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Astigmatism Control

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Over the past several years the concept of refractive cataract surgery has received increased attention from surgeons, and the need for its adoption has recently been made more urgent by the approval and availability of new presbyopia-correcting intraocular lenses (IOL). Indeed, the need to manage pre-existing astigmatism has become a requisite aspect of modern phacosurgery. Experience with keratorefractive surgery has proved that astigmatism of as little as 0.75 diopters (D) may leave a patient symptomatic with visual blur, ghosting, and halos. To embrace this notion of refractive cataract surgery fully, the dedicated surgeon must aspire to a level of accuracy that equates with corneal-based refractive surgery. Fortunately, techniques have emerged that afford the refractive lens surgeon the ability to effectively, safely, and reproducibly reduce cylinder error to acceptable levels of 0.50 D or less, either at the time of cataract surgery, or through a subsequent enhancement procedure.

Patient selection and considerations

Estimates of the incidence of significant, naturally occurring astigmatism vary widely from 7.5% to 75% [1]. In my experience with the general cataract population, approximately 10% of patients come to surgery with greater than 2 D of cylinder, 20% have between 1 and 2 D, and 70% have less than 1 D. One can therefore expect to treat pre-existing astigmatism in greater than one out of every three patients. Again, the goal is to leave the patient with a refractive outcome for both sphere and cylinder of 0.50 D or less.

When planning astigmatism correction, one must consider the location of the cylinder, the age of the patient, and the status of the fellow eye. Given that most patients drift against-the-rule over their lifetime (eg, toward plus cylinder at 180 degrees) many surgeons advocate a slightly less aggressive approach to the reduction of with-the-rule cylinder. Furthermore, some authors have suggested that residual with-the-rule astigmatism may favor better uncorrected distance acuity given that most visual stimuli are of a vertical nature [2]. Similarly, it has been contended that residual against-the-rule cylinder may improve uncorrected near vision [3]. The long-standing tenet that residual (myopic) with-the-rule astigmatism is a desirable goal to lengthen the conoid of Sturm and optimize depth perception has recently, however, been called into question [4]. In addressing today's cataract patient, given recent refinements in surgical technique and increased use of presbyopia-correcting implants, the goal of a spherical outcome seems to be optimal.

Options to reduce astigmatism

The first decision one is faced with is whether to address pre-existing astigmatism at the time of cataract surgery, or to defer and treat the cylinder separately. Historically, it has been argued that greater accuracy might be achieved if sufficient time were allotted for adequate wound healing, and a stable refraction documented before taking on astigmatic correction. Today, with the use of foldable IOLs and incision sizes now well under 3.5 mm, essentially neutral astigmatic outcomes may be consistently achieved [5]. As such, most surgeons opt to treat pre-existing cylinder concurrently with the implant procedure. This obviates the time and energy required for a second surgical sitting, and is the approach most widely taken when dealing with cataract patients, most often through the use of limbal relaxing incisions

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(LRIs) as described later. Given the exacting need for near-perfect refractive results today, however, particularly when using presbyopia-correcting IOLs, along with an increasing acceptance and use of bioptics (using excimer laser technology), some cataract surgeons are beginning to prefer a staged procedure should the patient possess any significant level of preoperative astigmatism.

The second fundamental decision is whether to treat the astigmatism through a lenticular approach (ie, to use a toric IOL) or to use a keratorefractive technique. From a theoretical perspective a toric IOL has the advantage of avoiding corneal manipulation and, as such, the possibility of inducing irregular astigmatism, and also potentially provides for reversibility. Their effectiveness has been widely reported [6,7]. Until recently, however, the availability of lens choices, at least within the United States, has been limited. In addition, postoperative rotation of the first Food and Drug Administration–approved device, the STAAR Toric (STAAR Surgical Co., Monrovia, California) single-piece plate-haptic IOL, has been a well-documented issue [6,8]. Fortunately, newer devices are reaching the marketplace and are proving to be more effective with better rotational stability, as seen with the Alcon (Alcon Laboratories, Inc., Fort Worth, Texas) single-piece acrylic lens [9,10]. As with any form of astigmatic correction, the key to obtaining propitious outcomes hinges on proper centration with the axis of astigmatism, in that relatively small degrees of misalignment may lead to a profound loss of effect, as discussed in more detail later [1].

Treatment options

The notion of reducing astigmatism at the time of IOL surgery, specifically by way of astigmatic keratotomy, dates back to the mid-1980s [11–13]. Throughout the 1990s a number of authors began to recognize the advantages of moving corneal-relaxing incisions out toward the limbus [14–16]. These so-called LRIs have become the most popular way to manage astigmatism at the time of cataract surgery and are discussed in detail later.

Another viable and relatively simple way to decrease astigmatism is to manipulate the cataract incision to impact favorably pre-existing astigmatism. This is accomplished by first centering the incision on the steep corneal meridian, and then by varying its size and design, affect a desired amount of wound flattening, and hence a decrease in cylinder [17]. This approach, however, presents logistical challenges including movement around the surgical table, often producing awkward hand positions. In addition, varying instrumentation may be needed from case to case, along with a dynamic rather than consistent mindset and repertoire. For these reasons, this technique has largely been supplanted by the use of a consistent and astigmatically neutral phacoincision (typically placed temporally for stability) and then adding supplemental relaxing incisions (LRIs). A recent study by Kaufmann and coworkers [18] concluded that LRIs in combination with a temporal clear corneal incision provided superior astigmatic outcomes to that of "on-axis" surgery.

Several other options deserve mention. Lever and Dahan [19] have suggested a novel technique of using opposing clear corneal incisions to address pre-existing astigmatism. In this technique, a second opposite penetrating clear corneal incision is placed over the steep meridian 180 degrees away from the main incision. This approach is technically simple and requires no additional instrumentation; however, a second substantial penetrating incision is now present, possibly increasing the risk of wound leak or even infection. In addition, single-plane beveled incisions are known to be less effective, for a given arc length, at flattening the cornea as compared with traditional perpendicular relaxing incisions [20,21].

Yet another important and increasingly popular alternative is that of bioptics, a technique originally described to address residual refractive error following implantation of myopic phakic IOLs, but one that is just as useful in the setting of pseudophakic lens surgery [22–24]. In this approach, one exploits the advanced technology and exquisite accuracy of the excimer laser. In a staged manner, one may treat both residual spherical and astigmatic error following implant surgery. In Zaldivar's original description, a laser-assisted in situ keratomileusis flap was created before the implant procedure, and then as necessary, the flap was lifted and residual refractive error was corrected with the laser. Today, most surgeons prefer to perform both the flap and laser ablation concurrently following cataract surgery, as needed, reducing the number of unnecessary flaps that would otherwise be created. It has been my experience that laser-assisted in situ keratomileusis may be performed safely following IOL surgery at 6 weeks, perhaps earlier. Wound stability and healing must be confirmed, along with a stable refractive error. It might be further argued that custom wavefront-guided ablation is particularly well suited in the pseudophakic eye because the dynamic lens component no longer exists [25]. For most refractive cataract surgeons, bioptics has become an integral part of the preoperative discussion with the patient, and in my experience its use is required in approximately 10% of cases, depending on the patient's preoperative refractive error. Finally, conductive keratoplasty used in an off-label fashion has also recently been described as a means by which residual hyperopia and hyperopic astigmatism may be effectively reduced following cataract surgery [26].

Limbal-relaxing incisions

The first description of the astigmatic effect of nonpenetrating incisions placed near the limbus dates back to 1898 and is credited to the Dutch ophthalmologist L.J. Lans [27]. As noted, LRIs have become the most popular technique used today to reduce pre-existing astigmatism at the time of cataract surgery. Although my preference is to use a temporal single-plane clear corneal phaco incision, one may use LRIs with any type of phaco incision as long as the astigmatic effect is known and factored into the surgical plan. LRIs offer several advantages over astigmatic incisions placed within the cornea, at smaller optical zones. These include less chance of causing a shift in the resultant cylinder axis. This presumably is caused by a diminished need for precise centration on the steep meridian. More importantly, there is less of a tendency to cause irregular corneal flattening, and hence less chance of inducing irregular astigmatism. Technically, LRIs are easier to perform and more forgiving than shorter and more central corneal astigmatic incisions, and patients generally report less discomfort. Another important advantage gained by moving out to the limbus involves the "coupling ratio," which describes the amount of flattening that occurs in the incised meridian relative to the amount of steepening that results 90 degrees away; paired LRIs (when kept at or under 90 degrees of arc length) exhibit a very consistent 1:1 ratio, and elicit little change in spheroequivalent, obviating the need to make any change in implant power.

Admittedly, these more peripheral incisions are less powerful, but are still capable of correcting up to 3.5 D of astigmatism in the cataract-aged population. One must keep in mind that the goal is to reduce the patient's cylinder, without overcorrecting or shifting the resultant axis. To achieve a given amount of correction, these peripheral intralimbal incisions must be longer in total arc length than more centrally placed corneal astigmatic incisions; however, unlike longer radial keratotomy incisions, they seem to be stable with regard to refractive effect, and show little sign of inducing problems, such as dry eye syndrome or other pejorative effects from corneal denervation [16]. Their stability may well be caused by the proximity of well-vascularized limbal tissue. There are, of course, potential complications with any surgical technique and these are addressed later.

The plan

Perhaps the most challenging aspect of astigmatism surgery involves the determination of the quantity and exact location of the cylinder that is to be corrected, and thereby formulating a surgical plan. Unfortunately, preoperative measurements (keratometry, refraction, and corneal topography) do not always correlate. Lenticular astigmatism may account for some of this disparity, particularly in cases where there is a wide variance between refraction and corneal measurements; however, some discrepancies are likely caused by the inherent shortcomings of traditional measurements of astigmatism. Standard keratometry, for example, measures only two points in each meridian at a single optical zone of approximately 3 mm.

When confounding measurements do arise, one may compromise and average the disparate readings. For example, if refraction shows 2 D of astigmatism and keratometry reveals only 1 D, it is reasonable to correct for 1.5 D. Alternatively, if preoperative calculations vary widely, one may defer placing the relaxing incisions until a stable refraction postimplantation is obtained, and then correct the astigmatism; LRIs may be safely performed in the office in an appropriate treatment-room setting. Corneal topography can be very helpful when refraction and keratometry do not agree, and it is increasingly becoming the overall guiding measurement on which the surgical plan is based. Topography is also helpful in detecting subtle corneal pathology, such as keratoconus fruste, which likely negates the use of LRIs, or subtle irregular astigmatism, such as that caused by epithelial basement membrane dystrophy.

Nomograms

Once the amount of astigmatism to be corrected has been determined, a nomogram must be consulted to determine the appropriate arc length of the incisions. A number of popular nomograms are currently available [28]. My nomogram of choice originated from the work of Dr. Stephen Hollis and incorporates concepts taught by Thornton [21], particularly his age modifiers. As seen in Table 1, astigmatism is considered to be with-the-rule if the steep axis (plus cylinder) is between 45 and 135 degrees. Against-the-rule astigmatism is considered to fall between 0 and 44, and 136 and 180 degrees. One aligns the patient's age with the amount of preoperative cylinder to be corrected and finds the suggested arc length that the incisions should subtend.

Paired incisions are preferred to optimize symmetric corneal flattening and they are expressed in degrees of arc rather than chord length. This is done to diminish overcorrections and undercorrections for unusually small or large corneas, because corneal diameter may significantly impact the relative length of the arcuate incision and its resultant effect (Fig. 1). An empiric blade depth setting is commonly used when performing LRIs, typically at 600 μm. This seems to be a reasonable practice when treating cataract patients; however, in the setting of refractive lens exchange surgery or when using presbyopia-correcting IOLs (where ultimate precision is required) it is my preference to perform pachymetry and use adjusted blade depth settings and a slightly more aggressive nomogram (Table 2). Pachymetry may be performed either preoperatively or at the time of surgery. Readings are taken over the entire arc length of the intended incision, and an adjustable micrometer diamond blade is then set to approximately 90% of the thinnest reading obtained. Refinements to the blade depth setting and nomogram adjustments are often necessary depending on individual surgeon technique; the instruments used; and, in particular, the style of the blade. As a final note, in eyes that have previously undergone radial keratotomy, the length of the incisions should be reduced by approximately 50%, and in eyes that have undergone significant prior keratotomy surgery, it may be best to avoid additional incisional surgery and use a toric IOL or laser technology instead.

Surgical technique

In most cases, the relaxing incisions are placed at the outset of surgery to minimize epithelial disruption. The one exception to this rule occurs when the phaco incision intersects or is

Table 1
Intralimbal relaxing incision nomogram for modern phaco surgery: empiric blade-depth setting of 600 μm

Spherical (up to + 0.75 × 90 or + 0.50 × 180)
Incision design: "Neutral" temporal clear corneal incision (ie, 3.5 mm or less, single plane, just anterior to vascular arcade)

Against-the-rule, (Steep axis 0–44°/136–180°)

Preoperative cylinder	Paired incisions in degrees of arc						
	30–40 y	41–50 y	51–60 y	61–70 y	71–80 y	81–90 y	91+y
	Nasal limbal arc only					35°	
+ 0.75 – + 1.25	55°	50°	45°	40°	35°		
+ 1.50 – + 2.00	70°	65°	60°	55°	45°	40°	35°
+ 2.25 – + 2.75	90°	80°	70°	60°	50°	45°	40°
+ 3.00 – + 3.75	90°	90°	85°	70°	60°	50°	45°
	o.z = 5 mm	o.z = 9 mm					

Incision design: The temporal incision, if greater than 40° of arc, is made by first creating a two-plane, grooved phaco incision (600 μ depth), which is then extended to the appropriate arc length at the conclusion of surgery.

With-the-rule, (Steep axis 45°–135°)

+ 1.00 – + 1.50	50°	45°	40°	35°	30°		
+ 1.75 – + 2.25	60°	55°	50°	45°	40°	35°	30°
+ 2.50 – + 3.00	70°	65°	60°	55°	50°	45°	40°
+ 3.25 – + 3.75	80°	75°	70°	65°	60°	55°	45°

Incision design: "Neutral" temporal clear corneal along with the following peripheral arcuate incisions.

When placing intralimbal relaxing incisions following or concomitant with radial relaxing incisions, total arc length is decreased by 50%.

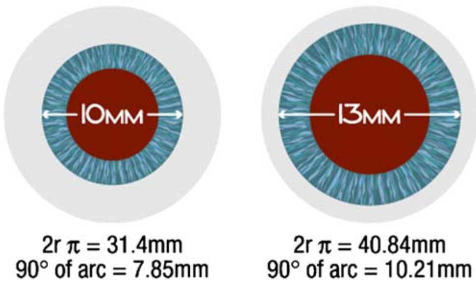

Fig. 1. Nomogram design. Note relative disparity in incision length between a large and small corneal diameter if measured in millimeters. Degrees of arc lend consistency irrespective of corneal size.

encompassed within a long LRI. For example, in the case of high against-the-rule astigmatism wherein the nomogram calls for a temporal arcuate incision of greater than 40 degrees of arc, the temporal LRI is superimposed on the (temporal) phaco incision and if it is extended to its full arc length at the start of surgery, significant gaping and edema may result secondary to intraoperative wound manipulation. In this setting, the temporal incision is first made by creating a shortened LRI whose arc length corresponds to the width of the phacoincision and IOL incision. This amounts to a two-plane grooved phacoincision whose depth is either 600 μm or has been determined by pachymetry, as described previously. Following IOL implantation and before viscoelastic removal, while the globe is still firm, the relaxing incision is extended to its full arc length as dictated by the nomogram. When an LRI is superimposed on the phacotunnel, the keratome entry is accomplished by pressing the bottom surface of the keratome blade downward on the outer or posterior edge of the LRI. The keratome is then advanced into the LRI at an iris-parallel plane. This angulation promotes a dissection that takes place at mid-stromal depth, which helps ensure adequate tunnel length and a self-sealing closure.

Proper centration of the incisions over the steep corneal meridian is of utmost importance. According to Euler's theorem, an axis deviation of 5, 10, or 15 degrees results in 17%, 33%, and 50% reduction, respectively, in effect [1]. This reduction in effect holds true for both relaxing incisions and

Table 2
Intralimbal arcuate astigmatic nomogram

With-the-rule (Steep axis 45°–135°)						
	Paired incisions in degrees of arc					
Preoperative cylinder (Diopters)	20–30 yo	31–40 yo	41–50 yo	51–60 yo	61–70 yo	71–80 yo
0.75	40	35	35	30	30	
1.00	45	40	40	35	35	30
1.25	55	50	45	40	35	35
1.50	60	55	50	45	40	40
1.75	65	60	55	50	45	45
2.00	70	65	60	55	50	45
2.25	75	70	65	60	55	50
2.50	80	75	70	65	60	55
2.75	85	80	75	70	65	60
3.00	90	90	85	80	70	65
Against-the-rule (Steep axis 0–44°/136–180°)						
0.75	45	40	40	35	35	30
1.00	50	45	45	40	40	35
1.25	55	55	50	45	40	35
1.50	60	60	55	50	45	40
1.75	65	65	60	55	50	45
2.00	70	70	65	60	55	50
2.25	75	75	70	65	60	55
2.50	80	80	75	70	65	60
2.75	85	85	80	75	70	65
3.00	90	90	85	80	75	70

Blade depth setting is at 90% of the thinnest pachymetry.

toric IOLs. Also, increasing evidence supports the notion that significant cyclotorsion may occur when assuming a supine position [29]. For this reason, most surgeons advocate placing an orientation mark at the 12-o'clock or 6-o'clock limbus while the patient is in an upright position. This is particularly important when using injection anesthesia wherein unpredictable ocular rotation may occur. An additional measure that may be used to help center the relaxing incisions is to identify the steep meridian (plus cylinder axis) intraoperatively using some form of keratoscopy. The steep meridian over which the incisions are to be placed corresponds to the shorter axis of the reflected corneal mire. A simple hand-held device, such as the Maloney (Storz, St. Louis, Missouri; Katena, Denville, New Jersey) or Nichamin (Mastel Precision, Rapid City, South Dakota) keratoscope, works well or a more robust and well-defined mire may be obtained through an elaborate microscope-mounted instrument, such as the Mastel Ring of Light (Mastel Precision). Another common way in which the steep meridian is marked uses a Mendez Ring or similar degree gauge, which is aligned with the previously placed limbal orientation mark, and then locating the cylinder axis on the 360-degree gauge.

The LRI should be placed at the most peripheral extent of clear corneal tissue, just inside of the true surgical limbus. This holds true irrespective of the presence of pannus. If bleeding does occur, it may be ignored and will cease spontaneously. One must avoid placing the incisions further out at the true surgical limbus in that a significant reduction of effect will likely occur because of both increased tissue thickness and a variation in tissue composition; these incisions are really intralimbal in nature. In creating the incision, it is important to hold the knife perpendicular to the corneal surface to achieve consistent depth and effect, and help to avoid gaping of the incision. Good hand and wrist support is important, and the blade ought to be held as if one were throwing a dart such that the instrument may be rotated between thumb and index finger as it is being advanced, leading to smooth arcuate incisions. Typically, the right hand is used to create incisions on the right side of the globe, and the left hand for incisions on the left side. In most cases it is more efficient to pull the blade toward oneself, as opposed to pushing it away.

The extent of arc to be incised may be demarcated in several different ways. My preferred method makes use of a modified Fine-Thornton fixation ring (the Nichamin Fixation Ring and Gauge, available from Mastel Precision, Storz, Rhein Medical, Tampa, Florida). This instrument serves to fixate and position the globe to optimize incision placement, and to delineate the extent of arc to be incised. One visually extrapolates from the limbus to marks on the surface of the ring. Each incremental mark is 10 degrees apart, and bold hash marks (180 degrees) opposite to each other serve to align and center the incision over the steep meridian. This approach obviates the need to ink and physically mark the cornea. If one desires, particularly when first gaining experience with LRIs, a two-cut radial keratotomy (RK) marker may be used to place ink marks upon the cornea to show the exact extent of arc that is to be incised, in conjunction with the fixation ring-gauge (Fig. 2). Alternatively, various press-on markers are available, such as the Dell-Nichamin Marker or Nichamin-Kershner Marker manufactured by Rhein Medical. ASICO and many other instrument companies also offer a full line of dedicated markers, rings, and blades for performing LRIs.

Various knives have been designed specifically for this application, ranging from disposable steel blades to exquisite gemstone diamond knives. Synthetic (and less expensive) diamond materials are also available and are intended for limited reuse. My preference is for diamond blade technology, which incorporates a single small and arced footplate for enhanced visualization at the limbus (Mastel Precision, Storz). Two models are available, one with a preset depth of 600 μm, and the other with an adjustable micrometer handle,

Fig. 2. The Nichamin Fixation Ring and Gauge serves both to fixate the globe and delineate the extent of arc to be incised; a two-cut radial marker may be used to mark the extent of arc to be incised, and the Mastel Nichamin Force AK Diamond Blade with preset depth of 600 μm. (Courtesy of Mastel Precision, Rapid City, SD; with permission.)

which is preferred for refractive lens exchange (RLE) surgery and when using presbyopia-correcting IOLs with cataract patients (Fig. 3).

Another less common method of creating peripheral relaxing incisions is to use a device such as the Terry/Schanzlin Astigmatome (Oasis Medical, Glendora, California), which circumvents the need to create a free-hand incision. This trephine-like device has been designed to produce consistent and symmetric peripheral arcuate corneal-relaxing incisions. It uses a vacuum speculum that mates with various reusable templates that are selected based on the amount of astigmatic correction that is desired. The incision is created by simply turning a disposable steel blade unit that fits inside of the template.

Fig. 3. Mastel Profile Blade. (Courtesy of Mastel Precision, Rapid City, SD; with permission.)

Complications

LRIs are proving to be a safer and more forgiving approach to managing astigmatism as compared with more central corneal incisions. Nonetheless, as with any surgical technique, potential complications exist, and several are listed in Box 1. Of these, the most likely to be encountered is the placement of incisions on the wrong axis. When this occurs, it typically takes the form of a 90-degree error with positioning on the opposite, flat meridian. This results in an increase and likely doubling of the patient's preexisting cylinder. Compulsive attention is required in this regard. The surgeon ought to consider using safety checks to prevent this frustrating complication from occurring, such as having a written plan that is brought into the operating room and is kept visible and properly oriented. Incisions are always placed on the plus (+) cylinder axis, and opposite to the minus (−) cylinder axis.

Box 1. Potential problems

- Infection
- Weakening of the globe
- Perforation
- Decreased corneal sensation
- Induced irregular astigmatism
- Misalignment or axis shift
- Wound gape and discomfort
- Operating on the wrong (opposite) axis

Although very rare, corneal perforation is possible. This may be caused by improper setting of the blade depth, or as a result of a defect in the micrometer mechanism. This latter problem may arise after repeated autoclaving and many sterilization runs. Periodic inspection and calibration is warranted, even with preset single-depth knives. When encountered, unlike radial microperforations, these circumferential perforations rarely self-seal and likely require placement of temporary sutures.

Enhancement techniques

LRIs lend themselves well to in-office "touch-ups." Although some surgeons place or extend incisions at the slit-lamp, it is my preference to use a small operating microscope and to perform the procedure within a dedicated treatment room. It has been my experience that this provides far better surgical control and patient comfort. In the case of residual astigmatism without prior incisional correction, one uses the same technique and nomogram as described previously.

In the case of an undercorrection following previous LRIs, one should inspect the length and positioning of the incisions. Placement of the incisions too far out into the true surgical limbus and beyond clear cornea often leads to undercorrection. If this is the case, new incisions may be placed inside of the original LRIs, but with a modest reduction in arc length from that which is dictated by the nomogram. If the incision placement seems to be appropriate then one can simply extend the original LRIs. When faced with an overcorrection, one should resist the temptation to place additional incisions in the opposite meridian. This can lead to an unstable cornea with unpredictable refractive results, or worse, induce irregular astigmatism. Rather, one should consider nonincisional modalities, such as photorefractive keratectomy or laser-assisted in situ keratomileusis.

To correct unusually high levels of astigmatism, LRIs may be used in conjunction with a toric IOL or excimer laser surgery (bioptics). In several rare cases I have combined all three modalities and safely corrected up to 9 D of pre-existing astigmatism.

Summary

Refinement of the refractive outcome may arguably be the single most pressing and important challenge faced by today's cataract surgeon. Along with spherical error, pre-existing astigmatism may now be safely and effectively reduced at the time of cataract surgery. Astigmatic relaxing incisions are the most common method used to accomplish this goal. By moving these incisions out to an intralimbal location, the complications and difficulties associated with astigmatic keratotomy have been greatly reduced. Toric IOLs represent another viable mode by which the surgeon may decrease or eliminate cylinder. Enhancement techniques are also important to help reduce residual astigmatism. LRIs may be used in a similar fashion, postoperatively, to accomplish this, or bioptics may be used with excimer laser technology. The future will undoubtedly yield further breakthroughs, such as wavefront-guided customized IOLs or perhaps laser-adjustable implants, all leading to better refractive outcomes and improved quality of vision for pseudophakic patients.

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