Vignetting and Negative Dysphotopsia with Intraocular Lenses in "Far Peripheral Vision"

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At very large visual angles, vignetting can occur at the edge of an intraocular lens (IOL) because it is much smaller than the natural crystalline lens that it replaces. Raytrace calculations show that by 80-90 degrees of input visual angle it is possible that about half the light is no longer focused by the IOL. This may create curved, peripheral, shadowlike regions, which are a clinical characteristic of negative dysphotopsia. The imaging characteristics for this "far peripheral vision" region are different from those of a phakic eye, whether or not negative dysphotopsia is experienced.

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1. Introduction

Intraocular lenses (IOLs) have been used for about 50 years to replace the natural crystalline lens of the eye during cataract surgery. However, the first clinical observations of "dark shadows", or "negative dysphotopsia", were only reported about 15 years ago [1]. Several improvements had come together at that time to create modern small incision cataract surgery, including phacoemulsification, the continuous circular capsulorhexis, small incisions, and foldable IOLs. There had also been a particular emphasis on cleaning the capsule during surgery in order to reduce the incidence of posterior capsular opacification (PCO), and sharp IOL edges had been shown to be beneficial in reducing PCO. These improvements had generally led to clearer postoperative lens capsules, and better overall vision.

There have been many discussions about negative dysphotopsia in the literature [1-11], but there is not yet a clear consensus about the cause. Many of the proposed causes involve a shadowing mechanism of some sort, including shadows involving the sharp edges of IOLs [3], which were becoming popular at the time when dark shadows were first noticed. Other unwanted optical effects have also been suggested as the source, such as the anterior capsule [5, 9-10] and the corneal incision [7].

More recently, a theoretical evaluation has been conducted of the imaging properties of light focused by the IOL in the far peripheral vision region of the eye [12-14]. Figure 1 demonstrates how light rays can take two separate paths at the edge of the IOL. Only a single object point is illustrated, but light comes from all directions in a normal illuminated environment where dark shadows are perceived. Two displaced images can be formed on the retina, with a shadowlike region where they overlap. Obstructions and light scattering from the capsule, particularly from something like Soemmerings ring, would have greatly reduced this imaging possibility with early IOL surgeries. Scattered light would also weaken the effect of a shadow.

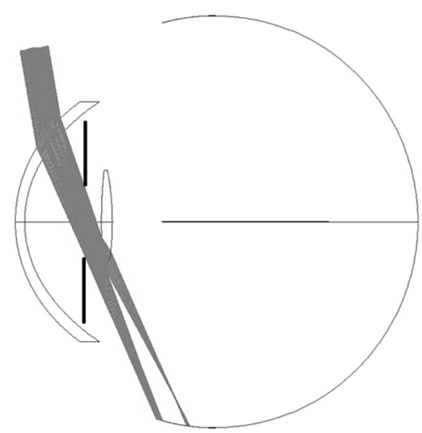


Fig. 1. Schematic eye from above, where light at 80 degrees of visual angle is partially focused by an IOL and partially bypasses the IOL

There is an ambiguity in the clinical reports about whether the shadow is bordered on both sides by brighter regions or not [3], which would be a specific characteristic of a double image. However, the double image evaluation has led to a simplified method for estimating the shadow location. This is illustrated in Fig. 1, where the shadow location is primarily determined by "vignetting" at the outer edge of the posterior optical surface of the IOL. A light ray is said to be vignetted when it is blocked in an imaging system, and vignetting typically leads to dark shadowlike regions at the periphery of an image, which is exactly the type of observation that occurs in clinical reports of negative dysphotopsia [1-11]. This approach greatly simplifies the optical modeling, since only the optical system up to the IOL needs to be included, and questions about scaling the image on the retina do not need to be addressed [12].

Unfortunately, the visual angle at which negative dysphotopsia is perceived has not typically been reported, and there are no specific clinical data for comparison. The calculations suggest, however, that both the visual angle, and the "darkness" of the shadow, might be used to objectively characterize the phenomenon in the future. Previous clinical reports have looked instead for trends and correlations between various parameters [1-11], but these studies have typically only found weak relationships, with few subjects, and limited controls. Even "far peripheral vision" in general does not appear to be a topic that has been extensively researched, and it is possible that objective data about the nature of the shadow may characterize visual properties of this region of the retina. One study that approaches the visual angles of interest here is a study of photorefractive keratectomy (PRK) patients that found a reduction in visual field thresholds for visual angles from 40^0 to 60^0 [15]. This is due to the change in power at the edge of the ablated region, which has some similarity to the change in power at the edge of the IOL, though shadows were not reported, and the measurements did not go beyond 60^0.

The approach here is to take the simplest description for the eye, with just a cornea, thin iris, and simple IOL optic, and to estimate the visual angle at which a shadow might be perceived. The evaluation is primarily of a change in the light energy that might be incident on the retina, and not an evaluation of the overall visual system.

2. Materials and Methods

The Zemax raytrace software (Radiant Zemax, Redmond, WA) was used to extend earlier work [12], where the schematic model eye and IOL were very similar to the ones described by Holladay et al [3]. The eye has a corneal power of about 43.5 D, and a 20D acrylic IOL was used that had a refractive index of 1.55, anterior surface power 7 D, center thickness 0.63 mm, and diameter 6mm. The retinal surface was assumed to be a 12 mm diameter sphere, with the center located at 11.84 mm from the corneal apex. The Zemax model eye was rotated by 90 degrees in order to perform calculations for input visual angles to the eye that are close to 90 degrees.

Figure 2 superimposes an estimated preoperative raytrace onto this average postoperative eye for light input at 80 degrees of visual angle. The IOL is much smaller than the natural crystalline lens, which is modeled here with a diameter of 9.5mm and a relatively youthful center thickness of 3.8 mm. The physical diameter of foldable IOLs is typically about 6 mm, and negative dysphotopsia has been reported for IOL diameters of both 5.5 mm and 6mm diameter [1, 7], though the IOL diameter is rarely specifically reported. The IOL thickness also varies with IOL power, material refractive index, and physical design attributes, but the IOL is always very much smaller than the crystalline lens that it replaces.

This type of optical modeling of the eye at very large angles is new, and verification of some of the parameters is limited. Most previous eye modeling has involved either foveal vision, or peripheral vision out to perhaps 50 degrees, but rarely any evaluation out to the "far peripheral vision" region. The cornea is not normally evaluated in detail at large input angles like this, and the optical surface values were those normally used for modest input angles [12], with the assumption that they would be accurate enough for these initial calculations (r1= 7.77 mm, Q = -0.18, r2 = 6.4 mm, Q= -0.6).

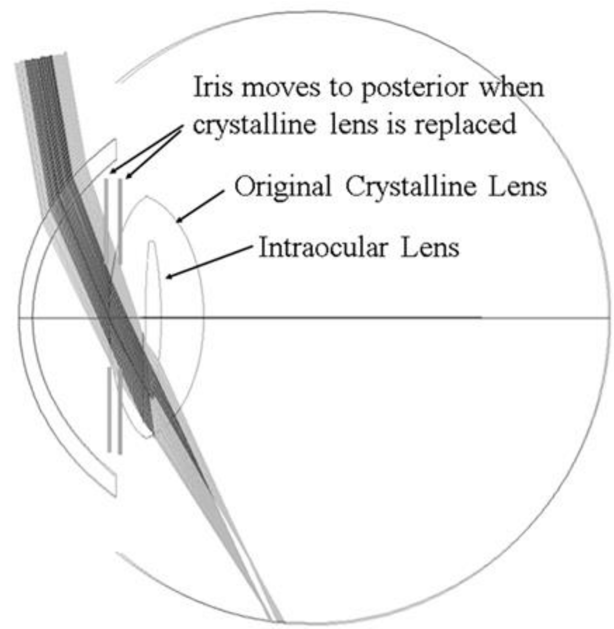


Fig. 2. View from above of superposition of pseudophakic right eye on original phakic eye for light at 80^0 visual angle and IOL at 5.1mm. The iris and the input beam move for the pseudophakic eye, and common input rays are depicted in dark gray. Rays not focused by the IOL stop when they reach the IOL plane.

The iris is originally at 3.6 mm from the anterior cornea in this example for the phakic eye [12], where the crystalline lens is assumed to essentially push the iris forwards as it grows, with very little clearance between the iris and the IOL. After the crystalline lens is removed, it is assumed that the iris moves 0.5 mm to the rear, to a location that is 4.1 mm from the anterior corneal apex. The parameters of the pseudophakic eye are generally those used in reference 3. The iris is modeled as a thin structure even though it obviously has considerable bulk. The separation between the iris and an IOL is rarely published [7-8, 11, 16-17], and two specific values were used, with values of 1 mm (which is a large separation) and 0.5 mm (which is perhaps more typical). These correspond to IOL locations of 5.1 mm and 4.6 mm from the anterior corneal vertex. The same IOL was used for both calculations, since the lens power should have relatively little effect on vignetting, even though the power would normally change for different axial locations. Calculations were made for several pupil diameters.

Light can be seen to enter the eye at a very extreme visual angle of 80 degrees in Figure 2, which depicts a right eye when looking down from above. Dysphotopsia is only experienced in the temporal direction because the nose, eyebrow and cheek create obstructions, and the light rays are depicted here in the horizontal plane at the level of the optical axis for a circularly symmetric eye model. In practice, a real eye would normally have modest tilts and decentrations for the various components, but these are not included here.

The main parameter of interest for this simplified calculation method is the percentage of light rays passing through the pupil that also pass through the posterior surface of the IOL, and this is illustrated in Figure 3. The input beam passes obliquely through the iris, and because there is a gap between the iris and the IOL, only part of the beam passes through the posterior IOL optic surface. Only the relative energy in the light actually focused by the IOL is evaluated, and this is done as a function of both input visual angle and pupil diameter. This evaluation does not take into account additional characteristics that are also of interest, such as what happens to the light that is not transmitted by the IOL optic, and how well the image is focused. Light not focused by the IOL is depicted in Figure 2 as stopping when it reaches the IOL plane. Visual acuity is also so poor in the far periphery that the level of focus is considered to be much less important than illumination when the main interest is in evaluating a shadowlike phenomenon. The effect of the finite thickness of the iris is also not modeled.

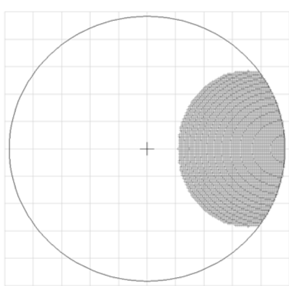
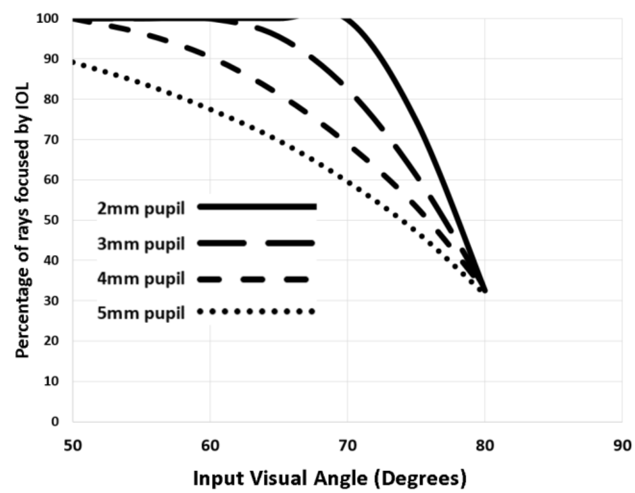


Fig. 3. Zemax "Footprint Diagram" of the posterior IOL surface, viewed from anterior, for right eye. Only the portion of the light shown in gray passes through both the pupil and the posterior IOL surface.

A routine was written in Zemax to calculate the percentage of light rays that pass through the posterior IOL surface from a distant monochromatic point light source (546 nm wavelength) at 6 meters. Calculations were made for input visual angles from 50^0 – 90^0 and for pupil diameters from 2-5 mm. The Matlab software (Mathworks, Natick, MA) was used to create images of the vignetting effect, where a rectangular image is used to represent visual angles covering 90 degrees horizontally and 50 degrees vertically, with the relative transmittance of the light used to set the pixel intensity for each visual angle. This is a much larger vertical range than images calculated previously [12], in order to clearly include the curvature of the shadowlike effect.

3. Results

Figure 4 gives plots for the vignetting of the light as a function of visual angle for several pupil diameters. The visual angle at which focused light starts to be truncated by the edge of the IOL posterior surface can be as low as 50 degrees, and by 80-90 degrees of input visual angle about half the light is no longer focused by the IOL. These visual angles are well within the maximum visual field, which may go out to over 100 degrees [3]. The plots indicate that the vignetting effect is relatively abrupt for smaller pupil diameters, and that as the pupil opens up there is a much more gradual change over a much larger range of visual angles. This would make the shadow phenomenon much less visible as the pupil gets larger, which would agree with clinical reports [2-3]. There may also be more scattered light with a larger pupil as more of the peripheral capsule becomes illuminated, which would further weaken a shadow.



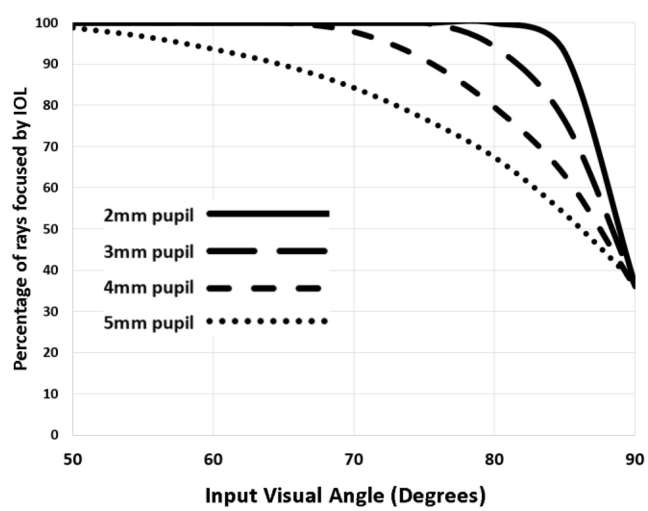


Fig. 4. Percentage of light rays focused by IOL at 1mm behind iris (upper plot) and 0.5 mm behind iris (lower plot). The IOL axial locations are 5.1 mm and 4.6 mm respectively.

Figure 5 takes the data for vignetting plotted in Figure 4 and displays the energy reduction in the form of images as a function of visual angle. These are visual field images for a right eye, where the fovea is on the left. The images match the orientation of figures 1 and 2, where the actual image on the retina would be inverted by the optical system, but the calculation is reoriented to match the view by the patient. The shadowlike region on the right is curved because the vignetting is determined by the radial distance from the optical axis. Curvature is a common characteristic of vignetting.

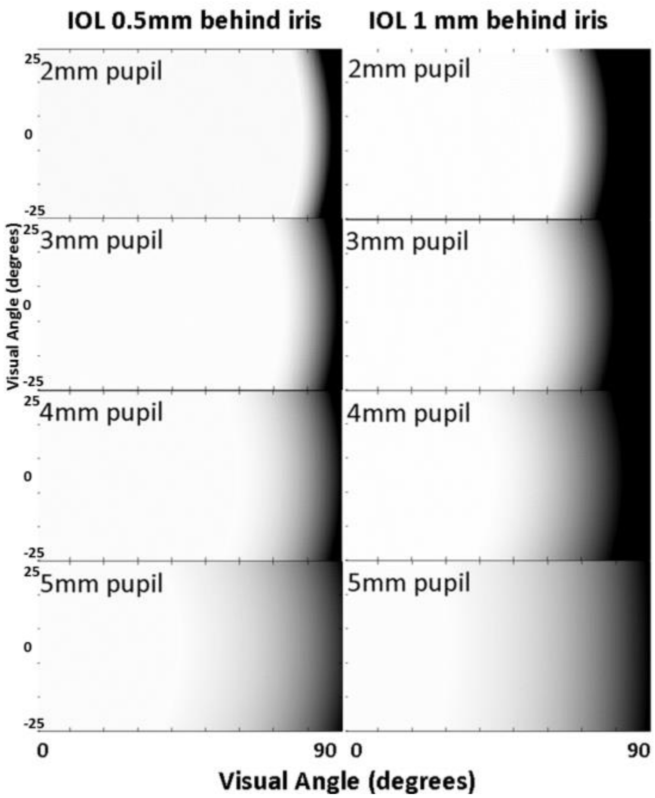


Fig. 5. Vignetting effect for right eyes displayed as images using data from Fig. 4.

4. Discussion

This evaluation indicates that the "far peripheral vision" of a typical eye with an IOL is actually expected to be different to that of a phakic eye, whether or not negative dysphotopsia is perceived. This is primarily because the IOL is very much smaller than the natural crystalline lens that it replaces, but also because the iris typically moves to the posterior following cataract surgery. The light paths for this visual region can be very different to those of the phakic eye. The results also indicate that the effect of vignetting is to create a reduction in intensity that corresponds qualitatively to clinical reports of dark shadows with IOLs.

In practice, very few patients find negative dysphotopsia to be persistently bothersome, and most patients are never aware of it at all. This is probably because visual acuity is very poor for this visual region, and also because the phenomenon has its greatest effect at a relatively fixed visual angle, which would tend to cause it to be ignored, in a similar manner to the way that spectacle frames are generally not perceived to be bothersome. Light that bypasses the lens may also still illuminate the shadow region, which would reduce its visibility, and scattering from the capsule and other locations will also affect the perception of a distinct shadow. An increase in capsular haze over a prolonged postoperative period should further reduce visibility.

For those people who are bothered by dark shadows, however, it is likely that the vignetting by the IOL described here may be the primary cause, since it involves the main component of the light. The focused image goes dim at very large visual angles, and if this happens relatively suddenly, it is more likely to be perceived as a distinct "shadow". The visual angle at which about 50% of the light is vignetted, may correspond to the main "dark shadow" location.

This theoretical evaluation leads to specific clinical questions that should confirm the predominant cause of negative dysphotopsia, while perhaps also evaluating far peripheral vision in general. Published reports typically do not include many of the parameters that are needed to model specific eyes where negative dysphotopsia is bothersome, and even the visual angle of the perceived shadow has typically not been reported. With additional measured data, the clinical location of the shadow could be compared to the calculated value for individual eyes.

There are also several additional aspects of this overall discussion that are relatively new, and it may be useful to discuss them further.

"Far peripheral vision" may not have a strict definition, but Figure 2 illustrates that light incident at 80 degrees of visual angle onto a typical phakic eye forms an image on the retina that is anterior to the equator [12] (where the "equatorial" terminology describes a supine patient undergoing ophthalmic surgery). The retina is oriented here towards the rear of the eye, rather than towards the front, which is a distinctive characteristic that is internal to the eye. The image would be formed on the equator itself for a visual angle of about 70 degrees for this particular eye model, and rounding down slightly to 60 degrees, the visual angle corresponding to the equator is broadly similar to the angle at which the eyebrow and the nose limit the visual field in other directions, which in turn is similar to the extent of the horizontal binocular visual field. All these parameters vary somewhat for individual eyes, but a "far peripheral vision" region above 60 degrees would include the region where peripheral dark shadows are perceived (negative dysphotopsia), and it would tend to exclude the region that is described more generally as "peripheral vision".

The light passes very obliquely through the pupil at these very large visual angles, and the effective aperture is very much smaller in the horizontal direction than it appears when viewed on axis. The thickness of the iris, its axial location, and its centration, can all affect the light transmission. This light then interacts with the IOL, which may also be decentered and tilted slightly with respect to the other eye parameters. All these parameters need to be known if the eye is to be modeled as accurately as possible. Many of these parameters are not typically measured or reported.

By the time the light hits the retina, the intensity of the imaged light in the far peripheral vision region is considerably reduced, even if a shadow is not perceived. However, even the phakic eye would experience reduced intensity at very large visual angles because of the limited effective aperture of the iris, and this must be normalized by the visual system for normal phakic vision, otherwise a dimming of the image, or a shadow, would always be an issue. A detailed evaluation of the difference between the pseudophakic and phakic situations may help clarify why shadows are not a problem for most IOL patients. The limited clinical details that have been published do not indicate that IOL patients bothered by dark shadows have distinctly different separations between the iris and the IOL in comparison to other patients who are not bothered [7, 8]. It is possible that there may be a characteristic of far peripheral vision itself that causes negative dysphotopsia to be more bothersome for certain patients.

The vignetting calculation helps to avoid the additional problems of scaling the retina of the eye for an eye model. With the natural crystalline lens, a particular input visual angle will generally correspond to a particular physical distance along the retina from the fovea. This may change slightly as the crystalline lens grows throughout life, but this relationship is not typically known, and there has never been a need to create a measurement method that relates these parameters. When the IOL replaces the natural lens, the relationship between the physical retinal location and the input visual angle is relatively unchanged for the imaged component [12]. However, any light that misses the IOL reaches the retina at a location that corresponds to focusing only by the cornea, as though it were an aphakic eye, and this does not match the retinal location for that visual angle of the phakic eye.

A related concern, that light bypassing the IOL may not fall on functional retina [3], appears to be misleading. Ray paths can be drawn on the figures in that paper between the pupil margin and the IOL that are incident on a normal retinal region, and this is confirmed by calculations in Reference 12. Scaling of the total physical extent of the useful retina appears to be very rare, however, and although there are recent evaluations of the overall shape of the retina [18], these do not appear to include a method that identifies the physical limit where the retina has a response. Retinal scaling questions are avoided here by only considering the primary focused image.

The use of IOLs with a sharp posterior edge are also mentioned in discussions of negative dysphotopsia, but this feature would apply to many IOL styles, and it is not particularly distinctive. The characteristics of the IOL edges themselves can vary, however, and common IOL edge profiles that are rounded, textured, or otherwise distinctively shaped have not been included in previous evaluations [3, 12]. Textured edges in particular are widely used, and they are involved with reports of negative dysphotopsia [12]. The diffuse nature of textured edges greatly reduces the accuracy of raytracing since the light would scatter instead. It has been assumed here that the edge itself can be largely ignored when evaluating the shadowlike characteristics created by vignetting.

Clinical reports use the word “arc” and the word “crescent” to describe the shadow, but there appears to be very little published information that includes objective measurement of either visual angles or darkness levels relating to the shadow, and the wording is unclear. A thin dark crescent, which is bounded by two different arcs, might be simply called an arc anyway. Patients have sometimes sketched what they perceive as a circle on a white sheet of paper with a thick black line near the outer edge [3, 7], but it is not really clear what this means. It seems unlikely that a reduction in the total visual field would be described as a “shadow”, and it seems more likely that there is a shadowlike change in intensity near the periphery.

The discussion here does not specifically evaluate clinical methods that have been used to ameliorate negative dysphotopsia, and typically only limited information has been published about these. Inserting an IOL in the sulcus to reduce the separation between the iris and the IOL has been found to be beneficial [8, 11], and this has been recommended as a clinical method for resolving complaints about negative dysphotopsia [11]. This is supported by the calculations here, where the shadow location moves more peripherally as the IOL moves closer to the iris, which presumably makes the shadow less visible. The effect that adjustments involving the lens capsule have on the shadow are less easy to explain, though capsule clarity and IOL movement may be involved [5, 9-10].

Only a limited range of eye parameters has been modeled here, and variations in corneal power, iris location, axial length, and IOL power may also have an effect on shadow visibility. The use of a smaller or larger IOL optic is another variable, though this may have a much smaller effect than might be expected because the ray paths are very oblique. The angular difference between the optical axis and the visual axis is also a variable. The angles used here are given relative to the optical axis for a simple eye model, but the visual axis is rotated on average by about 5 degrees in the nasal direction [19], and the actual visual angle would typically be reduced by this amount, making the shadow visible at a lower visual angle. The complex inter-relationship between these parameters, and other factors such as differences in capsule clarity, and defocus of the far peripheral image, tend to confound attempts to draw correlations with shadow visibility.

Overall, the calculations indicate that vignetting at the IOL can create shadows that have similar characteristics to the clinical reports of negative dysphotopsia. However, there is a need to generate objective clinical data about the nature of the shadows for comparison to theoretical calculations. What is the visual angle of the inner boundary of the shadow? If there is also an outer boundary, what is that visual angle? How dark is the shadow? Also, how do these characteristics vary with pupil diameter?

More generally, the evaluation asks questions about what a normal phakic eye sees in the far peripheral vision region. This may be important in explaining why the imaging differences in this region of the pseudophakic eye do not result in more clinical observations. There may also be changes in this visual region as a cataract develops that have not been previously evaluated.

Funding Information

None.

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