“Astigmatic keratotomy and limbal relaxing incisions: principles, indications, nomograms”
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In most surgical subspecialties, the patient views and evaluates two variables: the incision and the surgeon; however, in an ophthalmic case, we can include one additional and exceptionally formidable variable: the subjective result. Like it or not, most ophthalmic surgeries must now be viewed as having three primary end points that include safety, function, and now refractive outcomes. While safety, or the absence of operative complications is the outcome by which many of us have analyzed our results for decades, we have collectively advanced the field to a point where achieving an optimal refractive outcome holds an almost equivalent weight. As such, astigmatic keratotomies and limbal relaxing incisions alone or during cataract surgery provide the surgeon with a keystone procedure that improves patient quality of vision, quality of life, and satisfaction with the procedure. Limbal relaxing incisions and astigmatic keratotomies require careful management and execution.

Astigmatism results when the axes of the cornea are unequal and unevenly curved, and may result in glare, symptomatic blur, ghosting, and halos with as little as 0.50 diopters¹ [Figure 1]. Regular and irregular astigmatism can contribute to the meridional blur that leads to the decreased uncorrected visual acuity experienced by patients. In the astigmatic cornea, the incoming light rays pass through different meridians causing the light to focus at more than one location anterior, posterior, or directly on the retina.
Furthermore, regular corneal astigmatism can be subcategorized as with-the-rule (WTR), where the steep axis of the cylinder is within 15 degrees of the 90 degree vertical meridian, against-the-rule (ATR), where the steep axis of the cylinder is within 15 degrees of the horizontal meridian, or oblique, where the steep axis is not within 15 degrees of either the vertical or horizontal meridians [Figure 2]. While there are several different options for treating corneal astigmatism, such as toric intraocular lenses, excimer laser photoablation, femtosecond laser lenticule removal, conductive keratoplasty, limbal relaxing incisions (LRIs), and astigmatic keratotomies (AKs), not all of these options may be available to the cataract surgeon, or correct for the patient. At times the primary procedure may not correct astigmatism fully and a second procedure can be additive. Additional considerations in choosing the refractive procedure of choice include cost effectiveness, convenience, and safety.

LRIs are partial thickness corneal incisions placed adjacent to the limbus along the steep meridian. The incision for 3 diopters of astigmatism or less reduces the astigmatism by relaxing the steep axis of regular corneal astigmatism, while simultaneously steepening the flat axis in a one to one ratio, a phenomenon known as ‘coupling’ [Figure 3]. Arcuate AKs are a similar incisional procedure that is performed more centrally towards the visual axis. The advantages of LRIs include relative ease of performance, a reduced tendency to cause axis shift, less irregular astigmatism, less dependent on pachymetry, less likely to result in over correction, a smoother postoperative topography, and a quicker post-op stabilization of refraction. Advantages of AKs include a shorter
more powerful incision and a ‘multifocal’ effect.. Relative contraindications to AKs and LRIs include eyes that had previously undergone radial keratotomies (RKs), keratoconus, other topographic abnormalities including irregular astigmatism, or known peripheral corneal disease.\(^2\)

LRIs tend to work well for low to moderate amounts of astigmatism (<3D), and very well for 0.5D of cylinder up to 1.5D. When dealing with a patient who has >1.5D of astigmatism, one should always consider the increased risk for irregular astigmatism and dry eye disease. Additionally, combination of post-CEIOL excimer laser with an LRI is a reasonable strategy for “debulking” astigmatism.

Since the conception of the astigmatic incisions to efficiently minimize astigmatism during surgery, there has been concurrent research into the appropriate incision placement, length, and depth. Not surprisingly, several LRI and AK nomograms exist for correcting small amounts of cylinder, and many studies have been conducted in order to evaluate the efficacy, physics, and outcomes.\(^1,3-17\) One study by Bradley et. al. showed that LRIs produce a 60% average reduction in cylinder, with 79% of patients corrected to less than one diopter of cylinder, and 59% of patients corrected to less than one half diopter of cylinder.\(^18\) These results compare favorably with the results achieved using toric IOLs, which resulted in an average 58.4% mean reduction in cylinder.\(^19\)
Many AK and LRI nomograms are adjusted for age, gender, and cylinder axis, making them detailed and complex, and may give the impression that these procedures are extremely precise and unforgiving. However, in our opinion this simply isn’t the case, and astigmatic incision placement, especially manual ones, still remain as much of an art as a science. For the novice surgeon a simple nomogram may be favored (table 1), such as the Donnenfeld nomogram (DONO), which works extremely well for this purpose (available online at www.LRIcalculator.com) [Figure 4]. The online calculator employs vector analysis in order to calculate incision parameters based on preoperative patient keratometry, surgically induced astigmatism, and location of planned primary cataract incision. If the Donnenfeld or Nichamin nomogram is selected, a visual map of the axis and lengths of incisions will be provided, and a printout of the LRI calculator can be brought to the operating room and used as a guide when marking the cornea and performing LRI s. In general, it is best to practice the techniques of LRI s and develop your own nomogram to achieve consistent results.

The operating room is the best place to start performing astigmatic incisions, and can often be combined with routine cataract surgery. When performing cataract surgery it is important to account for astigmatism that may be preexisting or surgically induced. Residual astigmatism of 0.50 diopters (D) or even less may result in glare, symptomatic blur, ghosting, and halos. The reduced quality of vision associated with residual astigmatism following cataract surgery is magnified in patients with multifocal intraocular lenses. As a result, greater emphasis has been placed on treating corneal
astigmatism at the time of cataract surgery. In the beginning, peribulbar anesthesia and a conventional monofocal IOL may be preferred, as patients implanted with presbyopia-correcting IOLs are significantly more sensitive to even minor refractive errors. Astigmatic incisions should be performed at the start of the case while the eye is firm, and prior to any manipulation or dehydration of the cornea induced by instrumentation or operating microscope. The cornea may be marked, especially for larger cylindrical errors. For the incision, the episclera is grasped at the limbus with a 0.12 forceps approximately 180 degrees away from the intended incision site. While approaching perpendicular to the cornea, a pre-set diamond knife is advanced into the cornea 0.5mm central to the limbus, and centered on the axis as determined by vector analysis of residual cylinder. With multiple companies manufacturing various pre-set diamond knives, our preference is for the 0.6mm pre-set depth. After advancement, the knife is held into position for a full second to ensure the full depth of the blade is achieved (Figure 5). A shallow ineffective incision is one of the most common mistakes for a novice surgeon. The incision is then extended to its desired length. For control purposes, it is always preferable to cut towards oneself.

After the surgeon becomes more comfortable with the technique, astigmatic incisions may be employed on any patient undergoing cataract surgery, especially if they are likely to end up with half a diopter or more of residual cylinder. Alternatively, the experienced surgeon may elect to perform this as an in-office stand-alone procedure under the microscope or at the slit-lamp. Slit-lamp LRIs are a 30 second procedure, and typically
the patients are walking out of the room seeing better than they did entering. To perform this procedure, the phoropter is used to locate the incision axis and is placed adjacent to the patient’s eye with the cylinder stripe aligned on the steep axis of astigmatism. Lidocaine gel is administered into the operative eye, and the patient should be comfortable with their head placed forward against that slit-lamp’s headband. With an angled pre-set diamond knife and the surgeon coming from the side, the procedure is performed as previously described [Figure 6]. Following the procedure, we recommend topical antibiotics and anti-inflammatory drops four times daily for five days.

As with any surgical procedure, there are potential complications associated with astigmatic incisions, but most are either temporary or correctable. Possible complications include overcorrection, undercorrection, perforation of the cornea, infection, decreased corneal sensation, dry eye, irregular astigmatism, and discomfort. LRIs are generally not associated with glare or starbursts, but may be experienced by those undergoing AKs. For both under and overcorrection, we recommend waiting for the refraction to stabilize. A waiting period of 1-2 months is typically adequate, however this remains highly surgeon dependent. In patients with significant remaining astigmatism, it may be necessary to retreat by deepening or enlarging the original incision. For overcorrected patients, the original incision may be partially sutured closed with a 10-0 nylon or prolene after cleaning it with the assistance of a Sinskey hook. Placing additional LRIs perpendicular to the original incision for consecutive cylinder without suturing the original incision is
not recommended, as this may induce irregular astigmatism. In the event of a corneal perforation, only non-self sealing incisions may need a 10-0 nylon suture.

Not surprisingly, LRIs have been subject to the natural progression of any surgical procedure with the aim of reducing risk and improving outcomes. The treatment of astigmatism with femtosecond laser-assisted corneal incisions offers a greater degree of precision and accuracy than manual methods, and thus improves the risk profile for the possible complications mentioned previously. The recent developments in femtosecond laser technology have shifted the movement from manual LRI and astigmatic keratotomy procedures to femtosecond laser-guided procedures.

Femtosecond lasers are photodisruptive lasers, in contrast to photoablative and photocoagulative lasers, with extraordinarily short pulse duration of less than 800 femtoseconds (one femtosecond is $10^{-15}$ seconds). This extremely short pulse time allows the femtosecond laser to cut tissue with considerably less energy than traditional lasers. Per-pulse energies can be reduced approximately 1,000-fold, from around $1^{10}$ millijoules for nanosecond lasers (neodymium-yttrium aluminum garnet [Nd:YAG]) to $1^{10}$ microjoules for femtosecond lasers. Both the short 1053nm wavelength, which is not absorbed by optically clear tissues at low power densities, and the reductions in per-pulse energy, result in substantially reduced collateral tissue damage, shifting concomitant damage from a few spherical millimeters with the nanosecond lasers to a few microns with the femtosecond lasers.
The precision and extremely limited collateral effects of femtosecond pulses on the cornea have been established in millions of procedures performed using femtosecond lasers for the creation of LASIK flaps and lamellar and penetrating keratoplasties.\textsuperscript{23-27} Additionally, the corneal tissue does not absorb the laser wavelength, allowing for a higher margin of safety. Because a pre-programmed depth is applied to all incisions, a sizeable distance is kept from Descemet’s membrane, preventing corneal perforation during femtosecond-guided treatments.

Femtosecond laser-assisted cataract surgery is currently approved by the US Food and Drug Administration for four clinical indications: primary incisions, arcuate incisions, lens fragmentation and capsulotomy creation. The use of the femtosecond laser to create arcuate incisions is a major clinical improvement in that it allows greater precision due to more accurate arc length, depth, angular position, and optical zone. The femtosecond laser allows for exact and repeatable incisions, which are necessary for consistent results not ordinarily achieved through manual methods.\textsuperscript{20,29}

In an early study, using 8-mm arcuate incisions and a 33\% reduction of the Donnenfeld nomogram a 70\% reduction in astigmatism was achieved.\textsuperscript{28} An additional advantage of the femtosecond laser is that the corneal incisions may be placed intrastromally (sub-Bowman’s layer), which improves healing by sparing epithelial damage. This is a major area of interest and nomogram development is currently
Performing femtosecond laser arcuate incisions requires the parameters of length, position, depth, and distance from the visual axis where the incisions will be created. For our practice, we use a 33% reduction of the Donnenfeld nomogram to determine the length and axis at which the incision should be placed. The depth of our incisions is 85% of the corneal pachymetry in the area of the incision. We have set our distance from the visual axis at 9 mm. This programming information is downloaded onto the femtosecond laser. We then begin the surgical procedure by docking the laser onto the cornea. An overlay of the incisions is then visible on the surgical screen (Figure 7). Optical coherence tomography (OCT) imaging of the cornea in the area of the arcuate incision is then visualized, and the depth is confirmed (Figure 8). The femtosecond astigmatic incision is then performed (Figure 9). We first perform the capsulotomy, followed by the lens fragmentation, and then create our corneal incisions. Following the conclusion of the femtosecond laser treatment, the patient is brought to the operating microscope and the incisions are opened with a Sinskey hook (Figure 10). OCT confirms the postoperative depth of the incisions. Some surgeons prefer to open one or both of the incisions postoperatively under the guidance of the post-surgical refraction. By utilizing the low energy of the femtosecond laser, the incisions do not have significant effect until they are opened.
Femtosecond laser-assisted arcuate incisions have brought computerized accuracy and precision to astigmatism management and cataract surgery. Refractive incisions are now digitally assisted and do not solely rely on surgeon skill or experience. The use of a femtosecond laser system will provide faster, safer, easier, customizable, adjustable, and fully repeatable astigmatic incisions. The ability to perform intrastromal ablations cannot be achieved with manual incisions and offer major advantages in terms of patient comfort and safety. Femtosecond laser arcuate astigmatic incisions should enable the majority of ophthalmologists to enter the field of refractive cataract surgery with confidence.

In conclusion, astigmatic corneal surgery with a diamond knife or a femtosecond laser dramatically improves cataract surgery refractive results. Astigmatic corneal surgery can be performed intraoperatively or postoperatively in order to titrate residual corneal cylinder. The most common rate-limiting factor for refractive results following cataract surgery is residual astigmatism, and astigmatic incisional corneal surgery is often the solution to improve patient refractive results and overall satisfaction.
Figure 1: Figure demonstrates normal cornea (left) shaped like a basketball in which both axes are equal and astigmatic cornea (right) shaped like a football in which one axis is steeper than the other.

Figure 2: Figure demonstrates WTR (left), ATR (center), and oblique (right) astigmatism.

Figure 3: Diagram demonstrating the coupling effect of an LRI, before (left) and after (right).
Figure 4: The Donnenfeld Nomogram found at LRIcalculator.com

Figure 5: LRI performed at the microscope
Figure 6: LRI performed at the slit lamp
Figure 7: Overlay of the planned incision visible on the surgical screen

Figure 8: OCT of cornea with the femtosecond laser planned LRIs visible
Figure 9: The femtosecond astigmatic incision performed

Figure 10: Intraoperative picture showing the opening of an LRI with a Sinskey hook
Table 1: Nomogram table

<table>
<thead>
<tr>
<th>ASTIGMATISM (IN DIOPTERS)</th>
<th>INCISION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50 D</td>
<td>1 incision, 1 ½ clock hours (45 deg each)</td>
</tr>
<tr>
<td>0.75 D</td>
<td>2 incisions, 1 clock hour (30 deg each)</td>
</tr>
<tr>
<td>1.50 D</td>
<td>2 incisions, 2 clock hours (60 deg each)</td>
</tr>
<tr>
<td>3.00 D</td>
<td>2 incisions, 3 clock hours (90 deg each)</td>
</tr>
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- Use 5 degrees more for against-the-rule astigmatism
- Use 5 degrees more for younger patients
- Use 5 degrees less for older patients
REFERENCES


