REVIEW/UPDATE

Prevention and management of refractive prediction errors following cataract surgery

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Patient satisfaction after modern day cataract surgery requires excellent surgical technique but increasingly demands superior refractive outcomes as well. In many cases, there exists an expectation from patients, as well as surgeons, to achieve emmetropia after cataract surgery. This is particularly true in patients electing premium intraocular lens technology to correct astigmatism and presbyopia to minimize spectacle dependence. Despite continued advances in preoperative and intraoperative diagnostics, refractive planning, and surgical technology, residual refractive error remains a primary source of dissatisfaction after cataract surgery. The need to enhance refractive outcomes and treat residual astigmatic or spherical refractive errors postoperatively becomes paramount to meeting the expectations of patients in their surgical outcome. This article reviews the potential preoperative and intraoperative pitfalls that can be the source of refractive error, the various options to enhance refractive outcomes, and potential future technologies to limit residual refractive error after cataract surgery.

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In the current era of modern cataract surgery, surgeons have the enhanced ability to more accurately correct for refractive errors such as myopia, hyperopia, and astigmatism.[1] In addition to the surgical advances that have made cataract surgery extremely precise and efficient, the advent of technology to combine correction of both refractive errors and presbyopia has increased the expectations of patients. Patients who have undergone cataract surgery with implantation of presbyopia-correcting IOLs and/or toric intraocular lenses (IOL) are the most likely to desire an enhancement if emmetropia is not achieved, as residual refractive error remains one of the primary reasons for dissatisfaction after premium lens surgery.[2,3]

When a patient presents with residual refractive error following cataract surgery, several considerations should be made prior to performing any refractive enhancement. Was the patient undercorrected or overcorrected? What was their preoperative refractive error and biometric data? In addition, it is always important to take into consideration the age of the patient and their visual demands. Does the patient spend most of their day working on a computer or do they drive for a living? What are their hobbies? What is their tolerance to spectacle wear? All of these things are important in determining what the next steps should be for the patient. Finally, the risk tolerance for patient and surgeon needs to be considered. What is the general health of the patient? Does the patient have conditions that may risk zonular compromise? Are there risk factors for inducing ocular surface disease or irregular astigmatism with additional surgical procedures?

First and foremost is making every effort to achieve the intended refractive target in every patient undergoing cataract surgery. Inherent in this goal is identifying appropriate candidates for specific premium lens technology. Those with ocular conditions such as irregular astigmatism, zonular weakness, or macular pathology increase the likelihood of a refractive error after cataract surgery.[4] Nevertheless, even in the ideal candidate, setting expectations for potential ametropia is necessary for all patients given the current rates of refractive prediction errors due to the current limitations in biometric data and the prediction of effective lens position (ELP). These limitations require successful preoperative management of ocular surface disease such as keratoconjunctivitis sicca, anterior basement membrane disease (ABMD), pterygia, or Salzmann nodules to optimize keratometric measurements. Likewise, the use of optical biometry to more accurately measure the variables that can be used in more advanced IOL formulas

has been well documented to minimize refractive prediction errors.[5–8] When biometric data are unreliable across various measures or significant differences exist between the 2 eyes, it is essential to repeat biometry to minimize the potential for erroneous data and unpredictable outcomes.

When ametropic outcomes occur, it is imperative to determine identifiable causes for any residual refractive error. Cases involving larger degrees of refractive prediction error need further meticulous investigation as preoperative and intraoperative errors in biometry, planning, or iatrogenic causes for errors in refractive targeting are unfortunately present in cataract surgery.[9] If the reason for the residual refractive error in a post–cataract surgery patient is unclear, repeating biometry can help determine whether the correct power IOL was used.[10] Determining the underlying cause of the refractive prediction error will not only help determine treatment but also help avoid reproducing the same problem in the fellow eye or future cases.[11,12]

REASONS FOR RESIDUAL REFRACTIVE ERROR

A number of factors can influence the final refractive outcome and inaccuracies in achieving emmetropia. These can be divided into preoperative, intraoperative, and postoperative causes. Risk factors for residual refractive error include poor preoperative best-corrected visual acuity, ocular comorbidities, and previous eye surgery.[4] Iatrogenic errors such as incorrect IOL selection, incorrect patient identification, and mislabeling of an IOL by the manufacturer, although rare, have also been reported as causes for refractive errors after cataract surgery.[13]

Preoperatively, large sources of error in the predictability of IOL power calculations are found in the estimation of the ELP, as well as biometric measurements of corneal power and axial length.[9] For this reason, all preoperative topography and tomography should be performed before placement of ophthalmic drops. In addition, these measurements should be performed by a select group of skilled technicians. In unusual eyes, such as those at the extremes of axial length or eyes with higher levels of astigmatism, measurements should be repeated for reproducibility, compared across various platforms, and verified for binocular consistency before being used for final IOL determinations.

The limitation in achieving precise measurements of cornea curvature, axial length, and anterior chamber depth continues to hinder the accuracy of refractive outcomes in cataract surgery. Nevertheless, improved attention to detail has been outlined by several notable authors in a 3-part series on pursuing perfection in IOL calculations.[6–8] Since their inception in the 1950s, formulas for IOL calculations (Table 1) have continued to evolve and improve with each successive generation. Although controversy exists as to which formula is universally superior, the latest-generation formulas such as the Holladay 2, Barrett Universal II, Olsen, Kane, and Hill-RBF calculator have reported postoperative refractions within a half diopter in more than 70% of eyes.[1,5,14–20] A recent study by Melles et al. showed excellent refractive

Table 1. Advanced IOL formulas for calculating refractive predictions.
Vergence based (in order of increasing variables)
Holladay 1
SRK/T
Hoffer Q
Haigis
Ladas Super Formula
Barrett Universal II
Holladay 2
Artificial intelligence based
Hill-RBF
Kane
Ray-tracing based
Olsen

accuracy using the Barrett Universal II formula for the SN60WF IOL (Alcon Laboratories, Inc) with a mean absolute error of 0.31 diopter (D), a median absolute error of 0.25 D, and 80.8% of eyes within ±0.5 D or the intended correction.[14] Accuracy for all formulas is known to be less for short eyes and patients with a history of keratorefractive surgery.[21,22] Nevertheless, these formulas remain dependent on accurate biometry, which, as mentioned earlier, has its own limitations and degrees of error. Finally, optical ultrasound for axial length measurements remains the gold standard, yet in 8% to 17% of eyes, optical methods cannot be used.[23] Although recent advances in optical biometry using swept-source optical coherence tomography have been shown to reduce the percentage of examination failures, ultrasonography (contact or immersion) continues to play a role and might act as an additional source of error.[24]

Another common reason for inaccuracies in our preoperative measurements is ocular surface disease.[25–27] Conditions such as keratoconjunctivitis sicca, keratitis, ABMD, and Salzmann nodular degeneration can all influence the accuracy of measurements of the corneal power by contributing to an irregular ocular surface.[28] Similarly, other causes of irregular astigmatism such as corneal scars or ectasia can influence unanticipated postoperative refractive errors. It is essential that these findings be identified and addressed preoperatively to avoid residual refractive errors and patient dissatisfaction after surgery. It is also important to screen for a history of prior keratorefractive surgery, as keratometry values will have been affected by the alteration in anterior corneal curvature, thus altering the prediction of ELP from traditional formulas. As some patients may unintentionally omit having had a history of prior keratorefractive surgery, Scheimpflug imaging can aid in identifying higher-order aberrations or ratios of the back-to-front corneal radii that are outside of normal ranges and might be consistent with a prior history of laser in situ keratomileusis (LASIK) or photorefractive keratectomy (PRK) procedures.[29] Patients who have undergone keratorefractive surgery require additional considerations and separate IOL formula calculations in this setting.[30]

Intraoperatively, uneventful cataract surgery is integral to maintain the likely predicted ELP and to achieve the desired target refraction. Although a relatively good outcome can still be achieved in the event of capsular compromise or vitreous loss, a shift toward myopia in postoperative refractive error is found when vitrectomy is performed at the time of IOL implantation.[31] Decentration of the capsulorhexis by more than 0.4 mm is associated with a 0.25 D change in spherical equivalence (SE), and incomplete optic overlap is associated with a 0.5 D change in spectacle cylinder.[32] An IOL well centered over the visual axis has been found to be critical when placing multifocal IOLs; however, it is also optimal in monofocal aspheric IOLs in which decentration of the IOL has been shown to increase residual higher-order aberrations.[33] The amount of surgically induced astigmatism can vary significantly from one patient to the next and may also contribute to residual refractive error after cataract surgery.[34] Surgeons should measure their surgically induced astigmatism and calculate personal A-constants to optimize their refractive outcomes and be able to reduce prediction errors.

Postoperatively, sources of refractive error may result from an inaccurate refraction or shift in IOL position. Although unlikely in the early postoperative period, late capsular block syndrome results when retained ophthalmic viscosurgical device or the accumulation of fluid within the capsular bag behind the IOL results in a forward shift of the IOL. This can lead to an unexpected myopic shift and can be treated successfully with an Nd:YAG capsulotomy.[35] Anterior capsular contraction syndrome has been associated with significant lens tilt and even late dislocation in extreme cases. Lens tilt can also be a source of induced astigmatism, and capsular contraction can cause the haptics to bend forward or backward leading to late refractive errors not typically seen in the immediate postoperative period.[36,37]

MANAGEMENT CONSIDERATIONS FOR RESIDUAL REFRACTIVE ERROR
Treatment Modalities

Although there are several options available to correct refractive prediction errors, laser vision correction (LVC) procedures such as LASIK and PRK are the most commonly used options for treatment. Surgeons who perform refractive cataract surgery with premium IOLs should be capable of offering refractive corneal enhancements, whether they perform the procedure themselves or they refer to a colleague to complete the final treatment for the patient. LVC may also be the best option for a patient who is hesitant to return to the operating room for a second procedure. The primary advantage of these procedures compared with more invasive intraocular modalities of refractive enhancements such as IOL exchange or piggyback IOL is the avoidance of entering the eye and the potential for introducing the risk for endophthalmitis, macular edema, or capsular complications. Patients with pseudophakia undergoing LVC are likely to be older than patients undergoing LASIK as a primary procedure; thus,

excimer laser treatments may be less predictable and may exacerbate ocular surface disease in this vulnerable population.[38–40] In addition, some patients may not have been appropriately screened for LVC due to keratometry, pachymetry, irregular astigmatism, or underlying corneal diseases, which could potentially preclude these procedures. Finally, diffractive multifocal IOLs have been shown to reduce contrast sensitivity.[41] Similarly, LVC procedures have also been shown to cause a loss in contrast sensitivity.[42–44] The combination of a diffractive multifocal IOL and LVC may potentiate the loss in contrast sensitivity to a level of visual compromise for patients beyond residual refractive error. Despite this concern, 2 studies have looked at outcomes of LVC after multifocal IOL implantation and have not demonstrated any patients losing more than 1 line of corrected distance vision.[45,46]

Choosing between the various methods of LVC is surgeon dependent but is often determined by a thorough discussion of differences in risk and postoperative recovery for LASIK vs PRK in a patient who has recently undergone cataract surgery. Both LASIK and PRK have the potential for under- or over-corrections of the refractive error. Likewise, the use of LVC in any method can increase the risk for dry eye disease, neurotrophic keratitis, corneal ectasia, and viral or bacterial keratitis. The presence of clear corneal incisions or manual and femtosecond laser astigmatic keratotomies performed at the time of cataract surgery may represent a potential risk for wound gape with the use of an applanation suction device to create a LASIK flap. In cases in which a residual refractive error will be anticipated postoperatively, such as extremes of axial length or high astigmatic errors, the use of bioptics can be approached with the creation of a LASIK flap prior to cataract surgery.

IOL exchange and piggyback IOLs can also be considered as alternatives to LVC. Many ophthalmologists may have rarely performed a lens exchange or piggyback IOL, and as discussed with LVC, surgeons who perform refractive cataract surgery with premium IOLs should be capable of performing this procedure themselves or have a colleague to whom the patient can be referred. Intraocular procedures can be best considered in cases of larger refractive errors or especially in hyperopic prediction errors. Piggyback IOLs have been used in cases of extreme axial length where a single IOL power is unavailable to achieve emmetropia, and have been used to enhance residual refractive errors with the placement of a low-powered, 3-piece IOL in the sulcus.[47,48] IOL exchange is technically more challenging than piggyback IOL implantation, requiring more intraocular manipulation that may risk capsular complications and vitreous loss. Some consider the use of a piggyback IOL to be more accurate than an IOL exchange because the residual refractive error, IOL power, and the position of the primary IOL are already known and remain unaltered during implantation of the secondary IOL.[48] In an IOL exchange, the refractive calculations are predicated on knowing the exact IOL power of the existing lens and the assumption that the new IOL will occupy the same ELP as

the primary IOL being explanted.[3] These variables can be unknown or unpredictable. The risks of IOL exchange include vitreous loss, potential zonular loss or weakness, and the possible need to place the lens in an alternative position such as the sulcus, anterior chamber, or through a scleral fixation technique if capsular support becomes inadequate. This may further complicate the ability to align a toric IOL or center a diffractive IOL. There is also an increased risk for endothelial cell loss resulting in corneal edema and/or cystoid macular edema, particularly in cases that require significant manipulation and trauma during the IOL removal process.[49] Although an IOL exchange is more easily performed within the first several months after surgery, most 1-piece lenses in an intact capsular bag can be safely removed up to a year or more after surgery with careful viscodissection.

Formulas are available for determining the IOL power for the secondary implant. Gayton et al. study calculated piggyback IOL power using a minus IOL equal to the SE for myopes and a plus IOL 1.5 times the spherical equivalent for hyperopes.[48] More sophisticated formulas are available such as the Hill Refractive Vergence Formula, Holladay R Formula, or the Barrett Rx Formula.[2,3,9] Although complications are rare, secondary IOLs in the sulcus do pose a risk for iris chafing, uveitis, and elevated intraocular pressure.[50] There is also a risk for interlenticular opacification when an acrylic IOL is placed over another acrylic IOL.[51] A prospective case series comparing piggyback IOL with IOL exchange showed equivalent uncorrected visual acuities between the 2 groups. There was a higher percentage of patients in the piggyback IOL group achieving a refractive error within 0.5 D of the intended target (92% vs 82%; P value not published).[52]

There is little research to determine which procedure would be best for enhancing residual refractive error after cataract surgery. Jin et al. published a retrospective case series comparing LASIK with lens-based surgeries of IOL exchange and piggyback IOLs.[53] They found no statistically significant difference between the 2 groups in uncorrected visual acuity (UCVA), corrected distance visual acuity (CDVA), or SE. However, in subgroup analyses, the percentage of eyes having a UCVA of 20/20 was 38% in the LASIK group compared with 11% in the IOL group. When managing myopic treatments, there was a statistically significant difference in postoperative UCVA in the LASIK group compared with the IOL group (P = .004). No difference, however, was observed between the groups in hyperopic eyes (P = .521). Fernández-Buenaga et al. also performed a retrospective study comparing all 3 groups of LASIK, IOL exchange, and piggyback IOLs.[54] In evaluating the predictability, the percentage of achieving an SE within 0.5 D of the intended target was 93% in the LASIK group, 65% in the piggyback group, and 31% in the IOL exchange group (P = .000) Similarly, the efficacy measure, defined as the postoperative uncorrected distance visual acuity/ preoperative corrected distance visual acuity, was statistically significantly higher for LASIK at 0.91 compared

with the IOL exchange group at 0.58 (P = .003) as well as the piggyback IOL group at 0.75 (P = .004).

Myopic or Hyperopic Refractive Error

The magnitude of the residual refractive prediction may often determine the treatment modality best capable of achieving emmetropia. In general, patients may tolerate small amounts of residual refractive error after cataract surgery, typically within 0.5 D of emmetropia. In some cases, particularly with monofocal and extended depth-of-focus (EDOF) IOLs, refractive enhancements may not be necessary if patients are tolerant to these small refractive errors. Multifocal IOLs, however, tend to be less tolerant of residual refractive error in comparison to standard monofocal IOLs.[55] In recent surveys from the American Society of Cataract and Refractive Surgery, it was widely believed that multifocal IOLs will only tolerate up to about a half diopter of residual sphere or cylinder.[A] This also appears to differ from EDOF IOLs in which studies have shown that patients may be more likely to tolerate small amounts of myopia or astigmatism.[55–58] In 1 study, Son et al. shown that residual refractive error was more tolerated in patients who had an EDOF IOL compared with a monofocal IOL of the same design.[59] It is possible this may be due to the diffractive optical design maintaining higher levels of visual acuities at a wider dioptric range of defocus.

Myopic refractive errors after cataract surgery can be more easily managed than hyperopic surprises because patients may be more tolerant of residual myopia, and these errors are more amenable to LVC as an enhancement tool. Small amounts of myopia may result in an unexpected expanded range of vision that patients may tolerate with improved near visual acuity relative to a bilateral emmetropic outcome. Residual hyperopic errors are less easily treatable with LVC and may lead to higher degrees of wavefront aberrations.[60,61] Treatment of residual hyperopia involves a larger treatment zone making predictability less accurate.[62,63] Furthermore, hyperopic corneal treatments are more likely to regress variably over time.[64,65] Although there are no universally agreed-upon limits, laser corneal ablations work best with lower degrees of hyperopia under 1 D.

With cases involving more than 1 D of SE error, an IOL exchange or piggyback IOL procedure may be considered over LVC, particularly in cases with residual hyperopic error or when large refractive errors are identified soon after cataract surgery. If the cause and remedy are clear, and the patient accepts a return to the operating room, this may be the most effective solution for larger refractive prediction error. In the 2 studies discussed earlier evaluating treatment options for managing residual refractive error, IOL-based surgery showed the least accurate results; however, in both studies, IOL-based procedures were used in eyes with the largest preoperative refractive errors.[53,54] Fernández-Buenaga et al. showed that for myopic prediction errors, the SE reduction in the IOL exchange group was 6.12 D compared with 1.50 and 1.00 D in the piggyback lens and LASIK groups, respectively.[54] In hyperopic prediction

errors, IOL exchange reduced the SE by 3.80 D, whereas in the piggyback lens and LASIK groups, the reduction was 1.88 and 1.50 D, respectively.

Cylindrical Refractive Errors

In cases with residual astigmatism after IOL implantation, patient dissatisfaction may be minimal related to the tolerance of smaller amounts of residual with-the-rule astigmatism. This may also provide long-term success maintaining minimal astigmatism as an against-the-rule drift occurs with age.[66] Residual astigmatism has also been shown to enhance depth of focus, and patients may report improved uncorrected near visual acuity. In cases of more significant error, careful evaluation of the preoperative and postoperative keratometry is helpful to identify causes related to surgically induced astigmatism or IOL tilt. In cases in which a limbal relaxing incision (LRI) was performed, examining preoperative and postoperative keratometry can also help to determine whether an under- or over-correction of the preoperative astigmatism took place. There are several sources of toric IOL alignment error at the time of cataract surgery, including errors in biometry, preoperative planning, marking of the intended axis, and rotational errors. Identifying the current orientation of the IOL and determining whether there was an early rotation or malposition from the intended axis of alignment can often reveal a potential source of residual astigmatism. Nevertheless, surgically induced astigmatism may also contribute to residual cylinder and should be evaluated for even in the presence of misalignment. Using the patient's manifest refraction, the current toric IOL power, and the current axis of orientation of the toric IOL, one can determine whether there is a more ideal axis to rotate the IOL and reduce the residual astigmatic error. There are several online tools to assist with the assessment and plan of repositioning, the most common being astigmatismfix.com by John Berdahl, MD, and David Hardten, MD, available on the ASCRS website (ASCRS.org).[B] In addition, the Barrett Rx formula can be used to determine the ideal axis of alignment to which repositioning of the IOL will reduce the residual astigmatism.[9]

Table 2 details the online calculators and web-based applications available to assist surgeons in the treatment of astigmatism using toric IOLs, as well as those available to assist in repositioning toric IOLs due to rotation or alignment errors. With or without associated myopia or hyperopia, residual astigmatic error can complicate postoperative patient satisfaction. If the patient's refraction is purely mixed astigmatism or the residual SE is less than ±0.5 D, an IOL rotation to the ideal axis of astigmatism can be performed to reduce or eliminate the residual cylinder. In addition, LRIs can be used to correct smaller degrees of astigmatism. This can be performed as a manual approach with a diamond blade, or they can be performed with a femtosecond laser. Table 3 describes a standard technique for performing manual and femtosecond laser–assisted corneal relaxing incisions along with 2 accepted nomograms (however, personalization of surgeon nomograms is

Table 2. Online calculators and web-based applications available in the treatment of astigmatism with LRIs and toric IOLs, as well as those available to assist in repositioning toric IOLs due to rotation or alignment errors.

Johnson & Johnson LRI Calculator
  WWW.LRICALCULATOR.COM
Alcon Toric IOL Calculator
  WWW.MYALCON-TORICCALC.COM
Johnson & Johnson TECNIS Toric IOL Calculator
  WWW.AMOEASY.COM/CALC
Barrett Toric Rx
  CALC.APACRS.ORG/TORIC_CALCULATOR20/TORIC%
    20CALCULATOR.ASPX
Berdahl and Hardten Astigmatism Fix Calculator
  WWW.ASTIGMATISMFIX.COM
Barrett Rx
  CALC.APACRS.ORG/BARRETT_RX105/

IOL = intraocular lens; LRI = limbal relaxing incision

recommended as one gains more experience). If the predicted residual SE is greater than ±0.5 D, an IOL exchange and/or rotation of the secondary IOL to the ideal meridian may be warranted to refine the refractive target. Astigmatism in the setting of a larger myopic or hyperopic refractive error may also be treated with LASIK or PRK, keeping in mind the earlier discussion regarding the limitations of hyperopic excimer ablations.

WHO IS THE PATIENT?

A final question remains in the decision process as to "who is the patient" when approaching the management of enhancements following refractive cataract surgery. The use of questionnaires, such as the well-known Dell questionnaire, provides an efficient inventory of the patient's visual needs during their everyday living and even asks patients to self-assess their own personality level. Preoperative assessments of personality types and patients' goals for vision postoperatively not only will help determine the best procedure for the patient but also determine what might be the best decision for how to enhance a postoperative refractive error should it occur. As such, it might be prudent not to offer a refractive procedure to patients who claim that they are perfectionists based on questionnaire assessments or to those whose expectations exceed reality. Accurately identifying preexisting ocular pathology such as epiretinal membrane and/or ocular surface disease that can influence the outcome of a refractive cataract procedure can improve patient satisfaction by helping select the most appropriate IOL for a patient's specific situation. Patient expectations can be difficult to quantify, but setting appropriate expectations is critical to a successful outcome, especially when the potential for a refractive enhancement procedure remains a possibility after cataract surgery.

Many tools are available to help guide us in the assessment of the underlying source of dissatisfaction including corneal topography, optical coherence tomography of the macula, a thorough slitlamp examination, and a reliable, careful refraction. There are a variety of new

Table 3. The Authors' Guidelines for Performing Manual and Femtosecond Laser LRIs.

Manual and femtosecond LRI protocol
1. Mark reference marks on the patient eye while seated in an upright position to avoid misalignment related to cyclotorsion.
2. Incision depth should be calculated to 90% of the pachymetric depth when performing a manual LRI with an adjustable diamond blade or with pachymetry thick enough to support a preset blade of 550 or 600 μm.
3. When using a femtosecond laser, in general, 80% corneal depth of the optical coherence tomography image is preferred.
4. Create an incision perpendicular to the corneal plane, following the arcuate curvature of the limbus.
5. Incisions should be made at the 9 mm optical zone or larger, keeping in mind that the smaller the optical zone, the greater the effect of the incisions on astigmatic correction, and the greater the potential of creating a myopic shift or irregular astigmatism.
6. The most commonly used nomograms to create limbal relaxing incisions are the NAPA nomogram and the Donnenfeld nomogram.
7. When using these nomograms with femtosecond laser incisions, the arc length may be reduced by 20%, especially in cases of with-the-rule astigmatism.
8. It is important to become familiar with your preferred nomogram and analyze astigmatic outcomes to determine appropriate adjustments based on the magnitude of correction in your hands.

LRI = limbal relaxing incision; NAPA = Nichamin Age and Pachymetry-Adjusted

devices to help assess the dissatisfied postsurgical patient. Devices such as the HD Analyzer (Keeler/Visiometrics) analyze ocular scatter as light travels from the front of the eye toward the retina, identifying potential causes of reduced retinal contrast. A specific measure known as objective scatter index (OSI) is a quantitative way to measure the visual quality of patients' complaints postoperatively. OSI scores also correlate with LOCS III lens changes to determine whether a patient is a candidate for a corneal vs lenticular procedure preoperatively. Postoperatively, devices such as the HD Analyzer can help delineate whether a patient needs a YAG capsulotomy based on posterior capsular opacity severity or whether microstriae in a flap post-LASIK need to be surgically addressed to improve visual outcomes. OSI is a new and effective way to quantify the quality of vision both preoperatively and postoperatively and helps to determine the specific source of visual compromise differentiating the various components of the optical system.

TIMING TO PERFORM REFRACTIVE ENHANCEMENT

Setting appropriate expectations is of paramount importance to increase patient satisfaction following refractive cataract surgery. It is very important, particularly when multifocal or extended depth-of-focus IOLs are being used, that the patient understands that the process requires both eyes be operated on within a relatively short period. Two weeks between eyes is a common schedule and allows for assessment of the first eye outcome at 1 week. The patient should understand prior to surgery that it will take some time for the brain to adjust to the new optics, and, because the brain uses input from the 2 eyes together, this process is facilitated by performing both surgeries within a short period. Thus, even if a residual refractive error is detected at postoperative week 1 after first eye surgery, the patient can be reassured that as the brain learns to use the 2 eyes together, they may benefit from the residual refractive error as it may extend the range of vision the patient will achieve without spectacles. This has been seen in several studies whereby bilateral cataract surgery was performed implanting a multifocal IOL with various add powers in each

eye, as well as in studies demonstrating enhanced depth of focus with mini-monovision in 1 eye with EDOF IOLs.[56,67] Sufficient time should be given prior to any refractive enhancement to allow for resolution of corneal edema, refractive effects of LRIs, contraction of the capsule and final determination of ELP, and any resolution of keratitis or other forms of ocular surface disease that may confound the magnitude of the refractive error. In general, waiting 6 weeks or more is recommended unless there is a case of obvious wrong IOL power or type. In cases of toric IOL rotation, which typically occurs early in the postoperative course, a study by Oshika et al. showed that repositioning a toric IOL prior to 7 days postoperatively significantly reduced the residual misalignment compared with eyes in which the IOL was repositioned 7 days or later ($P < .001$).[68]

Figure 1 (see Supplemental Digital Content 1, http://links.lww.com/JRS/A121) provides general recommendations for the management of refractive prediction errors and an approach for the management based on the premium IOL type. Figure 1 provides a framework for the various modalities of correcting residual refractive error after cataract surgery based on the type and magnitude of the refractive error in light of the current trends within ophthalmology and the evidence-based studies that have been discussed. Such a framework is helpful for guiding surgeons in the management of refractive prediction errors; however, surgeon experience and comfort, as well as patient acceptance and personality, will continue to play a significant role in the variability of the different approaches and the decisions that will be made in each particular case.

FUTURE DIRECTIONS

Both patients and surgeons are benefitting from the continued improvements in technology and the rapid evolution of IOLs, measuring devices, and surgical instrumentation that allow us to provide better surgical outcomes with each passing day. However, the continuous advance of technology has also raised the bar for patient expectations for their cataract surgery. Current rates of refractive error predictability within 0.5 D of the intended target value are only between 62% and 81% of eyes.[14,69] Furthermore, patients desire more than increased clarity, striving instead
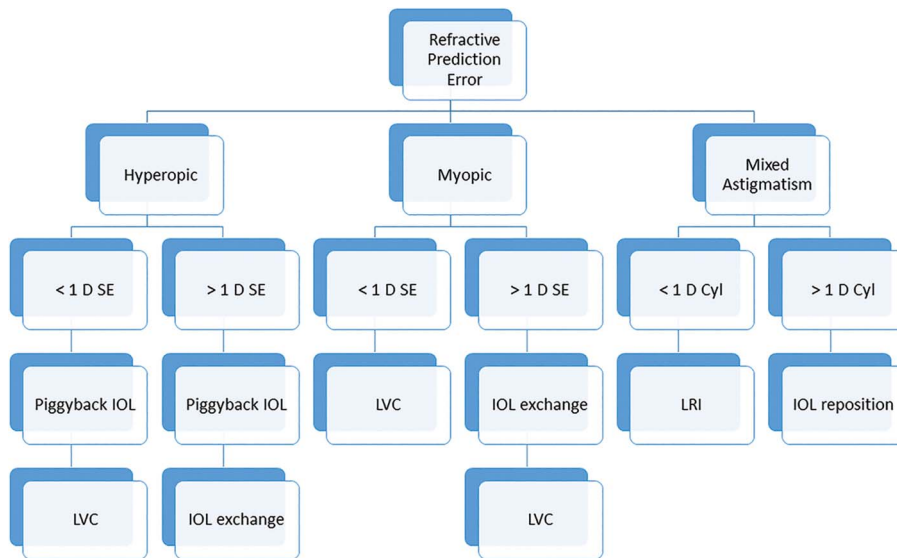
Figure 1. The flow diagram provides a framework for the various modalities of correcting residual refractive error after cataract surgery based on the type and magnitude of the refractive error.

for range of vision without dependence on spectacles. Fortunately, there is technology in the pipeline worthy of consideration, with several countries enjoying the ability to offer their patients a variety of accommodating, adjustable, bifocal, trifocal, and EDOF technologies. These future innovations strive to build on current lens technology, enabling modification of existing implants or implantation of a lens with a new design or the ability to be altered in the future.

Rather than building on an existing platform, the light adjustable lens (RxLAL, RxSight) integrates new technology. In 2017 the U.S. Food and Drug Administration approved the RxLAL, which has the ability to adjust the refractive power of the IOL for both residual spherical and cylindrical corrections. Typically, once the refraction is stable, ultraviolet light is used to correct up to 2 D of sphere or astigmatism.[70] Multiple treatments may be performed, and once the patient and doctor are satisfied, the entire IOL is treated with ultraviolet light to lock in the power. A patient is then required to wear spectacles with ultraviolet protection to avoid all ultraviolet light until the enhancement and lock-in step and must present a pupil that dilates beyond 6 mm.

Alternatively, the Perfect Lens (Perfect Lens, LLC) modifies previously implanted IOLs with a femtosecond laser to adjust the hydrophilicity, which will impact the refractive error of the lens.[71] This treatment takes seconds and can adjust up to 10 D all within 0.1 D. This technology has the ability to be repeated several times if necessary. With this technology, a surgeon may consider placement of a 20 D IOL in most patients, knowing that they will use the laser for adjustments of sphere and astigmatism in the future.

CONCLUSIONS

Patient expectations after cataract surgery have placed an increasing burden on surgeons to deliver superior refractive outcomes. Improvements in biometric technology, advances in IOL calculation formulas, surgical technique, and intraoperative technology have considerably improved refractive outcomes in cataract surgery. Yet despite our best efforts, we are often challenged with how to deal with residual refractive error in the postoperative patient. Residual refractive error plays a significant role in patient acceptance of the success in cataract surgery, and ametropia can be a cause of psychological stress for patients or even medicolegal concerns. As such, the need to manage these residual refractive errors becomes paramount to delivering patient satisfaction in their surgical outcome.

Preventing refractive errors after cataract surgery is critical to avoid the need for additional procedures to enhance patient refractive outcomes. Data show that optimizing the ocular surface, using the latest-generation IOL formulas, and optical biometry can all aid in minimizing refractive errors after cataract surgery.[2,25,26] As such, residual refractive errors after cataract surgery should first be evaluated for surgeon errors in IOL calculations or power selection. Patients should also be reexamined for evidence of dry eye disease, keratitis, or subtle ABMD. Topography and macular optical coherence tomography should also be reevaluated to rule out irregular astigmatism or macular edema as potential masqueraders of the residual refractive error.

There is a paucity of literature comparing treatment outcomes between the various keratorefractive procedures such as LRIs, LASIK, and PRK and those involving intraocular enhancements such as piggyback IOLs, toric IOL rotation, and IOL exchange. In cases involving purely residual astigmatic refractive error after a monofocal or multifocal IOL, patients should be evaluated for surgically induced astigmatism and can be managed with an LRI in cases in which the astigmatism is less than 1 D. In cases involving more than 1 D of residual astigmatism, consideration should be made for excimer laser ablation or IOL exchange for a toric IOL depending on the patient tolerance and surgeon experience. Management of residual refractive error after implantation of a toric IOL is dependent on the

residual spherical equivalent. In cases of mixed astigmatism, where the spherical equivalent is negligible, if the residual astigmatism is less than 1 D, the enhancement may be reasonably managed with an LRI. If the astigmatic error is more than 1 D, the enhancement is likely best managed with a rotation or an exchange of the toric IOL. If there is both a cylindrical and spherical equivalent error with a toric IOL, these enhancements are best managed by LVC if the error is small (<1 D) and there is a myopic spherical equivalent. In larger degrees of myopic or hyperopic SE, IOL exchange and rotation to the ideal axis is a reliable method of enhancement. Cases involving primarily small spherical errors alone can be managed more effectively with LVC.[53,54] However, with larger spherical errors, piggyback IOL appears to be more effective than IOL exchange as acceptable methods of correction.[52,54]

The approach to enhancing patients after cataract surgery is truly unique for every individual case based on the magnitude of the spherical equivalent and the amount of astigmatic refractive error. Likewise, patient factors such as personality, expectations, tolerance to refractive error, and acceptance of additional surgical procedures also dictate the timing and modality of treatment that is most appropriate. Each patient should be approached with unique considerations. The future looks promising with technology that will allow for minimally invasive means of refractive enhancements through IOL-based modulations that may be repeatable if needed. Until such technology is available, the current methods of enhancement using LRIs, LASIK, PRK piggyback IOLs, toric IOL rotation, and IOL exchange provide numerous options that not only enhance the refractive error but more importantly can enhance patient and surgeon satisfaction with refractive outcomes after cataract surgery.

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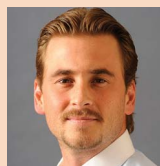
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