INTRODUCTION

Incisional corneal refractive procedures such as radial and astigmatic keratotomy, developed in the early 1980s, have been followed in increasing popularity by excimer laser refractive procedures. With laser-assisted in situ keratomileusis (LASIK) entering its 3rd decade, surgeons are being faced with the reality that many of these patients are now reaching the age of cataract surgery. Refractive surgery has become an increasingly safer and effective proposition since its inception in 1990, with both patients and surgeons expecting excellent predictability in the results.1 Conversely, when faced with the prospect of inevitable cataract surgery, now patients and surgeons must face a new reality: the fact that our lens power calculations in these circumstances are less than adequate.

In this chapter, we explore a new paradigm in the management of postrefractive surgery patients. We will review basic concepts in intraocular lens (IOL) calculations, the challenges faced in postrefractive surgery lens calculation and discuss the light-adjustable lens technology as a means to raise the bar in the predictability of these cases.

GENERAL CONCEPTS IN IOL CALCULATION

As cataract surgery has progressed, surgeons have become more concerned with IOL calculations. The advent of microincision cataract surgery technology has afforded the ability to use smaller incisions. This, in turn, has yielded less astigmatic induction following cataract surgery.2,4 That, coupled with the use of partial coherence interferometry with instruments, such as the Zeiss IOL Master (Carl Zeiss, Germany), has allowed surgeons to increase the predictability of refractive results.2,5 This has not always been the case. In a review by Apple (2006), the humble beginnings of cataract surgery were explored. The review focused on Harold Ridley, who performed the first IOL implantation in 1949. This first implantation resulted in a postoperative refraction of −20 diopters (D), a result that is almost unthinkable in modern ophthalmology.6 Even in the 1980s, some surgeons still used the single IOL approach, a model in which surgeons exclusively inserted a +19.0 D lens in all patients, based on Gullstrand’s schematic eye. Achieving a postoperative refraction accurate enough to obviate the need for glasses was not even a consideration; it was simply the expectation that glasses would be needed following cataract surgery.

Over the years, many formulas have been used to increase the predictability of IOL calculations following cataract surgery. There are two basic categories of calculations used to determine the IOL power that should be used in cataract surgery: the theoretical formulas and the statistical/regression formulas. The theoretical optical formulas include thin lens formulas, thick lens formulas and exact ray tracing or wavefront technique formulas.2,7-10 Modern theoretical formulas include the Haigis, Hoffer Q, and Holladay 2 IOL calculation formulas. These formulas take several variables into account: IOL power, keratometric readings, axial length, effective lens position (ELP), postoperative refraction, and vertex distance for postoperative refraction.11 The ELP is the only one of these variables that cannot be formally measured, and as such, the focus of new theoretical formulas is to most accurately predict the ELP.11

The statistical/regression model includes the Sanders Retzlaff Kraff SRK-1 and SRK-2 formulas. These
formulas, developed in the 1980s, estimate the power of the IOL implant based on an A-constant provided by the manufacturer and take into account keratometry readings as well as axial length.\textsuperscript{2,12} An example is $PIOL = A - (0.9 \times K) + (2.5 \times AL)$, where $PIOL =$ power of the IOL; $A =$ A-constant provided by the manufacturer; $K =$ keratometry readings and $AL =$ axial length. This most basic equation, while fairly simple mathematically, allows a straightforward understanding of some of the factors relevant in lens calculations, and the effect of the error in measuring them. In theory, a 1 mm error in AL measurement would result in a 2.50 D lens calculation error. The SRK-2 formula largely replaced the theoretical models due to its easier derivation and use.\textsuperscript{3} Binkhorst later modified these earlier SRK formulas to obtain the SRK-T formula, which became more popular in the 1990s.\textsuperscript{13}

As technology has improved, so has the ability to measure multiple variables and factors during IOL calculation. Surgeons have enjoyed increasing refractive predictability when moving from A-scan biometry, to A-scan immersion biometry, and furthermore, with different permutations and software changes using partial coherence interferometry. The caveats now include precise measurement of the corneal power, accurate measurement of the axial length, the appropriate prediction of postoperative anterior chamber depth (ACD), the refractive effect of the IOL implant itself, and finally optimization and accuracy of the results.

No keratometer measures corneal power directly, but rather the size of the reflected corneal image. This in and of itself represents a caveat in measurement of corneal power. Measurement of the axial length is different when partial coherence interferometry is employed compared to ultrasound biometry.\textsuperscript{2} Instruments such as the IOL Master target the retinal pigment epithelium as the end point in axial length measurement, while ultrasonic devices target the internal limiting membrane. Prediction of the postoperative ACD and refractive effect of the IOL are also important variables that must be considered when predicting postoperative refraction. As outlined in the review by Olsen, optimization and accuracy involve several factors, including the role of the capsulorrhexis, as described by Gimbel and Neuhann, and the accuracy of IOL power calculation.\textsuperscript{2,14} In Olsen’s review, the distribution of the prediction error was analyzed by comparing three types of IOLs.\textsuperscript{2} It was evident that although the calculations resulted in high predictability, there was still a spread in outcomes even when considering optical, regression and SRK-1 regression formulas.

In addition to the factors mentioned above, there are other variables, such as corneal radius, axial length, postoperative ACD and IOL power, where errors as little as 1 unit, either in millimeters or diopters depending on the variable, may result in a range of refractive errors from 0.67 to 5.7 D.\textsuperscript{2} To further compound the problem, even if all calculations were perfect, there would still be the issue of IOL manufacturing. For example, manufacturers often state that the ACD measurements reported for their lenses are simply estimates. This is because the ACD is dependent on each individual eye, and thus it is not possible for the single ACD measurement provided by the manufacturer to accurately reflect how the lens will behave within the eye.\textsuperscript{8} Using this estimated ACD value for a specific lens can result in up to 2.0 D of inaccurate estimation of IOL power.\textsuperscript{8} It is possible that a 0.25 D error during the manufacturing process, combined with a 0.25 error in calculation, would result, even before the surgical intervention, in a 0.50 D error from the expected result. The concept of fine-tuning this aspect of the procedure becomes, then, an intriguing proposition.

The increased popularity of the excimer laser in refractive surgery has also strengthened the ability to predict refractive outcomes. Outcome results amongst refractive surgeons revolve around percentages of eyes at or above 20/20, and even 20/16 of uncorrected vision. Refractively, high numbers of eyes are expected to have predictability within the ±0.25 and ±0.50 D ranges. Therefore, the bar has been raised in terms of refractive predictability for both cataract and refractive surgery. In spite of this, Olsen states that with current technology, the IOL refractive predictability would be (reasonably) expected at ±1.0 D in about 90% of eyes and ±2.0 D in 99.9% of eyes.\textsuperscript{2}

### IOL Calculation After Corneal Refractive Surgery

The cornea has two refracting surfaces, and both need to be taken into account in order to calculate corneal power accurately. Eyes that have previously undergone refractive surgery are less amenable to accurate keratometry measurements, due to alterations of these corneal surfaces. Standard keratometry uses four corneal focal points in the paracentral region to obtain its measurement of corneal power. Keratometry, however, becomes inaccurate for corneas that have undergone refractive surgery, because such corneas have experienced a flattening or steepening in the central cornea.\textsuperscript{15} Seitz and Langenbucher further outlined that not only does refractive surgery alter the
nature of the cornea, but different types of refractive surgery have differing effects on the new corneal measurements. Specifically, excimer laser procedures, such as LASIK and photorefractive keratectomy (PRK) result in different corneal properties when compared to radial keratotomy, in which peripheral relaxing incisions produce a central flattening of the cornea without the removal of central corneal tissue. Based on these findings, it is evident that when using the excimer laser, the relationship between the front and back surfaces of the cornea will be different than that obtained following radial keratotomy.

Many methods have been described to accurately calculate the proper IOL power to be inserted into eyes that have previously undergone refractive surgeries. One group of refractive calculations includes strategies that rely on accessing patient’s past optical measurements before they had refractive surgery. Some of these methods include the clinical history method, the Feiz-Mannis method, the Hamed method, the Aramberry double-K method, the Latkany method, the Masket method, and the Wake Forest method. Other methods are more practical, avoiding reliance on past optical history. Among these are the Shammas method, the Maloney/Wang method, the Smith method, the Savini method, and the Ianchulev method.

The inconsistency amongst these various calculations is reflected by the Consensus K technique, which is based on determining a mean of the K values obtained by some of these other formulas.

McCarthy et al. published a study regarding IOL power calculations following myopic laser refractive surgery. The authors compared methods in 173 eyes post myopic laser refractive surgery. They included several of the methods described above, such as the clinical history method, Aramberry Double-K method, Latkany Flat-K, Feiz-Mannis, R Factor, corneal bypass, Masket, Haigis-L, Shammas,cd, and optical version formulas. They compared this against the benchmark of standards for refractive outcomes following cataract surgery that was published by the National Health Services (NHS) in England. Interestingly, the IOL calculation predictability set as a standard by the NHS mentioned that 55% of eyes should be within ± 0.50 D of the targeted outcome, while 85% of eyes should be within 1 D of the desired outcome. McCarthy’s study showed that on the high predictability end, 58.8% of eyes were within 0.50 D, and 84.5% were within 1 D of the desired outcome. At the other extreme, low predictability results included 53.8% of eyes within half a diopter, and 80.9% of eyes within 1 D of the desired outcome. This is outlined in Table 1.

**Table 1: IOL calculation predictability**

<table>
<thead>
<tr>
<th>Report</th>
<th>±0.25 D</th>
<th>±0.50 D</th>
<th>±1.00 D</th>
<th>±2.00 D</th>
</tr>
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<tr>
<td>Olsen 2007</td>
<td>90%</td>
<td>99.9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NHS Stds</td>
<td>55%</td>
<td>85%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McCarthy(H)</td>
<td>58.8%</td>
<td>84.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McCarthy(L)</td>
<td>53.8%</td>
<td>80.9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chayet LAL*</td>
<td>93%</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*FDA Phase I: Sphere Adjustment. Data courtesy of Arturo Chayet, MD. See text for references.

NHS: National Health Services; LAL: Light-adjustable lens

The question then becomes whether surgeons can do better and improve on these refractive aspects. Scheimpflug imaging with instruments such as the Pentacam (Oculus, Germany) provides images of the front and posterior aspects of the cornea (Fig. 1). These are true elevation maps that can be correlated clinically. In particular, by utilizing the Pentacam’s Holladay report, which includes equivalent K readings at the 4 mm zone, keratometry values can be combined with axial length and white-to-white measurements from the IOL Master and inputted into the Holladay 2 formula from the Holladay IOL Consultant software.

As an example, we will discuss the case of an individual who underwent successful PRK in 1994, once for the right eye and with two enhancements for the left eye. The preoperative refraction for the right eye was −9.50 − 0.50 × 120 and for the left eye −7.50 D. Our typical patient discussion includes the fact that IOL calculation predictability is quite challenging following laser refractive surgery. Intraocular lens master version 5.4.3 with the postrefractive module was employed. Pentacam with the Holladay equivalent K reading report was used to obtain the K readings, and these were inputted into the Holladay 2 formula. Different printouts were compared, and the discussion explored the options of further vision correction following cataract surgery with the excimer laser, IOL exchange or a piggyback lens.

Postoperatively, uncorrected vision in the right eye for this patient was 20/32, with a refraction of +0.75 + 0.50 x 85 resulting in a corrected vision of 20/16 + 2. The left eye obtained an uncorrected visual acuity of 20/16 and was plano. While the result was better than expected, the patient wanted an enhancement for the right eye, which bares the notion that surgeons could still do better in terms of refractive predictability.
LIGHT-ADJUSTABLE LENS TECHNOLOGY

The light adjustable lens (LAL) is a recent exciting innovation in cataract surgery. Developed by Calhoun Vision Inc (Pasadena, CA), it is the first ever lens to allow for noninvasive power adjustment postimplantation. Essentially, the lens material is amenable to alteration postoperatively, such that the lens power can be changed in order to achieve a more optimal refractive outcome.

The LAL material was originally developed by Dr Robert Grubbs, the 2005 nobel prize winner in Chemistry. The LAL is composed of photosensitive silicone macromers embedded in an ultraviolet (UV) absorbing silicone lens matrix.35 Upon exposure to UV light, the photoreactive macromers being targeted by the light are photopolymerized. A gradient then develops between the irradiated and nonirradiated macromers of the lens. Adhering to the principle of diffusion, the nonirradiated macromers disperse towards the photopolymerized part of the lens. This causes lens swelling and leads to a change in the shape, and thus, the power of the lens (Figs 2 and 3).35,36

The unique features of this lens are exploited during the ensuing weeks following implantation. Once the lens is implanted using standard phacoemulsification techniques, the light delivery device (LDD) is utilized to customize the power of the lens. The LDD has been designed on a standard slit lamp platform, with unlimited flexibility for lens modification (Fig. 4). It consists of a digital mirror...
device, which allows customized generation of spatial irradiance profiles. Following surgery, patients are requested to wear UV protecting glasses at all times, both indoors and outdoors, in order to prevent premature unrestricted photopolymerization of the material (Hengerer, 2010). The specific UV treatment parameters, the irradiation dose and spatial irradiation pattern, are altered based on the patient’s postoperative refraction in order to achieve the desired change in lens power.35

Two weeks after surgery, one or two adjustment treatments are performed on separate occasions, which involve UV light application to alter the lens shape, as
explained above. If the desired refraction is achieved following one adjustment treatment, there is no need for a second. Adjustment profiles currently include negative, positive, and toric adjustment (Fig. 5). Twenty-four to forty-eight hours following these adjustments, one or two lock-in treatments are performed, during which UV light is applied to solidify the lens’ new shape. Twenty-four hours following the completion of the second lock-in treatment, patients can stop wearing the UV protecting glasses.

In vitro safety studies have shown that in terms of cytotoxicity, sensitization and genotoxicity, this lens meets safety requirements of the industry. In vivo animal studies as well as human clinical studies have demonstrated the safety and efficacy of this lens and the implantation material. Studies of the LAL in a rabbit model demonstrated that the UV light exposure does not result in retinal toxicity. The study by Lichtinger et al. diffused concerns that the UV light leads to any more endothelial damage than is incurred in standard cataract surgery. Clinically, the results achieved with the LAL have been very encouraging. Up to 2 D of correction for myopia, hyperopia, and astigmatism are possible with this nontoxic and biocompatible material. A pilot study by Chayet et al. showed that 93% of LAL patients achieved a refraction of less than 0.25 D of the intended refraction, and 100% of participants were within 0.5 D of the intended refraction at 9 months postoperatively (Table 1). Salgado et al. conducted a study on 20 eyes, in which all patients were within 0.5 D of the intended refraction at 6 months postoperatively. Furthermore, the spherical equivalent was reduced from +0.39 D preadjustments, to −0.07 D at 6 months postadjustments. A more recent study of 21 eyes by Hengerer et al. further confirmed these positive results: 96% of eyes were within 0.5 D of the intended refraction, and 81% had a predictability of 0.25 D. Such postoperative refractions significantly exceed the predictions set by Olsen in 2007 and the benchmarks established by the NHS Standards. The refractive benefits are not limited to myopic correction; Chayet et al. showed that residual hyperopia after cataract surgery, from +0.25 D to +2.0 D, could be significantly improved via UV adjustments.

These optimal refractive results have translated into equally positive visual acuities. In the study by Von Mohrenfels et al. all eyes gained 2 or more lines of corrected visual acuity, while 81% of eyes in the study by Hengerer et al. improved by 2 or more lines.

Light-adjustable lens technology provides certain unique features. For example, the LAL offers the option for presbyopic corrections. Multifocality is possible, as well as the creation of central near add or asphericity treatments as a third adjustment protocol. The LAL is also conducive to creating monovision, with the added bonus of being able to eliminate this feature if the patient becomes averse to it. If the patient is not agreeable to the monovision, a further correction can be made within a two-week period to convert the refraction to emmetropia. The LAL may prove particularly valuable in cases of astigmatism. Using the LAL, toric corrections are based directly on the postoperative position of the lens and the manifest refraction (Fig. 6). Thus far, such astigmatic corrections appear to be promising. In the first 13 eyes treated by one of the authors (GR), mean refractive spherical equivalent (MRSE) of all of the eyes was within 0.25 D of the expected outcome following adjustment and lock-in treatments. The reduction of cylinder was also dramatic, with only one patient having up to 0.5 D of cylinder following the adjustment and no eyes having more than 1.0 D of residual cylinder (Figs 7, 8 and 9).
The benefits of using the LAL in patients who have previously undergone refractive surgery are obvious. As already explored in depth, it is difficult to determine the accurate corneal power in an eye that has had prior corneal alterations, such as in refractive surgery. The LAL allows the flexibility of decreased precision of preoperative measurement of corneal power. The ophthalmologist no longer needs to strive for emmetropia right off the bat in these complicated cases; one can simply rely on the properties of the LAL and plan to adjust the corneal power postoperatively.

In the following two cases, we propose a new paradigm for the use of LALs after corneal refractive surgery.

**Case 1–RE**

A 55-year-old Caucasian male presented to our office with a diagnosis of a left visually significant posterior subcapsular cataract. He had been a patient at our clinic...
and had previously received bilateral wavefront LASIK seven years before. His pre-LASIK refraction for the right eye was \(-7.00 + 2.00 \times 130 = 20/20\). For the left eye, it was \(-7.25 + 1.75 \times 65 = 20/20\).

The LASIK procedure was uneventful and performed using an Amadeus microkeratome as well as a Visx Star S4 CustomVue excimer laser (AMO, California). He presented on January 12, 2011 with a plano correction in the right eye, giving him 20/20 vision, and a refraction of \(-1.25 - 0.50 \times 178\) in the left eye, giving him a vision of 20/40. A visually significant cataract was diagnosed, with a component of posterior subcapsular opacity. Due to his job as a truck driver, the decision was made to proceed with surgery.

Several options were discussed, but a LAL implant was used. The calculation involved performing Pentacam and iTrace analysis. From the Pentacam analysis, the Holladay equivalent K readings were obtained, and this, in combination with IOL master biometry, and the use of the
Holladay 2 formula, yielded a lens power of +18.0 D. The predicted refractive value was 0.07 D.

In March 2011, surgery was performed. Two weeks were allowed to elapse before adjustment. Preadjustment measurements included a distance uncorrected visual acuity of 20/40 and a refraction of +0.75 + 0.50 × 125 = 20/16 (Table 2). After the second lock-in treatment, uncorrected visual acuity was 20/20 with a manifest refraction of plano. Near visual acuity was measured at J6.

**Table 2: Case 1**

<table>
<thead>
<tr>
<th>Visit</th>
<th>UCDVA</th>
<th>M Rx</th>
<th>BCDVA</th>
<th>Near VA</th>
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</thead>
<tbody>
<tr>
<td>Preadjustment 1</td>
<td>20/40</td>
<td>+0.75 + 0.50 x 125</td>
<td>20/16</td>
<td>J10</td>
</tr>
<tr>
<td>Preadjustment 2</td>
<td>20/16</td>
<td>-0.25</td>
<td>20/16</td>
<td>J6</td>
</tr>
<tr>
<td>Prelock-in 1</td>
<td>20/20</td>
<td>+0.25</td>
<td>20/16</td>
<td>J6</td>
</tr>
<tr>
<td>Prelock-in 2</td>
<td>20/16 + 1</td>
<td>+0.25</td>
<td>20/16</td>
<td>J5</td>
</tr>
</tbody>
</table>

UCDVA: ******; BCDVA: ********
Case 2–RS

A 56-year-old Caucasian male underwent successful hyperopic PRK in the left eye in 1997 for a correction of +3.00 + 2.50 × 82 = 20/30. There was documented mild amblyopia in this eye. He was then referred to our clinic in 1999 for a LASIK procedure in the right eye. Preoperative correction in the right eye was +2.25 + 0.25 × 113 = 20/20 and was treated successfully. He presented again to our office on December 9, 2010, now with a cataract in the left eye. Visual acuity was 20/16 in the right eye, with a correction of +1.50. Visual acuity was 20/40 in the left eye, with a refraction of +2.25 + 0.50 × 35. He was diagnosed with a nuclear sclerotic cataract, and the option of a LAL was discussed. In addition, it was discussed that the presence of mild amblyopia would limit the final visual acuity result.

Intraocular lens calculation was performed using a similar approach with the Holladay equivalent K readings from the Pentacam analysis. That, in addition to the IOL Master data, and input into the Holladay IOL consultant and Holladay 2 formula, yielded a proposed lens of +23.0 D with a predicted refraction of +0.24 D (with LAL it is preferable to target for slight hyperopia). Cataract surgery was performed in March of 2011 and was uneventful. Prior to adjustments, uncorrected visual acuity was 20/40 in the left eye, and a refraction of −0.75 resulted in a vision of 20/30 + 2. Following second adjustment and lock-in treatments, his uncorrected visual acuity in the left eye was 20/32 with a near vision of J2. His refraction was −0.75. It was interesting that at one point prior to the second lock-in, visual acuity improved to an uncorrected and best corrected level of 20/25. This case demonstrates the flexibility of the technology, in that when an adequate result is obtained, lock-in can ensure such outcome is maintained (Table 3). The authors have since added a third postrefractive surgery case to their database (manuscript in preparation for publication). The end result was once again very precise, with a +0.25 correction, and uncorrected vision of 20/20 following the use of LAL.

In conclusion, the light-adjustable lens predictability achieves excellent distance visual acuity through accurate correction of defocus and astigmatism, and this translates into clinically successful results in postrefractive surgery eyes. With this, the age of true refractive corneal and cataract surgery has been entered.

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Note: The authors have no proprietary or financial interests in any aspect of this study.

REFERENCES


Table 3: Case 2

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<th>BCDVA</th>
<th>Near VA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preadjustment 1</td>
<td>20/40</td>
<td>−0.75</td>
<td>20/32+2</td>
<td>J2</td>
</tr>
<tr>
<td>Preadjustment 2</td>
<td>20/40</td>
<td>−0.75</td>
<td>20/40+1</td>
<td>J2</td>
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<tr>
<td>Prelock-in 1</td>
<td>20/25</td>
<td>−0.50</td>
<td>20/25</td>
<td>J2</td>
</tr>
<tr>
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<td>J2</td>
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UCDVA: ******; BCDVA: ******