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IOL optics and quality of vision

Daniel H. Chang, MD

In evaluating IOLs, surgeons typically think about the lens material and design from a structural perspective: How stable is the lens in the bag? Does the edge prevent lens epithelial cell migration? Less often, perhaps, do surgeons consider how the lens material and design affect image quality.

Our attention was first drawn to image quality several years ago, when spherical aberration garnered a significant amount of attention. The result has been the popularization of aspheric IOLs, to the benefit of our patients.

Two important trends are now changing how we think of cataract surgery. The first is presbyopia-correcting IOLs. The desire to achieve youthful vision for a spectacle-independent lifestyle has raised expectations and increased awareness of the visual tradeoffs we

make in trying to attain this goal. The second trend is the advancement of diagnostic and surgical technologies that are helping to tighten the standard deviation in cataract surgery, bringing more eyes to 20/20 or better visual acuity postoperatively. As *quantity* of vision edges closer to the goal, it may be time for renewed emphasis on *quality* of vision.

By considering important material and design features like refractive index, spherical and chromatic aberration, glistenings, and chromophores, we can make choices in clinical practice that improve both quantity and quality of vision.

For this supplement, I have assembled a dynamic group of experts in the field to explore the principles of optics that contribute to high quality of vision and patient satisfaction.



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IOL material properties: Contributions to visual quality and patient satisfaction

Gary N. Wörtz, MD

Use the human crystalline lens as your guide in seeking out materials that provide superior optics for your patients

There are many IOL material and design properties that go into providing excellent vision. The most important material quality on my priority list is the index of refraction. For intraocular lenses, the refractive index directly affects not only lens thickness but is also related to optical quality: chromatic aberration; the range of high quality vision; and how light rays reach the retina.

The crystalline lens has an index of refraction of 1.41, and I prefer to stay as close to this physiologic index of refraction as possible. The IOLs with similarly low indices of refraction include the older silicone IOLs (most of which are unavailable or rarely used now), the STAAR (Monrovia, Calif.) Collamer material, and the Abbott Medical Optics (Abbott Park, Ill.) Tecnis acrylic (Figure 1). In recent years, most other manufacturers have been focused on the mantra of “smaller is better,” opting for thinner, higher-index materials that can fit through smaller incisions. While there are some advantages of microincisional cataract surgery, I think the emphasis on shaving a few tenths of millimeters off the incision size may have come at the cost of optical quality.

A higher index of refraction spreads white light out across its spectrum, creating chromatic aberration. In the world of photography, it is well known that a high-index camera lens causes blue edge blur. Instead of a crisp contrast between the edge of an object and the background of the photograph, there is a slightly blurred border resulting from the out-of-focus blue light. The same type of image distortion can occur with a high-index IOL material. It is interesting that the highest-index lenses on the market have a blue-blocking chromophore. Without that chromophore, we would surely notice a much stronger optical effect from out-of-focus blue light.

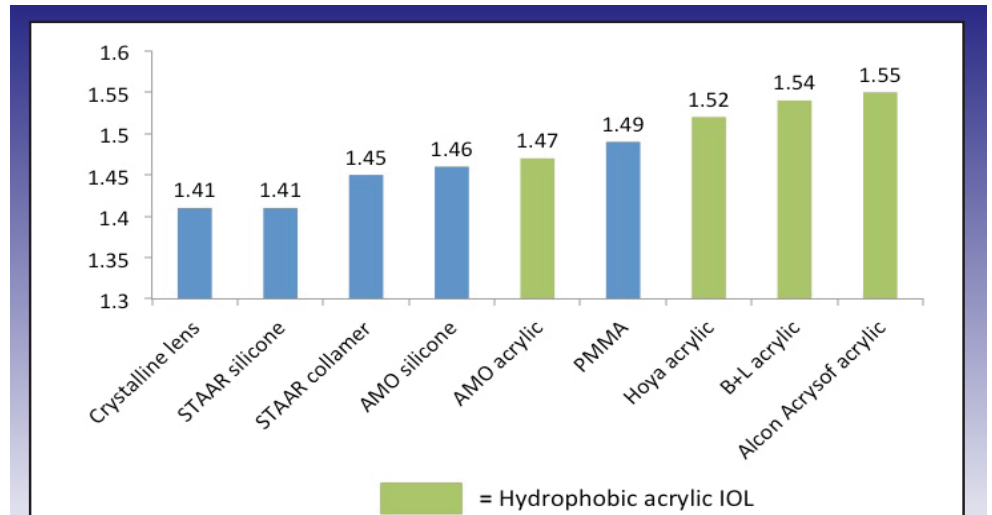


Figure 1. The index of refraction of various lens materials, including contemporary hydrophobic acrylic IOLs (in green).

Reflectance is also closely related to the index of refraction. Total internal reflection is the optical principle that makes fiber optic cable work so well. Light in one end of the cable keeps bouncing and propagating through the cable, allowing telecommunications signals to travel hundreds of miles without being lost because of the critical angle of the material. This critical angle is based on the change in index of refraction from the optical material to the surrounding media. IOL materials with a high index of refraction will have a shorter critical angle of, for example, 60 degrees. That means that light incident on the lens from an angle greater than 60 degrees gets bounced or reflected out of the eye, just as it would get bounced down the length of the fiber optic cable.

To make matters worse, a high-index lens will be thinner (that’s the benefit, remember?) and flatter. The flatter the lens, the more it will act like a mirror and allow light to bounce out more easily. A relatively thicker lens will have a shorter radius of curvature, and incoming light rays will strike at an angle and be reflected centrally inward toward the retina instead of outward.

We see reflectance as an external glint in patients who have had cataract

surgery with a high-index IOL.^{1,2} Although no one has yet shown that this cosmetic issue carries any optical consequences, we know that, at a minimum, light reflected out is not hitting the retina as intended. It may also contribute to the negative dysphotopsias that some patients complain about.³ These are always noted in the temporal field of vision, which is processed by the larger, nasal side of the retina (80 degrees compared to 60 degrees on the temporal side). It is possible that light reflected beyond the critical angle of the lens casts a shadow on that side of the retina.

Finally, a low index of refraction seems to provide a larger sweet spot in which patients are likely to be satisfied with their vision. In my practice, when I recently switched to a lower index-of-refraction lens, the technicians and I suddenly found that our “hug factor” (the percentage of my patients who are so thankful for their new vision that they hug me) had gone way up.

Not everyone will be interested in optical science and the complex interactions of index of refraction, reflectance, and chromatic aberration. But at the end of the day, it’s that hug factor that defines success in cataract surgery for all of us.

The role of spherical aberration

Jeremy Kieval, MD

Aspheric lenses have become widely accepted for their contribution to improved pseudophakic image quality

Light rays passing through a perfect lens will all focus at the same point. The human eye, however, does not represent a perfect lens. There are multiple refracting surfaces that all contribute to either positive or negative spherical aberration (SA). Positive SA occurs when light rays passing through the steeper periphery of a lens focus in front of the flatter central rays. Negative SA occurs when the periphery of the lens is flatter than the central portion, focusing light rays farther.

In the young eye, the positive SA of the cornea is countered by negative SA in the lens. At around age 20, everything is in perfect balance, providing the eye with zero SA and optimal visual quality. But over time, the lens develops more positive SA, resulting in a gradual loss of contrast sensitivity and visual quality.

More than a decade ago, Pablo Artal and colleagues compared the vision of pseudophakes with that of age-matched and younger phakic adults.⁴ They realized that while visual acuity in the pseudophakes was similar to that of the younger adults, retinal image quality was considerably worse in the pseudophakic patients, about the same as that of the older adults who had not yet undergone cataract surgery. Given the objectively high optical quality of the IOLs implanted, this was rather surprising. But it turns out that the reason for the poorer optical performance in the pseudophakes was largely due to the fact that IOLs at the time replicated the positive spherical aberration of the aged eye rather than the balanced SA of the young eye.⁵

Aspheric IOLs

Further studies demonstrated that the average SA of the human cornea at a 6.0-mm optical zone is +0.27 μm , meaning that most patients would benefit from an IOL that eliminated total SA by inducing

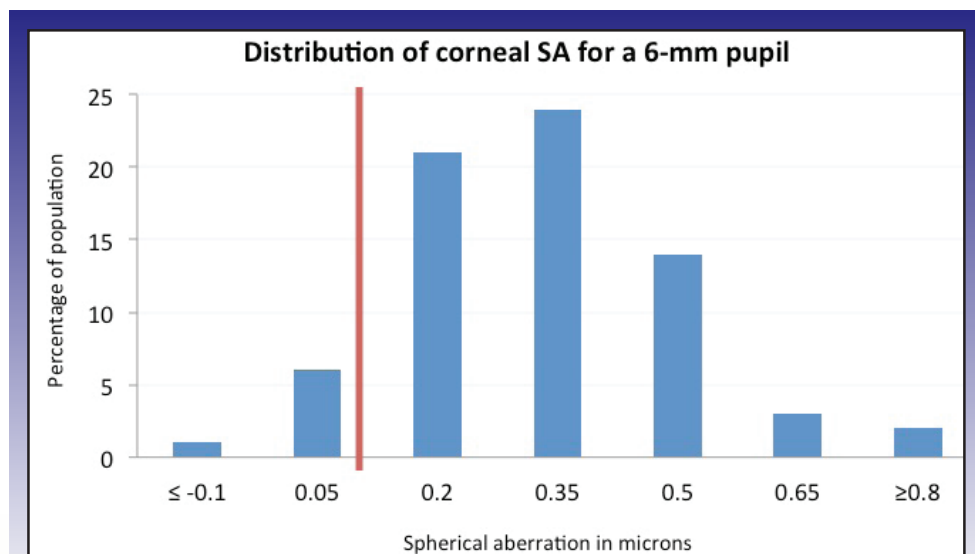


Figure 2: Approximately 90% of patients (those to the right of the red bar) benefit from an IOL with -0.27 microns of SA.

-0.27 μm of SA (Figure 2).⁶ It was later confirmed that this amount of SA correction did indeed result in better contrast sensitivity.^{7,8}

Over the past decade, asphericity has become a standard IOL feature, with contemporary IOLs featuring -0.27 D μm of SA (Tecnis platform, Abbott Medical Optics, Abbott Park, Ill.), -0.1 to -0.2 μm of SA (AcrySof platform, Alcon, Fort Worth, Texas, and Hoya Surgical Optics, Chino Hills, Calif.), or 0 SA (Bausch + Lomb IOLs, Bridgewater, N.J., and Lenstec, St. Petersburg, Fla.). All of these options lessen SA compared to positive SA IOLs that add to the cornea's positive SA.

In my practice, I try to target zero total SA to achieve that "perfect" balance of the 20-year-old eye. The average corneal SA of $+0.27$ μm is derived from population data, so of course individual eyes can vary around that average. I measure each patient's actual SA using Pentacam tomography (Oculus, Arlington, Wash.), which I find to be a better measure of corneal SA than topography-based devices. Most patients have $+0.25$ μm or more, so I usually choose lenses that offer the highest amount of SA correction (-0.27 μm). However, I alter that plan in patients who already have closer to 0 SA

or those with prior hyperopic LASIK who likely have a cornea with negative SA.

Correcting SA is even more important for the optical performance of multifocal IOLs. Because diffractive multifocal lenses reduce contrast sensitivity, we don't want to compound the effects on image quality by also leaving the patient with significant positive SA.

There is some debate about whether to err on the negative or positive side when we can't get to precisely zero SA. A small amount of negative SA will improve near focus, particularly when the pupil constricts with near effort and forces more light rays through the paraxial cornea. However, the near vision that is gained will still be aberrated. Some surgeons adjust their refractive target depending on the predicted residual SA, opting for a slightly myopic final refraction if they expect to leave the eye with some positive SA, or slightly hyperopic if they plan to leave it with negative SA.

It is important to remember that SA always affects the quality of the retinal image. In an ideal world, we would choose IOLs that fully correct each patient's actual SA while also achieving a plano refraction to maximize both acuity and retinal image quality.

Chromatic aberration: A new metric in IOL performance

Joseph J.K. Ma, MD, FRCSC



Figure 3: The effect of chromatic aberration is visible around the dark edges of the lower photograph (especially on the right). The images show only a part of the photo from the corner of the original image to emphasize the effect of aberration.

Source: Stan Zurek

What chromatic aberration is and why it matters for your pseudophakic patients

Chromatic aberration is important in the performance of any optical system. As white light passes through a lens, each component wavelength is refracted differently, depending on the lens material's index of refraction for that wavelength. The property of the lens that describes this is known as dispersion. Longer wavelengths bend less and shorter wavelengths bend more, resulting in a dispersion of light, as one sees in a prism. Essentially, CA is the failure of the different wavelengths of light to converge on a single point. In three dimensions, this happens both along the optical path (axial CA) and within the plane of focus (transverse CA).

Every refractive material has some degree of CA. However, depending on

the optical properties of the material, that dispersion of light into its component colors can be narrower or wider. The greater the dispersion, the less sharp the image can be, even when it is in maximal focus.

Photography provides a great way to understand this. Photographers use a number of tricks to avoid or reduce CA as they capture and process images. In the enlarged corner of a photograph, you can see how a photo without CA compares to the same image with CA (Figure 3). In the lower image, there is some blur and a color fringe of light, representing transverse CA.

CA and IOLs

In the eye, axial CA results in some wavelengths of light focusing beyond the retina and some in front of the retina, reducing image quality. Ophthalmologists take advantage of axial chromatic aberration when we use the duochrome

red/green test. The difference in focus between red and green light is what makes this test useful in refining the refraction. Although we rarely think of it this way, axial CA is also responsible for myopic shift at night. Our eyes use more blue-violet light at night, and that light focuses further in front of the fovea, inducing night myopia.

Following cataract surgery, the IOL that is implanted can either reduce or increase CA, and this can be influenced by both material and design features.

The most important contribution is from the IOL material. Each implant has a fixed level of CA that is intrinsic to the lens material itself. The CA and dispersion properties of lenses currently marketed today vary considerably (Figure 4). If the material has higher chromatic aberration and light dispersion (indicated by a lower Abbe number), there will be some blur or reduction in image quality even when perfect emmetropia is achieved, similarly to how a photograph can be in focus but still have color fringing along the edges of objects in the photo.

Secondly, the design of an IOL made of any given material can, to a degree, be manipulated to correct for chromatic aberration through a particular use of diffractive optics. For most ophthalmologists, “diffraction” is synonymous with reduced image quality and decreased contrast sensitivity because of their association of diffraction as an accepted tradeoff for multifocality. This is not a property of diffractive optics. In fact, diffraction results in the opposite dispersion of light from refraction, which is what allows a strategically designed diffraction pattern to minimize CA. In photography, diffractive optics have been used to improve optical image quality. Canon, for example, has used a multilayer diffractive element to decrease chromatic aberration in a high-end telephoto lens since 2001. A new IOL that was recently launched in Europe, the Tecnis Symphony, also uses a diffractive mechanism to correct for CA to improve contrast.

Lens material	Abbe number	Dispersion
STAAR Silicone	57	-0.007
AMO Tecnis acrylic	55	-0.009
Crystalline lens	47	-0.009
Hoya acrylic	43	-0.012
B+L enVista acrylic	41	-0.013
Alcon AcrySof acrylic	37	-0.015

Figure 4: Chromatic aberration and IOLs

Clinical relevance

So why should we pay attention to CA in IOL material and design? Does it really matter to our patients? I would argue that it matters a great deal, for three reasons.

The first is simply the pursuit of “super” vision, or the highest possible quality of vision. Since the images we process consist of all the colors of the spectrum, reducing CA increases contrast, allowing images to be as sharp and as crisp as they can be. To improve CA, we want to use IOL materials with low dispersion and an Abbe number that, if possible, exceeds that of the human lens (47). Increasing the Abbe number of optic materials has been shown to improve overall pseudophakic optical performance.⁹

If we can theoretically optimize vision in the daytime, bringing all wavelengths in focus and minimizing CA, then images will also be in focus at night when blue light is more dominant. Less CA reduces myopic shift and could potentially reduce difficulty with night driving.

Finally, a starting point of higher visual quality and sharper contrast provides patients with the ability to better withstand other challenges to their vision, whether intentional (multifocal IOLs) or unintentional (dry eye, age-related macular changes).

By choosing IOLs with low dispersion or design features that deliberately diffract light in such a way as to reduce CA, we can actually improve quality of vision after cataract surgery.

Blocking portions of the spectrum

Sumit “Sam” Garg, MD

Intraocular lenses have been designed with the intention of blocking specific wavelengths of light that have been considered harmful or potentially harmful, including ultraviolet, violet, and blue light.

Ultraviolet

The natural crystalline lens does a very good job of blocking ultraviolet (UV, <400 nm) light, and since at least the mid-1980s, IOLs have tried to replicate that ability. We know that UV radiation is harmful to the skin and can cause damage to the external surfaces of the eye, such as the eyelids, cornea, and conjunctiva. UV exposure is associated with cataract development and likely plays a role in retinal conditions like macular degeneration, although this is less well documented.

Most IOLs effectively block UV-B (280–315 nm) radiation, which is believed to be responsible for UV-related ocular pathology and UV-C (200–280 nm), most of which is absorbed by the atmosphere. Over the years, there has been some variation in how well different IOLs block UV-A (315–400 nm) light,¹⁰ and an early version of the Crystalens (Bausch + Lomb, B+L, Bridgewater, N.J.) provided very little UV protection. Blocking UV is a reasonable strategy and a desirable lens characteristic given the potential risks and the fact there is no detriment to blocking non-visible light.

Violet

At one time, B+L offered IOLs that blocked violet (400–440 nm) light, in addition to UV light. UV phototoxicity is highest in the ultraviolet range, still relatively high in the violet range, and drops off through the blue portion of the spectrum. The purported value of the violet-shield lenses was reduction of oxidative stress on the retina that causes cellular damage.^{11,12} However, this idea never really caught on with clinicians or IOL manufacturers.

Blue

There are currently two types of IOLs that block portions of the blue (440–500 nm) spectrum: the Alcon (Fort Worth, Texas) AcrySof platform and the Hoya (Chino Hills, Calif.) AF-1. Since blue-blocking lenses were first introduced in the 1990s, proponents have argued that blocking blue light could protect the retina from oxidative stress and prevent age-related macular degeneration, while critics have argued that they negatively affect circadian rhythms and color vision and reduce scotopic sensitivity. Studies have failed to conclusively prove that blue-blocking lenses provide any significant benefit or harm.^{13,14}

Given that there are no quality of vision or clear health advantages to blocking blue light transmission, I prefer to use clear lenses that more closely mimic the young human lens and transmit blue light fully. In my experience, there can be a subtle impact of blue blocking on color perception, particularly in highly discerning patients, so I also avoid mixing blue-blocking and clear lenses in the same patient.

In evaluating how IOLs transmit light, we should consider the potential positive and negative effects. A good principle is to mimic the properties of the crystalline lens but avoid unnecessarily blocking any portion of the visible spectrum.

Roundtable discussion: Choices in clinical practice

Daniel Chang, MD (moderator): As you all know, optics is something I'm passionate about. What are the optical principles that are important to you in evaluating new IOLs?

Jeremy Kieval, MD: Spherical aberration correction is very important. I'm starting to look at the role of correction of chromatic aberration, too, so I look for information about the lens material's Abbe number and index of refraction. The potential for glistenings is something I keep in mind, although I'm still waiting for data on whether glistenings truly compromise image quality.

Sam Garg, MD: I want to know that the manufacturing of the lenses is done within very tight parameters so I can feel confident that the optical results are reproducible. When I'm considering any new entrant to the market, I expect it to be at least on par with current IOLs and, ideally, a step better. I match my spherical aberration (SA) to the patient so that I get SA close to zero. My goal is to give patients vision that is as close as possible to what they had at age 20, or even better.

Dr. Chang: What have we learned about optical quality from experiences with multifocal IOLs?

Dr. Kieval: Multifocal IOLs are phenomenal devices with many advantages for our patients but, by virtue of the optical principles that provide multifocality, they do reduce image quality. That has forced all of us to work harder to control factors such as residual refractive error, dry eye, and higher-order aberrations that can otherwise compound the reduction in contrast sensitivity and image quality with multifocal IOLs.

Dr. Garg: I see a fair number of multifocal IOL patients for second opinions. In the vast majority of cases, everything went right with the surgery, but the patient is bothered by the quality of vision, either because their expectations were not set appropriately or their ocular surface issues are not being addressed.

Gary Wörtz, MD: I agree. When you implant a multifocal lens, it is essential to get everything else—material, capsulorhexis, centration, and ocular surface—right. If you are going to split incoming light rays for multifocal vision, you definitely want that light to be in crisp focus, with as little spherical and chromatic aberration as possible.

Dr. Chang: I agree. In addition to what we as surgeons can do to optimize visual quality, it is important for IOL manufacturers to balance the optical properties of refractive index, spherical aberration, and chromatic aberration to give us lenses that provide maximal image quality with as much forgiveness as possible.

Dr. Chang: Do you think spherical aberration (SA) or chromatic aberration (CA) is more important for optical quality?

Dr. Wörtz: SA has gotten more attention in the past but that may only be because it was an easier problem to solve with design modifications. CA is an optical property that is more material-related and harder to change. I think CA gets downplayed but it is really important.

Joseph Ma, MD: Do we have to choose? They are both important for high quality vision; how one might rank them might be patient and task dependent. For example, for most patients, night myopia from CA may be more important than SA for driving at night, while optimizing SA may have more effect on reading depending on that particular patient's amount of corneal SA. There are lenses and laser algorithms that attempt to increase effective depth of field and intermediate reading by inducing more SA than normal. On the other hand, we will also soon have a lens that uses chromatic aberration to help achieve improved contrast in a diffractive lens design.

Dr. Garg: To me, it's really the summation of SA and CA, along with other optical qualities, that is more important. Taken on its own, each one makes a

subtle contribution to visual quality, but added together they make for a perceptibly better visual outcome.

Dr. Chang: I agree that there is a synergistic effect. But if I have to split hairs, my personal opinion is that CA is likely even more significant than SA. SA is a surface curvature property, so the ability of an IOL to minimize SA of the entire eye depends on the specific SA of the cornea. CA is a material-dependent property that benefits every eye. Cataract surgery with an IOL with an Abbe number greater than that of the natural lens (47) can improve CA, so that our cataract patients could actually experience better vision quality than they did as young adults.

Dr. Chang: Let's talk about spherical aberration. Is it an advantage to leave some SA to increase depth of focus?

Dr. Garg: Hoya has an IOL that provides greater depth of focus through positive SA. That could be an advantage in terms of the flexibility of vision, but not in sharpness of vision.

Dr. Ma: An SA-induced increase in depth of field comes with a compromise in contrast sensitivity. In laser vision correction our goal has always been to achieve "super vision," so it's interesting that in cataract surgery we're talking about how much compromise people can tolerate. All things being equal, I'd rather not compromise on image quality if I don't have to.

Dr. Chang: For a patient who frequently drives at night, what optical considerations are important?

Dr. Wörtz: I believe you need to educate all patients about the potential for pseudophakic visual phenomena, which can include dysphotopsias, glare, and halos. Most patients have an easier time adapting to these symptoms if they understand that they are not out of the ordinary and are educated preoperatively about them. Also, aspheric optics tend to make a difference in night-time driving

as they perform well even when the pupil is dilated under scotopic conditions.

Dr. Kieval: I agree. Ideally we want vision under mesopic conditions to be the same as photopic vision, and it's easier to meet that standard with a lens that is less pupil-dependent. I am particularly cognizant of higher-order aberrations like spherical aberration because these increase in magnitude with a larger pupil. Scotopic vision is more reliant on blue and violet wavelengths of light, so I'm also more concerned about chromophores that block this part of the spectrum at night. We are talking about all of this in the context of night driving but good mesopic and scotopic vision are needed in lots of other situations. They are very important, for example, for mechanics, ultrasound technicians, and many others who routinely work in dim light conditions even during the day.

Dr. Chang: Do you think glistenings in the lens optic are a serious problem in terms of visual performance?

Dr. Ma: Certain materials are known to be prone to glistenings or microvacuoles.¹⁵ The visual consequences aren't uniform but they can and do matter in some patients. Furthermore, there is good evidence that glistenings worsen with time.¹⁶ What may not be visually significant at the 4- to 5-year mark could become visually significant a decade after that. With longer life expectancies and earlier implantation of IOLs in refractive cataract surgery, this is a major concern.

I have personally had several cases now in which the patient's vision was compromised by glistenings and the lenses had to be explanted 15 years after surgery. After IOL exchange, the vision returned to 20/20 so I am confident the loss of acuity was due to glistenings, rather than other causes.

Just recently, at the 2014 ESCRS meeting, the top video prize went to a film that discussed the opacification of IOLs.¹⁷ A key point in the film is that opacification in hydrophobic lenses from glistenings results from the temperature-dependent interaction of water

molecules with the lens polymer. Glistenings don't usually require surgical intervention, at least in the short term, but the degree of opacity increases incrementally over the long term, which correlates exactly with my clinical experience. In addition, even the relatively minor 10–20% reduction in light transmission may be more problematic in the context of multifocal IOLs that already reduce light transmission.

Dr. Chang: How important is it to you to minimize changes in lens thickness across the dioptric range of an IOL platform?

Dr. Ma: I think it's definitely worth paying attention to. The smaller the variation in lens thickness, the more predictable the effective lens position (ELP) will be throughout the full range of dioptric power. If there is a large variation, it is more difficult to predict ELP and, therefore, the refractive outcome. The ability to control the thickness range is related to both material and design. The material's index of refraction governs the thickness required to achieve the appropriate change in curvature over the dioptric range, and certain design features can help to compensate for variation in thickness.

We recently presented a paper at the 2014 ESCRS in London on a method for using three-dimensional morphology from intraoperative OCT in femtosecond ReLACS to predict postoperative lens position. A secondary outcome of this paper was that lens thicknesses do matter when we consider the accuracy that we can potentially achieve with this methodology.

Dr. Wörtz: I'm not as concerned about this from an optics perspective, but I do like a platform where I can standardize the incision size and the injector cartridge regardless of the IOL power. It's just one less thing to worry about.

Dr. Chang: Beyond the optics of the IOLs themselves, what are the surgical factors we can control that affect image quality?

Dr. Wörtz: I know I'm in the minority on this, but I like to make a relatively large capsulorhexis of about 6.0 mm, especially in younger patients. Sam Masket, MD, and Nicole Fram, MD, have shown convincing evidence that by reverse optic capture, negative dysphotopsia can be eliminated. This has led me to start making a larger rhexis so that I do not have much, if any, anterior capsule optic overlap. While I don't place the optic in the sulcus, it still has dramatically reduced the incidence of negative dysphotopsia, and it also ensures that the optical zone isn't reduced by capsular phimosis over time.

Good centration is also critical, especially with multifocal IOLs. The best clinical marker for centration is the subject-fixated coaxially sighted corneal light reflex, as Chang and Waring have recently described.¹⁸ Finally, the ocular surface has a huge impact on quality of vision. The tear film is the first refractive interface and can be the rate-limiting factor. For any patient with more than trace to Grade 1 SPK, I think we have to be willing to "press pause." We need to treat the underlying meibomian gland dysfunction or other ocular surface problems before proceeding with surgery. Otherwise, we can't even accurately calculate the IOL power and axis, let alone guarantee high-quality vision after surgery.

Dr. Kieval: Keep in mind that significant lens decentration or tilt can negate the benefits of asphericity. The femtosecond laser is a wonderful tool to aid in lens positioning and centration. In particular, being able to customize centration of the anterior capsulotomy is helpful in allowing the lens to center accurately.

Dr. Garg: I think IOLs usually center on the equator of the bag, so a capsule-centered opening works well in most eyes, especially if you perform diligent surgery with meticulous cortex removal. However, in patients with large angle kappa, there is a high risk of visual quality degradation because it's very difficult to

center the lens appropriately for the true visual axis. I always look at angle kappa preop. If it is >0.5 mm, I won't implant a multifocal IOL.

Dr. Chang: We're just beginning to learn the impact of centration on visual quality. Many surgeons get confused when discussing the particulars of visual axis, line of sight, and angle kappa. That represents not a lack of knowledge but rather the fact that current definitions are too ambiguous to fully address this issue. That's why George O. Waring IV, MD, and I have proposed a new reference marker and terminology such as subject-fixated coaxially sighted corneal light reflex (SF-CSCLR), foveal fixation axis (FFA), and chord μ .¹⁸

Dr. Chang: What do you think the future holds in terms of IOL materials and design?

Dr. Wörtz: In general, I want to see lenses that provide better refractive outcomes by making it easier to hit the target of emmetropia. I'm very interested in the extended range of vision lenses that will be coming soon. These are very user-friendly lenses that increase the "sweet spot" but eliminate glare and halo.

Dr. Ma: I agree. By taking advantage of the effect of diffractive gratings on chromatic aberration, the new Symphony lens has the potential to provide true blend-free vision without dysphotopsia or compromised contrast. It seems very promising to me. Oculentis (Berlin) and Morcher (Stuttgart, Germany) also have some new approaches to centration in the pipeline that will help us center IOLs based on the capsulorhexis instead of the capsular bag. And on a longer horizon, maybe 6 to 10 years away, I think we can look forward to new accommodative lens designs from several manufacturers.

Dr. Kievall: I think we'll achieve some consensus on the ideal index of refraction and Abbe number. Maybe we'll be able to customize spherical aberration to

every eye. On my wish list would be a lens that can function in a fluid, dynamic way to compensate for SA and other aspects of the optical system that vary at different points of focus.

Dr. Garg: I agree. What I really want in a lens is to duplicate the flexibility of focus, the optical clarity and quality, and the natural protections of the 20-year-old human lens. We are already very close to this goal, and I think we'll see more exciting developments in the next 15 to 20 years. Additionally, I think we'll continue to see more synergies between new IOL technology and developments in femto phaco surgery that will change how we think about cataract surgery.

Dr. Chang: This has been a great discussion. We can certainly look forward to having greater functionality and options with new IOL designs in the future. As we evaluate those new lenses, I think it remains important to always go back to the basic question: What are the lens material properties and how do they affect image quality in the eye? If we keep that question in the forefront, we'll be able to continue refining cataract surgery and making the best IOL choices to meet our patients' visual goals for years to come.

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