of the initial surgical effect are well-known phenomena in excimer laser refractive surgery. Although over 90% of eyes treated with LASEK, EpiLASIK or LASIK for an SE of –6.0 D are within ±1.0 D of emmetropia, myopic regression, primary undercorrection, or a combination of both may occur in some patients [7, 23, 29]. The remaining refractive error may leave the patient with unsatisfactory uncorrected vision so an enhancement procedure might be desired. The average enhancement rate after LASIK, LASEK, and EpiLASIK is currently between 5 and 10% of all myopic corrections up to –6 D. Several techniques can be used to treat residual myopia after myopic excimer laser refractive surgery. Laser in situ keratomileusis enhancement after initial LASIK

is effective and safe in correcting the remaining refractive error by re-lifting or re-cutting the flap [4, 6, 15, 20]. However, not all eyes are suitable for LASIK enhancement due to a residual stromal thickness that is too small. Photorefractive keratectomy re-treatment after primary PRK also reduces the residual myopia in most eyes, but there is a substantial risk of severe haze, loss of BCVA, and regression, especially in patients with significant corneal haze after primary PRK [9, 10, 21, 22, 24]. LASEK re-treatment after primary PRK or LASEK also reduces the residual myopia very well, with less risk of haze [8]. Photorefractive keratectomy enhancement after initial LASIK seems to be even more susceptible to these complications [2].

In EpiLASIK the epithelium is separated mechanically with a blunt blade between the basal membrane and Bowman's membrane of the cornea. In primary EpiLASIK this works very well, due to the minimal resistance between the basal membrane and Bowman's membrane. But after previous surface ablation (PRK, LASEK or EpiLASIK), the epithelium is normally more adherent.

Therefore, there are two main concerns of EpiLASIK re-treatment. First, is it possible to mechanically create an epithelial flap, or do we perhaps create incomplete flaps or even stromal cuts? Secondly, the postoperative refraction and time course are important.

So far, we have performed 25 re-treatment procedures after primary PRK, LASEK, and EpiLASIK. We used the same EpiLASIK settings as for primary EpiLASIK surgeries. In all cases of re-surgery the separation was carried out without any complications. Although the epithelium is normally more adherent after primary surface ablation, the epithelial separation has been performed without any problems. There were no holes in the epithelial flaps and there were also no incomplete or stromal cuts. The whole postoperative follow-up was uneventful. After the removement of the contact lens, the flap was a little bit loose in 3 eyes, and therefore a new contact lens was given for a further 2 days. After this time the epithelium was stable. No epithelial instability occurred in any of the treated eyes during the entire postoperative period.

6.8.1 Refractive Results (Re-surgery)

The SE before primary surgery was –6.53±1.22 D (range: –4.25 to –8.0 D). Before EpiLASIK enhancement the SE was –1.22 D±0.57 D (range: –0.38 to –2.0 D). One month after re-treatment, SE was +0.57 D±0.51 D (range: 0.00 to 1.25), at 3 months it was 0.20 D±0.28 D (range: –0.12 to 0.75), and at 6 months it was 0.25 D±0.36 D (range: 0.75 to –0.25 D). Six months after EpiLASIK enhancement 18 out of 20 eyes were within ±0.5 D of emmetropia and 100% were within ±1.0 D.

6.8.2 Visual Outcome

Uncorrected visual acuity (UCVA) was improved and reached at least 20/25 in all eyes following EpiLASIK enhancement (6-month follow-up) and 85% had an UCVA of 20/20 or better.

Best corrected visual acuity (BCVA) was 20/20 or better in all 20 eyes both before and 6 months after re-treatment. Before re-surgery 10% of all patients had a visual acuity of 20/15 or better. This increased to 20% after EpiLASIK enhancement. Fifty percent of all eyes had the same pre-re-treatment BCVA and 50% gained one line of Snellen visual acuity. None of the eyes lost one line of the pre-initial BCVA. All patients reported improved visual acuity and fewer problems in low ambient light.

6.8.3 Corneal Haze

The mean haze value before re-treatment was 0.23±0.30 (range 0 to 1). After the re-treatment the mean haze value was 0.34±0.31 (range 0 to 1) at 3 months and 0.27±0.29 at 6 months (range 0 to 1). There were no eyes with significant haze (i.e., worse than grade 1) throughout follow-up after re-treatment.

6.9 Complications

In our surgical experience we have so far had no major complications. There was one free flap. This surgery was converted into a PRK. The whole postoperative period of this patient was also uneventful, and the patient had a visual acuity of 20/20 at 3 months. If the patients had pain, this was only temporary and was completely gone after the re-movement of the bandage contact lens.

6.9.1 Possible Intra- and Postoperative Complications

6.9.1.1 Inability to Get Suction Even When Unit Shows Vacuum Attained

- If the vacuum ring is still mobile after maximum vacuum, check for trapped conjunctiva in the aspiration hole on the ring,
- Try one more time only—if still a problem, change to a 20-mm ring ("high" vacuum ring).

6.9.1.2 "Incomplete Flap"

- Often caused by deformed metal band (mishandling during assembly/disassembly),
- Loss of suction during cutting/dissection, usually due to the incorrect angle of the hand piece—too much upward or downward pressure exerted by user).

6.9.1.3 Conjunctiva "Too Allergic" (Chemosis)

- Reschedule case and change medication.

6.9.1.4 "Can´t Fit the Vacuum Ring"

- Check for "lid squeeze,"
- Use recommended speculum.

Summary for the Clinician

- EpiLASIK is a new technique for surface ablation. The refractive results are very encouraging with very fast visual recovery and reduced pain compared with PRK:
  - Good safety, stability, and efficacy,
  - Fast visual recovery,
  - Reduced pain,
  - Minimal haze,
  - Fast recovery of corneal sensitivity.
- The refractive results are comparable to those of LASIK and LASEK.
- The creation of the flap is more standardized and easier than with LASEK.
- No complications of stromal flaps, which can appear after LASIK (diffuse lamellar keratitis, infections, keratectasia, dry eye).
- In addition, wavefront-guided treatments are more effective when performing surface ablation than LASIK.
- Wavefront-optimized ablation profiles induce the same wavefront changes as wavefront- guided ablation.
- Wavefront-guided procedure is useful in patients with higher amounts of higher order aberrations.
- Re-EpiLASIK is possible and safe.
- In ablation depths higher than 100 µm, mitomycin C is recommended.

6.10 Pros of EpiLASIK

- No stromal cut; long term stability.
- Twenty-five years of clinical experience due to experiences with PRK.
- Faster visual rehabilitation compared with PRK, but still longer than after LASIK.
- Important: good re-adaptation of the epithelial flap and no movement beneath the contact lens.
- Less pain compared with PRK, but still more than after LASIK.

6.11 Cons of EpiLASIK

- Need for a bandage contact lens for the fixation of the epithelial flap.
- Not every contact lens fits every patient.
- Sometimes the epithelium can move during blinking.

6.12 Important

- Perfect repositioning of the epithelium,
- No fluid underneath BCL,
- Bandage contact lens,
- Carbomer artificial tears.

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Chapter 7

The Femtosecond Laser: a New Tool for Refractive and Corneal Surgery

7

Mitchell P. Weikert, Anne Bottros

Core Messages

- The short pulse width of the femtosecond laser permits photodisruption of corneal tissue at lower energy levels, allowing for tighter spot placement and smoother ablation patterns.
- The femtosecond laser creates flaps with more predictable and flexible dimensions than mechanical microkeratomes.
- IntraLASIK achieves visual and refractive results equivalent or slightly superior to those of mechanical microkeratomes.
- Although the femtosecond laser has an excellent safety profile, it still carries the risk of complications, such as decentration, diffuse lamellar keratitis, flap stria, and transient light sensitivity.
- The femtosecond laser can be programmed to create channels for intrastromal corneal ring segments, to produce more stable trephination patterns in penetrating keratoplasty, and to prepare the donor and host for lamellar keratoplasties.

7.1 Introduction

Laser-assisted in situ keratomileusis (LASIK) continues to be one of the dominant surgical procedures employed to correct refractive errors. Until recently, flap creation in LASIK was entirely dependent upon blade-based, mechanical microkeratomes with their inherent disadvantages. Although microkeratomes produce excellent results, laser-based technologies offer certain benefits, such as optical precision, liberation from cornea–blade contact, and flexibility in ablation pattern design. The femtosecond (FS) laser, with its low energy levels and ultrashort pulse widths, has emerged as the dominant laser platform used for LASIK flap creation. While mechanical microkeratomes continue to be more common, use of the FS laser has grown exponentially over the last few years. In addition to refractive applications, the flexibility of the laser platform has seen its use extend beyond LASIK, into other forms of corneal surgery. This chapter will discuss the fundamentals of FS laser mechanics and review its clinical performance with regard to LASIK, intracorneal ring segment implantation, and penetrating/lamellar keratoplasty.

7.2 Mechanism of Action

The femtosecond laser achieves its surgical effect through a process termed "photodisruption". Normally, the cornea is transparent to visible and near-infrared (IR) wavelengths, with minimal to no absorption of incident light. However, when the intensity (power per unit of area) of the focused laser beam exceeds a certain threshold (approximately 10^{11}–10^{12} W/cm^2), pronounced changes occur in the absorption characteristics of the tissue [14, 30]. Electrons within the tissue absorb incident photons and become liberated when the added energy exceeds their ionization potential. These free electrons impact adjacent molecules, creating new ions to feed the process. The resulting cascade converts the matter to a collection of freely moving electrons and ions, otherwise known as plasma. When energy is removed from the system (i.e., the laser pulse is

completed), the electrons and ions recombine to form a gas, which rapidly expands within the tissue, creating both a cavitation bubble and shock wave. These forces produce cleavage of the tissue surrounding the focal point of the laser, resulting in photodisruption.

As stated above, the laser intensity at its focal point must exceed a certain threshold to create photodisruption. Since power is defined as energy per unit of time, these high intensity levels can be achieved over a given focal area by increasing the laser's energy or by decreasing its pulse duration. Near-IR lasers are available with pulse widths on the orders of nanoseconds (10^{-9} s), picoseconds (10^{-12} s), and femtoseconds (10^{-15} s). Although photodisruption can be achieved with each of these lasers, the fluence (energy per unit of area) necessary to produce optical breakdown will decrease along with the pulse width. In addition, the predictability of the breakdown threshold also increases with shorter pulse duration [11]. Lower energy thresholds and higher predictability translate into smaller cavitation bubbles, decreased shock waves, and improved control of tissue disruption [14, 20]. Laser spots can be placed closer together, with reduced disruption of surrounding tissue, thinner intervening tissue septa, and smoother interfaces [12]. Because of these factors and its poor clinical performance, the picosecond laser was abandoned in favor of the femtosecond laser. The FS laser's narrow pulse width and lower energy make it an ideal instrument for corneal surgery. Laser spots can be placed side by side to produce lamellar cuts or stacked on top of each other to make vertical incisions.

Summary for the Clinician

- The short pulse width of the femtosecond laser permits photodisruption of corneal tissue at lower energy levels.
- The lower energy, smaller cavitation bubbles and reduced shock waves allow for tighter spot placement with smoother ablation patterns.

7.3 Clinical Applications of the FS laser

The IntraLase FS15 and FS30 (IntraLase, Irvine, CA, USA) are the only commercially available versions of the femtosecond laser approved for use in the United States. The FEMTEC (20/10 Perfect Vision, Heidelberg, Germany) is a version of the FS laser that is available in Europe. Currently, the primary clinical application for the FS laser is the creation of the lamellar corneal flap during laser in situ keratomileusis (LASIK). However, given the flexibility of the laser platform, surgical indications are rapidly expanding to include such procedures as channel creation for intracorneal ring segments, as well as various forms of penetrating and lamellar keratoplasty.

7.3.1 LASIK Using the Femtosecond Laser

The term "IntraLASIK" has been coined to describe laser in situ keratomileusis performed with the IntraLase femtosecond laser. To create the LASIK flap, the cornea is applanated with a flat glass lens. The laser energy is focused at a precise distance from the applanation surface, which determines the thickness of the flap. Laser spots can be placed in a spiral pattern that progresses from the central cornea to the mid-periphery, producing a lamellar cut. More commonly, they are placed in successive lines that progress from one side of the cornea to the other in a raster pattern. After the flap thickness has been defined, the spots are stacked vertically in a circular pattern to create the side cut. The flap hinge is defined by a portion of the flap circumference that is spared from the side cut. As discussed above, photodisruption produces gas in the interface. If the gas cannot escape from the interface, it will often penetrate the stroma causing temporary opacification of the cornea. To reduce this risk, a lamellar pocket can be produced by the laser adjacent to the hinge. This deeper opening can provide a place for gas to vent, increasing the likelihood of a clear stromal bed and timely progression of the LASIK procedure. After the laser dissection has been completed, the remaining microadhesions are bluntly dissected with a spat-

ula when the flap is lifted. The FS laser creates a square-edged, planar flap with a uniform thickness across its entire diameter. This is in contrast to a flap produced by a mechanical microkeratome, which has a tapered edge and a meniscus profile (i.e., thinner centrally and thicker peripherally). The even thickness and vertical edges of the FS laser flap may provide more stability, with increased resistance to displacement or stria formation.

Since the FS laser can only be used to create the LASIK flap, an excimer laser is still required to perform the refractive portion of the corneal ablation. Spacing issues and excimer platform designs often dictate that the two lasers must be in separate suites, requiring the patient to move from one room to another between procedures. However, when real estate and laser design permit, the two can be placed in the same room with a patient bed that pivots between them.

7.3.1.1 Laser Settings

The IntraLase permits adjustment of multiple surgical parameters, including the LASIK flap dimensions, pocket design, and the treatment patterns for both the interface and side cuts. A list of the adjustable parameters, their ranges, and typical settings are shown in Table 7.1. As experi-

Table 7.1 Surgical parameters available for adjustment with the IntraLase FS laser. The ranges and typical settings are given. Note: energy settings and spot/line separations are typically lower for the FS30 than for the FS15. *N* nasal, *S* superior, *T* temporal

Category	Parameter	Range	
Flap dimensions	**Thickness**	100–400 μm	
	Diameter	5.0–9.0 μm	
Lamellar cut	**Treatment pattern**	Raster/spiral	
	Hinge location	Raster	0, 90, 180° (N/S/T)
		Spiral	0–359°
	Hinge angle	Raster	45–90°
		Spiral	0–359°
	Raster spot separation	Spot	6–14 μm
		Line	6–14 μm
	Spiral spot separation	Tangential	6–14 μm
		Radial	6–14 μm
	Energy	15 kHz	1–6 μJ
		30 kHz	1–4 μJ
Side cut	**Angle**	30–90°	
	Energy	15 kHz	1–6 μJ
		30 kHz	1–4 μJ
Pocket	**Width**	0.100–0.500 mm	
	Start depth	100–300 μm	
	Energy	15 kHz	1–6 μJ
		30 kHz	1–4 μJ
	Spot separation	Tangential	4–14 μm
		Radial	4–14 μm

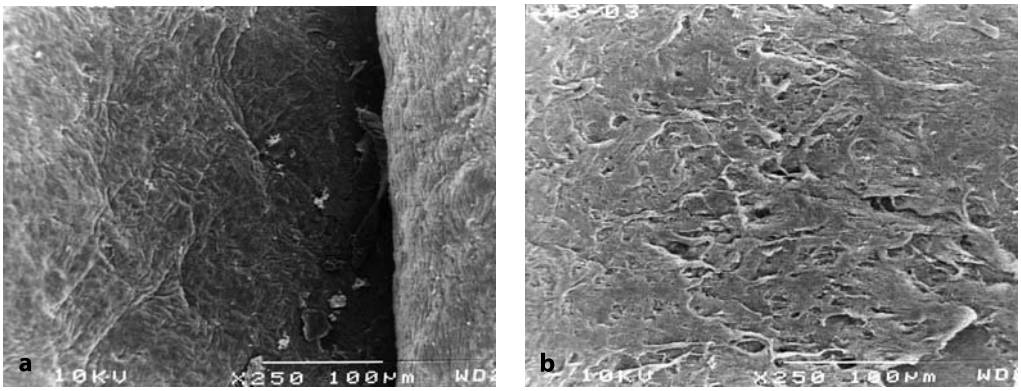


Fig. 7.1 Stromal interface following flap creation with the femtosecond laser. **a** demonstrates a smoother stromal interface produced with a spot energy of 1.8 mJ, a spot separation of 11 mm, and a line separation of 9 mm. **b** shows a rougher stromal interface when the spot energy is raised to 3.8 mJ, while the spot and line separations are unchanged.

ence with each laser accrues, the parameters can be refined to optimize the intraoperative performance of each system, as well as the postoperative surgical results. General goals are to decrease energy levels for the lamellar and side cuts, and to reduce the spot and line separations. The spot and side cut energies should be reduced until flap lifting encounters excessive resistance. Spot separations can be decreased until the procedure length becomes prohibitively long. Adequate adjustment of these parameters will eliminate postoperative inflammation and minimize resistance to flap lifting, while maintaining a smooth ablation surface (Fig. 7.1).

7.3.1.2 Surgical Technique

During LASIK flap creation, globe stability is achieved using a disposable suction ring attached to a spring-loaded syringe. The system results in relatively low intraocular pressures during flap creation (approximately 35 mmHg), in contrast to conventional, vacuum pump-based microkeratomes, which elevate intraocular pressures to about 70 mmHg. Placement of the ring is performed without draping and does not usually require an eyelid speculum. After suction is achieved, the cornea is applanated by a disposable, flat glass lens attached to the motorized arm of the laser (Fig. 7.2). Positioning of the lens along the x, y, and z axes is controlled with a joystick, while the surgeon supports the suction ring. As the lens assembly is lowered onto the cornea, the area of contact between the lens and corneal surface can be viewed on the laser's video monitor. Centration is maintained with the joystick as the applanated surface area increases until it fills the entire suction ring. When adequate applanation is achieved, a green light on the video monitor notifies the surgeon. To complete the docking procedure, the surgeon releases the clip on the suction ring, which reduces its inner diameter causing it to firmly grip the applanation lens. Further refinements in docking can be achieved by squeezing the suction ring to release its grip

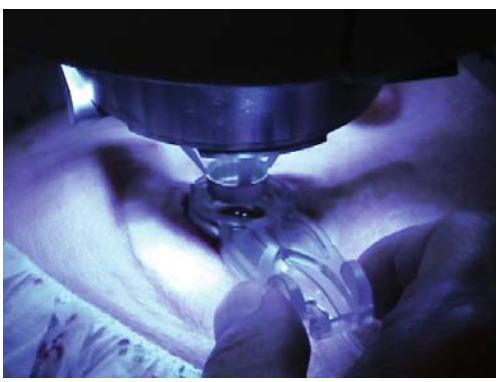


Fig. 7.2 Femtosecond laser docking of the applanation lens to the suction ring

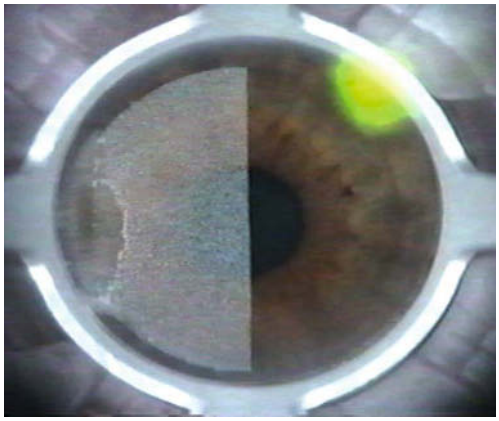


Fig. 7.3 Femtosecond laser interface cut demonstrating the raster pattern of spot placement

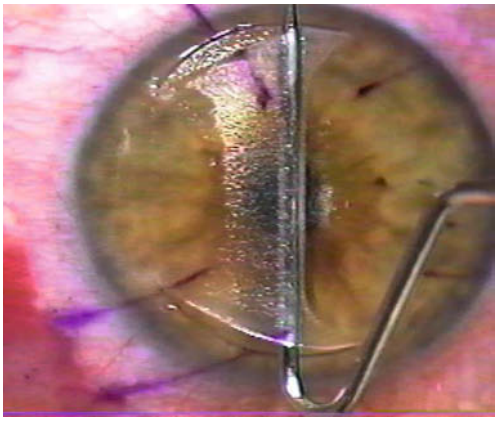


Fig. 7.4 Flap lifting and adhesion lysis using a spatula

on the applanation lens, followed by movement of the joystick or tilting of the ring.

Once docking is achieved, the laser displays the intended location of the LASIK flap. This location can be further adjusted via the system software to compensate for decentration of the suction ring. It should be noted that position adjustment is limited by the laser's optics and may result in reduction of the flap diameter. When the surgeon is satisfied with the intended flap location, laser application is initiated with depression of a foot pedal. When the raster pattern is selected, ablation begins near the hinge and proceeds across the cornea (Fig. 7.3). If creation of a pocket is desired, this will be performed first, followed by the lamellar cut across the stromal bed and finishing with the flap's side cut. The total ablation time is approximately 1 min with the FS15 and about 30 s with the FS30. After the laser treatment has been completed, suction is released at the syringe and the applanation lens/suction ring assembly is lifted off the ocular surface. A small hook or similar instrument is then used to open the side cut in a small area near the hinge to release bubbles from the interface.

During binocular procedures, both flaps are typically created prior to the refractive ablation. Once the patient is draped and the lid speculum is placed, the flap is marked prior to lifting. Because the laser energy is applied in successive rows of individual spots, small adhesions or septa remain in the interface, which must be released when the flap is lifted. A spatula is used to enter the interface beneath the flap near the hinge (Fig. 7.4). The spatula is first directed toward and then away from the hinge with a rocking motion. The patient can assist in the lysis of adhesions by looking toward the hinge to provide counter traction. Care must be taken to avoid excessive force during adhesion lysis, which may inadvertently tear the flap. The edge of the flap near the hinge is at greatest risk of tearing as it experiences the most stress during the lift. Once the flap is lifted, the refractive portion of the laser treatment can proceed. After the excimer ablation is completed, the flap is repositioned in the usual fashion. Typical postoperative medications include a broad spectrum topical antibiotic, as well as a topical steroid.

Summary for the Clinician

- The FS laser parameters (spot energy and separation) at each facility should be optimized to eliminate postoperative inflammation, minimize resistance to lifting, and produce smoother ablation surfaces.
- After docking is complete, the flap position can be adjusted with the FS laser software, but further adjustment may reduce the flap diameter.

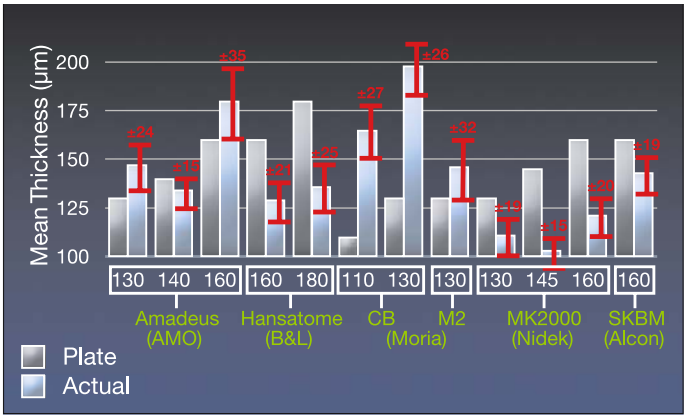


Fig. 7.5 Achieved flap thickness vs. labeled plate thickness for six different microkeratomes. For each model, the labeled plate thickness is shown with a *gray bar* and the measured flap thickness with a *blue bar*. The *red error bars* show one standard deviation above and below the mean flap thickness

7

7.3.1.3 Clinical Results

The incorporation of a FS laser into a refractive surgery practice requires a significant investment. While economic factors must be considered, the clinical performance of the laser also plays a key role in the decision-making process. As such, the clinical results of IntraLASIK must be thoroughly examined to assess the laser's performance with regard to flap dimensions, visual outcomes, refractive results, postoperative aberrations, and safety. Over the last 2 years, several studies evaluating the clinical results of IntraLASIK have been presented in peer-reviewed journals.

7.3.1.4 Flap Dimensions

The accurate prediction of LASIK flap thickness and diameter is very important, especially in patients with thinner corneas or in those who wish to have the option of future enhancements. Unfortunately, the actual flap dimensions achieved with mechanical microkeratomes often differ considerably from their labeled ring diameter and plate thickness. Solomon and associates conducted a prospective, multicenter study of 1,634 eyes to examine the accuracy of flap thickness, as well as the factors that influence flap thickness, for six microkeratomes, including the Advanced Medical Optics Amadeus, the Bausch & Lomb Hansatome, the Moria Carriazo-Barraquer, the Moria M2, the Nidek MK2000, and the Alcon SKBM [24]. Intraoperative flap thickness was measured using ultrasound subtraction pachymetry as follows:

FT = TT - SBT
where FT = flap thickness, TT = total corneal thickness, SBT = stromal bed thickness (after flap lift and before excimer ablation)

The plate thickness, the achieved flap thickness, and standard deviations are shown for the different microkeratome models in Fig. 7.5. The results showed that device labeling did not accurately reflect the mean flap thickness obtained with any microkeratome. The difference between the plate thickness and mean flap thickness for the devices varied from 6 µm (the Amadeus with a 140-µm plate) to 68 µm (the Moria CB with a 130-µm plate). The standard deviations for flap thickness also varied widely, ranging from 15 µm (the Amadeus with a 140-µm plate, the Moria MK200 with a 145-µm plate) to 35 µm (the Amadeus with a 160-µm plate). Several factors specific to each microkeratome were found to influence flap thickness, including the model number, plate thickness, serial number, and blade lot number. Additional variables that contributed to flap thickness variation were corneal pachymetry, the flattest keratometry measurement, surgery order, and surgeon. The patient's age, sex, average keratometry measurement, steepest keratometry

measurement, and white-to-white measurements had no effect. In general, thicker flaps were found in thicker corneas and first eyes. In addition, the investigators had an 8% rate of epithelial defects.

One of the first peer-reviewed studies evaluating the clinical performance of the IntraLase FS laser focused on flap dimensions. Binder prospectively measured flap thickness and diameter for the first 103 consecutive eyes in which he used the FS laser [2]. The flap diameter was measured with calipers, while thickness was measured with ultrasound subtraction pachymetry. The eyes were divided into four groups based on the attempted flap thickness, which varied between 140 and 110 µm in 10-µm intervals. The settings for flap diameter ranged from 8.4 to 9.4 mm. Although the initial setting for each case was 9.4 mm, the laser automatically adjusted the attempted diameter to account for decentration of the suction ring and/or treatment location. The number of eyes in each group ranged from 21 in the 130-µm group to 34 in the 110-µm group. The difference between the attempted and actual mean flap thickness was smallest in the 120-µm group at 2.4 µm and largest in the 110-µm group at 15 µm. Overall, the standard deviations improved as flap thickness decreased and experience increased. The largest SD was 18.5 µm, found in the initial group with the thickest setting of 140 µm. The SD decreased along with the attempted flap thickness to 16.6 µm in the 130-µm group, and 12 µm for both the 110- and 120-µm groups. The achieved flap diameters compared very well with the attempted diameters, with mean differences spanning -0.02 to 0.37 mm. The standard deviation for flap diameter was also tight with measurements decreasing from 0.26 mm in the 140-µm group to 0.12 mm in the 110-µm group. The author also noted smoother stromal beds, less resistance to flap lifting, and decreased postoperative inflammation as the spot separation and energy settings were decreased.

Kezirian and Stonecipher retrospectively compared the outcomes of myopic LASIK performed with the IntraLase FS laser (n=106 eyes) with those achieved with the Moria Carriazo-Barraquer (n=126) and the Bausch & Lomb Hansatome (n=143) microkeratomes [10]. In all cases, the refractive ablation was carried out using the VISX Star S3 excimer laser. Flap thickness was measured with ultrasound subtraction pachymetry, as described above. No statistically significant differences were found between groups with regard to preoperative spherical equivalent, pachymetry, keratometry, or age. The mean flap thickness created by the IntraLase measured 114±14 µm, compared with the programmed thickness of 130 µm. The Moria CB microkeratome with a 130-µm plate produced a mean flap thickness of 153±26 µm, while the Hansotome yielded flaps with a mean thickness of 156±29 µm using a 180-µm plate. The tighter SD (14 µm) and lower mean difference between attempted and achieved thickness (16 µm) suggest that the FS laser may create LASIK flaps with greater predictability.

Factors contributing to the variation in flap dimensions found with mechanical microkeratomes were noted previously. Since the FS laser employs a flat, single-use lens and positions the ablation depth relative to the applanated corneal surface, this method should be independent of corneal curvature, astigmatism, and surgical order. Since tissue compression is inherent to the process of applanation, preoperative pachymetry, intraocular pressure, and docking force may contribute to the variation found with the FS laser. Other sources of error include variation in the laser's focal point (±4 µm), the manufacturing tolerance for lens thickness (±5 µm), and the repeatability of pachymetry measurements (±5%). Given these factors, a standard deviation approaching 10 µm might be expected.

Summary for the Clinician

- Mechanical microkeratomes produce flap dimensions that can vary widely from the labeled plate thicknesses and ring diameters.
- The femtosecond laser creates flaps with predictable dimensions (thickness SD = 12–16 µm, diameter SD = 0.12–0.26 mm).

7.3.1.5 Visual and Refractive Outcomes

New technologies are usually embraced when they offer clinically significant advantages over existing methods. As discussed above, the FS laser may provide increased flap predictability. In addition, its "blade-free" design should decrease the risk of certain vision-threatening flap complications, such as free caps or buttonholes. However, even though these complications can result in permanent vision loss, they are still rare with current microkeratomes. Thus, for IntraLASIK to gain widespread acceptance, it must achieve comparable or improved visual and refractive results.

In their study comparing the IntraLase FS-15, the Moria CB, and the B&L Hansatome, Kezirian and Stonecipher also examined the visual and refractive results produced by each device [10]. As mentioned above, myopic LASIK was performed on 375 eyes using the VISX Star S3 excimer laser set for a 6.5-mm optical zone and pulse rate of 10 Hz. Preoperatively, there were no statistically significant differences between groups with regard to age, spherical equivalent, keratometry, or pachymetry. The post-LASIK uncorrected visual acuity (UCVA) and best spectacle-corrected visual acuity (BSCVA) were similar for each method of flap creation. At the 3-month postoperative visit, approximately two-thirds achieved uncorrected acuities of ≥20/20, while 99% were ≥20/40. The IntraLase demonstrated better refractive results at 3 months with 91% having a manifest refraction spherical equivalent (MRSE) of ±0.50 D, compared with 73% in the CB group and 74% in the Hansatome group. In all groups, the mean postoperative cylinder was <0.25 D, with no difference between groups. However, the IntraLase group had less surgically-induced astigmatism (0.22 D) than the mechanical microkeratomes (0.32 D in the CB group and 0.40 D in the Hansatome group) for spherical corrections.

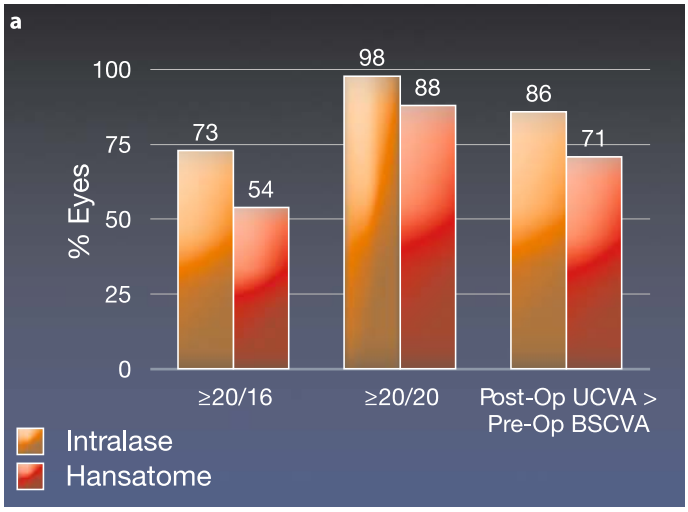
Durrie and Kezirian conducted a head-to-head comparison of the IntraLase and Hansatome by performing bilateral LASIK on fellow eyes of 51 consecutive patients using the microkeratome on one side and the FS laser on the other [6]. Eyes were randomized to each method of flap creation at the time of surgery and the excimer ablation was performed using the LADARVision 4000 (Alcon Labs). Both groups of eyes had similar preoperative spherical equivalents and refractive cylinder. At all time points following surgery (1 day, 1 week, 1 month, 3 months), more eyes in the IntraLase group achieved UCVA of ≥20/20 and ≥20/16 ($p<0.03$ and $p<0.05$ respectively). In addition, more IntraLase eyes had postoperative UCVA greater than preoperative BSCVA ($p=0.05$). The results for UCVA at 3 months are shown in Fig. 7.6A. The postoperative MRSE was within ±0.5 D in a higher percentage of IntraLase eyes at 1 week and 1 month. This difference was also present at 3 months, but was not statistically significant ($p=0.10$). Postoperative astigmatism was greater in Hansatome eyes at all postoperative visits. Although all eyes had superiorly hinged flaps, no consistent orientation was found in the axis of the postoperative cylinder. The refractive results at 3 months are shown in Fig. 7.6B. These studies demonstrate that the FS laser was able to achieve visual and refractive results that were better than, or at least comparable to those achieved with mechanical microkeratomes.

Summary for the Clinician

- IntraLASIK achieves visual and refractive results equivalent or slightly superior to those of mechanical microkeratomes.

7.3.1.6 Aberrations

The excimer ablation pattern computed for conventional LASIK is based on the subjective measurement of a patient's manifest and cycloplegic refractions. Recently, wavefront technology has emerged to become the dominant method used in designing refractive treatments. Wavefront-guided (WFG) ablations utilize aberration data obtained from the objective measurement of a patient's focusing error. In general, WFG treatments offer improved results with greater likelihood of achieving UCVA of ≥20/20. However, in both conventional and WFG LASIK, intraoperative ablation patterns are based on preoperative measurements obtained before flap creation.



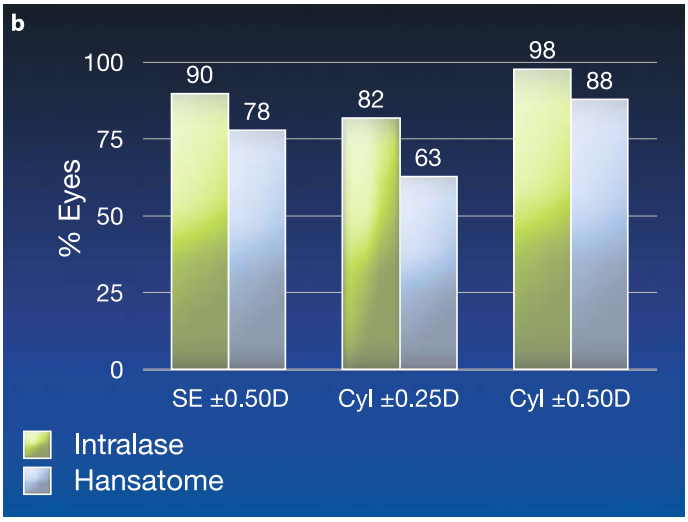


Fig. 7.6 a Uncorrected visual acuity and **b** refractive results 3 months after LASIK, with flaps created by the IntraLase femtosecond laser in one eye and the Hansatome microkeratome in the other

Therefore, if the act of flap creation alters the optical characteristics of the eye, the calculated treatment may not accurately reflect the ablation pattern required for full correction. This may result in residual refractive errors and uncorrected aberrations. The effect of flap creation varies in the literature, with some studies showing little induction of aberrations, while others show greater changes [17, 18]. Given the inherent differences between FS laser and microkeratome-produced LASIK flaps, it is worthwhile to compare aberration results for each method.

Durrie and Kezirian examined the pre- and postoperative aberration levels in their head-to-head comparison of the IntraLase and the Hansatome discussed above [6]. They specifically addressed the changes in astigmatism, coma, spherical aberration, and trefoil. No significant differences in preoperative aberration levels were found between the two groups. In addition, postoperative aberrations were similar for each group at 3 months, with the exception of astigmatism and trefoil. Astigmatism (Z_2^2) levels were higher ($p<0.01$) in the Hansatome group (mean root mean square [RMS] error = 0.152±0.232 μm) than in the IntraLase group (mean RMS error

= 0.028±0.233 μm), which was consistent with the refractive results. However, the manifest cylinder did not correlate with the astigmatism measurements produced by aberrometry for either group. This might indicate that other aberrations, such as coma, contribute to refractive astigmatism. The trefoil (Z_3^{-3}) levels were higher ($p<0.01$) in the Hansatome eyes (mean RMS error = 0.206±0.127 μm) than in the IntraLase eyes (mean RMS error = 0.136±0.095 μm). The higher trefoil also correlated with the difference in astigmatism, suggesting a contribution to the refractive cylinder.

Tran and colleagues conducted a prospective study comparing aberrations induced by LASIK using the FS laser and the mechanical microkeratome, both after flap creation and upon completion of surgery [29]. As with Durrie and Kezirian's study, this was a head-to-head comparison of fellow eyes with a Hansatome flap ($n=9$) on one side and an IntraLase flap ($n=8$) on the other. The IntraLase was set for a 120-μm flap thickness, 8.8-mm diameter, and superior hinge to match the mean flap dimensions produced by the Hansatome with a 160-μm plate and a 9.5-mm ring. Preoperative assessment of vision, refraction, topography, and wavefront aberrometry was followed by right/left randomization to a method of flap creation. After the flap was cut in each eye, it was lifted and repositioned. Ten weeks later, the measurements were repeated, the flaps were lifted, and conventional excimer ablations were performed with the Technolas 217A (Bausch & Lomb). Excimer treatments were based on the manifest refraction at the 10-week visit and not on the pre-flap measurements. Optical zones ranged from 6.4 to 7.0 mm in diameter, but both eyes were matched for each patient. The final measurements were taken 3 months after the completed procedure.

Ten weeks after flap creation, lower order aberrations showed a statistically significant decrease in defocus for both the Hansatome ($p=0.004$) and the IntraLase ($p=0.008$). Both groups had an increase in total higher order aberrations, although the increase was only significant for the Hansatome ($p=0.02$). The increase in the Hansatome group was primarily due to changes in trefoil and quadrafoil. Finally, the Hansatome eyes showed a significant hyperopic shift of approximately 0.25 D in the manifest refraction ($p=0.04$), while the IntraLase group remained stable. Three months after completion of LASIK, all eyes achieved UCVA of 20/20 or better. Coma was significantly increased with the Hansatome ($p=0.008$), but not with the IntraLase. Both groups showed identical increases in spherical aberration, but this was not statistically significant for either method ($p>0.05$). Several factors may contribute to the aberration changes produced by each device, including the flap profile, thickness, hinge angle, side cut angle, and extent of decentration. Although these factors may explain the increases in trefoil, quadrafoil, and coma found with the Hansatome flaps, the increase in spherical aberration for both groups is most likely due to the myopic excimer ablation. The uniform flap thickness, square edge profile, predictable hinge angle, centration adjustment, and sub-hinge lamellar dissection provided by the FS laser may produce flaps that are more structurally stable and resistant to the induction of aberrations.

Summary for the Clinician

- Both the FS laser and mechanical microkeratomes show similar alterations in total higher order aberrations.
- In various studies, mechanical microkeratomes have shown statistically significant increases in individual aberrations, such as astigmatism, coma, trefoil, and quadrafoil.

7.3.1.7 Complications

All surgical procedures, even the least invasive, carry a risk of complications. While the overall complication rates for blade-based microkeratomes are very low, some rare complications can still result in significant loss of vision. The FS laser, with its "blade-free" technology, may provide a safer alternative for LASIK flap creation. However, since IntraLASIK is still a surgical procedure, it too is associated with certain intra- and postoperative complications.

Three of the most feared intraoperative complications associated with LASIK are the creation of free caps, partial flaps, or button holes. One key advantage of the FS laser is that it is virtually impossible to create a free cap unless intentionally programmed into the software. When a raster pattern is chosen for the lamellar dissection, the software requires placement of a hinge. The only way to create a free cap is to choose a spiral pattern for spot placement with a hinge width of zero degrees, as one might do for anterior lamellar keratoplasties. Partial flaps and button holes are very unlikely with this technology and would require a progressive reduction in the depth of spot placement during the lamellar ablation. While this could potentially happen if a surgeon begins the ablation without locking the suction ring, it has not been reported in the literature. On rare occasions, a "hiccup" may occur during spot placement with a raster pattern. When this takes place, a small linear irregularity in the stromal bed may result. These irregularities appear to be visually insignificant, even when they involve the visual axis, but they can be associated with a slight increase in resistance to flap lifting.

Just as with mechanical microkeratomes, suction loss may occur at any point during flap creation with the FS laser. While this can be catastrophic with blade-based devices, loss of suction with the IntraLase causes immediate cessation of spot placement. Certain patients may be at higher risk of suction loss, such as those with narrow interpalpebral fissures, prominent brows, and/or deep set eyes, as these conditions may interfere with suction ring placement. Excessive patient movement may also compromise ring stability and suction loss may spontaneously occur, even under optimal conditions. If so, the suction ring may be replaced and the procedure started again from the beginning. The depth of the lamellar dissection is determined, in part, by the applanation cone, so it is imperative that the same one is used for repeated attempts. Conjunctival chemosis may interfere with ring placement, but usually resolves in 30–60 min. Adequate counseling can alleviate patient anxiety during this waiting period, or during subsequent procedures. If the suction break occurs during the side cut, the surgeon can elect to repeat only this portion of the procedure. It is essential that the technicians operating the laser are familiar with the appropriate protocols.

Flap decentration is another intraoperative complication that can occur with the FS laser. Several techniques have been described that aid in accurate centration of the LASIK flap. Some surgeons advocate marking the center of the cornea with a marking pen or gentian violet. The suction ring is then centered with regard to this position. Although the mark can be visualized following applanation, the view is often suboptimal in patients with large pupils or dark irides. Other surgeons align the suction ring with the corneal limbus. Once the suction ring is placed and the applanation cone is docked, the laser will allow the surgeon to refine the exact position of the flap. As mentioned above, adjustment of the flap position may result in reduction of the flap diameter. Since the pupil may dilate asymmetrically when suction is applied, its center may shift following placement of the ring. The surgeon should resist the urge to automatically center the flap on the dilated pupil. Although this may be appropriate, other data such as the pupil's original location, the corneal mark, or limbal positioning should still be factored into the final decision. Decentered flaps may still occur if the patient is improperly positioned, the cone and ring are tilted, or if the cornea is not adequately visualized on the video monitor during the docking procedure.

After the flap has been created, suction is released by disconnecting the syringe from the ring tubing. Rapid release of suction can result in subconjunctival hemorrhages. They are typically scattered over the bulbar surface, involving the conjunctiva that was directly under the suction ring. The hemorrhages are usually small and resolve in 1–2 weeks. Although they have no impact on vision or comfort, preemptive education and reassurance can alleviate patient concerns. Gradual, controlled suction release may prevent this from occurring. Some surgeons advocate placing a drop of vasoconstrictive medication on the ocular surface prior to ring application. However, others feel that topical vasaconstrictors may predispose the flap to postoperative slippage.

Diffuse lamellar keratitis (DLK), also known as "sands of the Sahara," may occur with both the mechanical microkeratome and the FS laser.

DLK is a sterile collection of inflammatory cells at the lamellar interface. Usually, this is a self-limited condition that occurs in about 4% of patients in which a mechanical microkeratome was used to create the LASIK flap [13]. The patient is usually asymptomatic and the eye appears quiet. The etiology of DLK remains unclear, although numerous factors have been implicated. These include residual chemicals from the microkeratome blade, talc or silicone oil from gloves [8], sterilization techniques [26], meibomian gland debris, overlying corneal epithelial defects, bacterial endotoxins, and blood in the interface. Since no single factor is clearly responsible, the etiology may be multifactorial [13]. Peer-reviewed literature examining the incidence of DLK following use of the FS laser is limited. It may be related to the spot energy used for the side cut or lamellar bed. When Binder decreased the side cut energy from 8 to 4.9 μJ, the incidence of DLK resolved [7]. Our own experience has demonstrated two varieties of postoperative DLK. The first occurs at the edge of the flap near the hinge, where the corneal epithelium has a tendency to become more disrupted. This variant is mild, does not extend into the visual axis, and responds within a few days to topical steroid use. The second type is more diffuse and appears to emanate from the hinge/pocket. Patients present on postoperative day 1 with a diffuse band of interface inflammation near the hinge, which often travels across the entire interface by day 2. This variant usually responds to hourly topical steroid drops, combined with a short, tapering course of systemic steroids. Occasionally, more persistent cases of DLK will require flap lifting with interface irrigation, in addition to topical and systemic therapy. When managed appropriately, most cases of DLK resolve without loss of vision.

Transient light sensitivity (TLS) appears to be a complication specifically associated with the FS laser. Patients experience the delayed onset of mild to severe photophobia with normal visual acuity. It has been known to occur as early as 2 weeks and as late as 3 months following IntraLASIK. The ophthalmic examination is unremarkable with no signs of corneal or intraocular inflammation. The exact cause is unknown, but several etiologies have been proposed, such as pro-inflammatory mediators released from damaged cells, cellular debris in the flap interface promoting inflammation of the perilimbal sclera, or iris/ciliary body inflammation. The condition usually responds to a short, intensive course of topical corticosteroids, but more severe cases may also need a tapering course of systemic corticosteroids. Topical cyclosporine and topical nonsteroidal anti-inflammatories have also been used. It may last from a few weeks to more than 6 months, if not treated promptly.

Epithelial ingrowth refers to the proliferation of corneal epithelial cells within the lamellar interface of the LASIK flap. This can result from migration of surface epithelial cells underneath the flap or the introduction of cells into the interface by the microkeratome blade or surgical instruments. Several risk factors may lead to epithelial ingrowth, including poor flap adhesion, excessive flap edema, improper flap alignment, epithelial defects, an irregular flap edge, thin flaps, button holes, decentered flaps, hyperopic laser ablation beyond the flap border, epithelial basement membrane dystrophy, recurrent erosions, older age, LASIK enhancement, and prior radial keratotomy [1, 9]. Clinically, the epithelial cells can range from a transparent nest of isolated cells to a collection of opaque gelatinous material in the interface. The areas of ingrowth may be connected to the flap edge by a migration tract. The overlying flap may appear thinned or "melted" secondary to keratolysis, which may create irregular astigmatism and result in loss of vision.

There are no published cases of epithelial ingrowth following use of the FS laser. This condition may be less common with the FS laser since there is no blade to drag cells into the interface. However, epithelial cells could still be introduced with other surgical instruments. The side cut architecture created by the IntraLase is very different from the microkeratome flap edge. The laser creates a more vertical cut into the stroma compared with the tangential cut produced by the mechanical microkeratome. This vertical edge creates a well-delineated "gutter," which allows for accurate flap realignment and positioning. It is unclear whether this gutter acts as a barrier (or reservoir) for epithelial cells, thereby increasing (or decreasing) the risk of ingrowth. If epithelial ingrowth is noted during the postoperative pe-

riod, the patient should be followed closely. The degree of ingrowth and the status of the overlying flap will dictate whether intervention is necessary. Several techniques have been described [15], such as interface irrigation, flap lifting with scraping of both the stromal bed and the posterior surface of the flap, phototherapeutic keratectomy following a manual scrape, scraping with flap suturing, and the use of tissue adhesives to promote flap adherence and create a barrier to recurrence.

Flap folds or macrostriae are visually significant wrinkles in the lamellar flap. They can be caused by poor flap quality (too thick or thin), irregular profiles, over-hydration, desiccation with contraction, misalignment, slippage, free caps, trauma, or higher correction levels seen with myopic treatments. This postoperative complication may be less common with the FS laser than with the mechanical microkeratome. The laser's planar flap with its uniform thickness may be more resistant to slippage and stria formation. Also, the vertical edge profile of the IntraLase flap may increase its stability within the stromal pocket. Biser and colleagues reported one case of bilateral flap folds following IntraLASIK [3]. The preoperative spherical equivalents were –7.25 D in both eyes with +0.50 D of astigmatism. Flaps were created with the IntraLase FS laser set for a thickness of 130 μm. The refractive ablation was performed with the Autonomous Laser (Alcon Labs) with an ablation depth of 134.5 μm in both eyes. Bandage soft contact lenses were placed at the time of surgery and removed 2 days later. Following contact lens removal, the patient noted glare, haloes, and blurred vision. Marked vertical striae were noted on examination. Lifting and stretching were first attempted, but the folds and symptoms persisted. Flap suturing was performed with successful resolution of the striae. The final UCVA and BSCVA were 20/30 and 20/20 in the right and left eyes, respectively. While rare, this report demonstrates that flap stria may still occur with the FS laser.

Both the FS laser and mechanical microkeratomes employ suction rings to stabilize the eye during flap creation. When suction is applied, the intraocular pressure (IOP) becomes elevated. It may reach 60–70 mmHg with a mechanical microkeratome and remains at this level for approximately 10–15 s. Pressure elevation is less for the FS laser with a maximum IOP of 30–40 mmHg, but remains at this level for a longer duration. The FS-15 laser requires approximately 60 s for completion, while the FS-30 takes about 30 s to create the flap. The sustained, elevated pressure is followed by a rapid reduction when suction is released. This rapid change may cause mechanical stress to ocular structures, leading to retinal tears, detachments, lacquer cracks, choroidal neovascularization, and/or retinal hemorrhages. These complications, which have been reported with mechanical microkeratomes [15], are more likely to occur in highly myopic patients, as they are more prone to scleral instability. Currently, there is one reported case of macular hemorrhage associated with the FS laser [19]. The hemorrhage occurred in the left eye of a 36-year-old woman following uncomplicated bilateral LASIK for moderate myopia. The UCVA on postoperative day one was 20/20 in the right eye and 20/40 in the left. Dilated examination of the left retina revealed a macular hemorrhage that was approximately one-third of a disc diameter in size. A fluorescein angiogram identified no macular pathology or other predisposing conditions. The hemorrhage cleared spontaneously over the next 6 months, with the BSCVA improving to 20/25. Since this case demonstrated that a macular hemorrhage can occur in the absence of identifiable risk factors, the authors recommend that all patients undergoing IntraLASIK should be advised of this potential complication.

Summary for the Clinician

- The risk of free caps, button holes, and partial flaps is virtually eliminated with the FS laser.
- Although the FS laser has an excellent safety profile, it still carries the risk of complications, such as decentration, diffuse lamellar keratitis, flap stria, and transient light sensitivity.

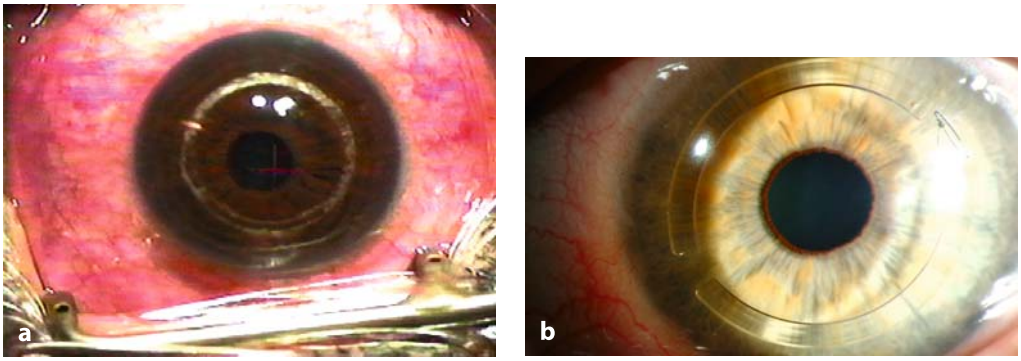


Fig. 7.7 Intracorneal ring segments implanted within the cornea to treat contact lens-intolerant keratoconus. Figure 7a shows the ICRS channels created by the FS laser and Fig. 7b shows the ring segment following implantation.

7.3.2 Intracorneal Ring Segment Implantation

Intracorneal ring segments (ICRS) or Intacs (Addition Technology, Des Plaines, IL, USA) consist of paired, 150° arcs of polymethyl methacrylate (PMMA) that are implanted within the mid-peripheral cornea (Fig. 7.7). Ring implantation produces a flattening effect in the central cornea, with a corresponding decrease in refractive power. The refractive change is titrated by varying the thickness of the ICRS, i.e., thicker rings cause greater flattening. Three sizes of Intacs are approved for use in the USA (0.25, 0.30, and 0.35 mm), while two additional sizes (0.40 and 0.45 mm) are available in Europe. All of the rings have an inner diameter of 6.8 mm and an outer diameter of 8.1 mm. They were originally designed to correct low levels of myopia (≤3.00 D) in patients with minimal astigmatism (≤1.0 D) [7]. ICRS have several advantages, including reversibility, sparing of the visual axis, and preservation of the prolate corneal shape. However, the narrow treatment range and variable patient response has limited their use in purely refractive applications. Recently, ICRS have been used to treat corneal ectasias in patients whose only remaining option is penetrating or lamellar keratoplasty [4, 5]. Implantation of the ring segments provides support to the weakened corneal stroma, decreasing the central curvature. They also may help to center decentered cones, reduce irregular astigmatism, improve contact lens fitting, and increase both corrected and uncorrected visual acuities. For a given ring thickness, a greater response is often seen in keratoconus patients because the cornea is thinner and more malleable.

The intrastromal channels are typically created using a vacuum-based system. An adjustable diamond blade is used to make a radial incision to a depth of about 70% in the mid-peripheral cornea. Specially designed instruments create intrastromal pockets at the base of the incision. After the eye is fixed with the vacuum system, curved blades are used to bluntly separate corneal lamella to create channels for the ICRS. The rings are then inserted into the channels and the incision is sutured. The vacuum system works well, but can expose the patient to elevated intraocular pressure and discomfort.

Recently, channel creation has also been performed with the IntraLase FS laser [20]. The flexibility of the laser platform provides the surgeon with significant control over channel design and placement. The laser first creates a deep lamellar dissection in a circular pattern using the spiral setting for spot placement. The surgeon defines the inner and outer radius of the lamellar ring, as well as the depth of the ablation. This is followed by creation of a vertical, radial incision centered over the dissected ring, connecting it to the surface of the cornea. The incision can be set to any meridian (in 10° increments) around the circumference of the channel. The ICRS are then manually inserted into the channels. Ring insertion is a little more difficult in the laser-created channels because the rings must separate the micro-adhesions that remain between laser

spots. Limbal pressure with a blunt instrument directed toward the central cornea at the leading end of the ICRS facilitates the insertion process. After the rings are placed, the incision is tightly sutured for 2 months. Postoperative medications include a topical antibiotic and steroid for approximately 2 weeks.

While the laser platform adds significant flexibility to channel creation, it has a few limitations. ICRS should be placed at a depth of at least 70%. The IntraLase is currently limited to an ablation depth of 400 μm. Thus, the corneal thickness at the planned location of the channel must be ≤570 μm to achieve the optimal effect. Since the FS laser references its ablation depth to the anterior surface of the cornea, the laser-created channels will cross corneal lamellae when the corneal thickness varies. The vacuum system, with its blunt dissection technique, may have a tendency to stay between the same lamellae for the entire circumference of the channel. Although this could play a role in the final flattening achieved, the clinical significance has not yet been determined.

Summary for the Clinician

- The FS laser can be programmed to create channels for the implantation of intracorneal ring segments.

7.3.3 Penetrating and Lamellar Keratoplasty

Compared with other ophthalmic procedures, the surgical techniques for penetrating and lamellar keratoplasty have remained fairly static for many years. Until recently, these procedures have been dependent upon manual dissection methods combined with vacuum-based or free-hand cylindrical trephination blades. While still very successful, the techniques have been burdened by awkward devices, inadvertent entry into the anterior chamber, and uneven corneal trephination, which can result in irregular astigmatism and differential healing of the graft–host junction (GHJ). With its ability to perform lamellar, as well as vertical dissections, the FS laser may provide a more flexible and controlled method of corneal trephination.

Standard penetrating keratoplasty (PKP) relies on a vertical, full-thickness corneal trephination. The vertical nature of the graft–host junction creates a 360° wound that is inherently weak. The flexibility of the FS laser may permit the use of shelved trephination patterns, with larger inner diameters and smaller outer diameters. These shapes can capitalize on the increased contact area between the host and donor corneas, as well as the IOP, to create stronger wounds. These new wound geometries may increase GHJ stability, with the potential for self-sealing, earlier suture removal, and less surgically-induced astigmatism. Seitz and colleagues described an experimental method to create inverse mushroom-shaped donor and host trephinations using an industrial FS laser [23]. They were able to produce shelved trephination patterns in porcine corneas. Although they had difficulty removing the corneal button, spot placement could be documented in the specimens, both during gross examination and by light microscopy. Similar studies are being conducted at other centers in the USA.

Recent advances in artificial anterior chambers, donor endothelial preparation, and lamellar dissection methods, have led to resurgence in the popularity of lamellar keratoplasty (LKP) [16, 27]. Fuch's corneal dystrophy and pseudophakic (or aphakic) bullous keratopathy are defined by endothelial cell loss and dysfunction, with secondary corneal edema. In these conditions, the host corneal epithelium and stroma are often normal. While PKP is a successful surgical option for both conditions, posterior lamellar keratoplasty (PLK) carries several advantages. These include a reduction in operative time, more rapid visual recovery, smaller and stronger corneal wounds, less surgically-induced astigmatism, and the potential for a reduced risk of rejection. Two predominant methods of PLK have emerged in the last several years: deep lamellar endothelial keratoplasty (DLEK) and Descemet stripping endothelial keratoplasty (DSEK). These methods differ primarily in their host preparation. DLEK relies on a deep lamellar dissection of the host cornea with intraocular trephination to remove a button containing endothelium, Descemet's membrane, and deep corneal stroma. DSEK uses an inverted hook to score Descemet's membrane

in a circular pattern encompassing the intended graft location. The Descemet's membrane is then peeled away from the overlying corneal stroma with a dull spatula and removed with forceps. Both techniques require preparation of a posterior lamellar donor corneal button. This is currently done with manual dissection or by using a mechanical microkeratome.

The FS laser is designed to create lamellar dissections and may be well suited to performing the donor preparation for both methods of PLK and the host preparation in DLEK. Several authors have published their experimental results for performing PLK using the FS laser. Terry and colleagues used the IntraLase to perform lamellar dissections of donor and host corneas in cadaver specimens [28]. They used the maximum depth setting of 400 μm currently permitted by the commercial laser platform. The posterior lamella of the donor cornea was separated with a trephine and standard DLEK techniques were employed to remove the posterior corneal button and replace it with the donor tissue. Pre- and postoperative corneal topographies and posterior corneal curvatures were similar. The quality of the lamellar dissection by scanning electron microscopy (SEM) was somewhat variable, but overall was similar to the manual dissection technique. Sietz et al. used the FEMTEC laser to perform lamellar dissections in porcine and human cadaver corneas with depths varying from 50 to 500 μm [22]. In addition, they were able to perform the vertical dissection connecting the lamellar plane to the endothelial surface, producing a complete delineation of the posterior corneal button. Most of the corneal buttons were easily separated manually and the cut surfaces appeared smooth on SEM.

Sarayba and colleagues performed PLK on cadaver corneoscleral rims using modified interface cones with the FS laser [21]. The cones were 300–600 μm shorter to provide a deeper focal point for the laser delivery system. With this method they were able to deliver laser pulses up to 1,400 μm deep, even through opaque porcine corneas. Simulated PLK was successfully performed on human cadaver specimens. Corneal thickness was measured with ultrasound and the depth of laser ablation was set accordingly. The vertical cut was performed first, followed by the lamellar dissection. Using the modified cones and ultrasonic pachymetry, they were able to create posterior lenticules with thicknesses ranging from 150 to 200 μm. The mean endothelial cell loss was 4.3±3.2% in the 150-μm lenticules and 4.5±6.2% in the 200-μm samples. The donor corneas were successfully implanted using standard PLK techniques. Soong et al. performed a similar study in cadaver eyes using modified interface cones that were 300 μm shorter [25]. After measuring the corneal thickness with ultrasonic pachymetry, they performed the trephination cuts and lamellar dissections with a target lenticule thickness of 150–300 μm. Thickness measurements of the excised lenticules exceeded the preoperative calculations by 55±61 μm. The vertical edges of the lenticules were very well defined and the stromal surface was described as a "fine stucco finish" on SEM. PLK was successfully performed on several specimens through vertical, full-thickness incisions created by the laser.

The distortion in the corneal shape produced by applanation with a flat lens may produce temporary irregularities or folds on the inner surface. These irregularities may be transferred to the lamellar surface, creating irregularities with deep ablations. As such, studies are being conducted with curved applanation lenses that may provide for more predictable dissection patterns in the deep cornea. In general, lamellar keratoplasties have had more limited visual potential compared with penetrating keratoplasties. This decrease in acuity has been attributed to the interface between the host and donor corneas. Further work is needed to characterize the surface quality produced by lamellar dissection with the FS laser and to determine its effect on final visual acuity.

Summary for the Clinician

- The FS laser can be programmed to create corneal trephination patterns that increase the contact area between host and donor corneas, forming stronger wounds in penetrating keratoplasty.
- The FS laser can be used to prepare the donor and host corneas in posterior lamellar keratoplasty.

7.4 Conclusions

The FS laser permits photodisruption of the cornea at low energy levels and with high precision, making it a very useful tool for corneal surgery. The flexibility of the laser platform permits the customization of LASIK flaps, as well as the production of unique trephination patterns in penetrating and lamellar keratoplasties. While offering an excellent safety profile, the FS laser also produces LASIK outcomes that are equivalent, or slightly superior to those of blade-based microkeratomes. As clinical experience with this new technology accrues, rapid expansion into other varieties of anterior segment surgery is anticipated.

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Chapter 8

Complications of Excimer Laser Surgery

8

Hiroko Bissen-Miyajima

Core Messages

- Application of the excimer laser allows precise correction of refractive error. However, its complications can cause irreversible visual disability.
- The complications related to the reactions of corneal tissue can be well controlled with eye drops. The timing and duration of treatment are important.
- Any complications relating to the development of corneal opacity are easy to diagnose. Most laser-related complications are not visible, and corneal topography, wavefront analysis, and pupillometry are recommended.

8.1 Introduction

Excimer laser surgery is usually performed to improve the patient's uncorrected visual acuity. Even if the surgery is uneventful, if the desired refraction is not achieved, this can be considered a complication. Currently, excimer laser surgery includes photorefractive keratectomy (PRK), laser in situ keratomileusis (LASIK), laser subepithelial keratomileusis (LASEK), and Epi-LASIK. LASIK is the procedure performed most often, and different types of complications have been reported. This chapter focuses on the complications related to the excimer laser itself; corneal flap and corneal interface complications are covered in Chapter 12 of Cataract and Refractive Surgery, vol I (Essentials in Ophthalmology, 2004).

The characteristics of laser-related complications often are not visible despite a precise examination using slit-lamp microscopy. Further examination of the alterations in corneal shape should be undertaken with corneal topography and of the functional changes with wavefront analysis, a pupillometer, and contrast sensitivity testing.

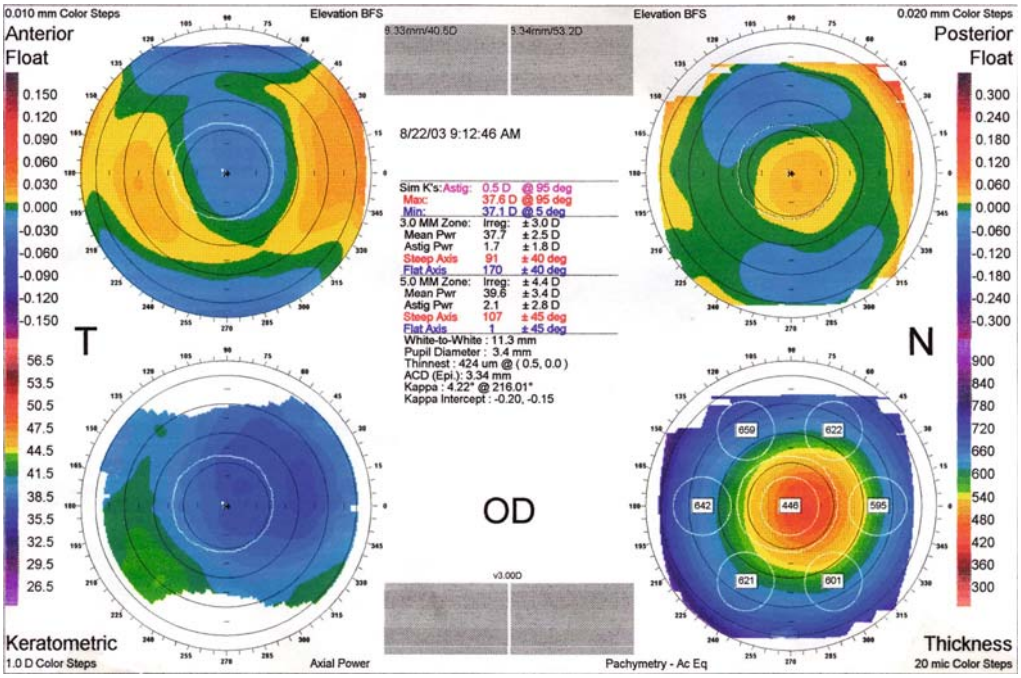
8.2 Preoperative Evaluation

Despite modern computer technology, human errors can occur. Input errors can be avoided by both the operator and the surgeon double-checking the system. Before surgery, the name of the patient, the eye to undergo surgery, and the refractions should be reviewed. The most modern technology using the picture captured by the wavefront analyzer has reduced the incidence of these mistakes, because the images of both the wavefront analyzer and excimer laser microscope should match.

Another basic but important issue is that the excimer laser should be in optimal condition. The operating room should be maintained at the recommended temperature and humidity. Before surgery, the fluence of the excimer laser should be checked.

8.3 Intraoperative Complications

Complications can be divided into two categories: those that occur intraoperatively and those that occur postoperatively. The characteristics of laser-related intraoperative complications are usually not recognized until the postoperative visit. Most patients with complications do not achieve the desired level of visual acuity, and corneal topography usually reveals the cause of the problem.



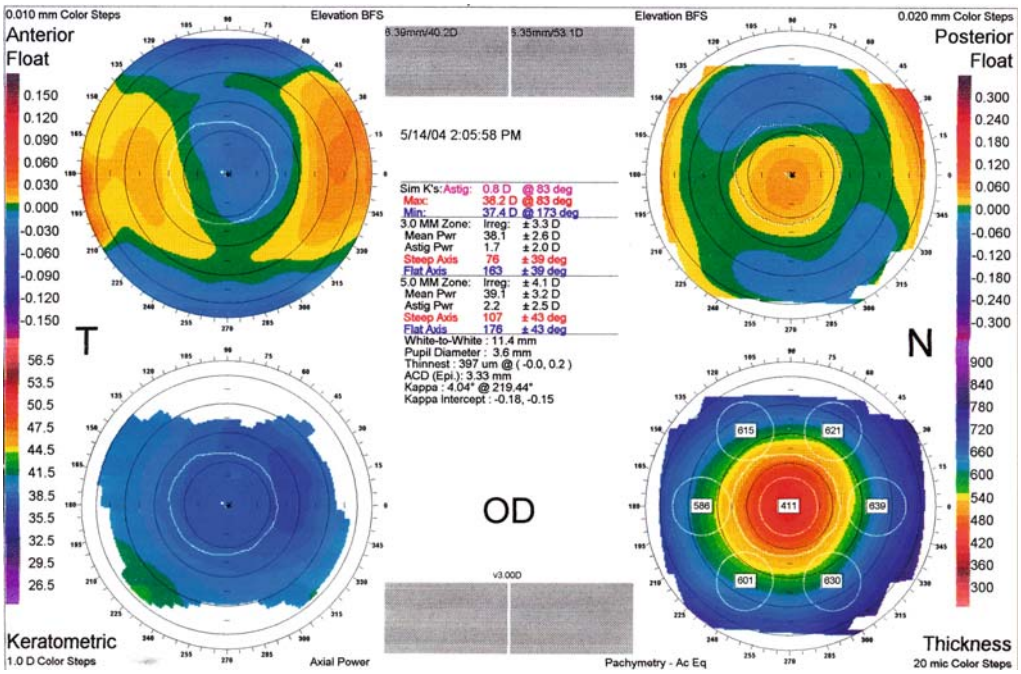


Fig. 8.1 Orbscan (decentered ablation). *Top*: keratometric map shows decentered ablation. The visual acuity is 0.7 (1.5 × sphere: +1.5 D; cylinder: –1.25 D; axis: 72°). The patient complained of monocular diplopia. *Bottom*: after wavefront-guided laser ablation, the uncorrected visual acuity improved to 1.5

8.3.1 Decentered Ablations

Each surgeon has a different definition of decentration; however, more than 1-mm decentration from the center often causes visual dysfunction [23]. Postoperatively, the centration of the laser ablation can be observed using corneal topography and Orbscan. After PRK and LASEK, the visual acuity and the patient's subjective observations can be examined once epithelialization is complete. Thus, recognizing a decentered ablation after PRK and LASEK takes longer than after LASIK. Even with good visual outcomes, topography should be performed postoperatively to confirm the centration. In uncomplicated cases, the displacement may not affect the correction [14]; however, in patients with high myopia, hyperopia, and irregular astigmatism, the centration is critical [26].

The typical symptoms are glare, halos, and monocular diplopia, which are well explained by the transition zone within the pupil diameter. Some patients have these complaints only at night; however, in cases of severe decentration, the patient has visual disturbances even during the day. These symptoms are not resolved easily with spectacles or contact lenses, and patients may not achieve a good best-corrected visual acuity. A decentered ablation may result in undercorrection and irregular astigmatism even though the patient does not complain of visual symptoms.

Prevention is the key issue. The importance of centration during laser ablation has been reported [22, 27]. The patient should be well informed about the importance of maintaining fixation during the procedure. Before draping the patient's eye, the surgeon should check the head position. Although there is a theoretical limitation to pupil tracking [6], a recent advance in the technology, namely, the active eye tracker, helps to avoid decentration. If the ocular movement is beyond the limitations of the instrument, the laser automatically stops. Thus, the learning curve of the inexperienced surgeon is reduced.

Retreatment for decentered ablations has been challenging. Topography-guided laser ablation has been reported [1, 35]; however, a sophisticated technique is required. With the introduction of topography-assisted or wavefront-guided laser ablation, the surgeon does not need to perform complicated calculations and eccentric ablations. Figure 8.1 shows a case of decentration in a patient with monocular diplopia and a ghost image. After wavefront-guided laser ablation, the quality of the vision improved. The retinal image calculated from wavefront analysis showed a blurred image that worsened with pupil enlargement. After wavefront-guided laser ablation, the image improved with the pupil size during the day and at night (Fig. 8.2). The uncorrected visual acuity improved from 20/30 to 20/15.

8.3.2 Irregular Astigmatism

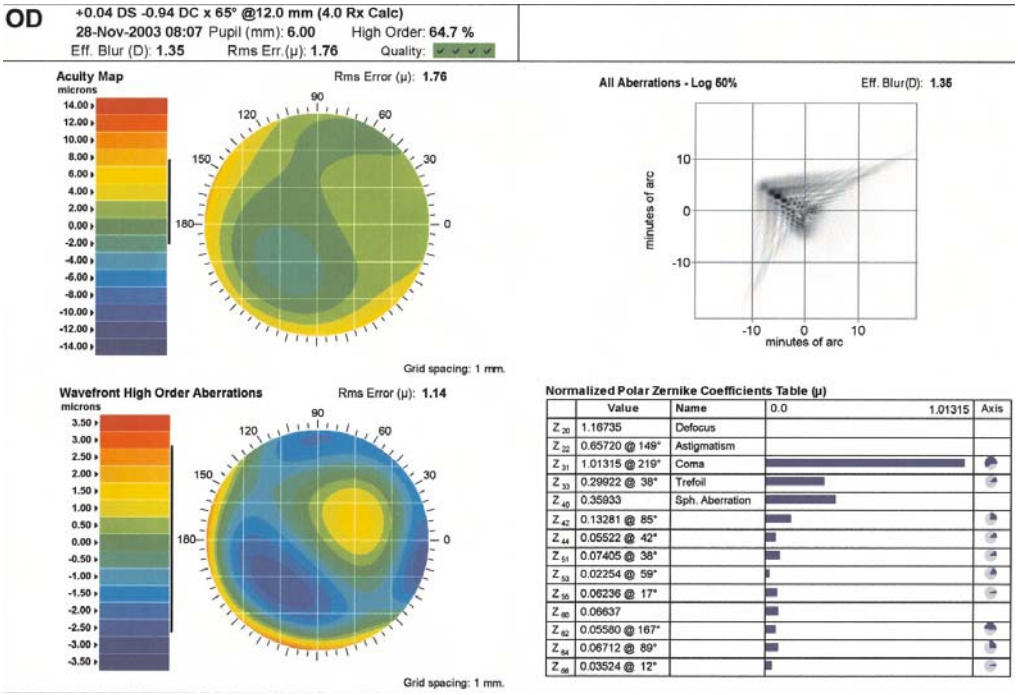
Irregular astigmatism is similar to a decentered ablation. A common cause of irregular astigmatism is irregular corneal moisture. The surface of the laser ablation should be uniform. The use of the active eye tracker has reduced the irregular astigmatism caused by eye movements. Patients usually complain of monocular diplopia and visual disturbances under dim light. Driving at night is a challenge and using hard contact lenses is sometimes necessary. Wavefront-guided laser ablation can be performed in the same manner as when treating a decentered ablation. Figure 8.3 shows a case of irregular ablation. The superior portion of the ablation zone was insufficiently ablated and the patient had monocular diplopia during the day and at night. After wavefront-guided laser ablation, the irregularity of the central area improved and the clarity of the retinal image improved markedly (Fig. 8.4).

8.3.3 Central Islands

A central island is a topographically steep center of the ablation zone measuring at least 3.0 D high and at least 1.5 mm in diameter [19]. This complication was common when the broad-beam laser was introduced; however, central islands have been occurring with decreasing frequency with the latest generations of laser delivery systems. The etiology of central islands includes the vortex plume theory and the differential hydration/acoustic shockwave theory. New software that applies additional pulses to the central area and

blows nitrogen gas during ablation has decreased the occurrence of central islands.

Central islands are usually characterized by undercorrection accompanied by monocular diplopia. With topography, the central elevated area is clear. These symptoms often disappear in 3 to 6 months. Several attempts have been made to treat symptomatic central islands [9, 21]. The topography-linked or wavefront-guided laser ablation is a helpful tool.



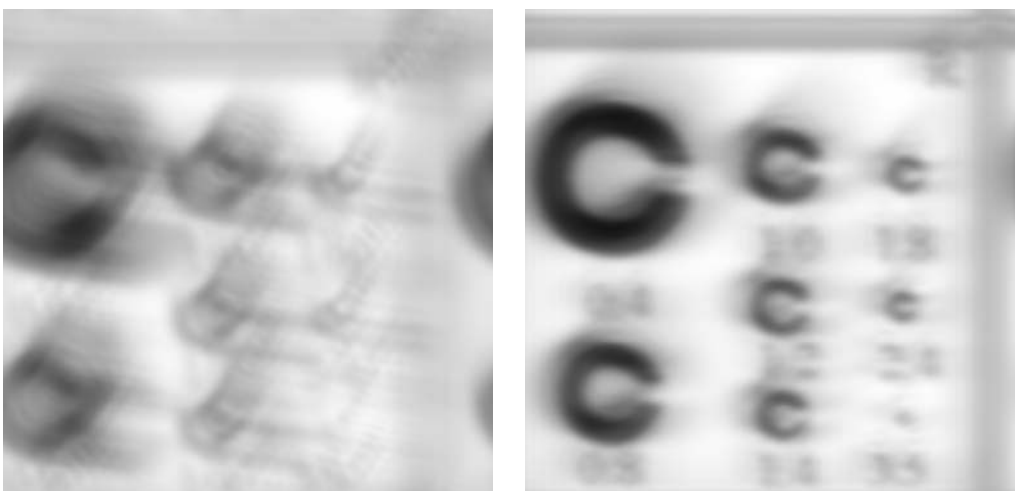


Fig. 8.2 Retinal images. *Top*: wavefront analysis. The higher order aberration is 1.14 µm. *Bottom*: the retinal image evaluated by wavefront analysis (pupil size, 3 mm). The blurred image left improved after surgery (right)

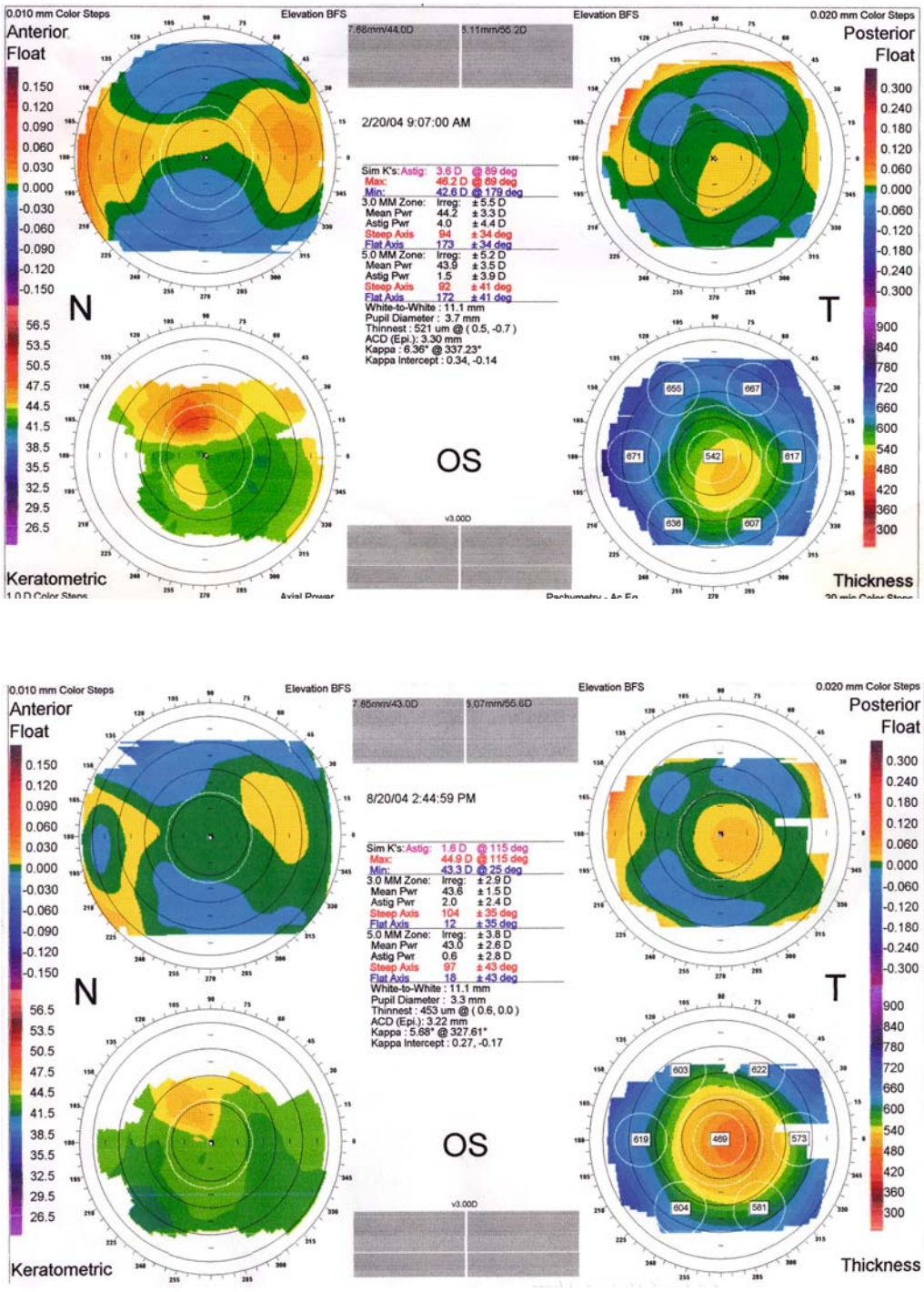
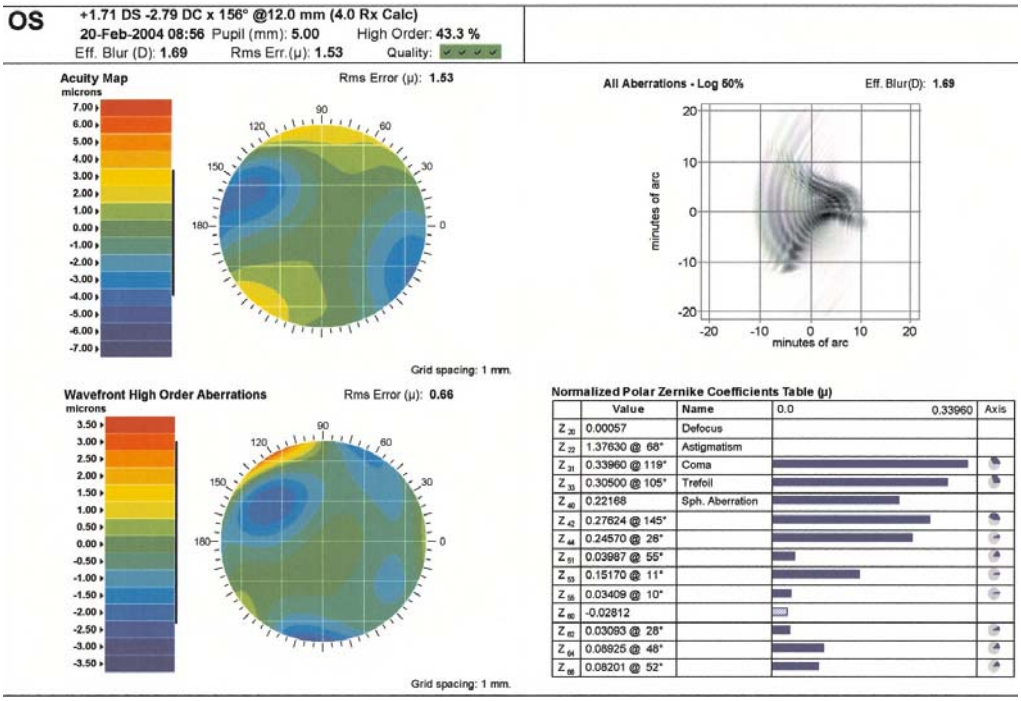


Fig. 8.3 Orbscan (irregular astigmatism). *Top*: keratometric map shows irregular astigmatism. The visual acuity is 0.7 (1.5 × sphere: −0.5 D; cylinder: −2.0 D; axis: 153°). The patient complained of monocular diplopia during the day and at night. *Bottom*: after wavefront-guided laser ablation, the uncorrected visual acuity improved to 1.5



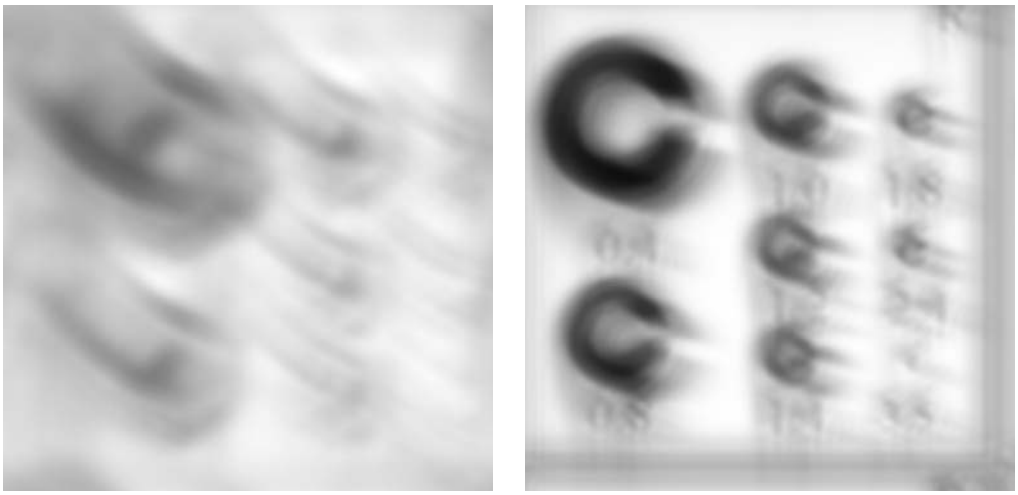


Fig. 8.4 Retinal images. *Top*: wavefront analysis. The higher order aberration is 0.66 µm. *Bottom*: the retinal image evaluated by wavefront analysis (pupil size, 3 mm). The blurred image (left) improved after surgery (right)

8.3.4 Undercorrection

Undercorrection is the result of incorrect preoperative evaluation of refraction, excessive moisture in the stromal bed, decentration, and problems with laser calibration. If the preoperative refraction is unstable, the refraction should be

repeated after an interval and the ablation postponed. If the patient uses hard contact lenses, the refraction should be done at least 2 weeks after the patient stops wearing them. Because the refraction is the key to achieving successful results, the examination should be repeated until the surgeon is comfortable with the status of the refraction. Some patients require more than 2 months to obtain a stable refraction after wearing contact lenses. If the cycloplegic refraction differs substantially from the non-cycloplegic refraction, the refraction should be repeated using both values at another visit. Using uncertain refractive results will cause unnecessary complications.

Excessive moisture in the stromal bed can result in undercorrection. This often happens when the surgeon is inexperienced. Undercorrection also can result if the patient's fixation is poor and the laser is not ideally applied. The laser calibration is also important. The laser operator should be aware of the condition of the laser. The laser should be recalibrated with each use.

Enhancement usually results in good refractive outcomes. The timing of the enhancement surgery depends on the cause of the undercorrection. If the refraction is stable, retreatment can be done at any time. To avoid repeating the problems that arose in the initial surgery, the cause should be well considered. In addition, the postoperative corneal thickness should be confirmed. If the total corneal thickness is less than 400 μm, further laser ablation should be avoided to prevent corneal ectasia. The patient's age also should be considered. If the patient is over 40 years, monovision may be an option. A surgeon can perform unilateral enhancement and see both far and near visual function. Some patients enjoy unplanned monovision.

8.3.5 Overcorrection

The causes of overcorrection are similar to those of undercorrection: the accuracy of the refraction, the condition of the stromal bed, and the laser calibration. Dryness of the stromal bed usually causes overcorrection. If the surgeon delays starting the laser ablation, the cornea becomes dry and the effect of the laser is intensified. Transient overcorrection after PRK is a well-known phenomenon. Although this problem has decreased with the latest generations of excimer lasers, the changes in the refraction should be observed over time.

Patient age also plays an important role. Younger patients can tolerate overcorrection; however, older patients are very sensitive to overcorrection. Unfortunately, the risk factors for overcorrection are age and attempted correction. The higher these factors are, the more frequently patients encounter this complication.

If overcorrection occurs after PRK, the administration of steroid eye drops should be stopped. Some physicians also recommend stopping the use of artificial tears. Regarding hyperopic correction, transient overcorrection is the goal because subsequent regression is common. Patients should be well informed about this before surgery.

The treatment of overcorrection after the treatment of myopia is mandatory. Recently, the use of diclophenac eye drops with contact lenses produced good results. If the correction meets the desired target, the eye drops should be stopped immediately. If this does not change the results, excimer laser with hyperopic correction or holmium laser thermoplasty is frequently performed.

Summary for the Clinician

- Preoperative examination of the refraction and calibration of the laser are fundamental to achieving the best visual outcomes.
- Corneal topography should be performed even if the patient achieved good visual outcome to confirm the ideal laser ablation.
- Wavefront-guided ablation is a helpful tool in patients with decentered ablation or irregular astigmatism.

8.4 Postoperative Complications

Even though patients achieve good outcomes, some complications can develop later. Since pa-

tients enjoy their improved uncorrected visual acuity, even a slight decrease in visual acuity is unacceptable. However, the cause of decreased uncorrected visual acuity should be well evaluated and the treatment planned.

8.4.1 Regression

Regression is a common problem for any laser surgery including LASIK. If regression occurs, retreatment is considered. Regression accompanied by corneal haze requires a different treatment approach, such as the application of steroid eye drops, PRK, or phototherapeutic keratectomy (PTK). Recently, the use of beta-blocker eye drops to decrease the intraocular pressure has achieved good results. The effect of improving the vision in these cases is still under discussion. Why beta-blocker eye drops work and Latanoprost eye drops do not is a question for future research. This approach does not work in every case; however, it is worth trying beta-blocker eye drops. The interval since the time of laser surgery, patient gender and age, and the preoperative refraction are not correlated with the amount of improvement. If this does not produce a satisfactory result, retreatment is planned after confirming that the refraction is stable. Generally, enhancements should be planned at least 3 months after the previous surgery. If the correction exceeds 6 D, waiting more than 6 months may be necessary to achieve a stable refraction.

8.4.2 Corneal Haze

Corneal haze is a well-known complication after PRK. Histopathologic and confocal microscopic studies revealed that haze is induced by activation and proliferation of corneal keratocytes [3]. The haze usually appears 1–3 months after surgery and gradually resolves within 1 year. With slit-lamp microscopy, subepithelial haze can be observed in the central area and classified from grades 0 to 4 [16]. Recently, objective scoring was introduced using digital images and confocal microscopy [2, 6, 10]. The incidence of haze was higher with previous laser treatment [30]; however, the incidence decreased with recent technological advances that produced a smoother ablation. The risk factors are greater tissue ablation such as in the treatment of high myopia, ultraviolet exposure, atopic dermatitis, and autoimmune conditions [8, 12, 24]. Despite the appearance of haze, most cases achieve good visual acuity. If the haze becomes substantial, the best-corrected visual acuity decreases with some regression (Fig. 8.5). Problems may develop with night vision and decreased contrast sensitivity [13, 18]. Most surgeons use steroid eye drops immediately or shortly after laser treatment and gradually taper the drops. Although the effects of corticosteroid eye drops used clinically have been positively or negatively reported, theoretical benefits have been described in experimental studies. Special attention should be paid to the side effects of corticosteroids, especially increased intraocular pressure.

Recently, the effects of chilled irrigation solution and mitomycin C were reported. Mitomycin C is used for glaucoma filtering surgery and pterygium surgery and has been introduced into laser surgery [17, 28, 34]. The concentration of mitomycin C and the duration of its application have been discussed; 0.01 mg/ml is the minimum concentration reported to be effective and 0.4 mg/ml is the maximum to avoid complications [4]. The 0.02% concentration is widely used. After laser application, a 6-mm diameter

Fig. 8.5 Corneal haze. The best corrected visual acuity decreases

sponge is soaked in 0.02% mitomycin C diluted with balanced saline solution (BSS) and applied over the ablated cornea for 2–3 min. The eye then is washed with BSS. Complications such as thinning of the scleral tissue and delayed epithelialization were reported in cases of glaucoma-filtrating surgery and pterygium. An experimental study showed dose-dependent corneal edema and endothelial apoptosis. However, the prophylactic use of 0.02% mitomycin C in laser surgery seems to be safe and effective at preventing haze [33] and achieved better visual acuity [7]. Mitomycin C is also used to treat haze [20, 29] in the same technique used during PRK, or the drug can be administered as an eye drop. Use of vitamin C and amniotic membranes also have been reported; however, the effects need to be studied further [33, 36].

8.4.3 Delayed Epithelialization

Following PRK, LASEK, and Epi-LASIK, bandage contact lenses are applied. After 3 days, most eyes achieve re-epithelialization and the contact lenses can be removed. The preservative in the eye drops sometimes delays the recovery of the epithelium. The use of eye drops without preservatives is preferable. If the eye developed epithelial problems due to the toxicity of eye drops, the drops should be discontinued.

8.4.4 Infections

Infections after refractive surgery are rare, but can be the most severe complications after any ophthalmic surgery. Regarding laser surgery, corneal opacity remains even though the infection was treated with antibiotics. The common cause is staphylococcus and mycobacteria; the prophylactic application of antibiotics is recommended [15].

An epithelial defect is the optimal site for the development of a bacterial infection. If the process of re-epithelialization is prolonged, special steps should be taken to avoid infections. In LASIK cases, the focus of the infection is under the flap and the risk of perforation increases. Cultures should be performed to confirm the bacteria in severe cases; however, topical antibiotics should be started immediately. Lifting the flap and irrigation are necessary in certain cases. After treatment, PTK can be performed if the opacity remains on the corneal surface. Penetrating or lamellar keratoplasty is needed in patients with poor visual acuity. Infection usually results in poor corrected visual acuity.

8.4.5 Adverse Effects on the Corneal Endothelium

Experimental and clinical studies have shown no side effects from refractive procedures on the corneal endothelium [3, 11]. One study reported that the number of endothelial cells decreased after a tranquilizer was administered to the patient before PRK [25].

8.4.6 Corneal Ectasia

After LASIK was introduced, a new complication, keratectasia, was reported [5, 26, 31] in which continuous regression with irregular astigmatism develops. The risk factors are form fruste keratoconus, thin cornea with high myopia, and pellucid marginal degeneration. Preoperative evaluation with corneal topography and pachymetry are necessary. The postoperative corneal condition should be assessed to maintain a corneal thickness greater than 400 μm or a residual stromal bed greater than 250–300 μm. Enhancements performed without measuring the corneal thickness can cause ectasia.

Orbscan can be performed to diagnose keratectasia. The posterior float map shows obvious thinning. If this complication occurs, hard contact lenses are fitted. If the vision cannot be corrected with contact lenses, ICR or cross-linking may be performed, followed if not successful by corneal transplantation. If the surgeon does not recognize the corneal thinning and continues to treat with the excimer laser to improve the vision, the cornea may be perforated.

Summary for the Clinician

- Some postoperative complications are well treated with eye drops.
- Regarding postoperative complications concerning the refractive error, enhancement should be considered when the refraction is confirmed to be stable.
- Before enhancement, the corneal thickness and shape should be considered.
- Some postoperative complications are related to the failure of the indication.

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Chapter 9

Refractive Lens Exchange: Risk Management

9

Emanuel Rosen

Core Messages

- Refractive lens exchange in myopic eyes carries a significant risk of postoperative retinal detachment.
- Particular risk factors are:
  - Higher myopia;
  - Younger age, (less then 50 years);
  - Surgical complications (capsule rupture and vitreous loss);
  - Neodymium:YAG capsulotomy relation to rhegmatogenous retinal detachment after refractive lens exchange is controversial and indeterminate

9.1 Introduction

About 60 years ago the concept of intraocular lens implantation was pioneered. About 30 years ago, small incision lens extraction by phacoemulsification was realized. Both pioneering efforts have subsequently led to perfecting the respective processes. Thus, refractive surgery, the correction of ametropia through lens-based surgery was initiated. The era of corneal laser surgery commencing about 25 years ago focused public and professional attention on the wider opportunity for permanent refractive correction and thereby created in practice the sub-specialty of refractive surgery. Lens-based refractive surgery was sidetracked for a time as the surgical process matured until it was able to offer ophthalmic surgeons with that interest more security and scope for intervention. Initially, surgical techniques evolved more rapidly than lens implant technology. The crystalline lens, whether cataractous or 'clear,' could be removed by sub-2.5-mm incisions. However, intraocular lens implants (IOLs), made of PMMA before the foldable materials were approved, required a 5- to 6-mm incision, not the ideal basis for a refractive surgical procedure. Gradually, though, lens implants became more refined and eventually developed spectacularly in form, effect, and enhanced small incision capability, an essential component of the refractive surgical process. Today, modern lens extraction and implant replacement is a safe, predictable, and stable process in general; however, nothing is absolute in this sense. All surgeons are aware that no surgical intervention is absolutely risk-free.

As we age, the crystalline lens is the ever-changing element in the eye. Its replacement (the lens implant) provides a permanent result in the optical sense, leaving the cornea for enhancement of effect if necessary. As with all surgical procedures there are risk factors to be weighed against the benefits. Refractive surgery in general is about risk management. One issue that requires in-depth exploration is retinal complications of refractive surgery. This applies in particular to refractive lens exchange (RLE) and especially its application in myopic eyes, which are more vulnerable in the retinal sense than hyperopic eyes.

9.2 RLE: Need to Know

A refractive surgeon needs to know the risks inherent in an RLE procedure, risks for hypermetropic eyes, and those for myopic eyes. The surgeon needs to know the risk odds so that the patient can be reliably informed what they are getting into. In the case of myopic eyes, evidence suggests that the degree of myopia or size of the globe is one type of risk that could be graded. Age is another as is surgical complications. A study of the literature enables the risks to be quantified,

Table 9.1 Meta analysis publications on refractive lens exchange (RLE) and myopic cataract surgery (1994–2005): variables

Variables include:
Eye axial length
Number of eyes studies
Follow up duration and range
Neodymium:YAG capsulotomy rates
Pre-operative retinal prophylaxis
Patient age range
Operative complications

despite the significant variations in study profiles (Tables 9.1, 9.2).

The literature is an aid to learning about the risk of RLE as well as the outcomes from cataract and lens implant surgery in myopic eyes. It is necessary to define risk factors as well as the outcome for myopic and hyperopic eyes that have suffered pseudophakic retinal detachments. Surgical complications are fortunately very rare in eyes undergoing RLE in experienced surgical hands. However, what are the risks and potential outcomes if complications do occur?

9.3 Cystoid Macular Edema

There are other retinal risks of RLE apart from rhegmatogenous retinal detachment (RRD), but they are of less importance in incidence and effect. Cystoid macular edema, which if unresolved will lead to permanent visual impairment through cystoid macular changes, is fortunately rare following uncomplicated surgery. It tends to be transient, causing short-term visual disturbances. Invariably, it will resolve with appropriate anti-inflammatory medication for it is mediated by the post-surgical inflammatory cascade and temporary loss of the blood–retinal barrier. The incidence and causes of clinical and angiographic cystoid macular edema (CME) after uncomplicated phacoemulsification and intraocular lens implantation in otherwise normal eyes were investigated by Mentes et al. [31]. Clinical and fluorescein angiographic macular edema was evaluated 45 days postoperatively in a study comprising 252 eyes following uncomplicated phacoemulsification with in-the-bag acrylic IOL implantation. Clinical CME was not detected in any eye at any postoperative visit, but angiographic macular edema was detected in 9.1% of eyes. The visual outcome did not differ between eyes with no clinical edema and those with fundus fluorescein angiography-detected edema. Treatment of clinically evident and visually disabling CME after RLE is by topical application of steroidal and non-steroidal anti-inflammatory agents coupled with low-dose acetazolamide. Only in circumstances where there is a poor response to topical therapy should systemic high-dose, short course steroid therapy be contemplated. Other aids include sub-Tenon's steroid or as a last resort intraocular steroids though this is a remote requirement.

9.4 Risk Management and Rhegmatogenous Retinal Detachment

A meta-analysis of papers concerning the incidence of retinal detachment after lens extraction and IOL implantation for 12 years between 1994 and 2005 reveals that these studies are not uniform in their protocols (Table 9.1) and most were retrospective reviews. There were many variables that have to be evaluated in an attempt to isolate the identifiable risk factors for RRD [1–3, 5–7, 9–12, 14, 16, 18–20, 22, 23, 25, 26, 28–30, 32, 36, 39, 40, 43–45, 48, 50, 52–54].

Factors not apparent from this study, but hinted at in some papers, are the consistently influential factor of age of the patient. Younger patients, i.e., less than 50 years old, have a disproportionately higher risk of RRD according to the general cataract studies of Polkingshorne and Craig [38], e.g. less than 50 years related to an incidence of 5.1% RRD (which is a more relevant rate for RLE comparisons) whereas over 70 years the rate was less than 0.7% [8]. One hundred and forty-one patients presented between May 1997 and April 1998 with an RRD, i.e., an annual incidence of 1.18 cases per 10,000 people (0.0118%), 5 of whom presented with bilateral RRD and the mean age at presentation was 53.9 years. RRD was more common in males than in females with a ratio of 1.3:1. *Ocular trauma, high myopia, and*

Table 9.2 Order of frequency of retinal detachment (RD) after refractive lens exchange (RLE) and cataract and IOL surgery in myopic eyes (1994–2005). *ECCE* extracapsular cataract extraction, *AC* anterior chamber, RRD rhegmatogenous retinal detachment

Reference	Year	Eyes in study	RD rate (%)	No. of eyes	Comment
[51]	2005	14	0	0	
[53]	2001	26	0	0	
[2]	1998	40	0	0	
[23]	1996	24	0	0	
[54]	1998	120	0	0	
[20]	1998	26	0	0	
[1]	1996	80	0	0	
[14]	2003	44	0	0	
[19]	2003	526	0	0	
[43]	2003	358	0.26	1	
[11]	1998	581	0.3	1	
Rosen	2005	583	0.3	2	Unpublished data
[52]	1999	38	0.7	1	
[12]	2002	72	0.7	1	
[39]	1995	430	0.8	4	
[18]	1997	386	0.8	1	Myopic cataract
[28]	1996	109	0.9	2	
[25]	1997	90	1.1	1	ECCE
[50]	2003	73	1.3	1	Aphakia
[32]	1998	245	1.4	4	ECCE
[22]	2002	125	1.7	2	
[9]	1999	118	1.7	2	
[10]	2004	190	2.1	4	
[30]	2005	194	2.1	4	Phakic IOL
[36]	2002	151	3.0	4	
[16]	2005	37	3.2	2	
[26]	1994	136	3.6	4	ECCE
[40]	2001	25	4.0	1	
[45]	1999	166	4.8	8	AC phakic IOL
[3]	1998	33	6.1	2	
[44]	2003	930	8.0	72	
[44]	2003	1020	1.2	10	Control group
[5]	1994	52	0	0	Same cohort
[6]	1997	49	1.9	2	Same cohort
[7]	1999	52	8.1	4	Same cohort

Table 9.2 *(continued)*

Reference	Year	Eyes in study	RD rate (%)	No. of eyes	Comment
Total eyes		**6,042**	**2.2**	(133)	**Mean RRD rate**
Hyperopia RLE					
[48]	1998	35	0	0	Hyperopia
Rosen	2005	433	0.25	1	Unpublished data
[29]	1997	20	0	0	Follow-up 3–60 months

cataract extraction were found to be significant risk factors in the development of RRD.

Lois and Wong [27] quoted an incidence of RRD after phacoemulsification cataract surgery ranging from 0 to 3.6% and averaging 0.7% in the general population. They calculated that the excess risk of developing a retinal detachment after cataract surgery in the first 10 years over eyes without surgery was 5.5. Desai [8] estimated that 94% of retinal detachments occurring in the first year after surgery were the result of the surgery.

Ivanesivic and colleagues [17] studied the epidemiological characteristics of non-traumatic phakic RRD in a defined population of a county in Croatia. Of 278 eyes (272 patients) developed RRD during an 11-year period, 1988–1998, with a population of 465,947. The annual incidence was 0.54 per 10,000 of the population (0.005%). The mean age of patients was 58.3 years, and the sex distribution corresponded with that in the general population. Bilaterality was observed in 2.2%. The presence of myopia was diagnosed in 46.9% eyes, although the range was not disclosed

Li, in China [24], estimated the incidence and epidemiologic characteristics of RRD in Beijing, in a prospective population-based incidence study with 6.5 million subjects. A total of 526 patients with RRD were newly diagnosed between October 1999 and September 2000. There was an annual incidence of 0.8/10,000 people (95% confidence interval = 7.30–8.67; 0.008%). The 60–69 age group had the highest incidence (2.22/10,000 (0.022%). Three subtypes of RRD were identified; 0.0093% were related to blunt trauma, 0.0080% were either aphakic or pseudophakic, and 0.006.25% for non-traumatic phakic retinal detachment. High myopia greater than 6D was more prevalent in bilateral RRD (57.1%) than in the unilaterally affected patients (32.4%).

However, in considering refractive lens exchange as opposed to cataract extraction, inevitably the age range will be much lower and as noted above a significant risk factor for RRD after lens extraction is being under 50 years of age. The cause presumably relates to the vitreo-retinal interface and the promotion of posterior vitreous detachment by the volumetric change in the eye after removal of the crystalline lens even if it is replaced by a lens implant.

9.5 Complicated Lens Surgery

The effects of complicated or traumatic surgery were reported by Onal et al. [34] in another general cataract study that indicates that the rate for RRD was significantly magnified by that event. Bearing in mind that RLE applies to presbyopic patients in general and younger patients rather than older, it seems reasonable to presume that the more vulnerable myopic eye entertains an additional risk factor above and beyond the general risk because of its inherent retinal instability as defined by the above statistics.

Ripandelli et al. [44] discussed cataract surgery as a risk factor for retinal detachment in very highly myopic eyes. Studying 930 in a retrospective, paired-eye, case-control trial in which axial length ranged from 29.7 to 35.5 mm with a follow-up of 36 months and an neodymium: YAG rate of 34% utilizing IOLs made of PMMA, they noted a RRD rate of 8%, whereas in their control group it was only 1.2%.

Uhlman et al. [51] combined RLE with simultaneous pars plana vitrectomy (PPV) in the

management of severe myopia. Retrospectively, they reviewed 14 eyes of 8 patients who had RLE to treat myopia of –19.0±5.4 D in whom phacoemulsification posterior chamber (PC) IOL implantation, and standard three-port vitrectomy were performed. With a mean postoperative follow-up time of 2.5 years (range 1–4 years), 21.4% required Nd:YAG capsulotomy for posterior capsule opacification. No retinal detachments or cases of CME were observed during the follow-up. The authors considered that simultaneously performed PPV may reduce the risk of postoperative retinal detachment, but they advised that a definitive conclusion would have to be based on a prospective study.

In our own clinic we studied 583 eyes (selected after V-R review and prophylactic treatment if indicated) in which the mean axial length was 27.1 mm (range 24–31 mm) with a follow-up range of 3–96 months. The Nd:YAG rate was 35% utilizing both silicone and acrylic IOLs. The RRD was 0.3%, i.e., 2 eyes affected, both of which resumed near normal vision after retinal surgery. One patient, who had RRD 18 months after surgery with a preoperative best corrected visual acuity (BCVA) of 20/40 (amblyopic), achieved a postoperative BCVA of 20/40 18 months after RRD surgery. Another patient, who had RRD 20 months after RLE with a BCVA of 20/15, achieved a postoperative retinal repair BCVA of 20/30 within 3 months.

Martinez-Castillo et al. [30] and Ruiz-Moreno and Alio [45] investigated RRD following phakic IOL implantation, which has some parallels with RLE in myopic eyes. Their studies provide important information, not only on the incidence of RRD, but the mechanisms, treatment, and outcome investigated (see prognosis for RRD).

9.6 Age and Pseudophakia in Myopic Eyes

Younger patients are more vulnerable to RD in pseudophakia so particular care in case selection, vitreo-retinal expert preoperative advice, and patient informed consent are essential.

An epidemiological study of RRD in a general population by Polkinghome and Craig [38] is provided for comparative purposes. Of 141 patients presenting between May 1997 and April 1998 with a RRD:

- Five presented with bilateral RRD;
- Mean age at presentation was 53.9 years;
- Annual incidence of RRD was 11.8 cases per 100,000 people;
- RRD was more common in males than in females (1.3:1);
- Ocular trauma, *high myopia*, and *cataract extraction* were found to be significant risk factors in the development of RRD.

9.7 Odds of RRD Occurrence

Because of the temporal sequence of events, RRD following RLE/cataract surgery is usually assumed to be causally related to the lens surgery. The evidence for this relation has been based on the observed frequency of such events following cataract surgery, particularly the excess frequency previously observed after intracapsular cataract extraction. Such studies were characterized by the lack of a control group of patients who did not have lens surgery and their experience of retinal detachment for comparison. Measures of effect, such as relative risk, provide some assessment of the magnitude of an association between myopic RLE/cataract surgery and RRD, indicating the likelihood of developing the condition in the exposed group relative to those who are not exposed. The identification of a control group (nonmyopic eyes) by Ripandelli and colleagues [44] permits this kind of assessment of the risk of RRD associated with RLE/cataract surgery in which they found a factor of 4 applied to the myopic group with very long eyes.

Norregaard et al. [33] suggested that about 60% of detachments following extracapsular cataract extraction (ECCE) and IOL occurred within 1 year, with about a quarter occurring after 3 or more years, which is consistent with previous reports that have indicated that up to 75% of detachments may occur within 1 year of surgery.

Polkinghome and Craig [38] demonstrated that for the general population undergoing Kelman's phacoemulsification (KPE) for cataracts the RRD rate was 1.17% per year, which is 100 times the rate for the unoperated eyes. Using their data,

in other words, removal of the crystalline lens and replacing it with a lens implant, dramatically increases the risk of RRD even if the actual rate is low, but nevertheless significant. The RRD rate in myopic eyes of axial length greater than 25 mm after KPE embracing both RLE and cataractous eyes was about 2.2% (see average of eyes affected by RRD in Table 9.2). This rate of occurrence of 220 eyes per 10,000 is double that of the general population rate or approximately 200 times the natural rate (Table 9.3). However, the rate of spontaneous retinal detachment in a population of myopic eyes with more than –10 D is quoted as 0.68% [35], which is equivalent to an axial length of more than 26 mm. Thus, comparing like with like as far as can be achieved, 0.68% increases to at least 2.2%, i.e., by a factor of 3 as a result of lens exchange.

Summary for Clinicians

- The overall rate of RRD in myopic eyes after RLE is a mean of 2.2% (range 0–8%).
- The mean time for occurrence of RRD after RLE is 39 months.
- PVD is an initiating factor.

9.8 Why Should Myopic Eyes Be Vulnerable to RRD?

Ramos and Kruger [41] articulate the widely held belief that volumetric changes in eyes undergoing removal of the crystalline lens induce the circumstances of exciting vitreo-retinal pathology.

Table 9.3 Annual incidence of RRD. *KPE* Kelman's phacoemulsification, *ICCE* intracapsular cataract extraction

Reference	Eyes in study	Incidence
[37]	General population	0.012% = 1.2:10,000
[24]	General population	0.008% = 0.8:10,000
	60–69 years	0.022% = 2.2:10,000
	Phakic blunt trauma	0.009% = 0.9:10,000
	Nontraumatic	0.006% = 0.6:10,000
[17]		0.005% = 0.5:10,000
[47]	General population	0.2% = 20:10,000
[35]	More than -10 D	0.68% = 68:10,000
[38]	After KPE	1.17% = 117:10,000
	<50 years	5.1% = 510:10,000
	>70 years	0.7% = 70:10,000
[24]	Pseudophakia and aphakia	0.008% = 0.8:10,000
Overall incidence of RRD following RLE for myopia		2.2% = 220:10,000
Risk of RRD following RLE for myopia		1 in 45 eyes
[41] RRD rate after	ICCE	= 0.40–3.6%
	ECCE	= 0.55–1.65%
	Phaco	= 0.75–1.65%.

The volume of the eye obviously varies according to its diameter. Myopic eyes are large and as is well accepted the retina does not expand but stretches. If the crystalline lens is removed the vitreous degenerates more so the larger the eye will expand to fill the void. Therein lies the problem, for if the vitreous is attached prior to lens exchange, the extra volume at its disposal sharply increases the risk of a posterior vitreous detachment. Because of the intrinsic vitreo-retinal pathology in large eyes, anomalous vitreo-retinal attachments are more likely than in emmetropic eyes or hyperopic eyes of smaller dimensions. As vitreous detaches it may tear the retina at the point of attachment and thereby create the conditions for the retina to detach (Table 9.4).

9.9 Prophylaxis

Therefore, retinal prophylaxis should have a marginal effect on the incidence of RD. The literature supports this view in terms of pre-existing identifiable retinal pathology (1999 data). Colin and colleagues' three papers [5–7] on retinal detachment in myopic eyes were based on a very small sample, of which 3 patients had 4 retinal detachments occurring some years after cataract extraction using methods not comparable to today's surgical procedure. He did demonstrate that prophylactic treatment seemingly had little value in preventing detachment. Particular risk factors he illustrated were higher myopia (>10 D) and the passage of time in a pseudophakic myopic eye, despite prophylactic retinal treatment. If a conclusion were to be reached on the basis of his findings it would have to be that regular sequential monitoring of myopic pseudophakic eyes is required to assess retinal pathology and then apply prophylaxis if clinical signs most likely to appear with or without symptoms warrant that degree of follow-up observation.

On the other hand Sharma et al. [46] studied 64 patients with an RRD in one eye, but who were phakic in the fellow eye. During an average follow-up of 57.4 months, 5 (7.8%) fellow eyes developed retinal detachment while still phakic. In addition to the 5 eyes with a phakic RD, 10 originally phakic fellow eyes underwent cataract surgery. Of these, 1 (10%) suffered an RRD. Thus, they concluded that the fellow eyes of patients with an RRD are at significant risk of RD even if they do not undergo cataract surgery. However, this does not mean that signs of impending RRD would be discernable or that prophylactic therapy was admissible. In terms of myopic eyes the need to carefully evaluate vitreo-retinal signs is thus demonstrated.

More circumstantial evidence of the effect of lens extraction on the eye's internal structures is offered by Grand [13], who studied the risk of a new retinal break or detachment following cataract surgery in eyes that had undergone successful repair of phakic break or detachment. In a 10-year study of patients who had undergone prior repair of retinal breaks or detachment, cataract surgery was associated with a 4.6% incidence of new breaks or detachment. Cataract surgery, i.e., lens extraction, appears to be an independent risk factor for retinal tears or detachments. It follows that a dilated retinal examination following cataract surgery is advisable in patients who have previously undergone repair of a phakic retinal tear or detachment, and even more so in myo-

Table 9.4 Axial length

Axial length	Approx. eye volume .	Approx. lens volume	Approx. IOL volume
26 mm	9 ml	0.5 ml	0.05 ml
28 mm	12 ml	0.5 ml	0.05 ml
30 mm	14 ml	0.5 ml	0.05 ml
32 mm	17 ml	0.5 ml	0.05 ml
34 mm	20.5 ml	0.5 ml	0.05 ml
36 mm	24 ml	0.5 ml	0.05 ml

pic eyes that become pseudophakic even without prior detachment or retinal tear, for this study seems to confirm the theory that expanding the internal volume of the eye by lens extraction and the internal dynamic changes that take place during the extraction process may be the precursor of retinal breaks and subsequent RRD.

Summary for Clinicians

- 75% of RRD after RLE occur within 12 months of RLE.
- 91% of RRD result in retinal attachment.
- The mean visual acuity loss is 2 Snellen lines.
- The corollary is that 9% do not repair, resulting in serious visual loss.

9.10 Nd:YAG Laser Posterior Capsulotomy and Retinal Detachment

Tielsch et al. [49] addressed the odds ratio for RRD after cataract surgery in general. "Conditional logistic regression models showed that a number of factors were associated independently with an excess risk of retinal detachment after cataract surgery. These included Nd:YAG laser capsulotomy (odds ratio [OR] = 3.8; 95% confidence interval [CI], 2.4–5.9), a history of retinal detachment (OR = 2.7; 95% CI, 1.2–6.1), a history of lattice degeneration (OR = 6.6; 95% CI, 1.6–27.1), axial length (OR = 1.21 mm; 95% CI, 1.03–1.43), refractive error (OR = 0.92/diopter; 95% CI, 0.88–0.95), and a history of ocular trauma after cataract surgery (OR = 6.1; 95% CI, 4.3–28.2)."

Other authors [19, 26, 39] are more reticent regarding the effect of Nd:YAG capsulotomy on RRD rates. Koch et al. [21] conducted a retrospective analysis of Q-switched Nd-YAG laser capsulotomies performed in 122 eyes between April 1984 and June 1987. Retinal complications occurred in 3 (2.5%) out of 121 eyes followed up for 1 year and in 2 (3.6%) out of 55 eyes followed up for 2 years. Four eyes developed RRD and 1 developed an acute symptomatic retinal tear that correlated with axial myopia, pre-existing vitreoretinal disease, male gender, younger age, vitreous prolapse into the anterior chamber, and spontaneous extension of the capsulotomy. However, if there is an increased risk of retinal detachment occurring in myopic pseudophakic eyes after Nd:YAG capsulotomy, the literature shows a significant variation of RRD rate and time after capsulotomy [1–3, 5, 6, 9, 10–12, 14, 16, 18–20, 22, 23, 25, 26, 28, 30, 32, 36, 39, 40, 43–45, 50, 52–54]. The methodology of Nd:YAG capsulotomy may be an explanatory factor causing the variance. The energy used during treatment, the diameter of the capsulotomy, and previous preoperative and postoperative retinal scrutiny may all play a part; however, this degree of detail can simply not be extracted from the literature [47, 49].

9.11 Relationship of RRD Occurrence to Surgical Complications of Lens Extraction

Several papers confirm the increased risk of retinal detachment if a capsular tear occurs, if an anterior vitrectomy is performed, or if vitreous loss is recorded [16]. Onal et al. [34] suggest that the odds for a complicated outcome of a capsular tear during phacoemulsification can be calculated. They suggest, for example, that retinal complications have the following ratios: 12:1 for RD and 26:1 for CME, which compare with 15:1 for raised IOP and 33:1 for IOL decentration (Tables 9.5–9.7).

9.12 Risk of RRD After RLE in Hyperopic Eyes

Hyperopic eyes do not have the intrinsic retinal pathology associated with myopia and increased axial length. In only one paper in the literature for RLE in hyperopia did the authors indicate that no retinal detachments occurred in that series [29]. This is mirrored in our (Rosen Eye Associates Clinic) results in a significant but unpublished series of 421 eyes studied with a minimum follow-up of 1 year and a maximum of 5 years in which 1 RRD occurred.

Table 9.5 Onal [34]: following capsule rupture during lens exchange. *CME* cystoid macular edema

• RD rate	8%	=	1:12
• CME rate	4%	=	1:26
• IOP rise	7%	=	1:15
• Dislocated IOL	3%	=	1:33

Table 9.6 Annual incidence of RRD and risk factors

In general population	=	**0.018%** [37]
After KPE in general population	=	**1.17% (100x) range** [8]
After KPE in myopic eyes	=	**2.2% (range 0–8.1%) (see Table 9.2)**
After KPE with capsular tear, etc.	=	**8.0%** [49]

Table 9.7 Annual incidence of RRD and risk factors expressed as :1,000 per annum

• **RRD in general population** [37]	=	**0.18:1,000**
• **RRD after KPE general population**	=	**11.7:1,000**
• **RRD after KPE myopic population**	=	**22:1,000**
• **RRD after KPE male myopic population**	=	**28:1,000**
• **RRD after KPE myopic population <50 years**	=	**55:1,000**
• **RRD after KPE myopic population with capsular tear**	=	**99:1,000**
Retinal reattachment rates after RRD	=	**90%+** [42]
Mean visual deficit	=	**2 lines** [42]
Retinal reattachment failure	=	**1 in 10 eyes** [42]

9.13 Prognosis of RRD Following RLE: Outcome of Pseudophakic Retinal Detachment

If retinal detachment does occur in pseudophakia, does it spell doom or can the retina be successfully reattached with a good visual outcome, i.e., what is the probable functional and anatomic outcome of RD in pseudophakic eyes?

In considering these issues in myopic eyes in particular, Ranta et al. [42] reported the outcome of 138 eyes treated by uncomplicated ECCE, but followed by RRD. There was a 35% Nd:YAG capsulotomy rate. Seventy-four percent achieved a successful retinal repair following one procedure. Overall, 91% achieved long-term retinal attachment, i.e., there was a 9% failure rate or 1 in 10 eyes. Many had some reduction of BCVA. Because of life-long risks of RRD in myopic eyes, those that undergo RLE or cataract extraction should have a large diameter IOL and wide CCC to facilitate postoperative retinal scrutiny. Silicone IOLs should be avoided to limit PCO and emulsification of silicone oil if it is required. It should also be noted that the mean time for an RRD to occur postoperatively is 39 months.

In a study of 114 cases of RRD after phacoemulsification, Haddad et al. [15] indicated that once RRD occurred, there was no statistically significant correlation between the final visual outcome and KPE intraoperative complications including: posterior capsular rupture, vitreous loss, and posteriorly dislocated lens fragments.

Christensen et al. [4] compared pre- and postoperative findings in 120 pseudophakic patients and 280 phakic patients who had RRD surgery over a 4-year period. An identical scleral buckling procedure was used for primary surgery in both groups. Cataract surgery had been performed using ECCE in most eyes; phacoemulsification was used in 67.5% of the pseudophakic eyes. The mean follow-up was 13.5 months. Pseudophakic patients with RRD presented with significantly worse preoperative visual acuity than phakic patients due to a higher frequency of total RRD and macula-off RRD. Retinal breaks were found significantly less frequently and reoperations were performed with a higher frequency in pseudophakic patients than in phakic patients.

Table 9.8 Data after phakic IOL implantation with regard to RRD [30]

- The incidence of RRD after PCP IOL implantation was 2.07%
- Mean patient age was 32.9 years (range, 23–46)
- Nine patients underwent bilateral PCP IOL implantation (60%)
- Primary RRD developed in 16 eyes of 15 patients
- Prophylactic laser photocoagulation was performed in 3 eyes in 3 patients (18.75%)
- Mean preoperative spherical equivalent (SE) was −17.3±2.47 D (range, −13.75 D to −22 D)
- Rhegmatogenous retinal detachment occurred between 1 and 70 months after PCP IOL implantation (mean, 29.12 months)
- Each of 11 RRDs (68.75%) had one causative break
- Fourteen breaks (60.86%) were horseshoe tears and 9 (39.14%) were atrophic holes
- Scleral buckling was performed in 10 eyes (62.5%)
- Pars plana vitrectomy alone was performed in 5 cases (31.25%) with posterior breaks. Initial reattachment rate was 90.9%
- Final retinal reattachment was 100%. Mean postoperative BCVA was 20/28 (0.72±0.25)
- Mean follow-up after retinal detachment surgery was 35.25±17.29 months (range, 12–67 months)

Table 9.9 Odds for RRD

Perkins [35] more than -10 D 1 in 140 unoperated eyes will suffer RRD
Polkinghome and Craig [37] suggest that 1 in 8,333 (all) eyes will suffer RRD on an annual basis
Polkinghome and Craig [38] suggest that 1 in 85 (all) eyes will suffer RRD on an annual basis after uneventful KPE
Table 9.2 suggests mean figure of 2.2% for RRD, i.e., for every 1,000 myopic eyes 22 will suffer RRD at some time after lens surgery = 1:48
If a peak figure of 8% is accepted (Ripandelli et al. [44] and Colin [7]) then 80 myopic eyes will suffer RRD at some time after lens surgery = 1:12
If a capsule rupture were to occur during lens surgery the rate increases to 1 in 12 (irrespective of myopia)
If the patient is less than 50 years, rates may increase by a factor of 5 (Polkinghome and Craig [38])
If the patient is male rates may increase by factor of 1.25 (Polkinghome and Craig [38])

The overall anatomic reattachment rate was 94% and 96% in the two groups respectively, and the visual outcome was also similar, with a visual acuity better than 0.4 in about 60% of patients. The authors concluded that the anatomic and visual prognosis of pseudophakic detachments was identical to that of phakic detachments.

In a recent study, Martinez-Castillo et al. [30] provide the most detailed information, albeit in relation to phakic IOL implantation in myopic eyes. Although the surgical process is different, the phakic IOL is an additive process, whereas RLE removes the crystalline lens. Nevertheless, it is reasonable to suppose that in many if not all operated eyes the interior milieu of the eye fluctuates with consequentially adverse effects on the vitreous body. Therefore, it is not unreasonable to infer that RRD data may be relevant to the consideration of RRD following RLE. The authors' data are summarized in Table 9.8. For a wider summary of odds for RRD see Table 9.9.

9.14 Ethical and Medico-Legal Considerations

While the potential benefits of RLE can be successfully argued, the Ophthalmic Mutual Insurance Company of USA (OMICS), which insures more than 3,500 policyholders (35% of whom perform refractive surgery), takes a conservative approach. According to OMICS data, the company has offered coverage for RLE since 1999 and revisited its guidelines when the Crystalens was approved by the FDA for use in cataract surgery.

Table 9.10 Percentage of Ophthalmic Mutual Insurance Company of USA (OMICS) ophthalmologists insured for different types of refractive surgery

Laser assisted in situ keratomileusis	**29.2%**
Photorefractive keratectomy	**28.9%**
Radial keratotomy	**12.7%**
Refractive lens exchange	**8.0%**
Conductive keratoplasty	**2.3%**
Laser thermokeratoplasty	**1.8%**
Intacs	**1.6%**
Phakic intraocular lens implantation	**0.6%**

Refractive surgery patients have higher expectations, but need to fully comprehend the risks of intraocular surgery. The frequency of complications may not be great but the seriousness of the possible risks is an issue. Ophthalmologists could have a difficult time in front of a judge or jury, to defend this procedure in the event of an adverse outcome, especially if the patient is relatively young with minimal refractive error and no evidence of cataract. Sometimes patients may have unrealistic expectations and be very disappointed with the ultimate results. Near, intermediate, and distance vision are considerations that may lead to patient dissatisfaction with outcome.

Insurance by OMICS generally provides cover only for cases performed on patients with more than -10 D of myopia or between +3 and +15 D of hyperopia, ranges for which other refractive procedures are not as effective as they are for lower refractive errors. OMIC is also willing to consider exceptions to these patient selection criteria on a case-by-case basis due to special situations (Table 9.10).

In the UK, professional indemnity to cover the practice of refractive surgery has escalated proportionately to the rise in litigation, although the majority of refractive litigation is laser corneal surgery-based.

9.15 Conclusion

Emmetropization of myopic eyes by lens exchange embraces risk the scale of which can be deduced by a comparison of RRD rates in a general population and by grading the severity of the myopia (axial length) and patient age in particular. Table 9.3 indicates the wide disparity in the annual incidence of RRD in unoperated eyes in a general population. To compare like with like requires an annual figure for RRD in myopic eyes after RLE or cataract surgery that is impossible to derive. Nevertheless, it does represent a starting point for comparisons that can be refined with the passage of time and accumulation of more data. Perkins' data suggest a natural risk of RRD in myopic eyes more than –10 D of 1 per 140 eyes over a lifetime [35]. This compares with Polkinghome and Craig's figure of 1 eye in every 8,333 eyes on an annual basis [37]. The same authors suggest that 1 eye in 85 is at risk of RRD following lens extraction by KPE (annual rate), i.e., lens exchange enhances the risk by a factor of 100. Assuming the overall figure of RRD following RLE/cataract surgery in myopic eyes is 2.2% (for the mean figure see Table 9.2), then the overall risk of RRD doubles again to 1 in 45 eyes. If the highest value of 8% (see Table 9.2) is accepted, then 1 in 12 eyes run the risk of RRD after surgery. Onal et al. [34] suggest that 1 in 12 eyes will succumb to RRD following lens extraction complicated by capsule rupture. Polkinghome and Craig [38] quantified the age factor noting that the annual rate of RRD after lens extraction was 1.17% increasing to 5.1% for the under 50 age group. In other words, a patient with myopic RLE aged less than 50 years who has had a complicated lens extraction is at exceptionally high risk of RRD, the longer the axial length adding to the cumulative risk.

Pseudophakia in myopic eyes carries a higher risk of RD than in formerly emmetropic or hyperopic eyes consequent upon the intrinsic vitreo-retinal pathology associated with greater eye globe axial length and the consequent stretching/degeneration of both vitreous and retina.

Refractive lens exchange for myopia, relevant to higher degrees of myopia, is a most effective process where risk factors are clearly identifiable and should be discussed fully with prospective candidates. Long-term case control studies of a high volume of myopic eyes undergoing RLE would undoubtedly be valuable in further quantifying risk (Table 9.8).

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Chapter 10

Pseudoaccommodative and Accommodative IOLs

10

Mark Packer, I. Howard Fine,
Richard S. Hoffman, H. Burkhard Dick

Core Messages

- The introduction of multifocal intraocular lenses and accommodative intraocular lenses represents a significant driving force behind the adoption of refractive lens exchange as a refractive surgery modality for the presbyopic age group.
- Multifocal technology represents a compromise between dysphotopsia and spectacle independence. Newer optical designs have reduced the incidence of moderate and severe halos and glare.
- Clinical results demonstrating the efficacy of single optic axial movement accommodative IOL technology indicate a high rate of spectacle independence for many near vision tasks. Accurate biometry and lens power calculation, as well as surgical technique, represent important keys to refractive success with accommodative IOLs.
- Dual optic accommodative IOL technology offers potentially greater accommodative amplitude. The achievement of spectacle independence for both distance and near with this technology demands consistent biometry, meticulous surgical technique, and a rigorous postoperative regimen.
- The future of refractive surgery lies in lens-focused modalities. Capable of addressing all refractive errors, including presbyopia, refractive lens exchange offers the refractive surgeon both challenges and rewards.

10.1 Introduction

Following cataract surgery and intraocular lens (IOL) implantation, options to extend the depth of field allowing distance and near function include monovision (that is, the assignment of one eye to distance activities and the other eye to near), multifocal intraocular lens implantation, and, most recently, accommodating intraocular lens implantation. The advantage of multifocal or accommodating IOL implantation over the monovision approach is that of the potential for binocular function at all distances. Multifocal lenses are designed to produce at least two axially separated focal points that create the functional equivalent of accommodation. The design of such lenses is rendered challenging by the demands of minimizing loss of incident light to higher orders of diffraction, minimizing optical aberration, and balancing the brightness of the focused and unfocused images [30].

Perhaps the greatest catalyst for the popularization of refractive lens exchange (RLE) has been the development of multifocal lens technology. Multifocal IOLs have been developed and investigated for decades. One of the first multifocal IOL designs to be investigated in the United States was the center-surround IOL, now under the name NuVue (Bausch & Lomb Surgical, Rochester, NY, USA). This lens has a central near add surrounded by a distance-powered periphery. The 3M diffractive multifocal IOL (3M Corporation, St. Paul, MN, USA) has been acquired, redesigned, and formatted for the foldable AcrySof acrylic IOL platform (Restor, Alcon Surgical, Ft. Worth, TX, USA). Pharmacia (Groningen, Holland) also designed a diffractive

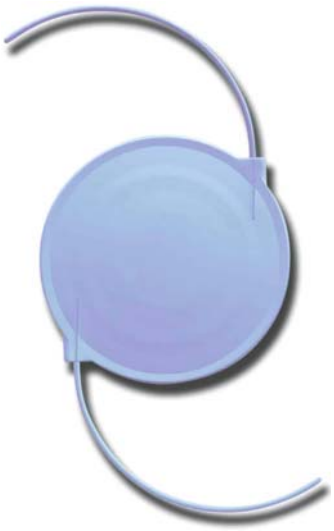


Fig. 10.1 Array Multifocal IOL (AMO, Santa Ana, CA, USA)

multifocal IOL, the CeeOn 811E, that has been implanted extensively outside of the USA and is now under clinical investigation in the USA on a foldable silicone modified prolate platform as the Tecnis Multifocal IOL (AMO, Santa Ana, CA, USA). Alcon, Pharmacia, and Storz have also previously investigated three-zone refractive multifocal IOLs that have a central distance component surrounded at various radii by a near annulus.

From 1997 until 2005 the only multifocal IOL approved by the FDA for general use in the USA was the Array (AMO). The Array is a zonal progressive intraocular lens with five concentric zones on the anterior surface (Fig. 10.1). Zones 1, 3, and 5 are distance-dominant zones while zones 2 and 4 are near-dominant. The lens has an aspheric component such that each zone repeats the entire refractive sequence corresponding to distance, intermediate, and near foci. This results in vision over a range of distances. The lens uses 100% of the incoming available light and is weighted for optimal light distribution. With typical pupil sizes, approximately half of the light is distributed for distance, one-third for near vision, and the remainder for intermediate vision. The lens utilizes continuous surface construction and consequently there is no loss of light through diffraction and no degradation of image quality as a result of surface discontinuities [10]. The lens has a foldable silicone optic that is 6.0 mm in diameter with haptics made of polymethylmethacrylate and a haptic diameter of 13 mm. The lens can be inserted through a clear corneal incision that is 2.8 mm wide, utilizing the Unfolder injector system manufactured by AMO.

In 2005, the US FDA approved two new multifocal designs, the ReZoom IOL (AMO) and the Restor IOL (Alcon Surgical). The ReZoom IOL represents new engineering of the Array platform, including an acrylic material and a shift of the zonal progression.

The Restor employs a central apodized diffractive zone surrounded by a purely refractive outer zone. It has a central 3.6-mm diffractive optic region, where 12 concentric diffractive zones on the anterior surface of the lens divide the light into two diffraction orders to create two lens powers. The central 3.6-mm zone is surrounded by a region that has no diffractive structure over the remainder of the 6-mm diameter lens. The near correction is calculated at +4.0 D at the lens plane, resulting in approximately +3.2 D at the spectacle plane. This provides 6 D of pseudo-accommodation at the 20/40 level.

The diffractive structure of AcrySof ReStor is apodized: there is a gradual decrease in step heights of the 12 diffractive circular structures, creating a transition of light between the foci and theoretically reducing disturbing optic phenomena like glare and halo. Current study results demonstrate excellent near visual acuity without compromising distance vision, with approximately 80% of investigated patients not needing spectacles for near, distance, or intermediate vision.

In the Restor, the logic of placing the diffractive element centrally depends upon the near synkinesis of convergence, accommodation, and miosis. As the pupil constricts the focal dominance of the lens shifts from almost purely distance to equal parts distance and near. This approach conserves efficiency for mesopic activities when the pupil is larger, such as night driving, but reduces near vision under mesopic conditions (such as reading a menu by candle light).

Summary for the Clinician

- Multifocal IOLs have served to catalyze the growth of refractive lens exchange, and recent history shows strong innovation in their technological development.

10.2 Clinical Efficacy and Safety

The efficacy of zonal progressive multifocal technology has been documented in many clinical studies. Early studies of the one-piece Array documented a larger percentage of patients who were able to read J2 print after undergoing multifocal lens implantation compared with patients with monofocal implants [27, 36]. Similar results have been documented for the foldable Array [4].

Clinical trials comparing multifocal lens implantation with monofocal lens implantation in the same patient have also revealed improved intermediate and near vision in the multifocal eye compared with the monofocal eye [37]. Of patients implanted bilaterally with the single piece AcrySof Restor in the FDA-monitored clinical investigation, 75.7% reported that they never wore spectacles, compared with 7.7% of participants in a monofocal control group [15]. For participants implanted bilaterally with the ReZoom IOL (AMO), data from a sponsored European study, which conformed to FDA standards and included more than 200 patients, demonstrated that 93.0% never or only occasionally wore glasses (personal communication, Ron Bache, AMO, May 11, 2005).

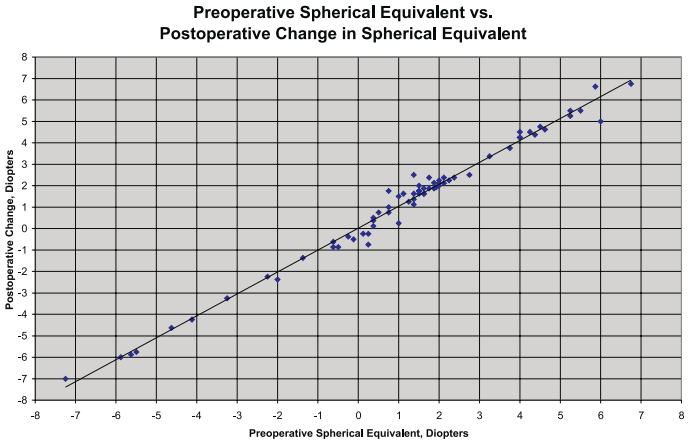
Many studies have evaluated both the objective and subjective qualities of contrast sensitivity, stereoacuity, glare disability, and photic phenomena following implantation of multifocal IOLs. Refractive multifocal IOLs, such as the Array, have been found to be superior to diffractive multifocal IOLs by demonstrating better contrast sensitivity and less glare disability [28]. However, more recent reports comparing refractive and diffractive IOLs have revealed similar qualities for distance vision evaluated by modulation transfer functions, but superior near vision for the diffractive lens [30].

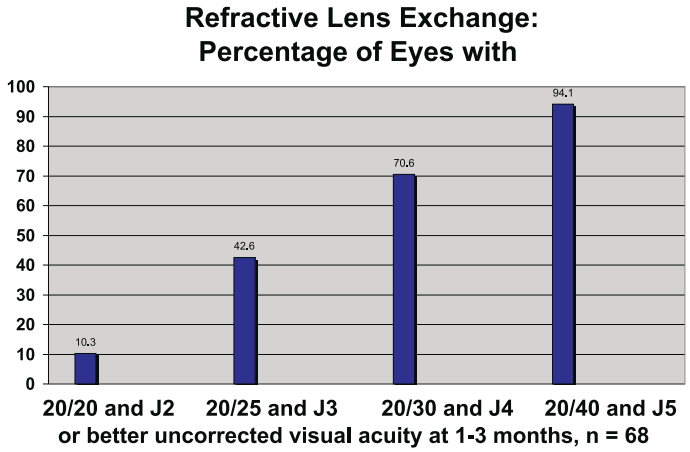
With regard to contrast sensitivity testing, the Array has been shown to produce a small amount of contrast sensitivity loss equivalent to the loss of one line of visual acuity at the 11% contrast level using Regan contrast sensitivity charts [36]. This loss of contrast sensitivity at low levels of contrast was only present when the Array was implanted monocularly and was not demonstrated with bilateral placement and binocular testing [1]. Regan testing, however, is not as sensitive as sine wave grating tests, which evaluate a broader range of spatial frequencies. Utilizing sine wave grating testing, reduced contrast sensitivity was found in eyes implanted with the Array in the lower spatial frequencies compared with monofocal lenses when a halogen glare source was absent. When a moderate glare source was introduced, no significant difference in contrast sensitivity between the multifocal or monofocal lenses was observed [33]. However, recent reports have demonstrated a reduction in tritan color contrast sensitivity function in refractive multifocal IOLs compared with monofocal lenses under conditions of glare. These differences were significant for distance vision in the lower spatial frequencies, and for near in the low and middle spatial frequencies [29]. A new aspheric multifocal IOL, the Progress 3 (Domilens Laboratories, Lyon, France), also demonstrated significantly lower mean contrast sensitivity with the Pelli-Robson chart compared with monofocal IOLs [16].

Ultimately, these contrast sensitivity tests reveal that, in order to deliver multiple foci on the retina, there is always some loss of efficiency with multifocal IOLs compared with monofocal IOLs. However, contrast sensitivity loss, random-dot stereopsis and aniseikonia can be improved when multifocal IOLs are placed bilaterally compared with unilateral implants [11]. A recent publication evaluating a three-zone refractive multifocal IOL demonstrated improved stereopsis, less aniseikonia, and greater likelihood of spectacle independence with bilateral implantation compared with unilateral implantation [34].

10.3 Photic Phenomena

One of the persistent drawbacks of multifocal lens technology has been the potential for an appreciation of glare or halos around point sources





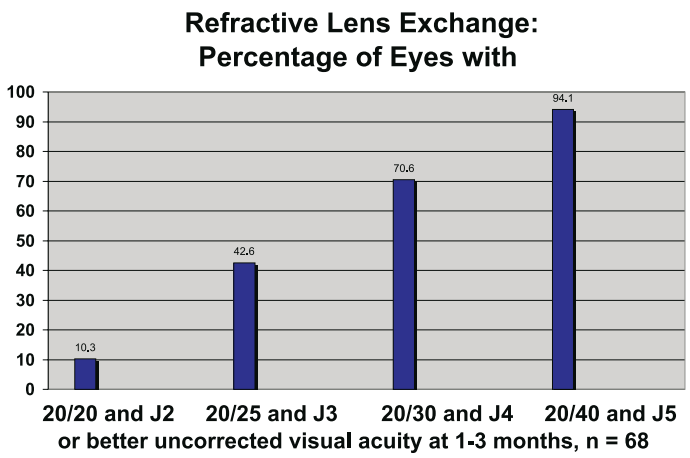


Fig. 10.2 Outcomes of refractive lens exchange with the Array Multifocal IOL

of light at night in the early weeks and months following surgery [12]. Most patients will learn to disregard these halos with time, and bilateral implantation appears to improve these subjective symptoms. The clinical investigation of the Restor IOL (Alcon Surgical) demonstrated that 23.2% of participants implanted bilaterally complained of "moderate" night halos while 7.2% complained of "severe" night halos, compared with 1.9% and 1.3% respectively of participants implanted bilaterally with a control monofocal IOL [15]. For the ReZoom IOL (AMO), 70.2% of participants with bilateral implantation reported no bother or only slight bother from halos (personal communication, Ron Bache, AMO, May 11, 2005).

Concerns about the visual function of patients have been allayed by night driving simulation studies required by FDA for approval of all multifocal IOLs in the United States. The results indicate no consistent difference in driving performance and safety between multifocal and monofocal IOL participants.

10.4 Refractive Lens Exchange

One recent study reviewed the clinical results of bilaterally implanted Array multifocal lens implants in refractive lens exchange patients [23]. A total of 68 eyes were evaluated, comprising 32 bilateral and 4 unilateral Array implantations. One hundred percent of patients undergoing bilateral refractive lens exchange achieved binocular visual acuity of 20/40 and J5 or better, measured 1–3 months postoperatively. Over 90% achieved uncorrected binocular visual acuity of 20/30 and J4 or better, and nearly 60% achieved uncorrected binocular visual acuity of 20/25 and J3 or better. This study included patients with preoperative spherical equivalents between 7 D of myopia and 7 D of hyperopia with the majority of patients having preoperative spherical equivalents between plano and +2.50. Excellent lens power determinations and refractive results were achieved (Fig. 10.2).

10.5 Complication Management

When intraoperative complications develop, they must be handled precisely and appropriately. In situations in which the first eye has already had a multifocal IOL implanted, complication management must be directed toward finding any possible means of implanting a multifocal IOL in the second eye to reduce the incidence of dysphotopsia. Under most circumstances, capsule rupture will still allow for implantation of a three-piece multifocal IOL as long as there is an intact capsulorhexis. Under these circumstances, the lens haptics are implanted in the sulcus and the optic is prolapsed posteriorly through the anterior capsulorhexis. This is facilitated by a capsulorhexis that is slightly smaller than the diameter of the optic in order to capture the optic in a position that is tantamount to "in-the-bag" fixation.

If patients are unduly bothered by photic phenomena such as halos and glare, these symptoms can sometimes be alleviated by brimonidine tartrate ophthalmic solution (0.2%; Alphagan). This agent has been shown to reduce pupil size under scotopic conditions and in some patients can be successfully administered to reduce halo and glare symptoms [17]. Most but not all patients report that halos improve or disappear with the passage of several weeks to months.

Summary for the Clinician

- Multifocal IOLs increase independence from spectacles and dysphotopsia. Understanding the likelihood of perceiving halos around lights after implantation should be part of the informed consent process.

10.6 Functional Vision and Multifocal IOL Technology

The youthful, emmetropic, minimally aberrated eye has become the standard by which we evaluate the results of cataract and refractive surgery today. Contrast sensitivity testing has confirmed

a decline in visual performance with age [31], and wavefront science has helped explain that this decline occurs because of increasing spherical aberration of the human lens [2]. Since we have learned that the optical wavefront of the cornea remains stable throughout life [40], the lens has started to come into its own as a primary locus for refractive surgery. What remains is for optical scientists and materials engineers to design an intraocular lens that provides high quality optical imagery at all focal distances. This lens must, therefore, compensate for any aberrations inherent in the cornea (as the youthful crystalline lens does), and either change its curvature and/or location or employ multifocal optics.

While accommodating IOL designs show promise for both restoration of accommodation and elimination of aberrations, multifocal technology also offers an array of potential solutions. Multifocal intraocular lenses allow multiple focal distances independent of ciliary body function and capsular mechanics. Once securely placed in the capsular bag, the function of these lenses will not change or deteriorate. Additionally, multifocal lenses can be designed to take advantage of many innovations in IOL technology that have already improved outcomes, including better centration, prevention of posterior capsular opacification, and correction of spherical aberration.

The fundamental challenge of multifocality remains preservation of optical quality, as measured by the Modulation Transfer Function on the bench or the Contrast Sensitivity Function in the eye, with simultaneous presentation of objects at two or more focal lengths. Another significant challenge for multifocal technology continues to be the reduction or elimination of unwanted photic phenomena, such as halos. One question that the designers of multifocal optics must consider is whether two foci, distance and near, adequately address visual needs, or if an intermediate focal length is required. Adding an intermediate distance also adds greater complexity to the manufacturing process and may degrade the optical quality of the lens.

Recent advances in aspheric monofocal lens design may lend themselves to improvements in multifocal IOLs as well. We now realize that the spherical aberration of a manufactured spherical intraocular lens tends to increase total optical aberrations [13]. Aberrations cause incoming light that would otherwise be focused to a point to be blurred, which in turn causes a reduction in visual quality. This reduction in quality is more severe under low luminance conditions because spherical aberration increases when the pupil size increases.

Three aspheric IOL designs are currently marketed in the United States, the Tecnis IOL, the AcrySof HOA and the SofPort AO. The Tecnis Z9000 intraocular lens (AMO) has been designed with a modified prolate anterior surface to reduce or eliminate the spherical aberration of the eye. The Tecnis Z9000 shares basic design features with the CeeOn Edge 911 (AMO), including a 6-mm biconvex square-edge silicone optic and angulated cap C polyvinylidene fluoride (PVDF) haptics. The essential new feature of the Tecnis IOL, the modified prolate anterior surface, compensates for average corneal spherical aberration and so reduces total aberrations in the eye. The FDA-monitored clinical investigation of the Tecnis IOL demonstrated elimination of spherical aberration as well as significant improvement in functional vision compared with a standard spherical IOL. The AcrySof HOA IOL Model SN60WF shares with the single piece acrylic AcrySof Natural IOL (Alcon Surgical) both UV and blue light-filtering chromophores. The special feature of this IOL is the posterior aspheric surface designed to compensate for spherical aberration by addressing the effects of over-refraction at the periphery. The SofPort Advanced Optics (AO) IOL (Bausch & Lomb) is an aspheric IOL that has been specifically designed with no spherical aberration so that it will not contribute to any pre-existing higher-order aberrations. It is a foldable silicone IOL with PMMA haptics and square edges, and it was specifically designed for use with the Bausch & Lomb SofPort System, an integrated, single-use, single-handed planar delivery IOL insertion system.

Clinical studies have demonstrated reduction of spherical aberration and improvement in contrast sensitivity with the Tecnis modified prolate IOL [3, 21, 24]. AMO has united this foldable IOL design with the PMMA diffractive multifocal IOL currently available in Europe (Pharma-

cia 811e). Improved visual performance and increased independence from spectacles constitute the fundamental concept behind this marriage of technologies. This new, modified prolate, diffractive, foldable, multifocal IOL has received the CE Mark in Europe. FDA-monitored clinical trials began in the United States in 2004. Optical bench studies reveal superior Modulation Transfer Function at both distance and near compared with standard monofocal IOLs with a 5-mm pupil and equivalence to standard monofocal IOLs with a 4-mm pupil. In comparison to the Array multifocal IOL, the Tecnis IOL has better function for a small, 2-mm pupil near and for a larger, 5-mm pupil at both distance and near. From these laboratory studies, it appears that combining diffractive, multifocal optics with an aspheric, prolate design will enhance functional vision for pseudophakic patients.

Summary for the Clinician

- Wavefront measurement of the eye as an optical system has led to the development of new IOLs designed to minimize postoperative spherical aberration. These IOLs may offer advantages to the patient in terms of improved functional vision for tasks performed under low light conditions.

10.7 Accommodative Intraocular Lenses

Accommodative intraocular lenses have now made their debut around the world (crystalens, eyeonics, Mission Viejo, CA, USA, and 1CU, HumanOptics, Erlangen, Germany). Clinical results indicate that restoration of accommodation may be achieved with axial movement of a lens optic [7]. Other accommodative IOL innovations include flexible polymers designed for injection into a nearly intact capsular bag [22]. These lens prototypes require extraction of the crystalline lens through a tiny capsulorhexis and raise concerns about leakage of polymer in the case of Nd:YAG capsulotomy following the development of posterior or anterior capsular opacification. Another unique approach now in clinical development involves the utilization of a thermoplastic acrylic gel, which may be shaped into a thin rod and inserted into the capsular bag (SmartLens, Medennium, Irvine, CA, USA). In the aqueous environment at body temperature it unfolds into a full-sized flexible lens that adheres to the capsule and may restore accommodation. Yet another unique design involves the light adjustable lens, a macromer matrix that polymerizes under ultraviolet radiation (LAL; Calhoun Vision, Pasadena, CA, USA). An injectable form of this material might enable surgeons to refill the capsular bag with a flexible substance and subsequently adjust the optical configuration to eliminate aberrations.

The inspiration for an intraocular lens with axial movement began with several observations made during the 1980s. In 1986 Spencer Thornton published evidence of anterior movement of a three-piece loop lens. With the administration of pilocarpine, the lens moved 0.5 mm forward compared with its position under atropine [38]. At about the same time Jackson Coleman demonstrated increased intravitreal pressure and decreased anterior chamber pressure during electrical stimulation of the ciliary body in primates, suggesting that a pressure differential occurs concomitantly with axial movement of the lens during accommodation [5]. Coleman's observation provided a potential explanation for the occurrence of axial movement of an IOL during accommodative effort. Meanwhile, Stuart Cumming investigated the ability of some patients to read well through plate haptic intraocular lenses with their distance correction in dim light. He showed an average of 0.7 mm of anterior movement of plate haptic IOLs with pilocarpine compared with a cycloplegic agent. Thus, he began the development of an IOL designed to maximize axial movement and restore accommodation to the pseudophakic patient.

Over 9 years, working with Jochen Kammann in Dortmund, Germany, Cumming investigated seven IOL designs. While the first six designs all demonstrated evidence of axial movement, they also tended to dislocate anteriorly. The second design, for example, displayed average accommodative amplitude of 2.06 D at 25 months. Two

Fig. 10.3 Crystalens Accommodative IOL (Eyeonics, Mission Viejo, CA, USA)

of the 24 lenses implanted subsequently dislocated. This design also demonstrated retention of accommodation after Nd:YAG capsulotomy.

The seventh and current design of this axial movement IOL is the AT-45 crystalens, produced by eyeonics (Mission Viejo, CA, USA). The lens features hinged haptics with a 4.5-mm silicone optic and a 12.5-mm overall diameter. Polyimide loops adhere to the capsule and prevent dislocation (Fig. 10.3).

The Oregon Eye Institute participated in the FDA-monitored clinical investigation of the crystalens in the United States. Beginning in May 2000, we implanted 97 eyes, nearly a quarter of the eyes in the study. Our preoperative evaluation included immersion A scan ultrasonography (Quantel Axis II and Prager shell), as well as partial coherence interferometry with the IOLMaster (Carl Zeiss Meditec, Jena, Germany). We employed computerized corneal topography for keratometry values (EyeSys Corneal Analysis System; Tracey Technologies, Houston, TX, USA), and the Holladay II lens power calculation formula. Patients with corneal astigmatism greater than 1.0 D were excluded from the study. For bilateral implantation we targeted a –0.50 D spherical equivalent in the first eye and a plano spherical equivalent in the second eye.

Key elements of the surgical technique continue to include temporal clear corneal microincision phacoemulsification, with construction of a 3.5-mm temporal clear corneal incision for implantation. A round, centered 4.0-mm capsulorhexis insures in-the-bag fixation of the IOL optic. Atropine 1% solution is administered at the conclusion of the case and at the first postoperative visit to ensure that the IOL will settle in the posterior capsule.

In reporting results, distance-corrected near vision and distance-corrected intermediate vision were primary variables. Distance-corrected near vision is the visual acuity measured with the ETDRS reading card at 16 inches (40.6 cm) using the best spectacle correction for distance as measured by manifest refraction. Distance-corrected intermediate vision is measured in a similar manner at 32 inches (81.2 cm).

At our center, 100% of eyes demonstrated best-corrected distance acuity of 20/32 or better, and 91.1% enjoyed uncorrected distance acuity of 20/32 or better; 88.9% exhibited uncorrected near vision of J3 or better. An even greater percentage, 93.3%, exhibited distance-corrected near vision of J3 or better.

One of the striking features of these data is the improvement of near vision with distance correction, demonstrating the accommodative nature of this IOL technology. Distance correction effectively removes corneal astigmatism and myopia as possible pseudo-accommodative mechanisms.

For 28 patients implanted bilaterally and examined 11–15 months postoperatively, 96.4% demonstrated binocular uncorrected distance vision of 20/32 or better. At the same time, 100.0% demonstrated J3 or better binocular uncorrected near vision, and 100.0% demonstrated J3 or better binocular uncorrected intermediate vision. When looking at those patients who achieved binocular vision of 20/25 or better, we find 89.3% at distance, 92.9% intermediate, and 71.4% near (Fig. 10.4).

Contrast sensitivity testing has shown that the AT-45 crystalens exhibits quality of vision comparable to standard monofocal IOLs. We have not found an increase in patient complaints

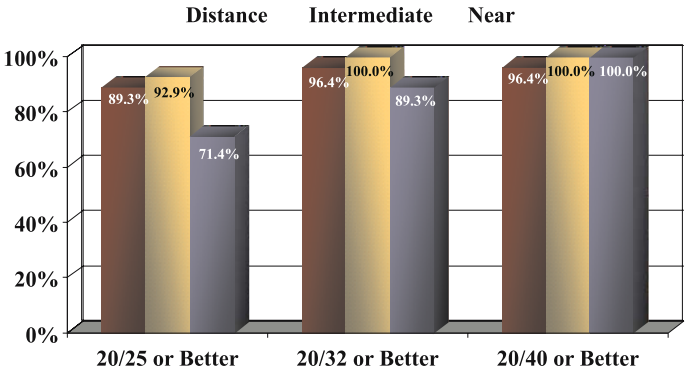


Fig. 10.4 Outcomes of crystalens implantation

about glare and unwanted optical effects with the crystalens compared with standard monofocal IOLs. Also, in the few patients who have undergone Nd:YAG laser capsulotomy, we have found that the ability to see well at both distance and near has been retained.

Attempts to actually measure the movement of the crystalens have met with variable success. Findl, using partial coherence interferometry, detected only a negligible counterproductive posterior movement of the lens optic with application of pilocarpine [9]. He also found that "the reading performance of the AT-45 IOL tested at 1 and 3 months was not significantly different from that of a standard IOL under similar testing methods." Stachs employed an in vitro simulation device to study IOL performance using an artificial capsular bag and a stretching device. In the simulation model, a maximal angulation change of 4.5° and a maximal forward shift of 0.33 mm were observed for the crystalens, corresponding to a theoretical approximate value of 0.50 D [35].

Marchini used ultrasound biomicroscopy to document ciliary body constriction and movement with the crystalens. During accommodation, the mean reduction in anterior chamber depth (ACD) was 0.32±0.16 mm at 1 month and 0.33±0.25 mm at 6 months. The mean narrowing of the scleral–ciliary process angle was 4.32±1.87° at 1 month and 4.43±1.85° at 6 months. There was a correlation between accommodative amplitude and a decrease in the ACD (r=0.404) and a decrease in the scleral–ciliary process angle (r=0.773). The authors concluded that anterior displacement of the crystalens and corresponding anterior rotation of the ciliary body occur during accommodation. The IOL displacement and rotation were proportional to the accommodation capacity [19].

10.8 Accommodative IOLs in Clinical Practice

One point of clear agreement among both users and critics of accommodative lens technology is the need for precise biometry and IOL power calculation. This requirement represents one of the important reasons that eyeonics requires surgeons to attend a full day workshop to learn a detailed systematic approach for using this lens. In the FDA study, investigators used either partial coherence interferometry (IOL Master; Carl Zeiss Meditec, Dublin, CA, USA) or immersion ultrasound (Axis II; Quantel Medical, Bozeman, MO, USA). There was a slight trend, not statistically significant, toward better results with immersion, but our study published in the *Journal of Cataract and Refractive Surgery* showed a correlation between these modalities of 0.997 [24]. Either way, applanation biometry is not sufficiently accurate and must be abandoned in order to succeed with this technology. In fact, we use immersion as a confirmatory test if we find variable test results with the IOL Master (0.1 mm in one eye or 0.2 mm between eyes).

The FDA protocol called for manual keratometry, but we have had good success using the autokeratometry from the IOL Master, supplemented

by simulated keratometry values from the EyeSys Corneal Topographer (Tracey Technologies) or the Atlas Topographer (Carl Zeiss Meditec, Dublin, CA, USA). We always use topography if we are going to correct pre-existing corneal astigmatism, or if the keratometry does not agree with the refractive cylinder (due to either irregular or lenticular astigmatism). In patients who have had previous incisional keratorefractive surgery, we use the Effective Refractive Power (EffRP) from the Holladay Diagnostic Summary of the EyeSys [26].

Once we have obtained accurate keratometry and axial length, we use the Holladay IOL Consultant to determine the IOL power. The Holladay II formula is the only widely available formula in the United States that allows in-house regression analysis and continual improvement. The formula is more accurate because it takes into account seven variables to determine the effective lens position, including the keratometry, anterior chamber depth, phakic lens thickness, axial length, corneal white-to-white distance, and patient age and gender. Implementing the Holladay II does require technician time to input the outcome data; however, it is well worth the extra time and the price.

Implementing new technology for biometry and IOL power calculation represents an important investment for the surgeon serious about refractive lens surgery. Given the premium price our client-patients pay for these procedures, we must continually examine the quality of our work and seek improvements that will enhance our outcomes.

As providers working under various non-governmental contractual agreements with third party payers, we have agreed to provide cataract surgery for a given surgeon's fee and a separate facility fee. The facility fee takes into account the price of a standard IOL, about $150, and the price of those IOLs designated by the Center for Medicare and Medicaid Services (CMS) as New Technology (NTIOLs), about $200. It does not take into account the $800 price of the crystalens. Nevertheless, patients with cataracts can receive the crystalens if the surgeon reaches an agreement with the payer to allow balance billing of the patient, and the patient signs a waiver agreeing to pay the difference. A recent ruling from CMS now allows US surgeons to bill Medicare patients separately for the correction of presbyopia during cataract surgery[14]. This change in policy will likely spur development and marketing of new multifocal and accommodative IOL technology.

Clinical judgment ultimately draws the line between refractive lens exchange and cataract surgery. The American Academy of Ophthalmology Preferred Practice Pattern for cataracts in the adult eye specifically states "no single test defines the threshold for performing cataract surgery [20]." Often, we use multiple tests, including brightness acuity, contrast sensitivity, and visual function questionnaires to try and decide if a lenticular opacity is causing a functional problem and should be called a cataract. Ultimately, it is what the patient says that matters most. If the chief complaint is essentially refractive, having to do with a desire to be independent of glasses or contacts, then the question is settled. If the chief complaint has to do with visual function (night driving difficulty, losing sight of the golf ball against the sky) then the problem is likely a cataract. Still, these same problems can be caused by advancing lenticular spherical aberration in the absence of a clinical cataract, and giving a new spectacle correction will not solve the problem. At present, spherical aberration remains a refractive problem, not covered by insurance carriers, but the climate is changing and the era of the "wavefront cataract" is dawning.

In setting patient expectation we routinely discuss the results of the FDA study. A questionnaire distributed to all patients in the FDA study at 1 year revealed that 73% never or only rarely wore glasses, while the rest continued to wear them some of the time (15%), most of the time (6%) or all of the time (5%). If patients still need glasses after surgery, they will most likely be a low-powered pair of reading glasses (+1.25 is the most common) for certain near tasks (reading the newspaper or doing needlework). Presbyopic hyperopes may be happy with this scenario. Presbyopic high myopes may be among the most satisfied crystalens patients, and demonstrate remarkably good uncorrected distance and near vision. Presbyopic low myopes may end up trading near for distance and should be approached a bit more cautiously.

Complications can occur with any procedure, and crystalens implantation is no exception. One of the most troubling complications specific to the crystalens is anterior subluxation of the lens optic within days of implantation. Typically, a patient will have excellent uncorrected acuity on day 1, and then report a sudden blurring within the next 2 weeks. Examination reveals that the optic has popped forward, producing a myopic shift of about 2 D. In our experience these optics must be repositioned. Conservative treatment with cycloplegia alone will generally leave residual myopia after a settling down period. The cause of this problem may be a wound leak; however, another possibility aside from wound leak is that some eyes may have a smaller capsular bag diameter, which does not permit the haptics to stretch out as the optic moves forward, so that with accommodative effort the lens pops forward. Finally, it is important to make sure that the lens is placed in the bag right side up, because the hinge grooves are on the front surface of the IOL. This can be checked with a hook or high magnification side-on view of the lens prior to insertion.

Summary for the Clinician

- Accommodative IOL technology represents an exciting new opportunity in refractive lens surgery. Although somewhat less predictable in achieving spectacle independence than multifocal optics, accommodative IOLs do not carry an increased risk of dysphotopsia compared with standard monofocal IOLs.

10.9 Dual Optic Accommodative IOL Technology

Visiogen (Irvine, CA, USA) has developed a dual-optic, silicone, single-piece, foldable, accommodating lens called Synchrony (Fig. 10.5). The IOL features a 5.5-mm high-powered anterior optic connected to a 6.0-mm negative power optic by haptics that have a spring-like action. The optical principle behind this lens design relies on axial displacement of the anterior optic. In order to respond to ciliary body action, energy must be stored and released in the system. The mechanism of action of this lens is based on a lens complex formed by two optics linked by a spring system, which, at rest outside the confines of the capsular bag, produces an outward force separating the axes of the optics by approximately 3.7 mm. When implanted within the capsular bag, bag tension compresses the optics, reducing the interoptic separation—that is, the resting ciliary body maintains zonular tension, which is transmitted to the bag producing outward circumferential movement of the equator, axial shortening of the capsular bag, and thus compression of the lens complex resulting in the storage of strain energy in the connecting arms. Elements are incorporated to control minimal separation, thus setting the resting distance refraction at emmetropia. With accommodative effort, the zonules relax, releasing the tension on the capsular bag, thus allowing release of the strain energy stored in the interoptic articulations and anterior displacement of the anterior optic. The posterior element is designed with a significantly larger surface area than anterior, thus reducing the tendency toward posterior axial excursion and maintaining the stability and centration within the capsular bag during the accommodation-disaccommodation process.

Fig. 10.5 Synchrony Accommodative IOL (Visiogen, Irvine, CA, USA)

The optical power of the anterior optic is within the range of 30.0 to 35.0 D, well beyond that required to produce emmetropia, and the posterior optic is assigned a variable diverging power in order to return the eye to emmetropia. The overall length of the device is 9.5 mm and the width 9.8 mm. When compressed, the total lens thickness is 2.2 mm. Ray-tracing analysis software (ZEMAX; Focus Software, Tucson, AZ, USA) using a theoretical eye model [8] has been used to analyze the expected optical effect of axial movement of this IOL when positioned at the posterior capsule plane.

Ray-tracing analysis suggested that anterior movement of the anterior optic of a dual optic IOL design with a high power anterior converging lens and a compensatory posterior diverging lens produces significantly greater change in object distance compared with similar displacement of a single optic IOL [18]. For example, a 1-mm anterior axial movement of a single optic 19 D IOL would produce a refractive power change of the eye of approximately 1.2 D. However, for a dual optic system placed in the same model eye, assuming an anterior +32 D lens separated by 0.5 mm from a posterior –12 D lens, 1 mm forward displacement of the anterior convex lens is calculated to produce a refractive change of approximately 2.2 D. Based on the optical calculations described above, it is evident that a greater change in refractive power per unit axial displacement can be generated by choosing a more powerful anterior lens, but the advantages of increased accommodative range must be weighed against the increased optical sensitivity of the system.

The power of the IOL is calculated by means of proprietary algorithms based on axial length, keratometry, anterior chamber depth, and lens thickness. These algorithms have been constantly improved in order to decrease deviation from target refraction.

Studies performed in laboratory settings using rabbit and human cadaver eyes have demonstrated that this lens can be implanted without distortion or ovalization of the capsulorhexis and the capsular bag. Folding and implantation into human cadaver eyes via a 4-mm clear corneal incision has been confirmed. In one such experiment, a standard phacoemulsification clear corneal incision was created in a cadaver eye [6]. A metal blade was used to create a 4-mm groove at the limbus and a shelved 2-mm entry into the anterior chamber created using a metal 3.2-mm keratome. This opening was then widened to approximately 4.0 mm by side-to-side motion of the keratome, and the dimensions of the opening were confirmed with calipers. Without removal of the crystalline lens, ophthalmic viscosurgical device (OVD) was injected to deepen the anterior chamber. The two optics of the IOL were brought together with lens forceps, the lens depressed and folded around the forceps into a taco configuration, and then guided through the wound into the anterior chamber. The wound width was then re-measured with calipers, and found to be approximately 4 mm. In two subsequent experiments, phacoemulsification was performed on cadaver eyes, and using the procedure described above, the lens unfolded within the capsular bag via a 4-mm clear cornea wound.

Clinical trials are being conducted for pseudophakic correction after cataract surgery. By the middle of 2004, the Synchrony IOL had been implanted in more than 70 human eyes in different centers around the world (e.g., University of Mainz and University of Heidelberg, Germany). The lens can be safely implanted in the capsular bag after conventional phacoemulsification. Special care is necessary to create a "perfectly centered" continuous curvilinear capsulorhexis, with a size between 4.5 and 5 mm. After complete removal of the lens nucleus and cortical material, careful polishing of the anterior lens capsule is performed in order to diminish lens epithelial cell proliferation over the anterior capsule, thus reducing the incidence of anterior capsule opacification (ACO), a theoretical limiting factor for the correct performance of the lens. The capsular bag is filled with an OVD and the IOL is folded with forceps. The incision size is increased to 4.4 mm for easy implantation (some surgeons may feel comfortable implanting the lens with a 4.0-mm incision), and the lens is delivered into the capsular bag in a single-step procedure. All the OVD must be removed, with special attention to the space behind the posterior optic, and the interface between the two optics. Typically no sutures are required.

Dick et al. performed a prospective clinical study with 15 eyes (12 patients) [6]. All surgeries were performed by one surgeon (HBD) with no

intraoperative complication. Both optics of the IOL were placed in the capsular bag in all cases. With a minimum follow-up of 3 months no evidence of interlenticular opacification was observed. We did not observe major complications, sight-threatening complications nor explanted an IOL. All patients were very satisfied with the visual functioning and achieved accommodation ranges between 0.5 and 2.5 D. Especially in the bilateral group (3 patients), the patients described better daily functioning and reading ability. However, a longer follow-up and a larger series are mandatory to make final conclusions.

It is important to emphasize the significance of an intact continuous curvilinear capsulorhexis, and in-the-bag placement of the IOL to achieve pseudoaccommodation. Unfortunately, it is very hard to address the ideal continuous curvilinear capsulorhexis (CCC) size. A previous report based on the HumanOptic's 1 CU Akkommodative IOL found that the ideal CCC size for visual performance was between 4.5 and 5.0 mm [39]. A smaller CCC (more overlapping) can increase the risk of anterior capsule fibrosis, which can lead to capsular phimosis and, as shown in this study, lower near visual acuities. A larger CCC (very low overlapping), as shown in previous studies, can increase the odds of decentration and PCO formation [32].

Current accommodating intraocular lenses might be expected to provide superior image quality compared with multifocal lenses, since competing retinal images are avoided, but as described above, the accommodative range of a single rigid optic design that depends upon axial displacement of the optic is limited by the range of excursion generated. The Synchrony IOL has the potential to allow the extremes of distance and near focus characteristic of multifocal designs, but additionally offers improved function at intermediate distance, and improved image quality at all object distances.

The Synchrony IOL is a new alternative in the field of refractive lens exchange for cataract and presbyopic surgery. Refractive lens exchange is increasingly seen as an advantage over keratorefractive procedures. The function of the dual optic offers the opportunity to achieve accommodative amplitude of 3–4 D. This represents a huge technological leap in the advancement of cataract and refractive surgery for the world's aging population. To optimize surgical outcomes with the dual optic IOL design (as with any other new IOL technology), we emphasize the importance of careful patient selection, adequate and consistent biometry for accurate power calculation, and the implementation of a consistent surgical technique: CCC size and shape, complete cortical clean-up, anterior capsule polishing, in-the-bag IOL implantation, and a rigorous postoperative regimen.

Summary for the Clinician

- Dual optic IOL technology will likely provide an enhanced amplitude of accommodation. As with the introduction of most new technology for cataract and refractive surgery, this innovation will require greater attention to detail and strict adherence to protocol in order to achieve success.

10.10 Conclusions

Thanks to the success of the excimer laser, refractive surgery has increased in popularity throughout the world. Corneal refractive surgery, however, has its limitations. Patients with severe degrees of myopia and hyperopia are poor candidates for excimer laser surgery, and presbyopes must contend with reading glasses, monovision or multifocal ablation to address their near visual needs. Phakic intraocular lenses are restricted to patients with deep anterior chambers, which limits their utility in hyperopes. Additionally, patients in the presbyopic age range or those developing early cataracts are best served with the one step process of refractive lens exchange. The rapid recovery and astigmatically neutral incisions currently utilized for modern cataract surgery have allowed this procedure to be used with greater predictability for refractive lens exchange in patients who are otherwise not suffering from visually significant cataracts.

Successful integration of refractive lens exchange into the general ophthalmologist's practice is fairly straight forward since most surgeons are currently performing small incision cataract

surgery for their cataract patients. Although any style of foldable IOL can be used for lens exchanges, multifocal and accommodative IOLs currently offer the best option for addressing both the elimination of refractive errors and presbyopia. Refractive lens exchange with multifocal or accommodative lens technology is not for every patient considering refractive surgery, but does offer substantial benefits, especially in presbyopic hyperopes, presbyopes, and patients with borderline or soon to be clinically significant cataracts who are requesting refractive surgery.

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Chapter 11

Selecting Phakic Intraocular Lenses for the Correction of Refractive Errors

11

Thomas Kohnen, Thomas Kasper

Core Messages

- Different types of foldable and rigid anterior (iris-fixated or anterior chamber angle-fixated) and posterior (fixated in the ciliary sulcus or freely rotating) chamber phakic intraocular lenses (pIOL) are available to correct higher ametropia.
- The indications for pIOL implantation include stable refraction, moderate to high myopia or hyperopia. In addition, the patient should be more than 18 years of age.
- Regarding astigmatism, preferable options may be a foldable nontoric pIOL for eyes with low astigmatism, a rigid pIOL with incision on the steep meridian or a foldable pIOL in combination with corneal refractive surgery for eyes with moderate astigmatism, and toric pIOL for highly astigmatic eyes.
- Anatomical requirements are an endothelial cell density of more than 2,000 cells/mm^2, anterior chamber depth of more than 3.0 mm with a distance between the pIOL and the endothelium of more than 1.5 mm, no pathologies, and an open anterior chamber angle. Furthermore, the exact measurement of anterior and posterior chamber diameter for appropriate pIOL sizing is imperative, and the mesopic pupil diameter should not cause postoperative glare and halos.
- pIOL implantation should not be performed in eyes with chronic inflammation, glaucoma or cataract; in cases of eyes with ocular hypertension, corneal pathologies or rheumatic diseases the patients should be thoroughly informed regarding risk factors, and in some cases the surgeon should refrain from implanting pIOLs.

11.1 Introduction

Current options to correct refractive errors can be divided in subtractive methods like excimer laser surgery (LASIK, PRK, LASEK, Epi-LASIK) and additive surgery like IOL implantation without extraction of the crystalline lens (phakic intraocular lens; pIOL) or with extraction of the crystalline lens followed by implantation of an IOL (refractive lens exchange; RLE). Phakic IOLs are manufactured as angle-supported or iris-fixated anterior chamber lenses and posterior chamber lenses that are fixated behind the iris in the posterior chamber of the anterior eye segment. The implantation of phakic IOLs has proven to be an effective, safe, predictable, and stable procedure for correcting higher refractive errors. Complications are rare and differ for the three types of pIOLs; these are mainly pupil ovalization and endothelial cell loss for angle-supported phakic IOLs, endothelial cell loss and inflammation for iris-fixated anterior chamber lenses, and cataract

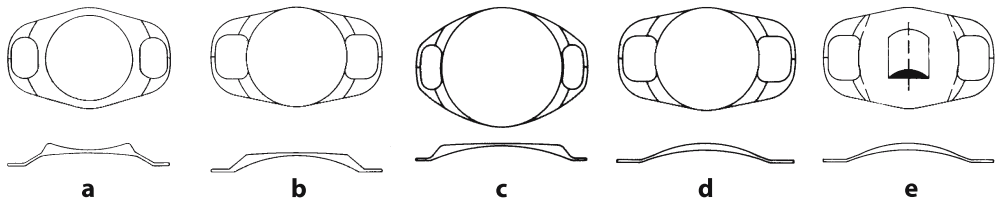


Fig. 11.1 Development of iris-fixated pIOL. **a** 1986, Model 209W, Worst Fechner Claw Lens. **b** 1991, Model 206W, Artisan Myopia, 5-mm optic diameter. **c** 1997, Model 204W, Artisan Myopia, 6-mm optic diameter. **d** 1992, Model 203W, Artisan Hyperopia, 5-mm optic diameter. **e** 1999, Artisan Toric, 5-mm optic diameter

formation and pigment dispersion for posterior chamber lenses. Based on the outcome demonstrated and the potential complications, different types of pIOL should be chosen on an individual basis.

11.2 From Past to Present: Evolution of Phakic IOLs

11.2.1 History of Anterior Chamber Phakic IOLs

The first experience of phakic IOLs was by Barraquer and Strampelli in the middle of the 20th century using an anterior chamber design [8, 63]. Because of the high complication rate (mostly endothelial cell damage), which often demanded IOL explantation, this new method was abandoned for some time. For the next 20 years, no phakic IOLs for routine implantation were manufactured.

In the 1970s, Jan Worst from the Netherlands developed an iris-fixated anterior chamber lens that was first implanted into aphakic eyes by Paul Fechner [19]. In the following years, the design of this PIOL, especially of the "lobster claw," was modified and used to correct myopia [20, 67]. Several modifications of the IOL were performed to change the early biconcave shape into the convex–concave form in order to gain more space between the IOL and the cornea and therefore increase safety for the endothelium [22, 47]. In 2004, the current model of the Worst-Fechner lens (Artisan, Ophtec/Verisyse, AMO) was approved by the FDA and is today the most implanted pIOL worldwide (Fig. 11.1) [1, 45].

In addition to the development of iris-fixated pIOLs, Baikoff modified the Kelman multiflex IOL, which was implanted in the anterior chamber angle of aphakic eyes [4]. He designed the rigid "Baikoff ZB" IOL (Domilens) with negative power, which made it possible to correct myopia in phakic eyes. Refractive results were predictable and stable, but contact of the IOL and endothelium producing a high rate of endothelial cell damage led to a modification of the IOL haptic angulation [51]. Further design changes of the Baikoff IOL were introduced into the NuVita IOL model (Bausch & Lomb) [3, 37]. Just like the Baikoff IOL, the NuVita also showed the problem of pupil ovalization with glare and halo symptoms, but to a lesser degree [3, 46]. Today, the NuVita has been withdrawn from the market.

Current studies with newly developed foldable anterior chamber angle pIOLs like the AcrySof (Alcon) have to prove that pupil ovalization can be reduced and that safety of the endothelium is ensured.

11.2.2 Current Models of Anterior Chamber pIOLs

11.2.2.1 Rigid pIOLs with fixation in the anterior chamber angle

11.2.2.1.1 Phakic 6 (Ophthalmic Innovations International)

The Phakic 6 IOL (Fig. 11.2A) is a rigid pIOL that is placed into the anterior chamber angle. To reduce glare and halos, it has an optical diameter of 6.0 mm. This lens is available to correct myopia

Fig. 11.2 Current models of anterior chamber angle-fixated pIOLs. **a** Phakic 6 (Ophthalmic Innovations International). **b** ACRIOL (Soleko). **c** Vivarte (Ciba). **d** Kelman Duet (Tekia). **e** Acrysof (Alcon)

(–2 to –25 D) and hyperopia (+2 to +10 D). It is the only pIOL on the market with heparin IOL coating to reduce inflammation and synechia. For this pIOL, no long-term studies have yet been performed.

11.2.2.1.2. ACRIOL (Soleko)

The ACRIOL (Fig. 11.2B) is a rigid one-piece pIOL of PMMA that has a manipulation hole at the haptic. This makes this IOL unique. It is manufactured for the correction of myopia (three IOL lengths between 12.3 and 13.3 mm; –9 to –22 D). In the literature, no clinical studies of this pIOL are available.

11.2.2.1.3. ZSAL-4 (Morcher)

This lens looks similar to the NuVita IOL, but has an optical diameter of 5.5 mm with a refractive optical zone of 5.0 mm. It is made of rigid PMMA and available for the correction of myopia (overall diameter of the IOL is 12.5 and 13 mm; –6 to –20 D). In a study over a period of 24 months, the ZSAL-4 (Fig. 11.3A) delivered effective and stable refractive results, but pupil ovalization and lens rotation also occurred [54].

11.2.2.2 Foldable pIOLs with fixation in the anterior chamber angle

11.2.2.2.1 Vivarte (IOL Tech)

The Vivarte IOL (Fig. 11.2C) is a one-piece IOL of hydrophilic acrylate. Because the haptic is more rigid than the optical part, a stable three-point fixation in the anterior chamber angle is possible. This pIOL is available for the correction of myopia (overall diameter of the IOL is between 12.0 and 13.0 mm; –7 to –22 D; optic diameter 5.5 mm). An advanced design is the bifocal Vivarte presbyopic IOL with an integrated part for near vision (overall diameter of the IOL is between 12.0 and 13.0 mm; –5 to +5 D with the addition of +2.5 D; optic diameter 5.5 mm).

11.2.2.2.2. Kelman Duet (Tekia)

The Kelman Duet IOL (Fig. 11.2D) is a two-piece IOL with a rigid three-point fixation haptic of PMMA (length between 12 and 13.5 mm) and a foldable optical part of silicone (diameter 5.5 mm). Both parts are implanted separately through a small incision and put together in the anterior chamber.

11.2.2.2.3. AcrySof (Alcon)

The AcrySof IOL (Fig. 11.2E, 11.3B) is a one-piece pIOL of foldable hydrophobic acrylic ma-

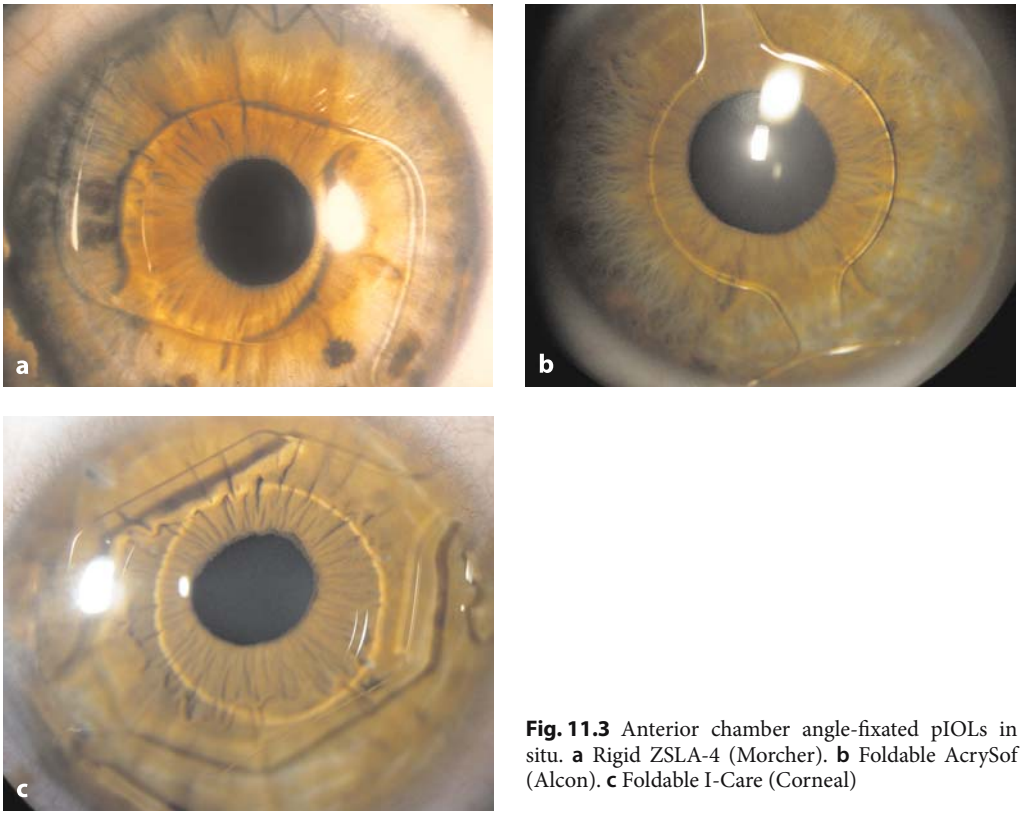


Fig. 11.3 Anterior chamber angle-fixated pIOLs in situ. **a** Rigid ZSLA-4 (Morcher). **b** Foldable AcrySof (Alcon). **c** Foldable I-Care (Corneal)

terial that is implanted by injector through a 3.2-mm incision. The pIOL has two T-style haptics with four foot plates to fixate the IOL in the anterior chamber angle. Its optical diameter is 6.0 mm. Studies for clinical investigation (FDA study) of the AcrySof IOL are currently being performed.

11.2.2.2.4 I-Care (Corneal)

The I-Care (Fig. 11.3C) is a one-piece pIOL of foldable hydrophilic acrylate. It has two T-style haptics with four foot plates to fixate the pIOL in the anterior chamber angle. This pIOL is available for the correction of myopia (overall diameter of the IOL between 12.0 and 13.5 mm; –5 to –20 D; optic diameter 5.75 mm). In the literature, no clinical studies of this pIOL are available.

11.2.2.3 Rigid Iris-Fixated pIOLs

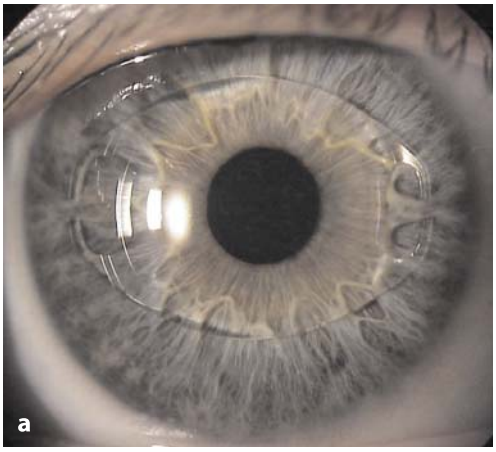
11.2.2.3.1 Artisan (Ophtec); Verisyse (AMO)

Today, the Artisan/Verisyse IOL (Fig. 11.4A) is the most implanted pIOL worldwide. It is a rigid pIOL consisting of PMMA with flexible "lobster-claws" to fixate the pIOL at the mid-periphery of the iris [9]. It is manufactured to correct myopia (overall diameter of the IOL of between 7.5 and 8.5 mm; –1 to –23.5 D; diameter of the optical zone for correction of up to –15.5 D is 6.0 mm, for higher myopic corrections it is 5.0 mm) and hyperopia (overall diameter of between 7.5 and 8.5 mm; +3 to +12 D; optic diameter 5.0 mm). Several clinical studies have shown safe and effective implantation with good mid-term stability [1, 12, 42, 43, 45, 50]. The Artisan/Verisyse IOL was approved by the FDA in 2004 [1, 55].

11.2.2.4 Foldable Iris-Fixated pIOL

11.2.2.4.1 Artiflex (Ophtec)

Based on the rigid Artisan/Verisyse, the foldable Artiflex IOL (Fig. 11.4B) was developed. It has a foldable optical part of silicone and rigid haptics made of PMMA (overall diameter of the IOL of 8.5 mm; –2 to –14.5 D; optic diameter 6.0 mm). Because of the foldable optical part, the implantation through a sutureless small incision (approximately 3.2 mm) is possible. Studies for the clinical evaluation of the Artiflex IOL are currently being performed [64].



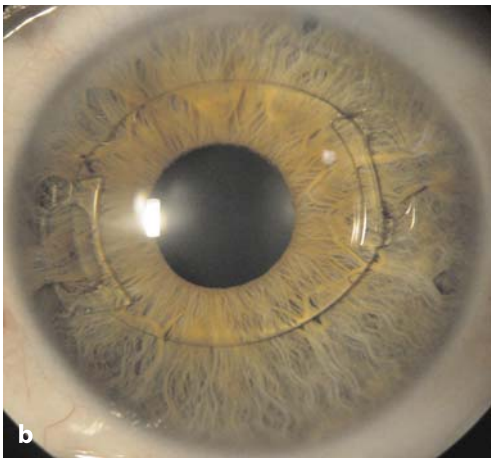


Fig. 11.4 Iris-fixated pIOLs in situ. **a** Rigid Artisan pIOL (Ophtec). **b** Foldable Artiflex pIOL (Ophthec)

11.2.3 History of Posterior Chamber Phakic IOLs

First implantation of a posterior chamber pIOL to correct myopia was performed by Fyodorov in 1986 [23, 24]. He used a one-piece silicone plate haptic IOL and placed it between the iris and the crystalline lens. Based upon this IOL, the Adatomed IOL (Chiron) was developed and implanted for some years. Several clinical studies examined this pIOL; the refractive results were satisfactory, but there was a high rate of cataract formation, often during the first year after implantation [11, 21, 49]. However, if the vaulting of the IOL over the crystalline lens was sufficient, the IOL remained clear for many years [35, 38]. Nevertheless, the Adatomed IOL was withdrawn from the market, but changes in the IOL design and material led to the development of the ICL (Staar) and PRL IOLs (IOL Tech) used today. These pIOLs appear to reduce cataract formation. The ICL lens even achieved FDA approval [15, 31, 32, 35, 41, 59, 69].

11.2.4 Current Models of Posterior Chamber pIOLs

11.2.4.1 Implantable Contact Lens (ICL, Staar)

The ICL (Fig. 11.5A) is a foldable, one-piece plate haptic pIOL of collamer material. The lens has to be implanted into the posterior chamber between the iris and the crystalline lens and is fixated at the ciliary sulcus [9, 32, 65]. It is used for correction of myopia (ICL model V4; –3 to –23 D), hyperopia (ICL model V3; +3 to +22 D), and also as a toric myopic model with implemented cylinder (addition of cylinder +1 to +6 D). The ICL is FDA-approved [59].

11.2.4.2 Phakic Refractive Lens (PRL, IOL Tech)

The PRL (Fig. 11.5B) lens is a foldable one-piece plate haptic pIOL made of hydrophobic silicone.

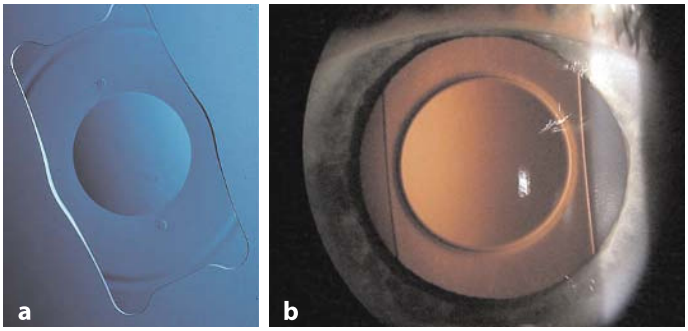


Fig. 11.5 Actual posterior chamber pIOLs. **a** ICL (Staar), **b** PRL (IOL Tech)

The lens is placed between the iris and the crystalline lens, but floats freely over the crystalline lens (according to the manufacturer). Nevertheless, in clinical examinations with ultrasound biomicroscopy, the lens was positioned on the zonule fibers or in the ciliary sulcus [26, 27]. The lens is made for correction of myopia (PRL models 100 and 101; –3 to –20 D) and hyperopia (PRL model 200; +3 to +15 D).

Summary for the Clinician

- Modern pIOLs are the result of more than 30 years' experience with different designs and materials and constant modification.
- Rigid and foldable pIOLs are available.
- Different types of anterior chamber pIOLs are available: iris-fixated or anterior chamber angle-fixated.
- Different types of posterior chamber pIOLs are available: fixated in the ciliary sulcus or freely rotating.

11.3 General Factors for the Selection of a pIOL

Like all refractive interventions, the implantation of pIOLs to correct high ametropia represents elective surgery in healthy eyes. Some general factors should be clarified before performing pIOL implantation.

- As a general rule, the patients should be 18 years of age or older.
- The patients' refraction should have been stable for a minimum of one year; in the case of high myopia, preferably 2 years.
- The correction of the high refractive error should be the main goal, and not the patients' expectations of "super" or "perfect" vision.
- In countries where approval for devices is necessary (i.e., the FDA in the USA) only lenses that have been approved can be implanted.

If these general factors are fulfilled, implantation of a pIOL may be an option for correcting high ametropia, with high satisfaction for the patient. To reach this goal with precision and safety, different criteria have to be checked, as described below.

Summary for the Clinician

- The indications for phakic IOL implantation include stable refraction, moderate to high myopia or hyperopia, and age older than 18 years.

11.3.1 Preoperative Refraction

For complete screening of refraction data, manifest and cycloplegic refraction should be performed.

Implantation of pIOLs to correct ametropia is chosen by most refractive surgeons if refraction values are beyond the indication for excimer laser correction (LASIK, LASEK, PRK, Epi-LASIK) or if the corneal tissue is not sufficient for corneal

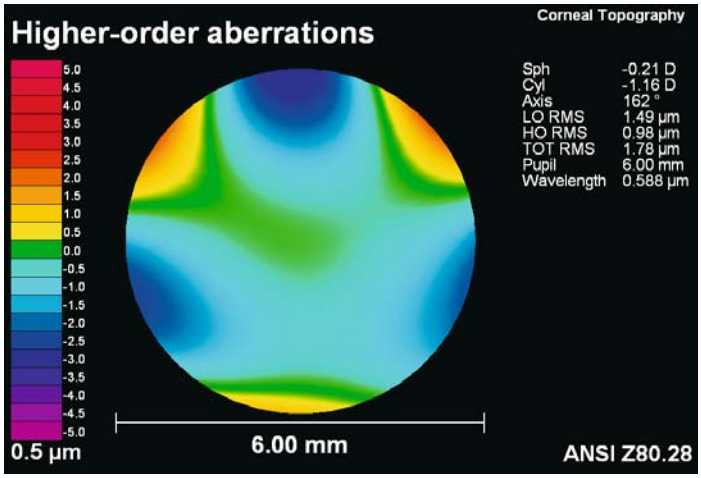


Fig. 11.6 Trefoil induction after Artisan PIOL implantation

ablation. In most cases, this will apply to myopic patients, but hyperopic and highly astigmatic patients are also candidates for pIOL implantation. Most of the pIOLs on the market are produced in myopic and hyperopic ranges.

For presbyopic patients, refractive lens exchange (RLE) is increasingly popular as the alternative method for correcting higher ametropia. In many cases, this is combined with implantation of multifocal IOLs to restore near vision.

11.3.2 Preexisting Astigmatism

When implanting pIOLs, induced astigmatism may reduce or increase preexisting astigmatism. The incision size influences the induced astigmatism: larger incisions induce higher astigmatism than smaller ones [36, 62]. Additionally, the location of the incision plays a role, as temporal incisions induce less astigmatism than superior or nasal incisions [34, 56, 61]. Another influencing factor concerning induced astigmatism is the distance to the limbus. Incisions near the limbus (e.g., clear cornea incisions) induce more astigmatism than scleral incisions [56]. Additionally, incision length and distance to the limbus influence higher order aberrations. Larger incisions that are close to the limbus may induce trefoil and coma-like aberrations (Fig. 11.6) [13].

Incision size and location may be varied for the different pIOLs, which may be a criterion for the selection of a particular pIOL. Foldable pIOLs (ICL, PRL, Artiflex, foldable angle-supported pIOLs) can be implanted through an approximately 3.2-mm incision, which is almost neutral in terms of astigmatism induction. On the other hand, rigid pIOLs (Artisan, Verisyse, rigid-PMMA-PIOL) require incision sizes that correspond to their optic diameter (5.0 or 6.0 mm). Additionally, these larger incisions have to be closed by sutures, which may induce even higher astigmatism because of suture tightness. Suturing larger incisions is recommended after the implantation of pIOLs because anterior chamber flattening postoperatively would cause endothelial cell damage and cataract formation due to contact of the pIOL with the anatomical structures.

Because of these different ways of influencing preexisting astigmatism, the authors use the incision size and location as one parameter for choosing the appropriate phakic IOL. For patients with preexisting astigmatism of less than 0.75 D, foldable pIOLs are an advantage. Corneal astigmatism between 1 and 2 D may be reduced by a larger incision on the steep corneal meridian and thus rigid pIOLs can be implanted. Even larger values of preexisting astigmatism should be treated with toric pIOLs or a combination with other refractive procedures (e.g., LRI, LASIK) [14, 17, 29].

We believe that in the future, foldable phakic IOLs will become the standard for phakic IOL

technology, which will allow incisions to be more or less neutral in terms of astigmatism. Astigmatism will either be corrected intraoperatively using cornea-relaxing incisions or toric foldable pIOLs, or postoperatively with corneal refractive surgery. This can then also be combined with the correction of residual myopia and hyperopia.

Summary for the Clinician

- Preoperative manifest and cycloplegic refraction have to be measured.
- Foldable pIOLs are used for eyes with low astigmatism.
- Rigid or foldable pIOLs with an incision on the steep meridian or foldable pIOLs in combination with corneal refractive surgery are used for moderate astigmatism.
- Toric pIOLs are used for high astigmatism.

11.3.3 Anatomical Requirements

11.3.3.1 Endothelial Cell Density

In terms of safety of the implantation of pIOLs (Fig. 11.7), the determination of endothelial cell density turned out to be a very important factor. Endothelial damage can occur due to surgical trauma during IOL implantation or by direct or indirect contact of the pIOL with the endothelium, mostly caused by changes in the position of the pIOL [43, 48, 52, 53]. Since anterior chamber pIOLs are anatomically closer to the endothelium, the risk of endothelial cell loss is higher, while endothelial cell loss has also been reported after implantation of posterior chamber pIOLs [16, 18, 32, 60]. Postoperative subclinical inflammation may also lead to endothelial cell loss through direct toxicity.

Because of these risks, endothelial cell count is mandatory before each pIOL implantation (anterior as well as posterior pIOLs), and the IOLs should only be implanted if more than or at least 2,000 cells/mm^2 are present in the patient's cornea. After implantation, annual checks of endothelial cell density are recommended to recognize increased cell loss before corneal decompensation occurs.

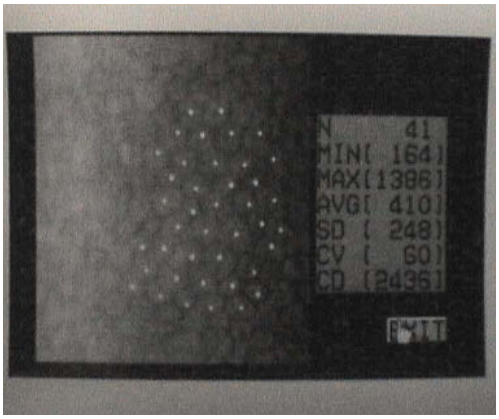


Fig. 11.7 Endothelial cell photography

11.3.3.2 Anterior Chamber Depth

In view of endothelial cell density, anterior chamber depth (Fig. 11.8) is a major issue to be considered when implanting pIOLs. This is extremely important for anterior chamber pIOLs. To avoid damage or loss of endothelial cells, a minimal safety distance of 1.5 mm between the pIOL and the endothelium must be maintained. With an minimal anterior chamber depth of 3.0 mm (preferably 3.2 mm), safe long-term results can be achieved [30, 45, 55]. Anterior chamber depth can be evaluated using different methods like ultrasound, slit scanning systems (Orbscan II, Bausch & Lomb), Scheimpflug photography, or new anterior segment optical coherence tomography (OCT; Visante, Zeiss) [5, 6].

11.3.3.3 Anterior Chamber Angle

Different pIOL designs for anterior chamber implantation are available; the designs can be divided into angle-supported (Phakic 6, Vivarte, Kelman Duet, I-Care, Acrysof) and iris-fixated

pIOLs (Artisan/Verisyse; Fig. 11.8). Comprehensive examination of the anterior chamber angle with gonioscopy is necessary to exclude patients with pathological alterations in this structure, especially for angle-supported pIOLs. In eyes with a narrow anterior chamber angle (like most hyperopic eyes), the implantation of posterior pIOLs should be performed with special attention to intraocular tension. With anterior segment OCT (Visante, Zeiss) measurements of the anterior chamber angle are possible and may help to indicate the correct phakic IOL type and size with greater accuracy [5]. Since posterior chamber pIOLs may push the iris forward, pupillary block with acute glaucoma may occur. Therefore, it is imperative to perform intraoperative iridectomies or preoperative iridotomies with Nd:YAG laser [11, 15, 65, 66, 69]. YAG laser iridotomies may cause anterior subcapsular cataracts and can close over time [68].

11.3.3.4 Anterior and Posterior Chamber Biometry

For determination of the appropriate overall diameter of anterior angle-supported pIOLs, white-to-white measurements of the horizontal diameter are made. These measurements can be performed using different methods, for example by Orbscan or the IOL Master (Zeiss) [10]. With new optical coherence tomography of the anterior segment (Visante, Zeiss), these measurements may be more accurate in the future [5, 6]. Determining the correct size of posterior chamber pIOLs is even more difficult because sulcus-to-sulcus distance is needed and the pupil prevents visualization. For that reason, white-to-white measurements are often used to estimate the correct IOL diameter. With the new very high frequency (VHF) ultrasound eye scanner (Artemis, UltraLink LLC) it will be possible to determine the sulcus-to-sulcus distance in the posterior chamber [33, 57]. Correct sizing is necessary to prevent dislocation and rotation in anterior angle-supported and posterior chamber pIOLs [3, 25, 31, 52]. Pupil ovalization may also occur after implantation of anterior angle-sup-

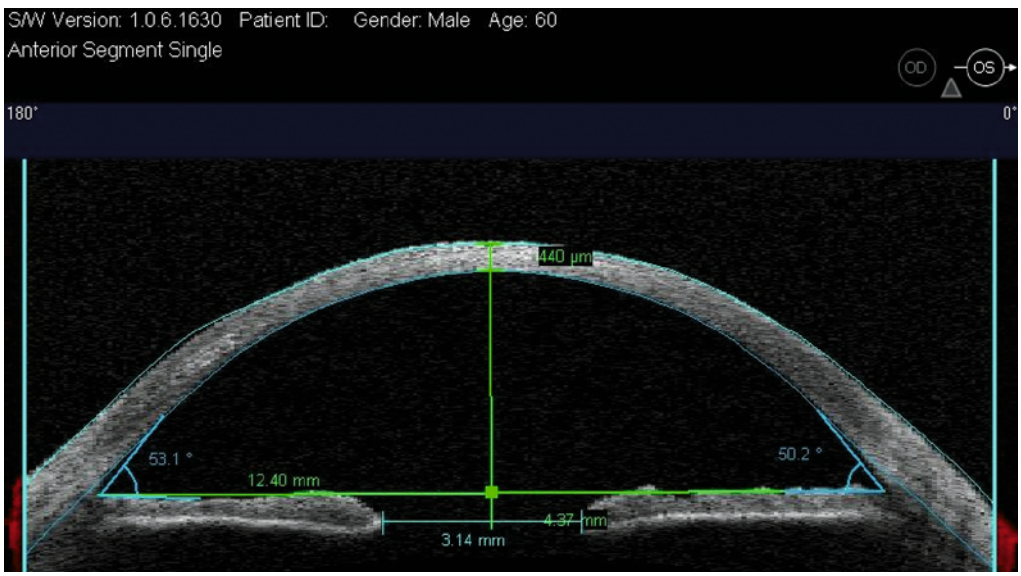


Fig. 11.8 Anterior segment optical coherence tomography (OCT, Visante). Anterior chamber depth is 3.14 mm, anterior chamber angle is between 50.2° and 53.1°

ported pIOLs, particularly if the IOL diameter is excessive [2, 3, 54].

11.3.3.5 Pupil Diameter

Postoperative symptoms like glare, halos, and night driving disturbances may be the result of the diameter of the optic of the implanted pIOL being smaller than the mesopic pupil diameter of the eye [31, 46, 49]. Therefore, preoperative pupil diameter measurements should be performed under mesopic and scotopic lighting conditions (Fig. 11.9). Several devices have become available over the last few years [39, 40]. Patients with a large mesopic pupil diameter must preoperatively be informed of possible optical disturbances and inability to drive at night. If necessary, the implantation of a pIOL should not be performed. However, it is our clinical experience that undesired postoperative symptoms are observed much less frequently in highly ametropic patients following implantation of a pIOL than after the correction of high refractive errors using excimer surgery.

Fig. 11.9 Pupil diameter measurement using infrared technologies (P2000, Procyon): 10 pictures in a 2-s sequence

11.3.3.6 Opacification and "Crystalline Lens Rise"

Examination of the crystalline lens should be performed in maximum mydriasis to detect preexisting lens opacification. For advanced lens opacification or formation of cataracts, as well as for older presbyopic patients, refractive lens extraction may be a better option to treat ametropia than pIOL [28, 44]. It is known that cataract formation after posterior chamber pIOL implantation increases with age, which could be taken into consideration when deciding on the method of choice for correcting the refractive error [41].

To prevent pigment dispersion after implantation of iris-fixated pIOLs (e.g., the Artisan/Verisyse IOL), it may be helpful to determine what Baikoff calls "crystalline lens rise" using anterior chamber OCT. In a study by Baikoff, hyperopic eyes showed a higher lens rise and a higher rate of pigment dispersion than myopic patients [7]. He concluded that higher lens rise (>600 μm) may induce more pigment dispersion by pressure on the iris, which is sandwiched between the pIOL and the crystalline lens [7]. With the introduction of new anterior chamber imaging like OCT, the measurement of crystalline lens rise should be another safety criterion for the implantation of pIOLs.

11.3.3.7 Status of the Retina

Since retinal detachment is a grave complication, it is imperative to examine the retina in maximum mydriasis before pIOL implantation. Retinal degenerations and tears have to be detected and, if necessary, treated prior to pIOL implantation. Nevertheless, retinal detachment is a rare complication after implantation of any type of pIOL [2, 58, 69]. In comparison to refractive lens extraction, no volume is taken from the eye, which may cause vitreous detachment and subsequent retinal detachment.

Summary for the Clinician

- Endothelial cell density must be more than 2,000 cells/mm².
- Anterior chamber depth must be more than 3.0 mm with an anticipated distance from the pIOL to the endothelium of more than 1.5 mm.
- There must be no structural ocular abnormalities.
- Anterior chamber angle must be wide open.
- Ensure exact measurement of the diameter of the anterior and posterior chambers for correct pIOL sizing.
- Large mesopic pupil diameter may cause postoperative glare and halos.
- Refractive lens exchange should be performed for patients with lens opacification or presbyopia.
- Crystalline lens rise is a safety criterion for pIOL implantation, especially in hyperopic eyes. It should not exceed 600 μm.
- Preoperative retinal screening and, if necessary, laser coagulation of degeneration.

11.4 Excluding Pathologies

Some preexisting eye diseases do not allow implantation of pIOLs. Phakic IOLs should not be implanted in eyes with glaucoma because of the risk of decompensating eye pressure. Ocular hypertension may also be considered a contraindication because the long-term development of glaucoma cannot be excluded. Chronic recurrent inflammations like iritis, uveitis or chorioretinitis are also exclusion parameters for pIOL implantation. Patients with cataract formation should undergo cataract extraction and IOL implantation into the bag to treat cataract and ametropia in one step. If necessary, implantation may be combined with other refractive procedures (e.g., LASIK). Rheumatic diseases and corneal pathologies like corneal dystrophies or herpes should be considered a contraindication for pIOL implantation

while no long-term studies of these illnesses are available.

Summary for the Clinician

- No pIOL implantation in eyes with chronic inflammations, glaucoma, and cataracts.
- Caution and controlled pIOL implantation in patients with ocular hypertension, corneal pathologies, and rheumatic diseases.

11.5 Conclusion

Detailed and exact preoperative examinations are required to secure postoperative results that are highly satisfactory for the patients. The most important measurements are refraction, corneal topography, biometry of the anterior and posterior chamber, as well as endothelial cell density.

Each of the various pIOL types has special advantages, but may also entail risks. Anterior chamber pIOLs may influence endothelial cells and may cause pupil ovalization. Posterior pIOLs can provoke cataract formation and pigment dispersion. Since the implantation of a pIOL is elective surgery indications have to be fulfilled and possible contraindications have to be validated carefully. Finally, it has to be mentioned that only a few of the pIOLs described above have been tested in other studies and that only a few long-term examinations were available. Because of this, careful postoperative examinations of the mostly young patients have to be performed over a period of several years in order to minimize long-term complications.

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Chapter 12

Intracorneal Implants

12

Jorge L. Alió y Sanz, Mohamed H. Shabayek

Core Messages

- Intracorneal implants are manufactured from either a biocompatible and water permeable material such as hydrogel or incomplete thin polymethyl methacrylate (PMMA) segments to maintain normal corneal physiology.
- The most recently investigated intracorneal implants are intracorneal hydrogel lenses and intracorneal ring segments.
- Intracorneal ring segments originally designed for low myopia are investigated as a way to correct corneal ectatic diseases such as keratoconus, pellucid marginal corneal degeneration, and post-LASIK ectasia with encouraging results.
- There are two main types of intracorneal ring segments, INTACS and KERARING, which differ in their design as well as their diameter of implantation.

12.1 Introduction

The cornea is the most important and effective optical element of the eye. Surgical reshaping procedures of the anterior surface of the cornea for the correction of ametropia are performed by tissue removal, such as automated lamellar keratoplasty, by laser ablation or by tissue addition, known as "additive refractive keratoplasty."

Additive refractive keratoplasty modifies the refractive condition of the eye by implanting a foreign material, a biological or synthetic "intracorneal implant," into the corneal tissue. Barraquer first introduced synthetic intracorneal implants in 1949 to correct refractive errors by altering the radius of curvature of the anterior corneal surface. However, necrosis, corneal opacification, and extrusion occurred in all cases because of the impermeable nature of the materials that were used [7, 20, 21, 33].

Recently, new permeable materials such as hydrogel have been investigated that maintain normal corneal physiology by allowing exchange of water and nutrients between the posterior and anterior layers of the cornea [19, 30], or incomplete thin intrastromal implants such as intracorneal ring segments with their potential advantage of reversibility—if necessary, the segments may be removed and another treatment may still be performed.

Summary for the Clinician

- Synthetic corneal implants must be biocompatible and either incomplete or water permeable for marinating normal oxygen and nutrient transport between the anterior and posterior corneal tissue to avoid serious complications as anterior stromal necrosis.
- Although still under investigation, the main advantage of intracorneal implants is reversibility, i.e., they can be explanted without permanently affecting the cornea tissue.

12.2 Intracorneal Hydrogel Lenses

12.2.1 Introduction

Intracorneal lenses are hydrogel lenses implanted into the corneal stroma to correct refractive errors by altering the radius of curvature of the anterior corneal surface. The first hydrogel lens to be evaluated for refractive keratoplasty was made of hydroxyethyl methacrylate (HEMA) and was reported by Dohlman et al. [14] in 1967 and later

on by other authors in refractive keratoplasty research [21–23, 36, 37].

12.2.2 Indications

Hydrogel intracorneal implants have been investigated for the correction of high myopia, hyperopia, and aphakia [2, 4, 8, 37]. Indication for correction of aphakia by intracorneal hydrogel lenses should be limited only when intraocular lenses implantation are contraindicated either due to lack of capsular support with high risk scleral fixation or low endothelial cell count contraindictating anterior chamber lens implantation.

12.2.3 Characteristics

These hydrogel lenses have a refractive index similar to that of the cornea of approximately 1.37 and a high water content, which varies between 68 and 80%, with the diameter ranging from 5.00 to 6.5 mm [2, 4, 23]. The thickness varies according to the lens type: in general, plus lenses are thicker in the center than at the periphery, while minus lenses are thinner in the center than at the periphery. Once implanted in the corneal tissue the thickness of the lenses varies due to their permeability, allowing water and nutrients to diffuse between the anterior and posterior corneal layers.

12.2.4 Surgical Technique

The intracorneal hydrogel lenses are implanted under topical anesthesia after the creation of a corneal cut "flap" 8.5 mm in diameter using a mechanical microkeratome varying in thickness from 180 to 300 μm, Some surgeons [8, 37] perform a complete 300-μm corneal cap technique while others [2, 4] implant the intracorneal hydrogel lenses after creating a 180-μm corneal flap with a 4-mm inferior hinge.

The lens is implanted in the pupil zone of the stromal bed, the interface is not irrigated after the microkeratome cut or after intracorneal hydrogel lenses implantation, and suturing is required only after the complete cap technique.

12.2.5 Postoperative Treatment

Topical antibiotics are administered three times daily for 3 days and topical corticosteroids three times daily with tapering over 15 days [2, 4, 7, 37].

12.2.6 Outcome

Intracorneal hydrogel lenses are biocompatible with corneal tissue and have no effect on the corneal endothelium as proven by various studies on primates [21–23, 36, 37]. Because of the long-term success achieved in primates, small clinical trials of hydrogel implants have been undertaken

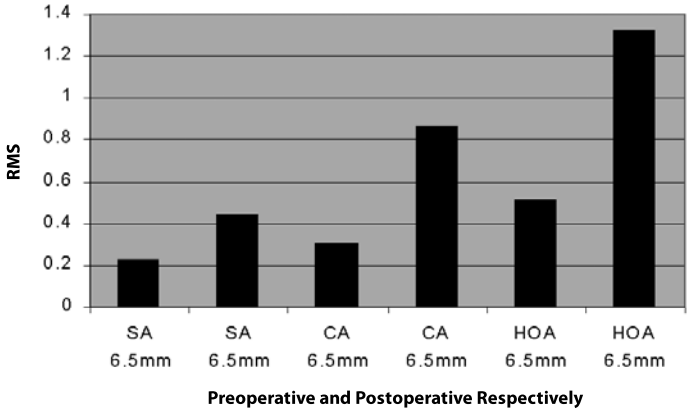


Fig. 12.1 Mean changes in corneal aberrations (μm) after intracorneal hydrogel lens implantation for 6.5-mm pupil. *SA* spherical-like aberration, *CA* coma-like aberration, *HOA* higher-order aberration

in humans for high myopia, hyperopia, and aphakia correction. The results of this limited number of studies have not been encouraging.

In 1992, Werblin, Peiffer, and co-authors [36] were the first to report 5 highly myopic eyes implanted with hydrogel implants and followed them up for 18 months, followed by Barraquer and Gomez [8] in 1997, who reported on 5 highly myopic eyes for 72 months. Both studies showed good corneal tolerance to hydrogel implants. However, predictability and refraction stability were not achieved [8, 37]. In aphakia, hydrogel implants produced unpredictable but stable results at 72 months [8].

In cases of hyperopia, in addition to unpredictability [2, 4], as in high myopia and aphakia, a marked increase in corneal higher order aberrations, especially in mesopic conditions (6-mm pupil diameter) after implantation of hydrogel corneal implants, was reported by Alió, Shabayek, and co authors (Fig. 12.1) [4].

12.2.7 Complications

In spite of the limited number of studies, and the limited number of human eyes that were implanted with hydrogel lenses, clinical complications such as membrane formation around the lens (Fig. 12.2) [2, 8], epithelial cyst, and complete regression [8], and an increase in corneal higher order aberrations [4] were reported in addition to lack of predictability and stability.

Summary for the Clinician

- The development of intracorneal hydrogel lenses with regard to their design, better power calculation, and with more specific depth of implantation could render them a good refractive alternative in cases of high hypermetropia and myopia.
- Correction of aphakia by intracorneal hydrogel lenses is limited when intraocular lens implantation is contraindicated.

12.3 Intracorneal Ring Segments

12.3.1 Introduction

In late 1978 Fleming and Reynolds first proposed intrastromal rings as synthetic intracorneal implants for the correction of various degrees of myopia [15]. The initial implant was a complete ring (Fig. 12.3), inserted through a peripheral single corneal incision. Later on, and due to technical difficulties in surgery, it was re-fashioned into an incomplete ring (Fig. 12.4), and finally, into two C-shaped rings and hence renamed intrastromal corneal ring segments [11, 17, 25–27].

Patel and collaborators [27] studied different mathematical models to predict the effect of intracorneal ring segments on refractive error, es-

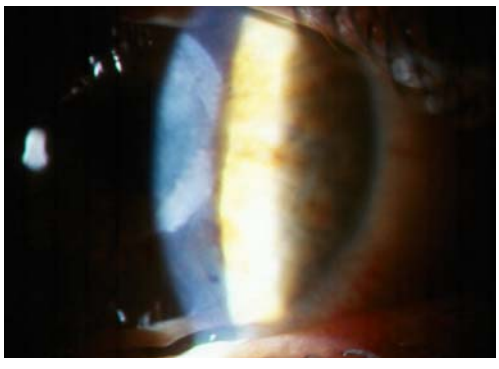


Fig. 12.2 Intrastromal epithelial opacification of intracorneal hydrogel lens in a hyperopic eye

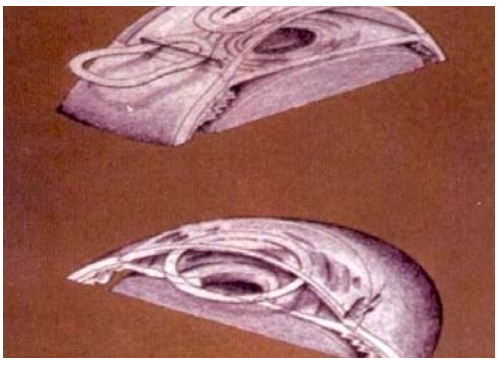


Fig. 12.3 The initial design of the intracorneal rings [34]

pecially for myopia in relation to corneal asphericity and the spherical aberration of the eye. They concluded that a larger diameter (9 mm) and a thinner ring (0.1 mm) are less likely to adversely affect corneal asphericity and therefore does not enhance induction of spherical aberration. Also, they concluded that an intracorneal ring could not correct more than –4 D of myopia without significantly increasing the spherical aberration, which, in turn, will compromise the final visual outcome. In a simplified way, in order to achieve a more flattening effect, either a thicker segment or a more centrally implanted segment is chosen, taking into consideration that a significant increase in spherical aberration should be expected postoperatively [27].

12.3.2 Mode of Action

Intracorneal ring segments act as a spacer element between arching bundles of corneal lamellae producing a shortening of the central arc length (arc shortening effect with almost a linear relationship between the thickness of the spacer elements and the degree of the corneal flattening [28].

12.3.3 Types

Two commonly used corneal ring segments are currently available to ophthalmic surgeons. The first is known under the trade name INTACS (in-

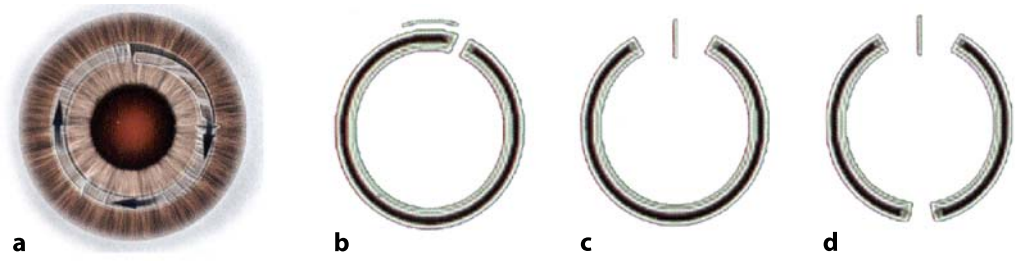


Fig. 12.4 Evolution of intracorneal ring segments [34]

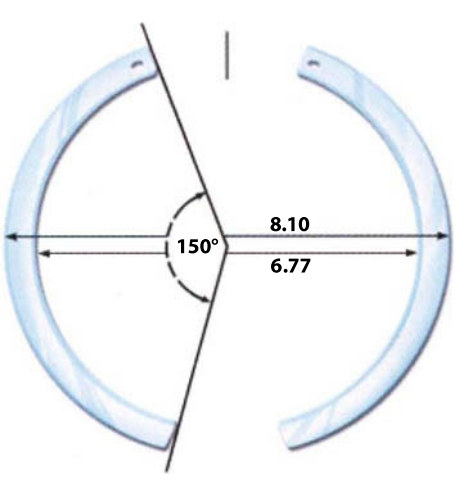


Fig. 12.5 INTACS segment

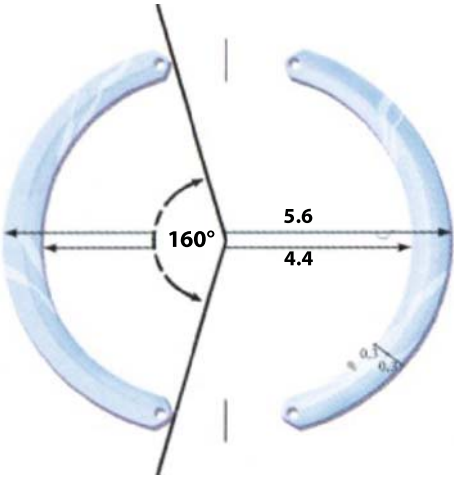


Fig. 12.6 KERARING segment

tracorneal ring segment)and is produced by KeraVision, now distributed and marketed by Addition Technologies, Fremont, CA, USA (Fig. 12.5), and KERARING, originally designed by Pablo Ferrara and produced by Mediphacos, Belo Horizonte, Brazil (Fig. 12.6). Technical specifications and differences between the two types are shown in Table 12.1.

Intracorneal ring segments originally designed for the correction of low degrees of myopia have been commonly and recently investigated to correct irregular astigmatism associated with ectatic corneal diseases such as keratoconus, pellucid marginal degeneration, and post-laser in situ keratomileusis (LASIK) ectasia.

The effect of intracorneal ring segments on keratoconic cornea is much greater than that on a normal cornea, such as in cases of myopia. The aim of implanting intracorneal ring segments is not to treat or eliminate the existing disease or should not be considered as a traditional refractive surgical procedure, but as a surgical alternative aimed at decreasing the irregular astigmatism and corneal abnormality and thus increase the visual acuity to acceptable limits as a way of at least delaying, if not eliminating, the need for corneal grafting [12, 35].

Summary for the Clinician

- Intracorneal ring segments are intracorneal implants implanted to correct irregular astigmatism associated with keratoconus, pellucid marginal corneal degeneration, and post-LASIK ectasia.
- Intracorneal ring segments flatten the central cornea by an arc-shortening effect as well as giving biomechanical support to the ectatic cornea, especially in cases of keratoconus.
- Thicker and more centrally implanted segments achieve a more flattening effect, but theoretically with an increase in spherical aberrations.
- The aim of implantation is not to treat the corneal pathology, but to correct the associated irregular astigmatism, acuity to acceptable limits as a way of delaying if not eliminating the indication for keratoplasty in patients with ectatic corneal disease.

Table 12.1 Technical specifications of both types of intracorneal ring segments

	INTACS	KERARING
Design (cross section)	Hexagonal	Triangular
Inner diameter	6.77 mm	5.40 mm
Outer diameter	8.10 mm	6.60 mm
Implantation in respect to	Center of the cornea	Center of the pupil
Implantation depth	70% of the corneal thickness	70% of the corneal thickness
Arc length	150°	120 and 160°
Available segment thickness	0.25, 0.30, 0.35, 0.40, and 0.45 mm	0.15, 0.20, 0.25, 0.30, and 0.35 mm
Material	Polymethyl methacrylate	Polymethyl methacrylate or Acrylic Perspex CQ
Method of implantation	Surgical or with femtosecond laser	Surgical or with femtosecond laser

12.3.4 Surgery Plan

12.3.4.1 INTACS

Making the decision regarding the number and the thickness of the rings to be implanted is important for achieving better results. In patients with keratoconus [3, 5, 6, 10, 13, 17, 35], post-LASIK ectasia [1, 18, 29], and pellucid marginal degeneration, corneas with inferior steepening "cones" not exceeding the 180° meridian are implanted with one segment where corneas with cones exceeding at the 180° meridian by at least 1 mm are implanted with two rings [1, 3, 5, 6, 10, 13, 17, 18, 29, 35].

Alió et al. [5, 6], Boxer Wachler et al. [10], and Colin et al. [13] proposed asymmetrical INTACS implantation where the thicker segment is implanted with regard to the steepest corneal half "cone," which is mostly inferior (keratoconus, post-LASIK ectasia, and pellucid marginal degeneration) to achieve the maximum flattening, lift the cone and give biomechanical support, add the relatively thinner ring segment superiorly to counter-balance the thicker segment and flatten the rest of the corneal surface at the less steep corneal half. The thickness of the segment is decided according to the spherical equivalent, that is to say, the greater the spherical equivalent the thicker the segment.

12.3.4.2 KERARING

The KERARING norm gram is shown in Tables 12.2 and 12.3.

Table 12.2 KERARING norm gram according to ectasia distribution area

MAP	Percentage Distribution	Description
	0%/100%	All the ectasia in one half of the cornea.
	25%/75%	75% of the ectasia in one half of the cornea and 25% situated in the other half.
	33%/66%	Two thirds of the ectatic area in one half of the cornea and one third in the other half.
	50%/50%	The steepest corneal meidian divides the cornea in two halves.

Table 12.3 KERARING norm gram according to spherical equivalent

	Topographic distribution of the ectatic area				
		0%/100% 	25%/75% 	33%/66% 	50%/50% 
S.E	>–10 D	25/35	25/35	30/35	35/35
	–8 –10 D	20/30	20/30	25/30	30/30
	–6 –8 D	15/25	15/25	20/25	25/25
	–2 –6 D	0/20	0/20	15/20	20/20
	<–2 D	0/15	0/15	15/15	15/15

12.3.5 Implantation Technique

12.3.5.1 Surgically

The procedure is performed in the majority of cases under topical anesthesia. Preoperative medication includes proparacaine (0.5%), ciprofloxacin (0.3%), and oxybuprocaine (0.2%) [5, 6].

Marking the geometrical center of the cornea is a must in implanting INTACS as they are implanted in respect of the corneal center, while KERARING are implanted in respect of the pupil's center. Intraoperative ultrasonic pachymetry is performed at the site of the incision. Seven readings should be made. The highest and lowest readings are discarded and the average of the remaining five readings is taken [5, 6]. A calibrated diamond knife is set at 70% of the mean measured corneal thickness (Fig. 12.7) and a radial incision 1.8 mm in length is made. The incision is situated 7 mm from the optical zone for INTACS implantation and 5 mm for KERARING. The incision site is either perpendicular to the steepest axis usually implanting the segments superior and inferior or on the steepest axis "mostly near the 90° axis" where the segments are implanted nasally and temporally.

The stromal pocket is dissected on both sides of the incision using a modified Suarez spatula. For KERARING implantation widening the tunnels is carried out manually with a 270° dissecting spatula followed by wound suturing after segment implantation.

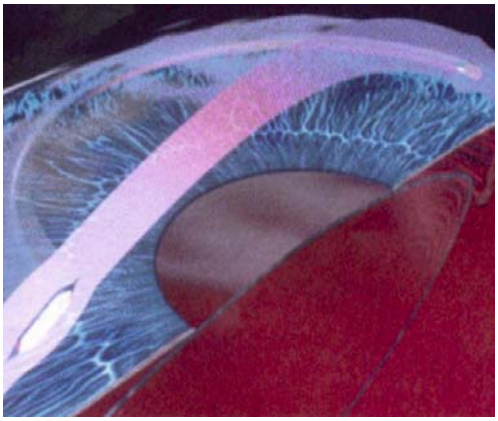
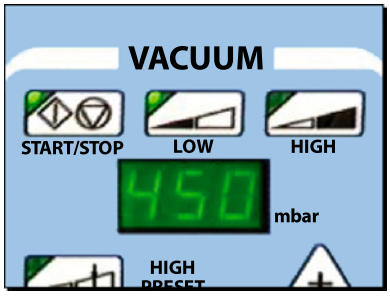
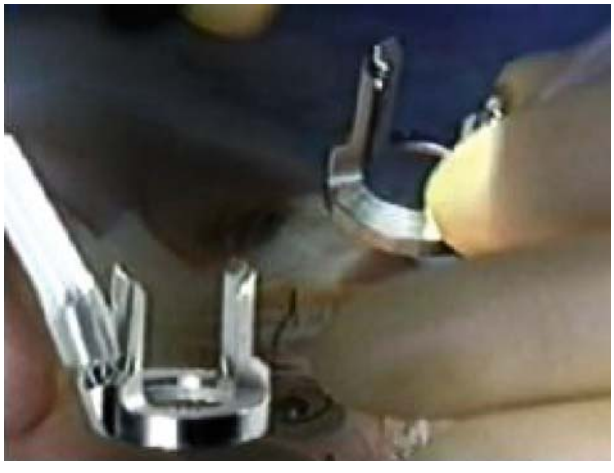


Fig. 12.7 Depth of intracorneal ring segments [34]

As for INTACS, a semi-automated vacuum device (Fig. 12.8A) is needed. This device contains a suction ring (Fig. 12.8B) that can be placed around the limbus guided by the previously marked geometrical center of the cornea. Following careful checking of the suction force, two semicircular lamellar dissectors are placed sequentially into the lamellar pocket to be steadily advanced by a rotational movement. As a result, two 180° semicircular dissections of the stroma

Fig. 12.8 Semi-automated vacuum device for INTACS implantation





are achieved with an approximate diameter of 7.5 mm. After removing the suction device, the two segments of the INTACS are inserted into each of the semicircular channels. The placement of both segments of the INTACS will leave a gap of approximately 15° nasally and 35–40° temporally. The radial incision "wound" is then gently hydrated or closed with one or two carefully embedded 10-0 nylon sutures. The edges of the stroma are then approximated to prevent epithelial ingrowth. A topical antibiotic and steroid combination is applied [5, 6].

12.3.5.2 Intracorneal Ring Segments with the Femtosecond Laser (IntraLase)

The femtosecond laser (IntraLase 15 kHz; Fig. 12.9) is a neodymium-glass infrared (wavelength 1,053 nm) ultra fast (10^{-15} of a second) photodisruption laser, which is optically focused to a specific predetermined intrastromal depth ranging from 90 to 400 μm that allows the precise placement of intracorneal ring segments inserted at the desired intrastromal depth. As there is no introduction of any foreign material into the corneal stroma the risk of infection is therefore minimized. Peripheral pachymetry is recommended before the procedure, especially in keratoconus and pellucid marginal degeneration, where the peripheral cornea is expected to be thinner than the central cornea. A disposable low vacuum device suction ring provided by the company is applied to the surface of the globe. Careful placement and inspection of the suction ring is carried out to minimize any excessive decentration. The software that gives almost perfect centration can compensate for the small degree of decentration. The disposable glass lens applanates the cornea to maintain a precise focal distance between the laser emission aperture and the desired focal point, as well as forming a planer tunnel of an equal depth of 180° all the way through. After intracorneal ring segment placement no suture is usually required [34]. Parameters for intracorneal ring segments with IntraLase are shown in Table 12.4.

Table 12.4 IntraLase parameters for intracorneal ring segments implantation

	INTACS	KERARING
Inner diameter	6.6 mm	4.8 mm
Outer diameter	7.4 mm	5.4 mm
Incision length	1 mm	1 mm
Tunnel energy	6 mJ	5 mJ
Incision energy	5 mJ	5 mJ

Fig. 12.9 The femtosecond laser IntraLase

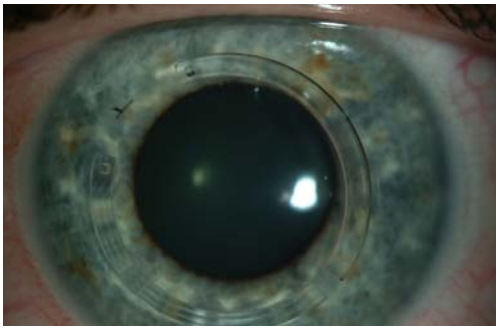


Fig. 12.10 Keratoconic eye 1 week after surgical implantation of INTACS before suture removal

12.3.5.3 Postoperative Treatment

Combination of antibiotic and corticosteroids is administered 4 times daily for two weeks. The corneal suture is removed two weeks following surgery to minimize the potential occurrence of induced astigmatism (Fig. 12.10) [5].

Summary for the Clinician

- Asymmetrical implantation with the incision perpendicular to the steepest axis of intracorneal ring segments are indicated in irregular astigmatism associated with keratoconus where the thicker segment is implanted in the ectatic half of the cornea, mostly inferiorly in the keratoconus "cone," and the thinner segment is implanted in the opposite half of the cornea.
- INTACS are implanted approximately 7 mm from the geometric center of the cornea while KERARING are implanted approximately 5 mm from the pupil's center.
- Implantation can be performed surgically or using the femtosecond laser IntraLase.

12.3.6 Outcomes of Intracorneal Ring Segments

As shown from many results intracorneal ring segments improve both uncorrected visual acuity and best corrected visual acuity in addition to decreasing the manifest refraction. Also, topography quality improves after implantation in cases of keratoconus [5, 6, 10, 13, 17, 35], post-LASIK [1, 18, 29] ectasia, and pellucid marginal degeneration [24, 31]. However, in cases of keratoconus Boxer Wachler and collaborators [10] did report a small group of eyes that had decreased best spectacle-corrected visual acuity (BSCVA); however, they correlate the loss of the visual acuity to the initial preoperative high spherical equivalent. Alió and collaborators [6] reported 5 eyes that showed decreased BSCVA after INTACS implantation, but they correlated that to the preoperative keratometric values. They also reported 20 eyes that gained at least three lines in the BSCVA after INTACS implantation as well as providing better results regarding corneal topography quality in addition to significantly reducing the SE and average K values in mild to moderate keratoconus with average keratometric values ≤53 D and a decrease in BSCVA in advanced keratoconus in spite of the decrease in the keratometric values, with average keratometric values ≥55 D (Table 12.5) [6]. These results clarify new indications for INTACS implantation to correct kera-

Table 12.5 Preoperative and 6 months postoperative K values of both groups showing less significant effect in advanced keratoconus

	Preoperative		Postoperative		Change 6 months after INTACS implantation	
	K max	K min	K max	K min	K max	K min
Group A	50.19	45.37	48.05	43.10	2.138	2.27
Group B	57.10	51.55	52.83	48.13	4.276	3.41
Difference	6.91	6.17	4.77	5.03	2.138	1.14
P value	0.009	0.002	0.04	0.003	0.29	0.44

Group A (all eyes with average keratometric value ≤53 D)

Group B (4 eyes 80% with average keratometric value ≥55 D)

toconus, and that thicker and more central segments like the KERARING should be indicated for advanced keratoconus according Patel et al.'s concept [27].

12.3.7 Complications

Complications reported after intracorneal ring segment implantation include channel deposits, which is the most common (Fig. 12.11), superficial and bacterial keratitis [9, 16, 32], migration and extrusion of the segment, and corneal tunnel neovascularization [3, 5].

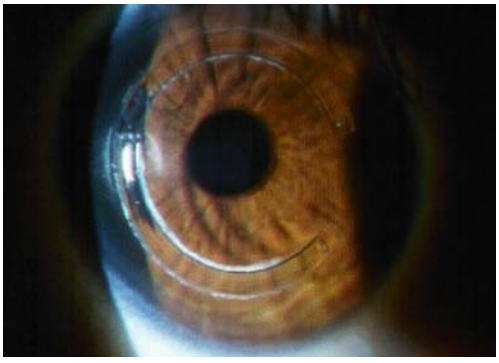


Fig. 12.11 Channel deposits around INTACS in a keratoconic eye

Summary for the Clinician

- Intracorneal ring segments decrease the spherical, astigmatic, and the spherical equivalent dioptric powers, and the keratometric values.
- Intracorneal ring segments increase both uncorrected visual acuity and best spectacle-corrected visual acuity, and provide a better corneal anterior surface, as shown by the corneal topography, without permanently affecting the corneal tissue or surgically affecting the central cornea "visual axis."
- Better results are achieved in mild to moderate keratoconus (with average K less than 53 D).
- Decrease in visual acuity is reported with a low incidence and is related to advanced keratoconus (with average K more than 55 D).
- Clinical complications such as depositis, infectious keratitis, extrusion and vascularization occur, although implantation aided by IntraLase is expected to lower the incidence of such complications.

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