Intraocular straylight measurement as a new parameter in visual quality assessment

Gustavo Adolfo Montenegro Martínez

Universitat Autònoma
de Barcelona

Intraocular straylight

Intraocular straylight measurement as a new parameter in visual quality assessment

Doctoral thesis of

Gustavo Adolfo Montenegro Martínez

Barcelona 2015

INSTITUT UNIVERSITARI BARRAQUER

UNIVERSITAT AUTÒNOMA DE BARCELONA

DEPARTAMENT DE CIRURGIA

Intraocular straylight measurement as a new parameter in visual quality assessment

Author:

Gustavo A. Montenegro Martínez

Directors:

Prof. Joaquín Barraquer Moner

Dr. Ralph Michael

Tutor:

Dr. José García Arumí

Barcelona, 2015

Table of Contents

1. Introduction

1.1 Visual quality parameters

1.1.1 Visual acuity

Historically, visual acuity measurement has been the standard parameter when assessing visual quality. It refers to the resolution capacity of the eye to discriminate fine details, this is, the minimum distance needed between two objects so the eye can identify them as two different objects. This resolution is limited by the cones disposition over the fovea and corresponds to light deflections over the retina in small visual angles, typically in the order of 1 minute of arc (0.02º). In order for two points to be resolved as separate objects, two cones have to be stimulated leaving an unstimulated one between them. Visual acuity can be affected specially by optical imperfections in that scale, that is, optical aberrations, of which defocus is usually the most important.

In 1862, Hermann Snellen published an acuity chart based on the disposition of the cones over the fovea. The chart consisted on high contrast black letters on a white background, that he called optotypes and fitted in a 5x5 grid, each grid subtending 1 minute of arc. The optotypes were arranged in lines, with the largest one on top of the others and decreasing in size as the lines go down (figure 1.1.1).

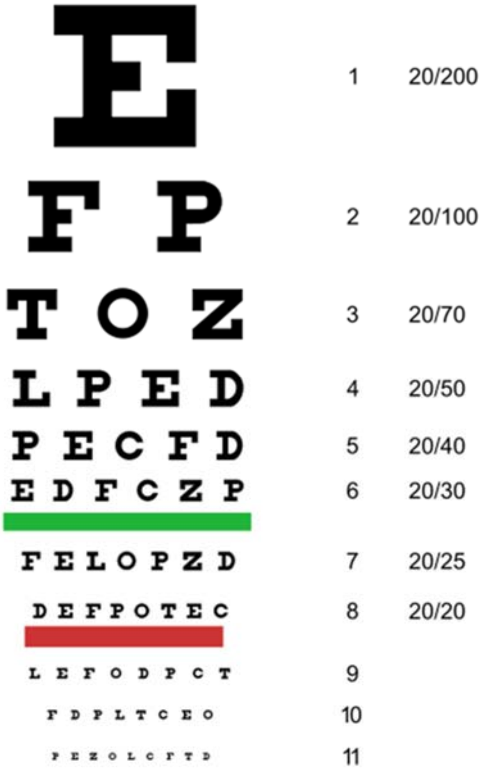


Figure 1.1.1. Snellen's chart is still used today for measuring visual acuity.

A few years later, John Green proposed a reading chart with geometric progression of the letter sizes and proportional spacing between them, but it was not well received at that time.

In more recent years, the Early Treatment of Diabetic Retinopathy Study group designed a reading chart that is nowadays used as the standard method for visual acuity testing in clinical trials. This chart has similar characteristics to the John Green's chart (figure 1.1.2).

Figure 1.1.2. ETDRS visual acuity chart used for clinical trials.

1.1.2 Contrast sensitivity

Contrast is the difference in luminance of two different objects or within the same object. Unlike visual acuity testing, where the optotypes have high contrast (black letters on a white background), visual tasks in the real world involve varying contrast. Photoreceptors in the retina need a determined difference in luminance level to distinguish objects. The minimum difference in the contrast needed is called the sensitivity threshold.

The Pelli-Robson chart is one of the most commonly used methods for testing contrast sensitivity. Similarly to a visual acuity chart, the Pelli-Robson chart uses letters over a white background, but instead of having letters with decreasing size in every row, it has equally sized letters on every row, but with decreasing contrast with respect to the background (figure 1.1.3).

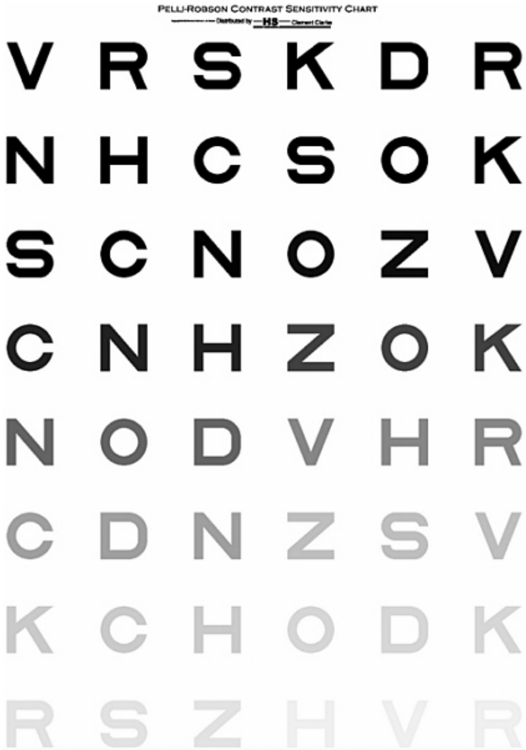


Figure 1.1.3. The contrast on the Pelli-Robson chart decreases every three letters.

Another common way to measure the sensitivity threshold is by using sinusoidal grating patterns that can be adjusted to any size so they can also be used for assessing the resolution capacity of the eye. The size of the grating can be expressed in cycles per degree of visual angle, one cycle consisting of one dark line and one light line. Contrary to the Pelli-Robson chart, where the cycles per degree would be constant, other contrast sensitivity testers like the CSV-1000 (Vector Vision; Haag Sereit, Harlow, UK) or the Optec® 6500 (Stereo Optical Co.) use grating patterns with varying spatial resolution, or cycles per degree, that progressively decrease in contrast until a threshold is reached (figure 1.1.4). With these charts, the contrast sensitivity is measured at different spatial frequencies.

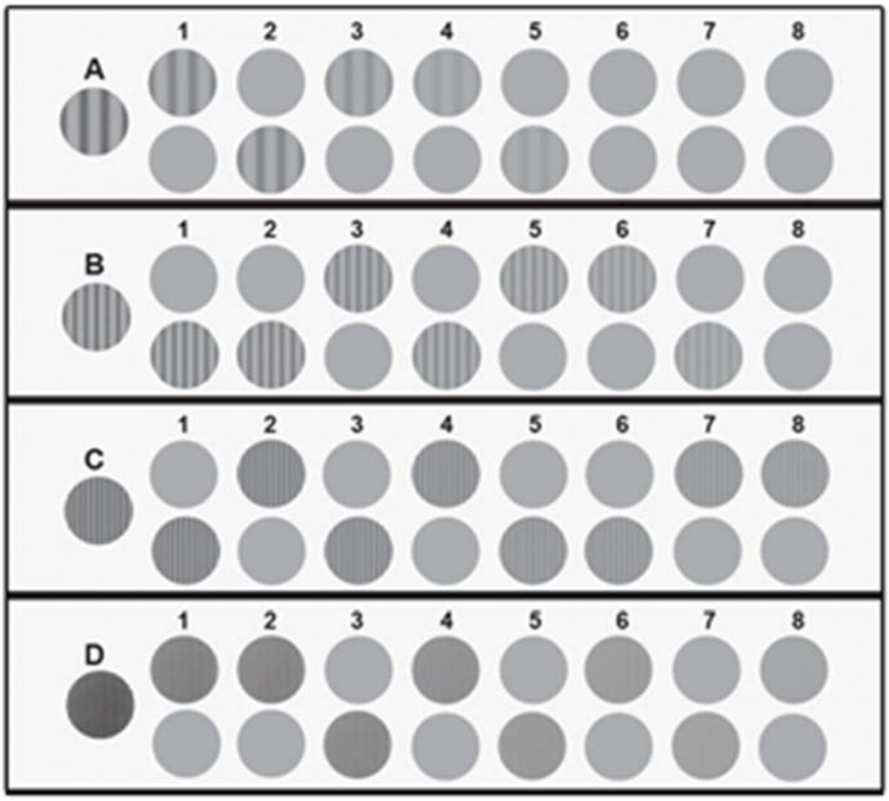


Figure 1.1.4. Front panel of the CSV-1000 contrast sensitivity test instrument. The front panel of the instrument is back illuminated.

1.1.3 Intraocular straylight

Intraocular straylight can be defined as the scatter of light, coming from a glare source, in the optical media of the eye producing a veil of light on the retinal image. An increase of intraocular light may produce not only discomfort but also deleterious effects on visual quality such as hazy vision, loss of contrast and color, or glare disability (Franssen, 2006).

The International Commission on Illumination (CIE) defines disability glare as straylight, which is measured by the equivalent luminance, a concept introduced by Cobb (Cobb, 1911). The equivalent luminance adds to the luminance of the background and the object, reducing the luminance difference threshold of the scene, i.e., reducing the contrast between the object and the background.

Since the eye is not optically perfect, there is a small amount of straylight normally present in the eye. This scatter can increase in the presence of ocular pathologies that course with disturbance of the optical eye media, producing the effects mentioned above.

1.2 Sources of straylight in the eye

Every component of the optical media, even in a normal eye without media disturbance, can cause a scatter of the light going to the retina. Main sources of straylight within the eye are: cornea, iris, sclera, crystalline lens and fundus (figure 1.2.1). Each of these elements contribute a different percentage of the total straylight and may vary with age, pigmentation, associated ocular pathologies, or even as a side effect of ocular surgery (Franssen, 2007).

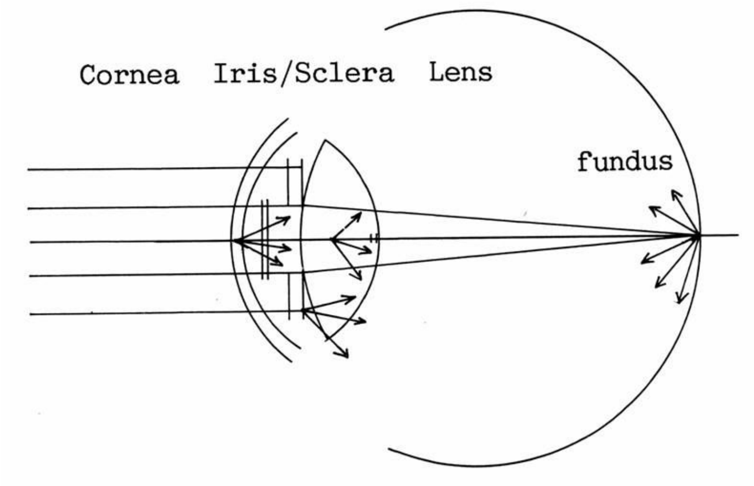


Figure 1.2.1. Schematic of light scattered in the eye. (image taken from (Franssen, 2007)).

1.2.1 Cornea

In a normal healthy eye, the cornea accounts for about one third of total intraocular straylight (Franssen, 2007; Vos, 1963). This proportion remains rather constant with age, although certain corneal pathologies may increase it, as in the presence of opacities or edema (figure 1.2.2a), with a greater impact on intraocular straylight than on visual acuity, especially in some corneal dystrophies (figure 1.2.2b).

Intraocular straylight may also increase with the simple fact of wearing contact lenses, in particular if they are smudged, scratched, or have deposits on them. Furthermore, increased intraocular straylight may persist after taking the contact lenses off, in the case of rigid ones (van der Meulen, 2010). Experimental induction of corneal edema from contact lens wearing yielded a 50% increase of intraocular straylight for every 10% of corneal swelling (Elliott, 1993).

Some authors have also reported a transient increase of intraocular straylight after laser refractive surgery, like photorefractive keratectomy (PRK) and LASIK (Li, 2011; Veraart, 1995), and in most cases it returned to normal values. Nonetheles, other studies sugest that intraocular straylight may remain elevated in about 5% - 20% of the cases, even in the absence of clinical signs (van den Berg, 2010). Furthermore, it has been documented that post-operative complications may markedly increase intraocular straylight or even become permanent, in such cases as a diffuse lamellar keratitis (DLK) (figure 1.2.2c) after radial keratotomy (Veraart, 1992) or a persistent haze after PRK (Veraart, 1995).

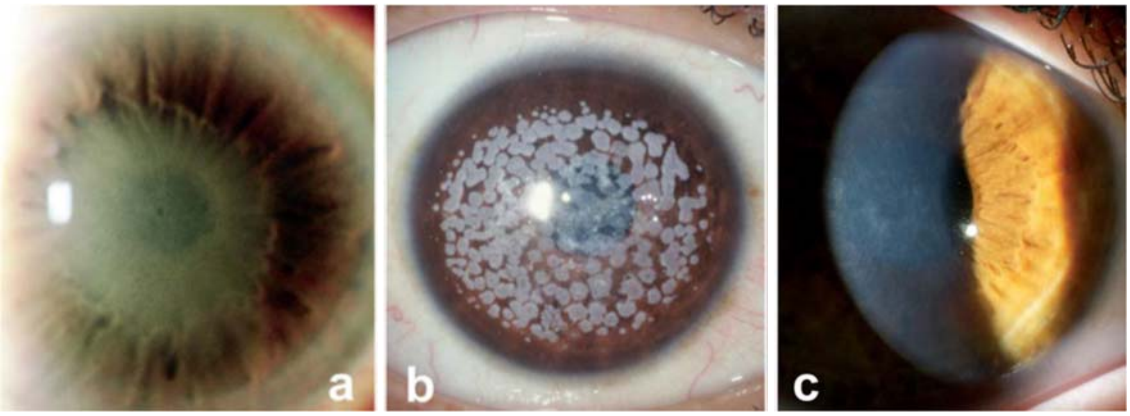


Figure1.2.2. Corneal conditions that may affect intraocular straylight more than visual acuity. a) Central corneal edema in Fuchs dystrophy, b) Granular corneal dystrophy type II (homozygous), and c) Interface scaring due to Diffuse Lamellar Keratitis after LASIK

1.2.2 Crystalline lens

Another one third of the total straylight in a normal eye is due to the crystalline lens (Franssen, 2007), which on the other hand, does increase with age due to nuclear sclerosis and cataract formation. Measured intraocular straylight apparently continuously increases with cataract severity as estimated by the mean lens opacity classification system (LOCS) score. Mean intraocular straylight for the lowest mean LOCS score (0.1) is about 1.0 log(s) and with a mean LOCS score for mild cataract (> 0.75) is about 1.4 log(s), this corresponds to a more than threefold increase of intraocular straylight. Cataract severity scores seem to be much better correlated to intraocular straylight than to both visual acuity and contrast sensitivity (Michael, 2009). A low correlation has been found between LOCS scores of individual cataract components and the Visual Functioning Questionnaire VF-14. Only the LOCS score on posterior subcapsular opacity gave a high correlation (Heys, 2008).

Nischler et al (Nischler, 2010) found that with a low to moderate cataract grade, individual cataract components alone showed lower intraocular straylight values than the mixed cataracts. The lowest values of intraocular straylight were found in nuclear cataracts (1.19 log s), followed by cortical (1.20 log s) and posterior subcapsular cataract (1.23 log s). Mixed nuclear and cortical cataracts had a mean of 1.30 log(s) and mixed nuclear, cortical and posterior subcapsular cataracts had a mean intraocular straylight of 1.35 log(s). With cataract progression, intraocular straylight values of 2.0 log(s) or higher can be reached.

Even though increased intraocular straylight due to cataract formation can be reduced after cataract surgery, light scattering inside the eye can be elevated again due to the development of certain conditions after surgery, such as posterior capsule opacities. Also, opacities in the intraocular lens (IOL) or the lens material itself may influence the amount of light that is scattered. Guo et al. found that intraocular straylight was lower in patients implanted with hydrophilic acrylic IOL as compared with hydrophobic acrylic and PMMA IOLs (Guo, 2014). Hydrophobic acrylic IOLs have largely been studied for their high incidence of glistenings. A recent study suggests that IOL glistenings may increase intraocular straylight (Henriksen, 2015). In cases of opacification of the IOL material, the main clinical manifestation could be a hazy vision, which is associated to an increase of intraocular straylight, and is usually more pronounced than the decrease on visual acuity (figure 1.2.3).

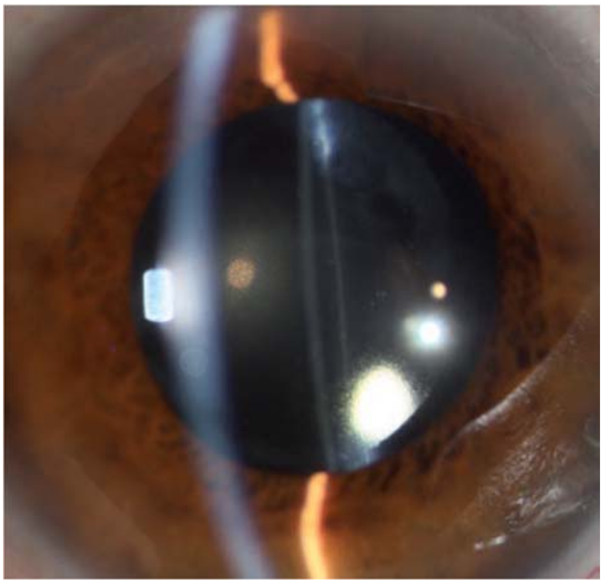


Figure 1.2.3. Opacification of an acrylic hydrophilic IOL that resulted in an important intraocular straylight elevation.

Posterior capsule opacification (PCO) is the most common complication with a visual impact after cataract extraction surgery (figure 1.2.4a). This opacification may significantly increase intraocular straylight. Laser capsulotomy performed to treat this condition, generally improves intraocular straylight (figure 1.2.4b). Nonetheless, studies have shown that small capsulotomies with large capsule remnants inside the pupillary area are the cause of maintained or even increased intraocular straylight after posterior capsulotomy (van Bree, 2008; van Gaalen, 2010).

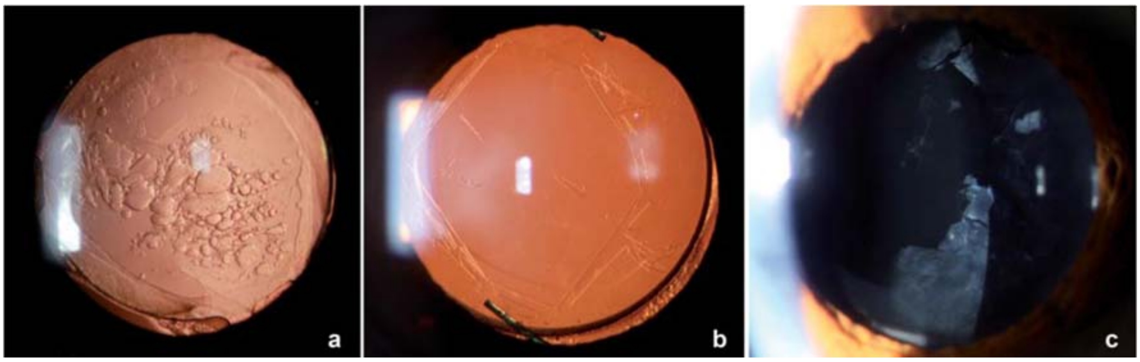


Figure 1.2.4. Posterior capsule opacification (a) causes an increase in intraocular straylight, which can be improved by a laser capsulotomy (b). Small capsulotomies or capsular remnants inside the pupillary area may produce a maintained or even increased intraocular straylight.

1.2.3 Iris, sclera and fundus

The remaining part of the intraocular straylight in the normal eye is mainly originated in tissues away from the visual axis, as a function of ocular tissue pigmentation. Especially in low pigmented eyes (blue eyed Caucasians), these tissues may produce up to one third of the total intraocular straylight in the normal eye.

Light that reaches the iris and sclera can be transmitted to the retina in eyes with low pigmentation (van den Berg, 1991). As in the iris and sclera, light that falls on the fundus is not completely absorbed and can be scattered back to other parts of the retina. This will depend particularly on pigmentation of the pigmented epithelium and the choroid (Delori, 1989).

Even though glare is more frequent during nighttime, pupillary size has generally a low influence in intraocular straylight. Although light scatter increases with a large pupil size, also non-scattered light that reaches the retina will increase in the same amount, maintaining the scattered and non-scattered light ratio the same. This relation may vary according to each specific situation, for instance in the presence of a central crystalline lens opacity, where the intraocular straylight could be lower in mydriasis. Whatever the cases, there is no need for pupil dilation for the measurement of intraocular straylight (Franssen, 2007).

1.2.4 Vitreous and aqueous humor

Normally, the vitreous and the aqueous humor have only a small contribution for the scatter of light in the eye. Certain ocular pathologies that course with an inflammatory reaction usually produce turbidity of the aqueous humor (Tyndall), which may increase straylight. Similarly, disturbances in the vitreous such as floaters, asteroid hyalosis, or any other opacities, may produce an increase of intraocular straylight (figure 1.2.5).

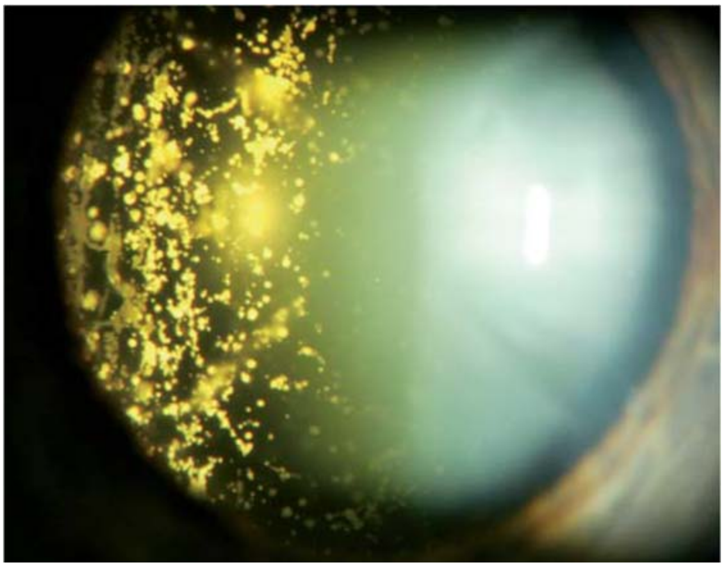


Figure 1.2.5. Vitreous condensations, as in this case of asteroid hyalosis, may increase intraocular straylight.

1.3 Forward and backward light scattering

Light going into the eye suffers from diffraction and scattering on its way to the retina. The scattering occurs in a forward and backward direction (figure 1.3.1). The scattering in the same direction as the incident light is the forward scattered light. In the ocular media, this forward directed scattering will result in a veil of light over the retinal image, which is responsible for the glare related symptoms in the patient. The backward light scattering, on the other hand, refers to the scatter of the light away from the retina, going to an opposite direction of the light entering the eye. In the present work, 'intraocular straylight' refers to the forward light scattering.

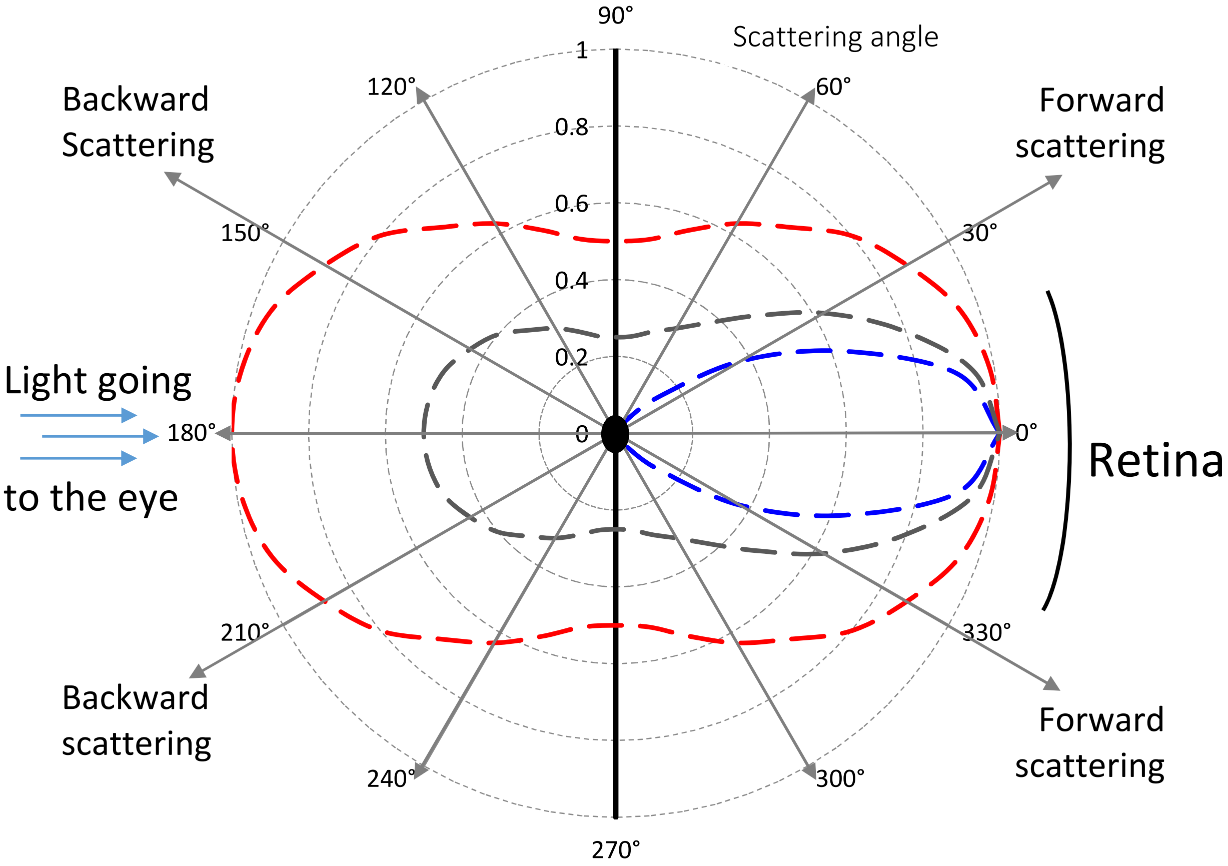


Figure 1.3.1. Light going into the eye towards the retina suffers scattering in the forward or backward direction depending on particle size. In this schematic representation, the scattering particle is in the center of the plot, the circular lines show the intensity of the scattered light and the radial lines represent the scattering angle. The blue discontinue line represents the scatter for the largest particles (larger than the light wavelength), the gray line for large particles (smaller than the light wavelength) and the red line for small sized particles (much smaller than the light wavelength).

The direction of the scatter will depend on the size of the particle that is producing this scattering of the light on the optical media. Small particles (smaller than the light wavelength, e.g. proteins) scatter light in the forward and backward direction almost equally, large particles (e.g. protein aggregates) scatter light asymmetrically to both directions, and the largest particles (larger than the light wavelength, e.g. rough surface reflectance) scatter light almost exclusively in the forward direction (van den Berg, 1999) (figure 1.3.1).

In the clinical setting, a slitlamp is commonly used by the ophthalmologist to examine the optical media of the eye and assess the severity of any opacity that may be present. But when a slitlamp is used to illuminate the eye, the image obtained comes from the backward directed scattering.

It is important to emphasis the relationship between the symptoms perceived by the patient and the assessment performed by the ophthalmologist with the slitlamp. As mentioned above, the glare related symptoms are produced by the forward scattering of the light, or intraocular straylight; but the image obtained with the slitlamp comes from the backward scattering. In the schematic representation of light scattering presented in figure 1.3.1. it's clearly observed that light scattering is not always symmetrical for the backward and forward direction. For this reason, it would not be appropriate to use the slitlamp as a way to assess intraocular straylight and there is a need to use a method that measures the forward scattered light.

1.4 Straylight measurement

Different strategies have been used to try to measure intraocular straylight. Glare testers such as the Niktotest (Rodenstock GmbH, Ottobrunn, Germany) and the Mesotest II (Oculus) measure contrast sensitivity and visual acuity in the presence of a glare source (called glare sensitivity), but it has been shown that their measurements are unreliable and unrelated to patients' complaints (Elliott, 1993; Puell, 2004; van Rijn, 2005).

Some instruments use optical techniques to directly measure the forward directed scattering on the retina, whereas other instruments use indirect methods to do so.

The OQAS (Visiometrics S.L., Terrassa, Spain) has been proposed as an objective way for measuring the forward scattered light by a double-pass system, using infrared light. Although this system shows good repeatability and reliability, it only measures scattering in small angles, around 20 minutes of arc (Iijima, 2015). Moreover, the use of an infrared light has been questioned given the wavelength dependence of the light transmission and reflection on the ocular media (van den Berg, 2011).

A newer optical straylight meter, based on a double-pass optical integration method, measures forward scattered light in visual angles between 3 to 8 degrees, using green high brightness LEDs as the straylight source (Ginis, 2014).

Forward scattered light can be measured in an indirect way by measuring the additional luminance needed to equal the luminance threshold of a background and an object. This method is based on the concept of the ‘equivalent veiling luminance’ that was introduced by Cobb (Cobb, 1911), and is the basis of the later developed disability glare formula (Holladay, 1926; Stiles, 1929), which has been well accepted for the measurement of forward light scattering in the eye and is applied in a currently clinically used ‘straylight meter’ called C-Quant (Oculus GmbH, Wetzlar, Germany) (figure1.4.1).

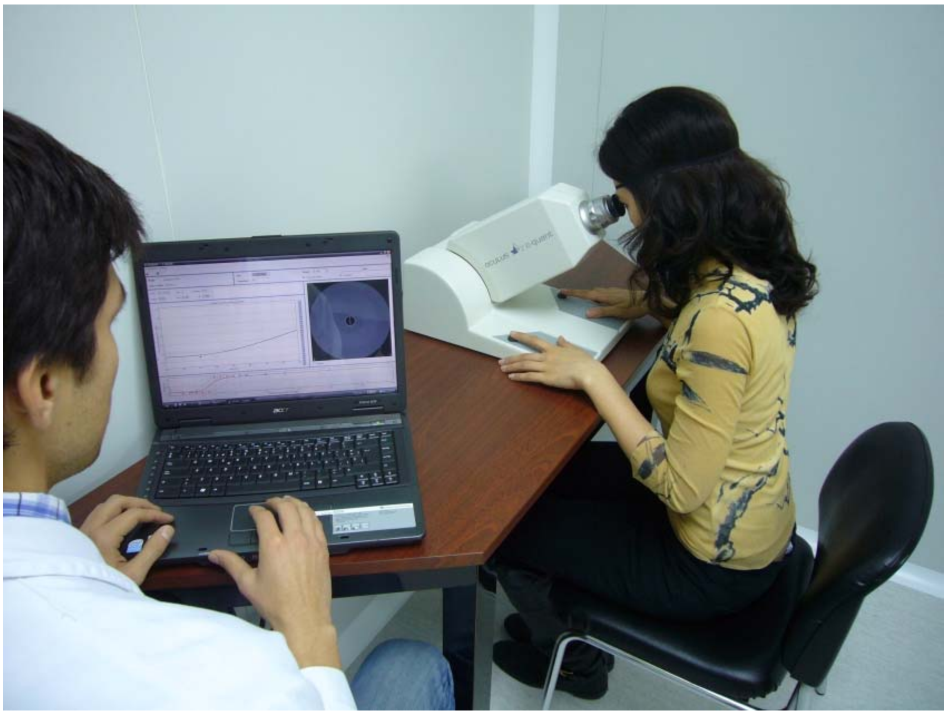


Figure 1.4.1. The C-Quant instrument measures straylight using a psychophysical compensation comparison method.

To measure intraocular straylight, this device makes use of a psychophysical test that is based on a method called *compensation comparison*, where the subject taking the test has to compare the intensity of a flickering induced by a glare source, with that of a counterphase compensation light.

The test field consists of a central dark circle, which is divided into two semicircles (left and right), and an outer ring that serves as the glare source (figure 1.4.2). The subject has to fixate on the central circle while a flickering light is emitted from the outer ring. A flickering will also be perceived in the central circle due to the forward scattering of light in the eye media. The intensity of the perceived flickering will depend on the amount of intraocular straylight.

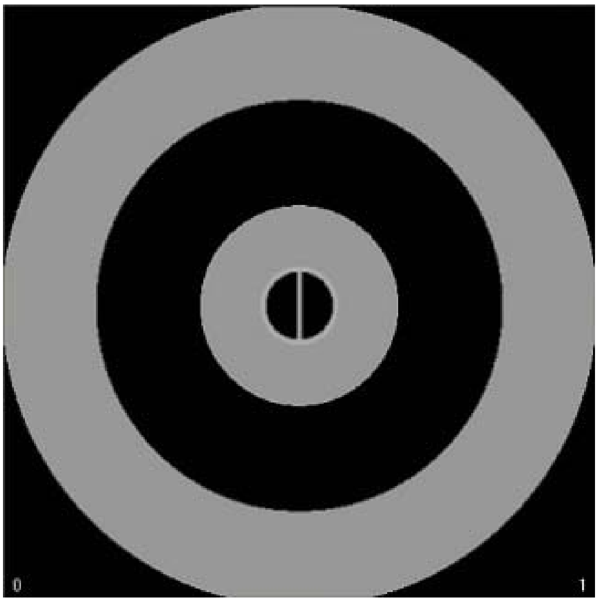


Figure 1.4.2. The outer ring of the test field (in black) of the C-Quant flickers to induce a blinking of the central circle (divided in two halves) due to straylight.

To determine this intensity, a counter phase compensation light is presented randomly in one of the semicircles a set number of times with different levels of compensation. The patient has to compare both semicircles and decide which one is flickering stronger. The amount of straylight would be given by the intensity of the compensation light necessary to make the flickering in the semicircle disappear. The value obtained is the logarithm of the straylight parameter (s) measured at a mean visual angle of 7 degrees. It has been demonstrated that this method provides repeatable and reliable measurements (Cervino, 2008).

1.5 Interrelation between visual quality parameters

If we try to describe optical quality by the point spread function (PSF), visual acuity would only comprise the most central part, whereas intraocular straylight would comprise a much larger angle domain (figure 1.4.1). Thus, intraocular straylight and visual acuity should only have a weak correlation (Franssen, 2007).

The effect of increased intraocular straylight on vision should be different from the effect of visual acuity alterations. As mentioned earlier, visual acuity charts measure the eye capacity for resolution of small details. This is determined by light deflections over small visual angles on the retina (1 minute of arc or 0.02°), whereas intraocular straylight measurement determines light scattering over larger angles.

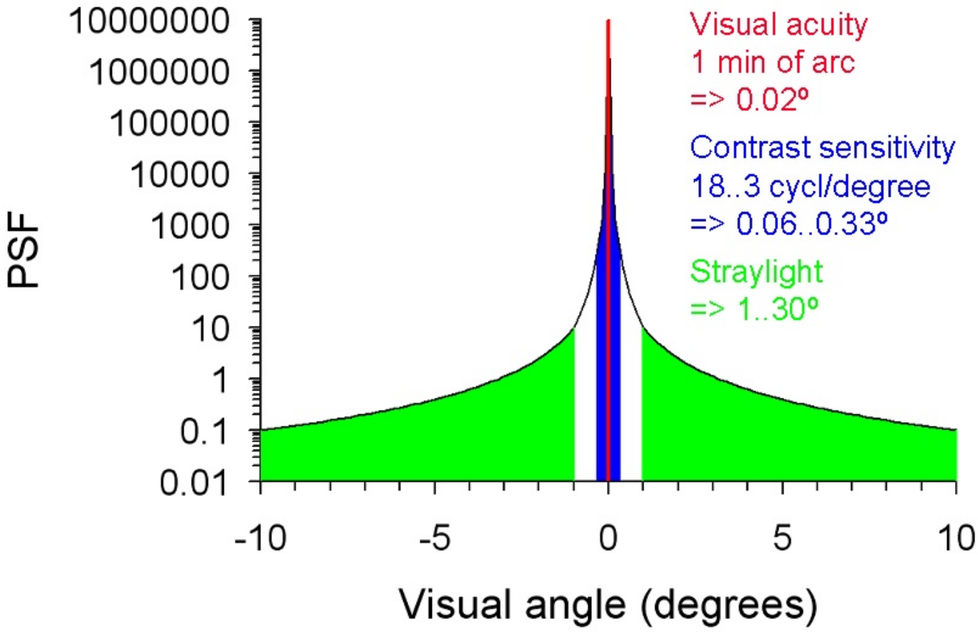


Figure 1.4.1. The point spread function is comprised by different angle domains. The most central part is given by visual acuity (in red); contrast sensitivity function has a slightly bigger domain (in blue); intraocular straylight domain starts from 1° (in green). (Image taken from (van den Berg, 2010))

As in visual acuity, the angular domain of contrast sensitivity is also more restricted than that of intraocular straylight. For spatial frequencies between 3 and 18 cycles per degree, the angular domain is less than one degree (0.06º - 0.33º). Although intraocular straylight reduces the contrast of the retinal image, the relationship between intraocular straylight and contrast sensitivity should also be very weak.

As mentioned in the previous chapter, the C-Quant instrument used in this work, measures the forward scattered light at a mean visual angle of 7 degrees (within the green area of figure 1.4.1). This visual angle is quite larger than the angles measured with visual acuity and contrast sensitivity tests.

2. Aims of the study

The aims of this study were to:

- Study the effect of LASIK refractive surgery on intraocular straylight.
- Study the effect of cataract and posterior capsule opacities on intraocular straylight.
- Study the effect of posterior capsulotomy on intraocular straylight
- Analyze the interrelation of visual acuity and intraocular straylight and determine if intraocular straylight measurement offers an additional value for the evaluation of visual quality.

3. Methods

3.1 Study population

For **Chapter 4.1 'Visual quality after refractive surgery'** (paper 1, 'Intraocular straylight and contrast sensitivity two months after LASIK'), 46 eyes from 28 patients who were scheduled for LASIK surgery at the *Centro de Oftalmología Barraquer* in Barcelona, were included in a prospective study. Thirty nine eyes were myopic and 7 were hyperopic. Exclusion criteria were: lens opacities, macular lesions, or any other anatomic anomaly of the eye globe. Mean age of the patients was 30 years, ranging from 22 to 50 years.

Chapter 4.2 'Visual quality and its relation with cataract grading' (unpublished study), was based on a retrospective study that included 218 eyes from 171 patients who were evaluated for lens cataract extraction surgery at the *Centro de Oftalmología Barraquer* in Barcelona. Exclusion criteria were: previous ocular surgery of any kind and patients with history of ocular pathologies (surface problems, high astigmatism, macular disease, amblyopia, etc.). Mean age of the patients included was 65 years, ranging from 31 to 86 years.

Results for **Chapter 4.3 'Visual quality in the presence of posterior capsule opacities'** (paper 2, 'Posterior capsule opacification assessment and factors that influence visual quality after posterior capsulotomy') come from a joint study from the *Centro de Oftalmología Barraquer* in Barcelona and the *Universitätsklinik für Augenheilkunde und Optometrie der Paracelsus Medizinische Privatuniversität* (University Eye Clinic from the Paracelsus Medical University) in Salzburg. This prospective study included 41 patients (26 from Barcelona and 15 from Salzburg) who were scheduled for neodymium-yttrium-aluminum-garnet (Nd:YAG) laser capsulotomy. Exclusion criteria were: diabetes mellitus, glaucoma, retinal or macular pathologies, optic nerve atrophy, astigmatism greater than 4 diopters, any kind of keratoplasty, and corneal opacities. Mean age of the patients was 67 years, ranging from 44 to 82.

Chapter 4.4 'Interrelation of visual quality parameters' summarizes the results related to visual quality outcomes from the previous chapters.

3.2 Intraocular straylight measurement

Intraocular straylight was measured using the C-Quant (Oculus GmbH, Wetzlar, Germany), a portable device that implements the compensation-comparison (CC) method; the technique is described in the introduction. The measurements were performed on all patients, with undilated pupils, and with spherical equivalent correction when needed, before and after being subjected to LASIK and posterior capsulotomy, but only before cataract extraction surgery. To make sure of obtaining reliable results, the expected standard deviation (ESD) was set to ≤ 0.08 and the quality (Q) to ≥ 1. A log(s) difference of ≤ 0.15 units in the before and after values was considered an intrapatient variance (Montenegro, 2012).

3.3 Visual acuity measurement

Visual acuity was measured using a Snellen based chart implemented with a wall projector. The results were registered in a decimal notation which was afterwards converted into logMAR for statistical analysis.

3.4 Contrast sensitivity measurement

Contrast sensitivity was measured using the CSV-1000 (Vector Vision; Haag Sereit, Harlow, UK) at different spatial frequencies, namely 3, 6, 12 and 18 cycles/degree. The test field consists of a backlighted chart that presents sine wave gratings with four different special frequencies. Each frequency is presented on a separate row on the chart. There are 17 patches for each row. The first patch has a high contrast grating and identifies the spatial frequency for that row. The remaining 16 are paired in eight columns across the row. For each pair, one patch presents the grating, whereas the other is blank but of the same luminance. The patches decrease 40% in contrast across the row from left to right. The patient must choose which patch has the grating for that column. The contrast threshold is measured from the last correct response. The contrast sensitivity levels in each row range from 0.7 to 2.08; 0.91 to 2.29; 0.61 to 1.99; and 0.17 to 1.55 log units for 3, 6, 12, and 18 cycles/degree respectively (User manual CSV-1000).

Results from the measurement are graphically represented on a chart for an easy visualization and recognition of the normal values (figure 3.4.1).

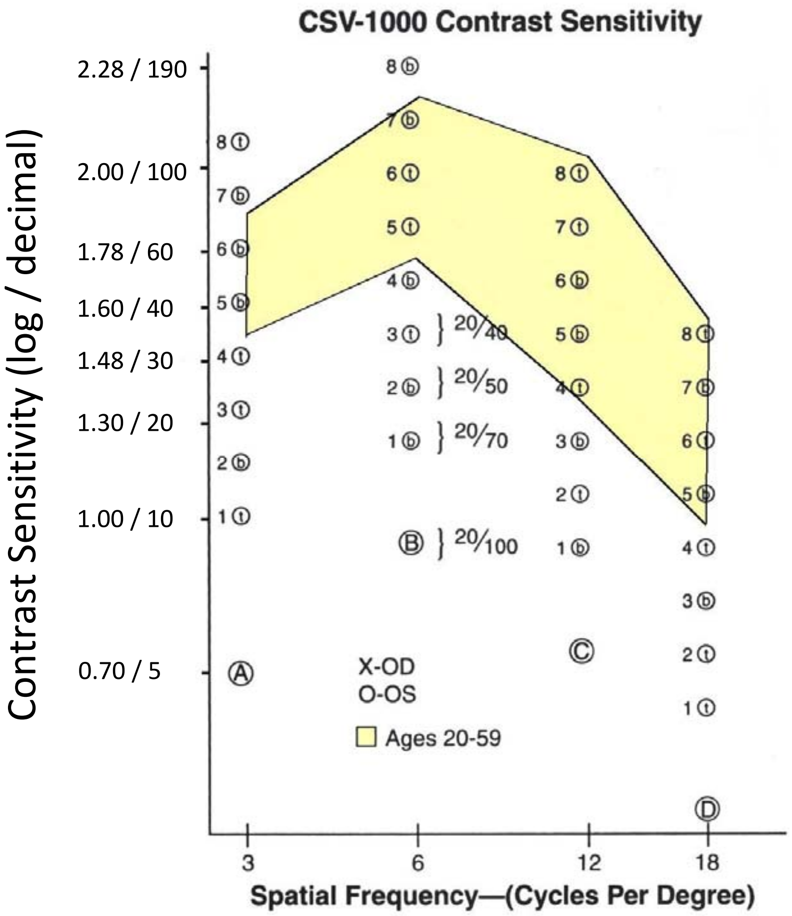


Figure 3.4.1. Contrast sensitivity measurement is graphically represented in a chart where normal values for each spatial frequency (yellow area) are easily recognized.

3.5 Cataract grading

Pupils were fully dilated using a combination of topical Tropicamide 0.5% and Phenilephrine 2.5% before taking the pictures. Two photographs of each crystalline lens were obtained using a digital camera attached to a slit lamp with different settings. One photograph was from a frontal view and with a wide beam, and the other was with a narrow beam producing a cross-section of the lens, with the camera at a 45° angle.

The images obtained were used to grade the nuclear, cortical and subcapsular components of lens opacification. The *Lens Opacities Classification System III* (LOCS III)(Chylack, 1993) was used to grade the cortical and subcapsular components (figure 3.5.2), and the decimal classification system (BCN-10), developed by Drs. Rafael I. Barraquer, Felipe T. Tsiplakos, Marco Álvarez Fischer, and Alejandro Álvarez López, from the *Institut Universitari Barraquer* in Barcelona, was used to grade the nuclear and subcapsular components (figure 3.5.1). The latter system was used for the grading of the nuclear component because it has a wider range of positions on the grading scale.

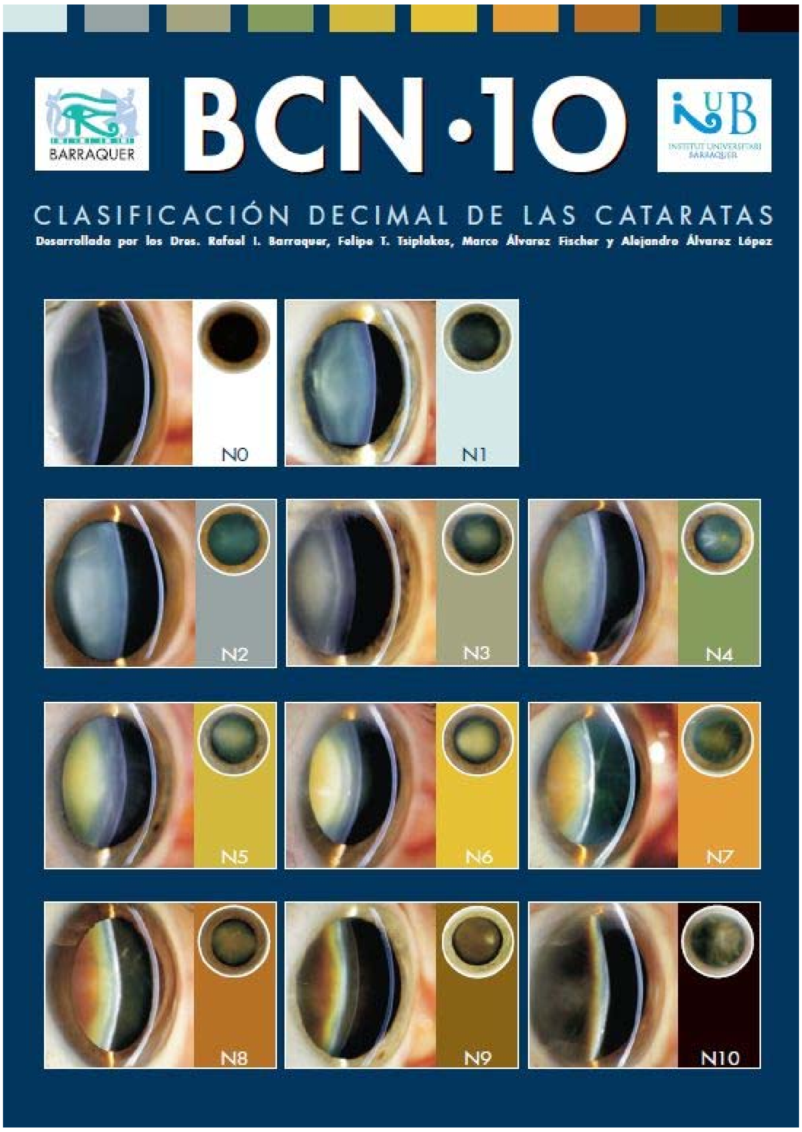


Figure 3.5.1. BCN10 cataract severity grading system is based on color and density.

Three different observers graded the cataracts and the average of the observations was used for the statistical analysis. To study ‘pure’ nuclear cataracts, i.e. the nuclear component alone, the score for the cortical component should be <1 and for the subcapsular component it should be <0.5.

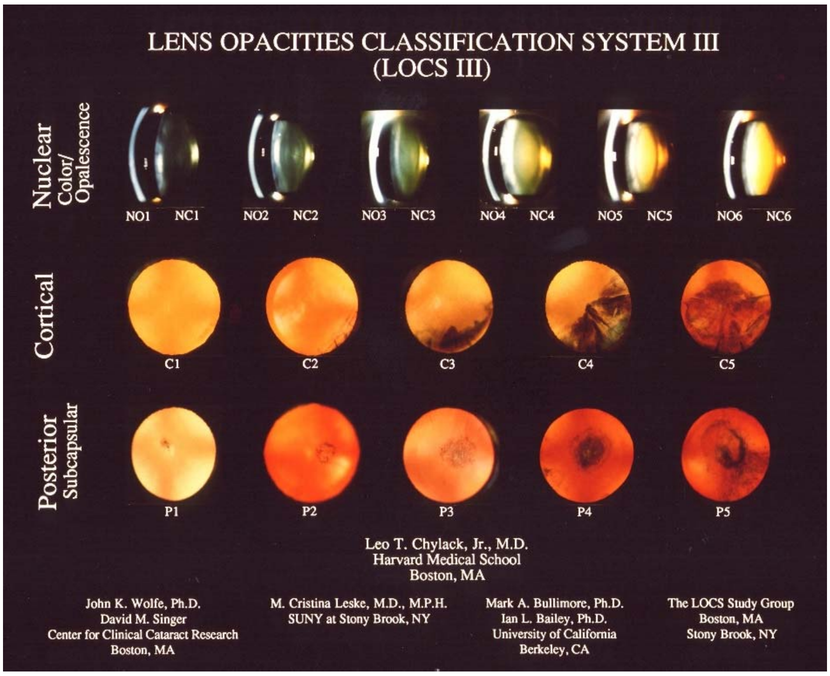
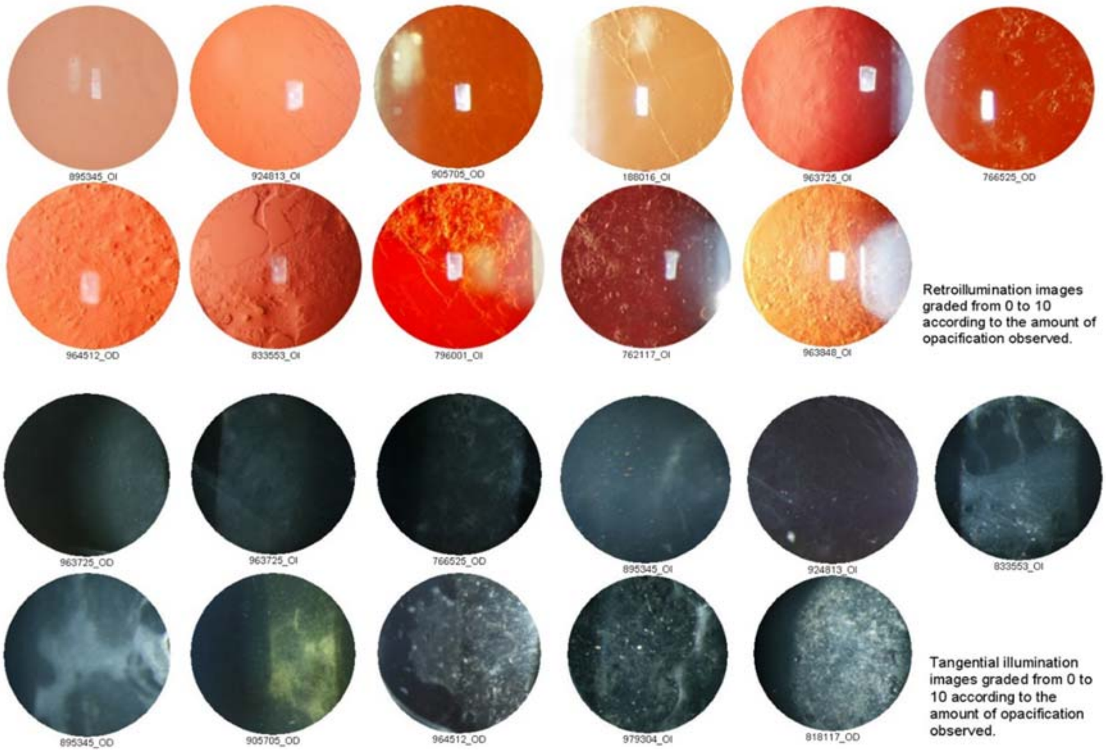


Figure 3.5.2. Lens opacities classification system III (LOCSIII), developed by Chylack.

3.6 Posterior capsule opacities grading

Pupils were pharmacologically dilated using a combination of Tropicamide 0.5% and Phenilephrine 2.5% applied topically. When fully dilated, the posterior capsule was photographed using a digital camera attached to a slit lamp. Two different images were obtained from each eye, one of retroillumination and one of the light reflected from the posterior capsule. To obtain the reflected-light images, we used a wide slit-beam at an angle of 45° focused on the posterior capsule (figure 3.6.1).



Retroillumination images graded from 0 to 10 according to the amount of opacification observed.

Tangential illumination images graded from 0 to 10 according to the amount of opacification observed.

Figure 3.6.1. Retroillumination (upper) and slit-lamp-derived reflected-light (lower) images were subjectively graded from 0 to 10 according to PCO severity.

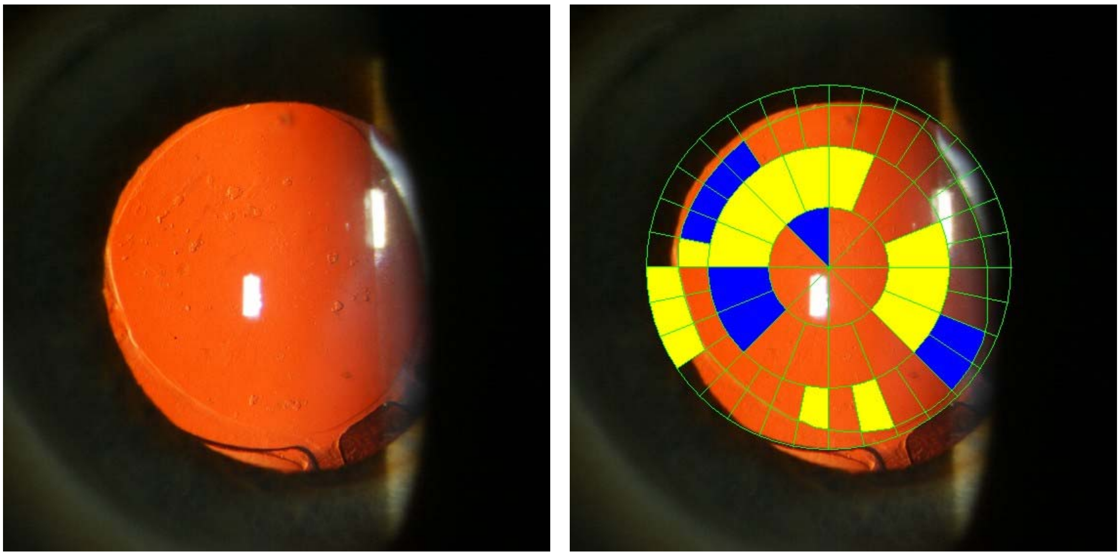


Figure 3.6.2. Retroillumination images (left) were used for scoring PCO severity with the POCOman software (right).

The corresponding photopic pupil diameter was delimited on each image and PCO inside that area was then subjectively graded by three different observers on a scale from 1 to 10 for the retroillumination (figure 3.6.1 upper) and reflected-light images (figure 3.6.1 lower), and from 0 to 3 using the POCOman computer software (Bender, 2004) on the retroillumination images (figure 3.6.2). The average of the results was used for the statistical analysis.

Additionaly, we measured the total capsulotomy diameter (referred to as *absolute capsulotomy*) on the retroillumination images and compared it to the corresponding photopic pupil diameter. The area of the capsulotomy inside the pupil diameter was considered as the *effective capsulotomy*. We measured the *area of the posterior capsule* that remained visible within the photopic pupil diameter and then calculated its percentage in relation to the photopic pupil area.

3.7 Surgical procedures

3.7.1 Laser-assisted in situ keratomileusis (LASIK)

LASIK is a photorefractive surgery used for the correction of myopia, hyperopia and astigmatism. During the procedure, a thin corneal flap is created with the use of a femtosecond laser. The flap is then folded back to allow an excimer laser to ablate the required corneal stroma depending on the reshaping needed. After the corneal stroma ablation is done, the flap is repositioned over the treated area.

In our study, LASIK was performed with the Bausch & Lomb Technolas Z100 Excimer Laser System. Conventional (*Planoscan* and *Cross Cylinder*) and wavefront guided (*Zyoptx*) ablation profiles were included.

3.7.2 Laser posterior capsulotomy (Nd:YAG)

Laser posterior capsulotomy is performed to treat posterior capsule opacification. Short pulses of a neodymium-yttrium-aluminum-garnet laser are used to achieve a circular opening of the posterior lens capsule.

3.8 Statistical analysis

A paired t-test were used to compare visual quality parameters before and after treatment for LASIK and posterior capsulotomy patients and regression coefficients (r^2) were calculated. Linear regressions to study the relationship between the variables were tested for significance by an F test. Only if significant, the regression line was drawn in the graphs. A multiple regression analysis was performed in posterior capsulotomy patients to study intraocular straylight after surgery. A p value of <0.05 was considered statistically significant for all tests. The computer based statistical software SPSS 13.0 for Windows (SPSS Chicago, Ill.) was used for the analysis of the data.

4. Results and discussion

4.1 Visual quality after refractive surgery

Mean post-operative uncorrected visual acuity (UCVA) was 0.091 ± 0.041 logMAR (0.81 decimal), improving significantly from its pre-operative values. Pre-operative best corrected visual acuity (BCVA) of 0.029 ± 0.011 logMAR (0.93 decimal) showed no statistically significant improvement after LASIK, with a mean post-operative value of 0.041 ± 0.014 logMAR (0.91 decimal). Mean safety index (BCVA post / BCVA pre) was 0.98 and a mean efficacy index (UCVA post / BCVA pre) was 0.90. Only one eye out of the 46 eyes treated during the study presented a 2-line decrease in BCVA. This decrease could be explained by a post-operative complication.

It is well know that laser refractive surgery yields excellent results in terms of visual acuity improvement (Alio, 2008; Fares, 2011; Kaminski, 1997; Knorz, 1998; Mrochen, 2001; O'Doherty, 2006; Salchow, 1998; Shaheen, 2013; Tahzib, 2005; Tuan, 2006), making it a safe procedure for the correction of myopia. Laser refractive surgery, evidently, acts on the refractive power of the cornea by changing its curvature. Changes on refraction will certainly have an effect on visual acuity, which is the ultimate goal of this type of procedure. Furthermore, with today’s technology we can predict with a minimum margin of error the visual acuity outcome after a laser refractive surgery.

Mean intraocular straylight at 2 months after LASIK was 0.96 log(s), a value within normal limits for the average age of the subjects. There was no statistically significant difference when compared to the mean value of 0.98 log(s) before the procedure. Nonetheless, 1 eye showed an increase of more than 0.25 log(s) units; this was the same subject that presented the 2-line decrease in BCVA. This patient presented a diffuse lamellar keratitis (DLK) with an increased optical density within the flap-cornea interface.

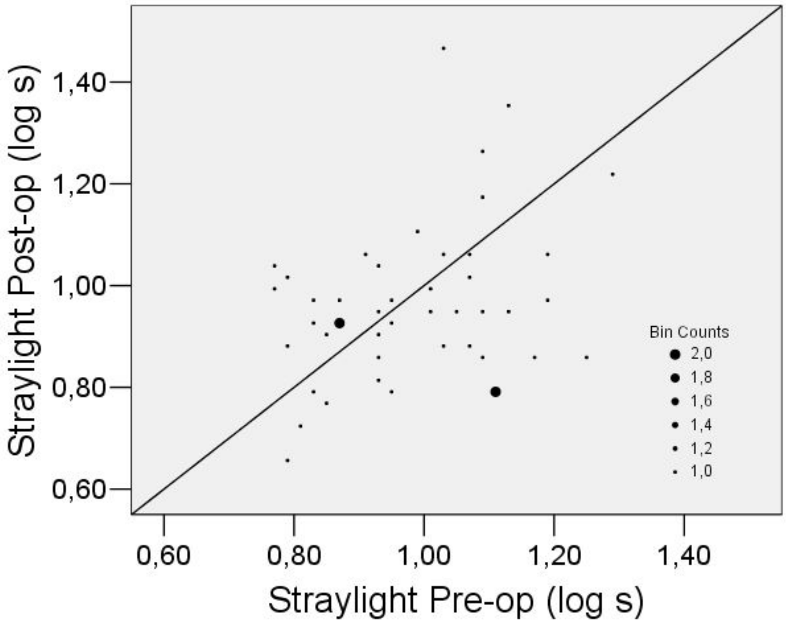
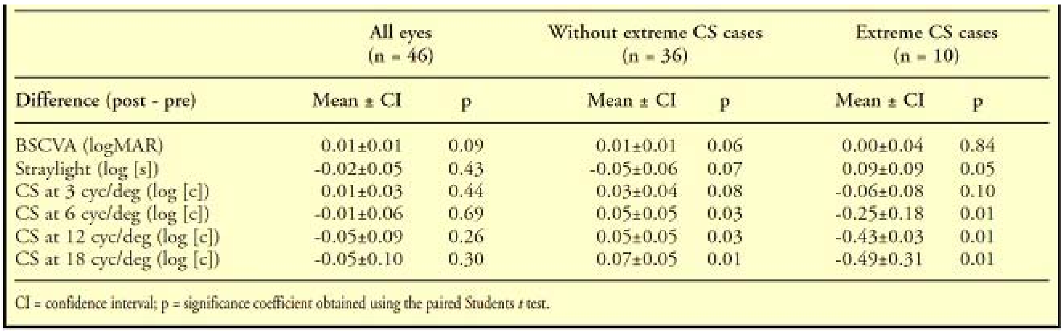


Figure 4.1.1. Intraocular straylight values before and 2 months after LASIK. Data points below the equality line reveal a decrease in post-operative intraocular straylight values.

The results obtained in the measured intraocular straylight in our study is in accordance with other studies found in the literature. In general terms, intraocular straylight seems not to increase 1-10 months after refractive surgery, although in some cases there may be a small transitory increase or even a decrease (Beerthuizen, 2007; Li, 2011; Lorente-Velazquez, 2010). Although other studies found a persistent statistically significant decrease in intraocular straylight after refractive surgery, this decrease was not clinically relevant (Lapid-Gortzak, 2010; Nieto-Bona, 2010). Other authors have used different approaches to try to determine glare sensitivity/disability after refractive surgery. Neeracher et al. (Neeracher, 2004) and Kim et al. (Kim, 2007) have likewise not found variation in glare after surgery at 1 year using the Berkeley glare test and at 6 months using the ALC Glare test respectively. Lee et al (Lee, 2006), on the other hand, found an increase in glare sensitivity at 6 months after surgery using the ALC Glare test.

Mean contrast sensitivity showed no statistically significant variation after surgery at any of the 4 spatial frequencies measured, presenting mean values of 1.87, 2.01, 1.69, and 1.27 for the 3, 6, 12 and 18 cycles per degree, respectively. However, 9 eyes presented a decrease of 2 or more positions in the CSV-1000 log scale at one or more spatial frequencies, and one eye showed an increase of three lines. The decrease on contrast sensitivity could be related to the post-operative complications in two of the cases, but it could not be explained for the rest.

We reevaluated the results dividing the subjects in two groups; one group for the cases with extreme values of contrast sensitivity (n = 10) and another for all the cases without the extreme contrast sensitivity values (n = 36). The new analysis showed a slight improvement of the post-operative contrast sensitivity values, which was significant for the 6, 12 and 18 cyc/deg spatial frequencies in the group without the extreme values. BCVA didn't increase significantly after surgery in either of the two groups. However, intraocular straylight did present a post-operative increase in the group with decreased contrast sensitivity. Even though this increase was statistically significant, it was not clinically relevant, with a mean increase of only 0.09 log(s) (Table 4.1.1).



	All eyes (n = 46)		Without extreme CS cases (n = 36)		Extreme CS cases (n = 10)	
Difference (post - pre)	Mean ± CI	p	Mean ± CI	p	Mean ± CI	p
BSCVA (logMAR)	0.01±0.01	0.09	0.01±0.01	0.06	0.00±0.04	0.84
Straylight (log [s])	-0.02±0.05	0.43	-0.05±0.06	0.07	0.09±0.09	0.05
CS at 3 cyc/deg (log [c])	0.01±0.03	0.44	0.03±0.04	0.08	-0.06±0.08	0.10
CS at 6 cyc/deg (log [c])	-0.01±0.06	0.69	0.05±0.05	0.03	-0.25±0.18	0.01
CS at 12 cyc/deg (log [c])	-0.05±0.09	0.26	0.05±0.05	0.03	-0.43±0.03	0.01
CS at 18 cyc/deg (log [c])	-0.05±0.10	0.30	0.07±0.05	0.01	-0.49±0.31	0.01

CI = confidence interval; p = significance coefficient obtained using the paired Students *t* test.

Table 4.1.1. Mean individual difference in BSCVA, intraocular straylight and CS before and after LASIK. Results are presented for three groups: all eyes together (n=46), all eyes excluding extreme values (n=36), and the extreme values alone (n=10). A negative BSCVA and straylight or a positive CS difference reveals a post-operative improvement. BSCVA: best corrected visual acuity, CS: contrast sensitivity (Appendix A).

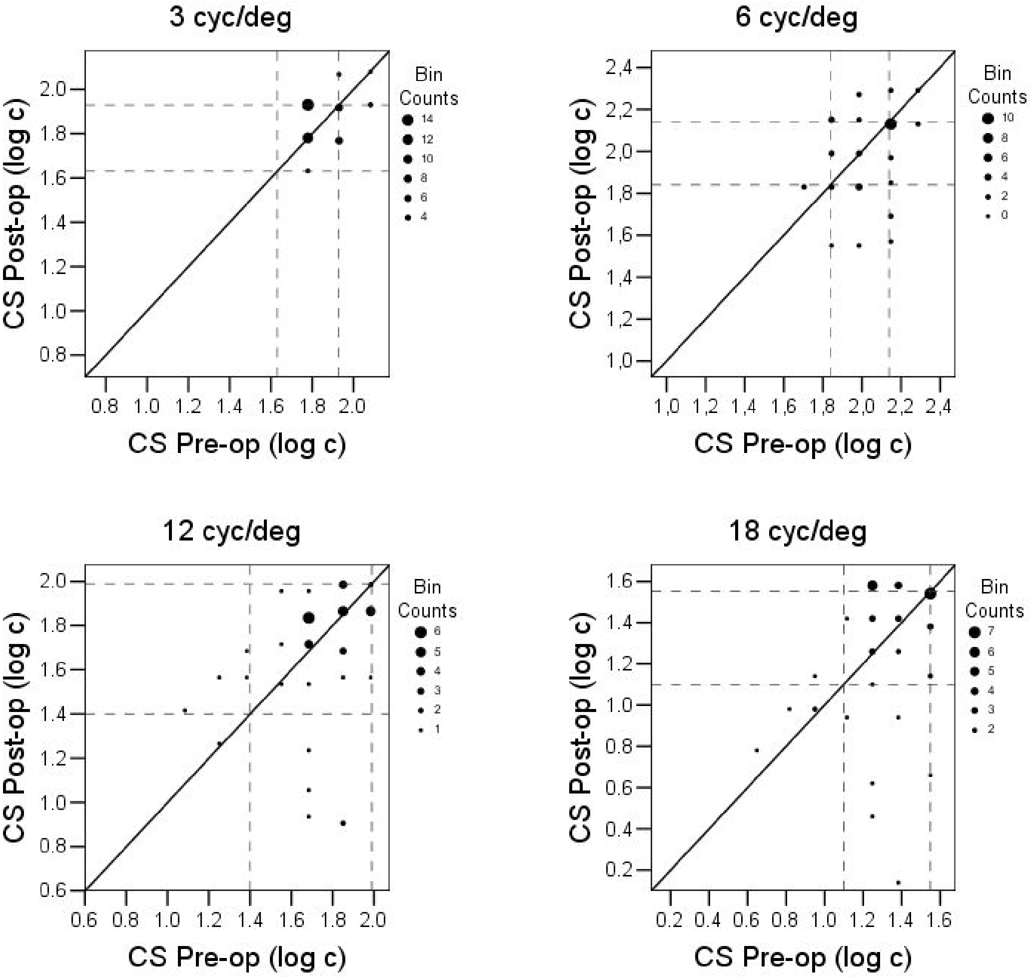


Figure 4.1.2. Contrast sensitivity values before and 2 months after LASIK for each spatial frequency measured with the CSV-1000 (n=46). Data points above the solid line represent improved values post operatively. Dashed lines indicate the normal range values for ages 20 to 59 years. (Appendix A)

There is no general consensus of how contrast sensitivity is affected after LASIK in the literature. Some earlier studies revealed a decrease in contrast sensitivity at 1, 2 or 6 months after surgery (Donate, 2005; Marcos, 2001; Yamane, 2004). More recent studies suggest that contrast sensitivity can return to baseline values or even improve depending on the surgical technique (Kim, 2007; Lee, 2006). Lee found a decrease in contrast sensitivity at 1, 3 and 6 months after conventional LASIK and no change at 6 months after wavefront-guided LASIK. One year later, Kim found no change after 2 and 6 months post conventional LASIK.

In view of the many and varied results obtained after LASIK in terms of visual quality parameters, namely contrast sensitivity and intraocular straylight, we can't certainly tell how refractive surgery affects visual quality. Without a doubt, we can say there is an improvement on UCVA, but visual quality could be affected in other ways. In our experience, we could observe there was not a significant modification on the visual quality parameters on the majority of the cases at two months after surgery.

It is safe to say that in the presence of post-surgical complication, visual quality parameters can be compromised. In our study, two eyes presented a clinically significant postoperative complication that affected some of the visual quality parameters. One eye had a diffuse lamellar keratitis (DLK) with an increased optical density within the flap-cornea interface (figure 4.1.3). The DLK produced a clinically and statistically significant decrease of BCVA, CS, and an increase of the intraocular straylight. The other complication was a light paracentral superficial punctate keratitis (SPK), which decreased BCVA and CS but didn't affect intraocular straylight (figure 4.1.3).

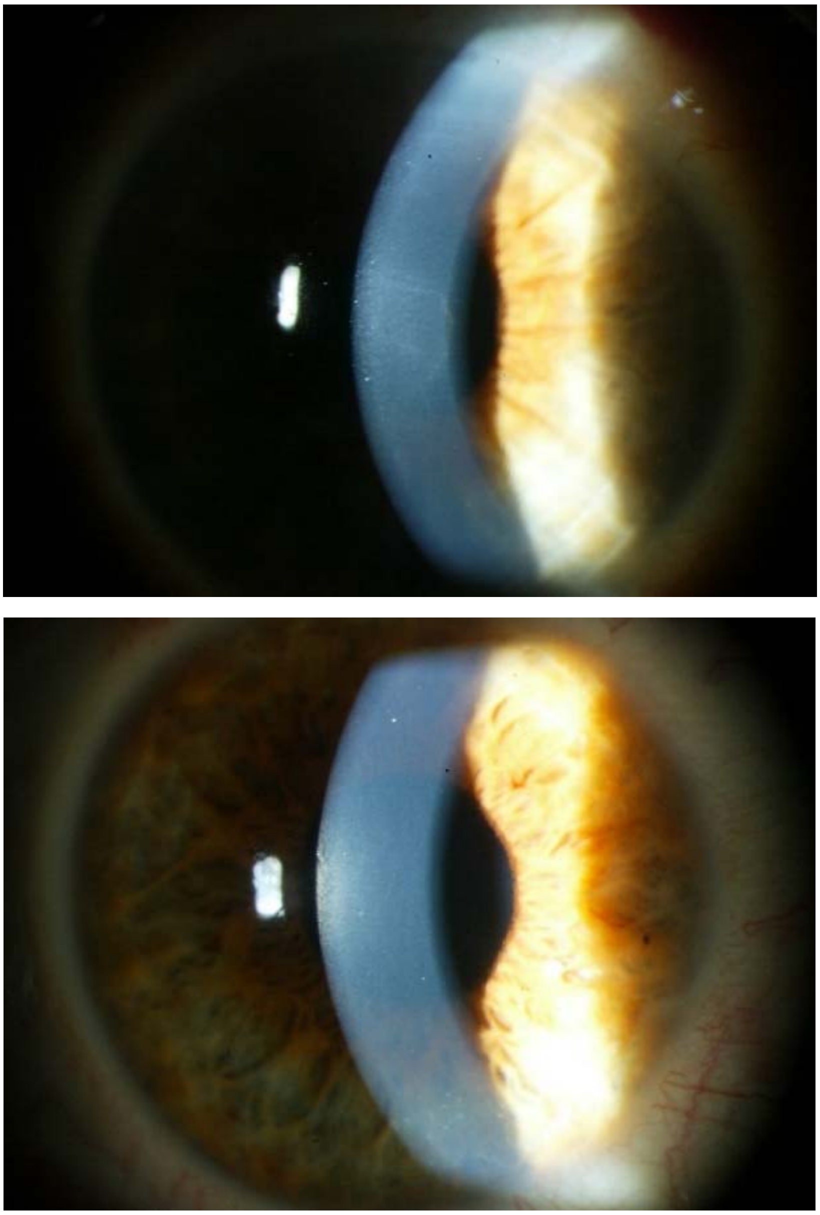


Figure 4.1.3. Diffuse lamellar keratitis (upper) can affect both visual acuity and intraocular straylight, whereas superficial punctate keratitis (lower) can lower visual acuity without major effects on intraocular straylight.

4.2 Visual quality and its relation with cataract grading

Mean age of the patients included in this study was 64 years (range from 31 to 85). It has to be noted that the subjects included in this study were scheduled for cataract extraction surgery, thus, they should have some cataract related symptoms of visual quality alterations. Nuclear cataract was the most frequent type with 74% of the cases in the population studied (figure 3.2.1). In our patients, we could observe that the percentage of cases with cortical cataract alone was practically inexistent (0%), whereas patients with a mixed component of cortical and nuclear cataracts represent a 23% of the sample. Altogether, nuclear cataract alone or in association with cortical, posterior sub-capsular or both components, comprises 99.5% of the studied subjects.

Given this distribution, it is one way to assume that patients with a mixed cortical and nuclear cataract were scheduled for cataract extraction mostly for the visual quality alterations produced by the nuclear component, rather than for the cortical one.

Posterior sub-capsular component was present in 3% of the patients, but only in 0.5% of the cases it presented alone.

In order to avoid a bias by including mixed groups, we only included the ‘pure’ nuclear cataracts in the statistical analysis.

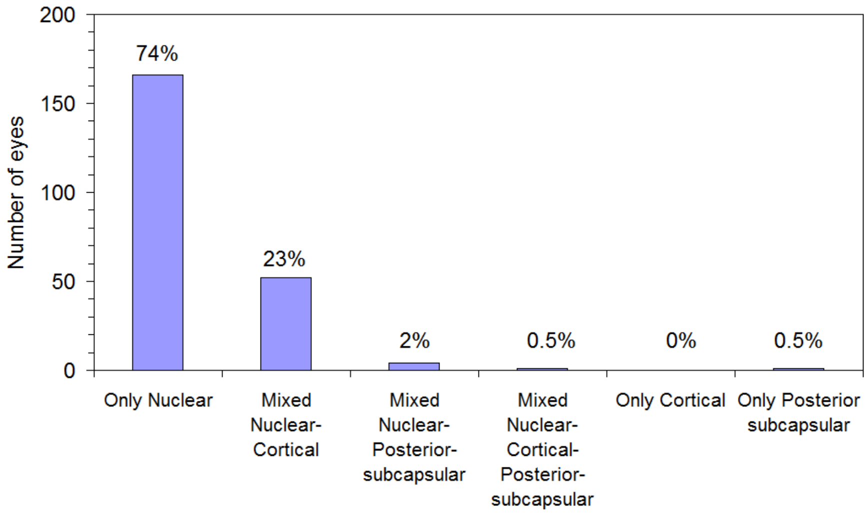


Figure 4.2.1. Distribution of the different components of lens cataracts. Nuclear cataract is present in 99.5% of the subjects, either alone or in association with other components. Note that this distribution is based on patients scheduled for cataract extraction, not on a general population.

Mean best corrected visual acuity (BCVA) in the nuclear cataract group was 0.13 logMAR (0.74 decimal). The measured BCVA was below the normal values according to the age of the subjects. When we plotted visual acuity against the BCN10 grading score, there seemed to be a tendency of worsening in visual acuity with a higher score on nuclear cataract grading. Although the linear regression test was statistically significant, the correlation was weak ($r^2 = 0.160$) (figure 4.2.2).

Similarly, mean intraocular straylight value (1.45 log s) was above the average for the mean age of the subjects (1.28 log s). There was also a tendency towards an increase in intraocular straylight with higher nuclear cataract grades, with a statistically significant correlation, but in this case, the correlation was very weak ($r^2 = 0.028$).

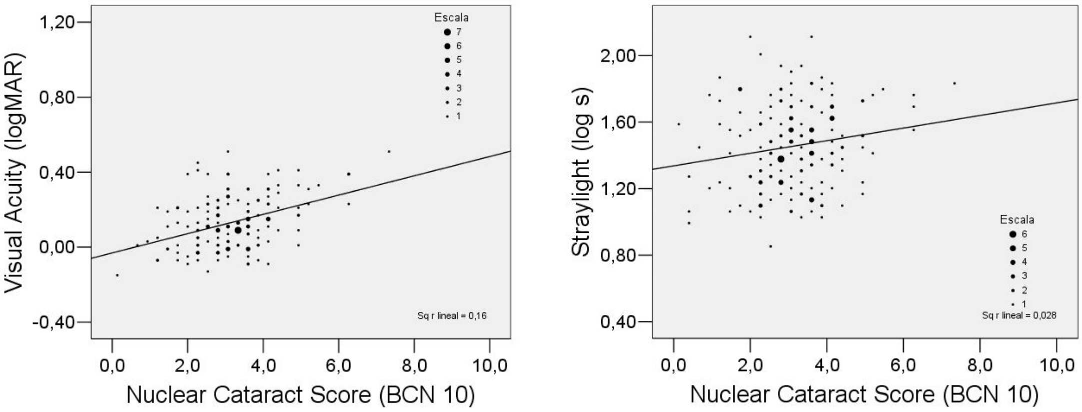
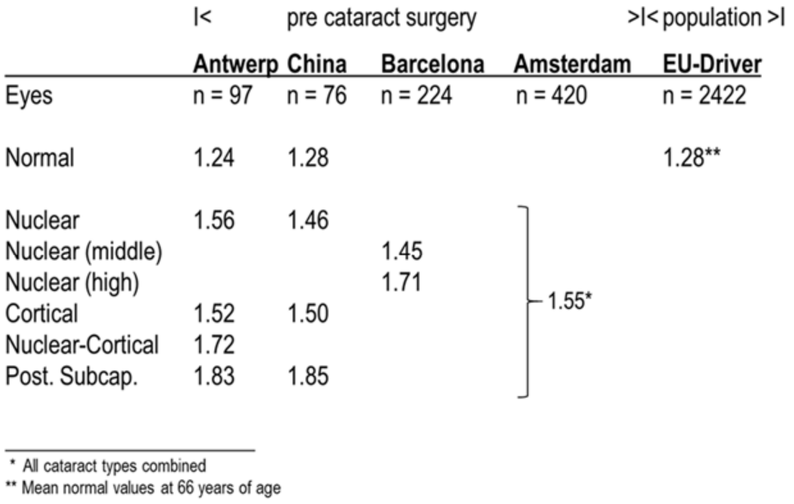


Figure 4.2.2. The correlation between nuclear cataract score and visual acuity was weak (on the left, r^2 = 0.160), and between the nuclear cataract score and intraocular straylight was very weak (on the right, r^2 = 0.028).

The weak correlation between nuclear cataract grade with intraocular straylight and visual acuity could have some explanation. For one part, we have to point out that the cataract scoring was performed by different physicians based on previously obtained pictures of the cataracts, and not directly on the patient. This could possibly yield to some inaccurate scoring of the cataract grade.

Another explanation for the weak correlation could be that simple fact that what we are measuring is not the same as what we are observing. This is explained by the nature of straylight itself. To obtain the intraocular straylight value, we measure the forward scattered light that goes on to the retina, whereas what the examiner observes on a photograph, or with the slitlamp, is the backward scattered light, thus yielding a different perception for the patient and the examiner.

Nevertheless, our results are in accordance with previous studies that have shown that intraocular straylight increases in the presence of cataract as compared to the normal value in respect to age (table 4.2.1), according to the values proposed by van den Berg et al. on a European drivers study (van den Berg, 2007). Van der Meulen et al (van der Meulen, 2012) found a mean intraocular straylight of 1.55 log(s) in patients scheduled for cataract extraction surgery, nonetheless, in that study, cataracts were not classified according to the different components and the values reported were for all cataract types combined. Bal et al. and Peng et al. (Bal, 2011; Peng, 2011), on the other hand, did classified cataracts on the basis of the different components and found a mean intraocular straylight of 1.56 and 1.46 log(s) for nuclear cataracts, respectively. They also found that posterior subcapsular cataract induced greater values of intraocular straylight (1.83 and 1.85 log(s) respectively. See table 4.2.1). As mentioned above, isolated posterior subcapsular cataract was a very infrequent finding in our patients so we didn't include this type of cataract in our analysis.



	I<	pre cataract surgery		>I<	population >I
	Antwerp	**China**	**Barcelona**	**Amsterdam**	**EU-Driver**
Eyes	n = 97	n = 76	n = 224	n = 420	n = 2422
Normal	1.24	1.28			1.28**
Nuclear	1.56	1.46		1.55*	
Nuclear (middle)			1.45		
Nuclear (high)			1.71		
Cortical	1.52	1.50			
Nuclear-Cortical	1.72				
Post. Subcap.	1.83	1.85			

* All cataract types combined
** Mean normal values at 66 years of age

Table 4.2.1. Lens cataracts increase intraocular straylight from normal levels, according to different studies.

Although the correlation between intraocular straylight values and cataract grade was weak, we observed that patients that presented nuclear cataracts with higher scores (6.1 and above) showed intraocular straylight values that were well above the values obtained from patients with lower nuclear cataract scores (below 3). This difference was also statistically significant and clinically relevant (figure 4.2.3). It is important to point out that the patients with higher nuclear cataract grades where only four, even so, with very little variability. These results have to be considered carefully. The before mentioned studies, didn't show results of the relation between intraocular straylight values with cataract grading so we can't compare our findings. Moreover, cataract grading performed by other authors was based on the LOCSIII system, which differs from the BCN10 system used in our study.

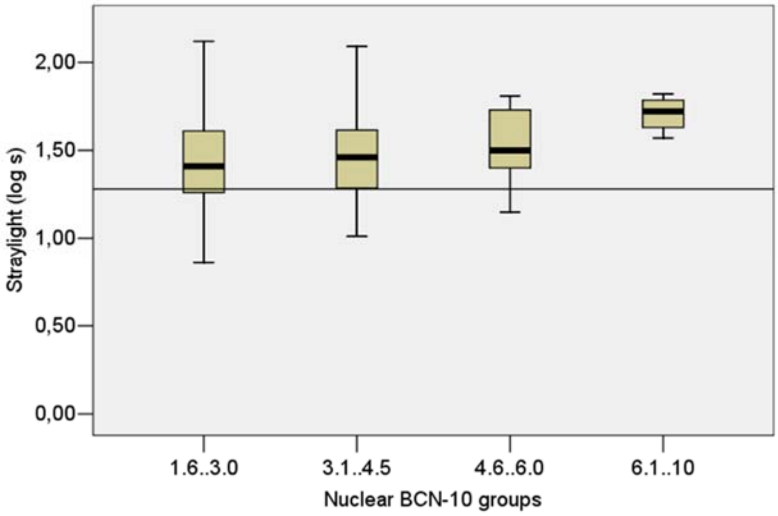


Figure 4.2.3. Intraocular straylight seems to be affected more markedly with higher nuclear cataract scores. The line indicates the normal intraocular straylight of 1.28 log(s) at 66 years of age.

4.3 Visual quality in the presence of posterior capsule opacities

Posterior capsular opacification severity appearance varies with the illumination technique applied. When using retroillumination, Elschnig's pearls and wrinkling in the posterior capsule can be observed in great detail; whereas fibrosis of the capsule can only be seen with the reflected-light technique (figure 4.3.1). Fibrosis appears as a white, hazy layer, and gives the impression of having a greater impact on visual performance. These different aspects of PCO morphology may explain the different results when correlating visual acuity and intraocular straylight with the PCO severity scores (Table 4.3.1).

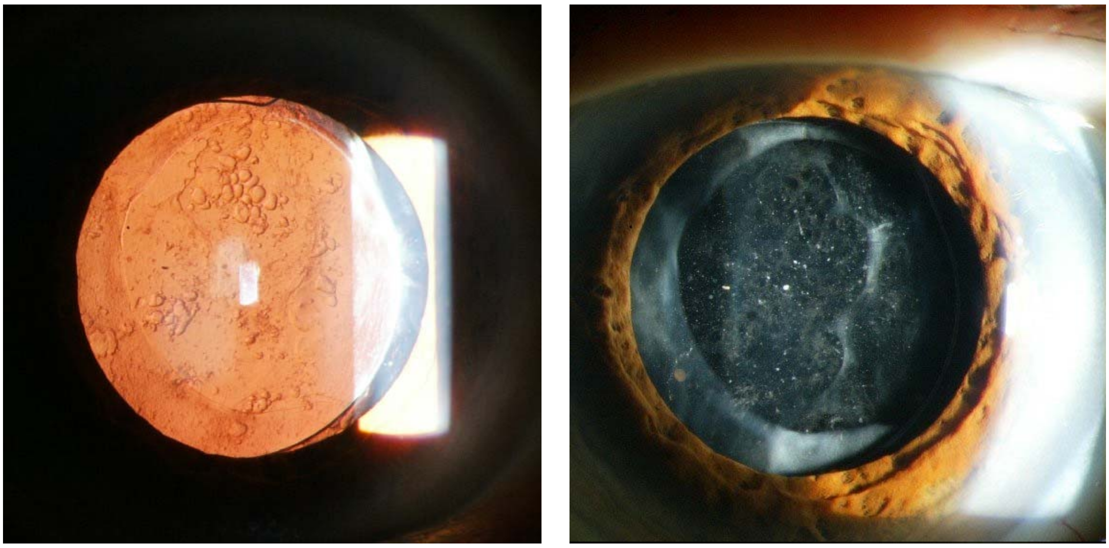
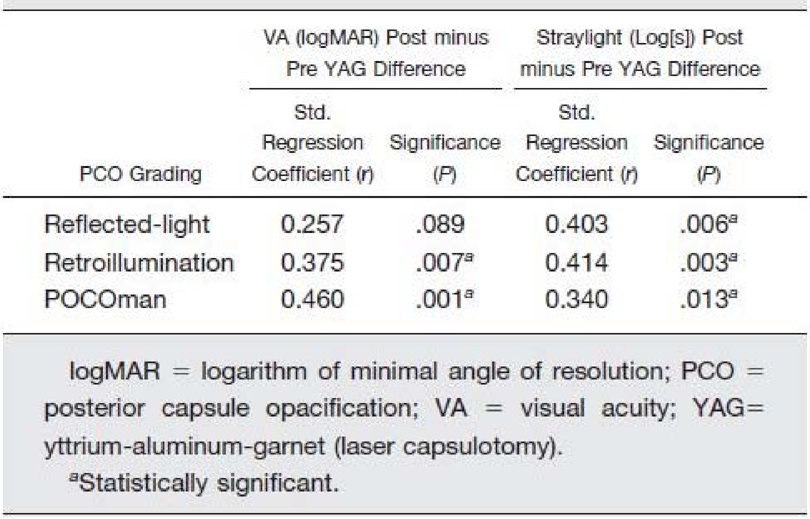


Figure 4.3.1. Retroillumination (left) and slit-lamp-derived reflected-light (right) images of posterior capsule opacification (PCO) in the same eye. Different aspects of PCO morphology are observed with each illumination technique. (Appendix B)

In this study, mean best corrected visual acuity (BCVA) in patients with posterior capsule opacification (PCO) prior to laser capsulotomy was 0.298 logMAR (0.5 decimal). This value is lower than expected for healthy non-cataractous subjects (-0.03 logMAR [1.1 decimal]), and even lower than the values observed in our study on patients with cataracts scheduled for extraction surgery (0.130 logMAR [0.7 decimal]).

There was no statistically significant correlation between BCVA with PCO scores by reflected-light (figure 4.3.1). Best corrected VA showed a weak correlation with PCO severity scores performed by retroillumination ($r^2 = 0.106$) and by the POCOman software ($r^2 = 0.179$), which is also based on retroillumination images. These correlations were statistically significant



	VA (logMAR) Post minus Pre YAG Difference		Straylight (Log[s]) Post minus Pre YAG Difference	
PCO Grading	Std. Regression Coefficient (*r*)	Significance (*P*)	Std. Regression Coefficient (*r*)	Significance (*P*)
Reflected-light	0.257	.089	0.403	.006[a]
Retroillumination	0.375	.007[a]	0.414	.003[a]
POCOman	0.460	.001[a]	0.340	.013[a]

logMAR = logarithm of minimal angle of resolution; PCO = posterior capsule opacification; VA = visual acuity; YAG= yttrium-aluminum-garnet (laser capsulotomy).

[a] Statistically significant.

Table 4.3.1. Visual acuity and intraocular straylight and their relation with posterior capsule opacification severity scores. (Appendix B)

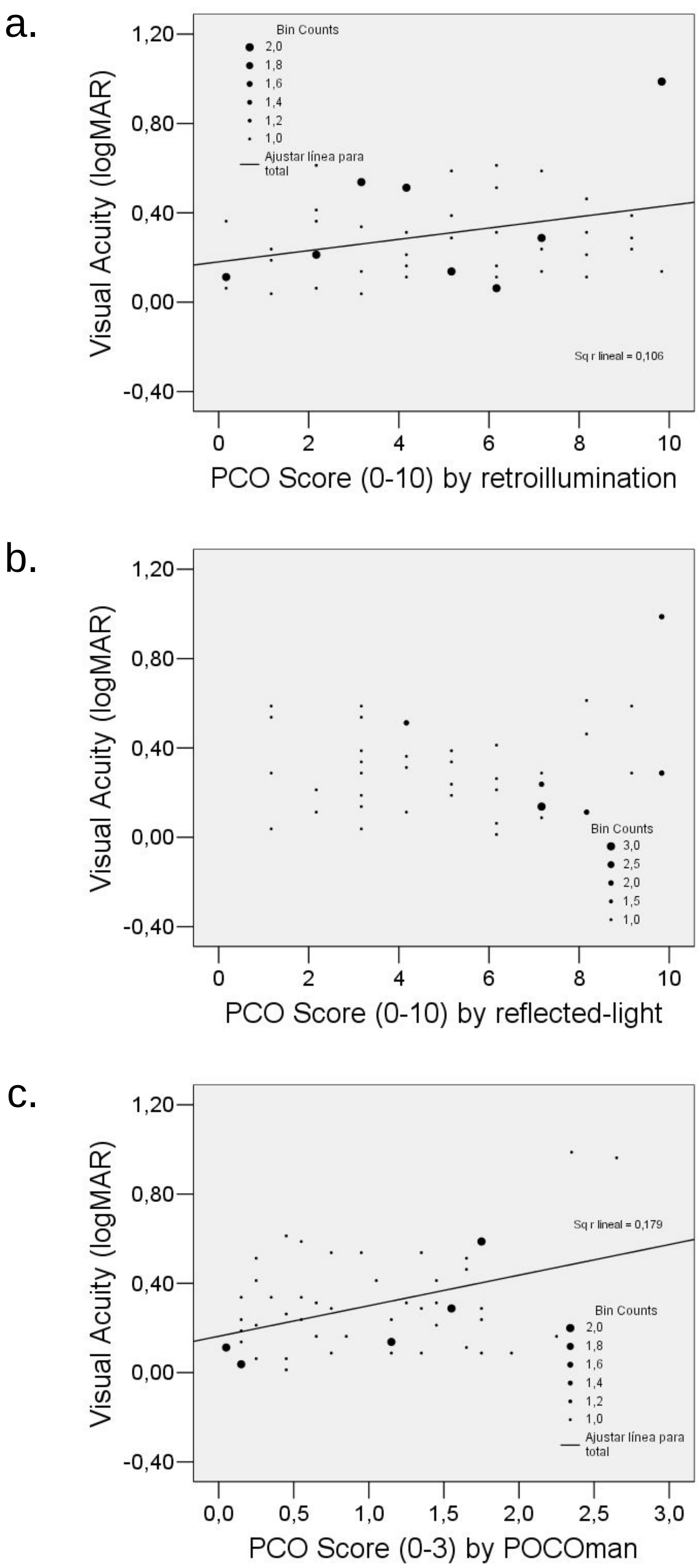


Figure 4.3.1. Visual acuity showed a weak correlation with PCO severity scores based on retroillumination (a) and the POCOman software, also based on retroillumination (c). There was no correlation with the reflected-light technique (b).

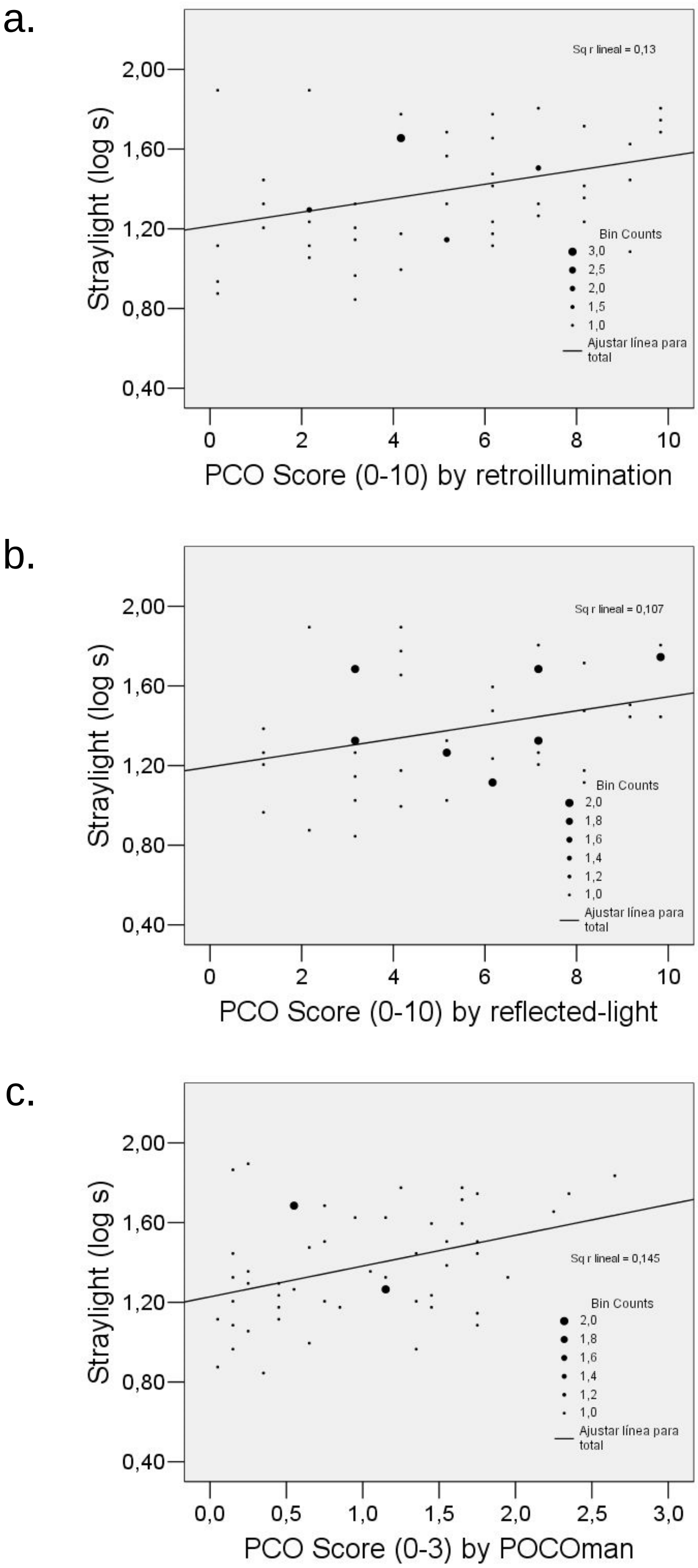


Figure 4.3.2. Intraocular straylight showed only a weak correlation with retroillumination (a), reflected-light (b), and POCOman (b) PCO severity scores.

Intraocular straylight presented a mean value of 1.38 log(s) in the presence of PCO, which is higher than normal in relation to the mean age of 67 years (1.28 log *s*), and showed a statistically significant correlation with the three PCO severity score techniques, but again, the relation was only weak, presenting an r^2 of 0.130, 0.107 and 0.145 for retroillumination, reflected-light and POCOman, respectively (figure 4.3.2).

It is possible that the images obtained with the reflected-light technique relate less to visual acuity than the ones obtained by retroillumination technique due to the different angle of illumination for each technique. For the reflected-light technique, the angle of incidence of the slit-lamp is greater than for retroillumination, which is a very small angle, usually not more than 1 degree. The smaller angle of the retroillumination is closer to the angles of resolution measured with visual acuity testing, whereas, the larger angles of the reflected-light technique is closer to the angle domain of intraocular straylight.

Retroillumination and reflected-light images may lead the examiner to overestimate the real influence of PCO on visual quality. The appearance of Elschnig's pearls and the fibrosis might seem more impairing than they really are for the patient. Both images capture the backward-scattered light from the capsule opacification, whereas the C-Quant instrument, used to obtain the intraocular straylight values, measures the forward-scattered light. The light that scatters in the forward direction will superimpose to the light that is focused on the fovea, thus affecting quality of vision. There is some correlation between forward and backward light scattering, but it depends on the size of the particle that produces the scatter (van den Berg, 1999). This may explain the only moderate correlation between the measured intraocular straylight and the subjective PCO severity scoring based on backward scattering. Similar results are reported by Hull et al. (Hull CC, et al. IOVS 2009;50:ARVO E-Abstract 6128).

After capsulotomy, mean BCVA showed a statistically significant improvement, going from 0.298 to 0.078 logMAR (0.5 to 0.8 decimal), and none of the eyes presented a decrease. Similarly, mean intraocular straylight decreased after capsulotomy, going from 1.38 log(s) to 1.21 log(s), a difference that was statistically significant. As in earlier studies (Michael, 2009; van den Berg, 2007), we also found that visual acuity and intraocular straylight are independent descriptors of visual quality. After capsulotomy, there was no correlation between the two parameters, and the change in intraocular straylight was independent of the gain in visual acuity (figure 4.3.4).

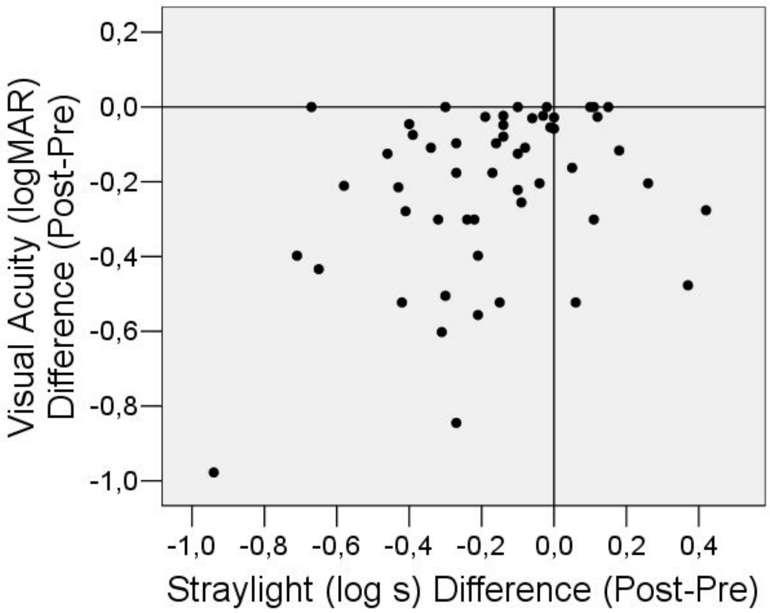


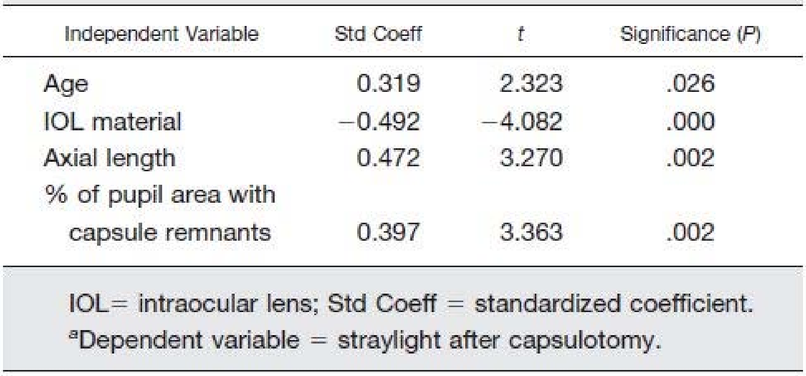
Figure 4.3.4. Before and after capsulotomy difference in intraocular straylight compared with before and after difference in visual acuity . Some eyes gained very much in visual acuity, but little in straylight; others gained in straylight but not in visual acuity. (Values below the horizontal line represent gains in visual acuity, values to the left of the vertical line represent a decrease in straylight.

Considering a change in straylight of more than 0.15 log(s) units as treatment effect (Montenegro, 2012), our results showed that patients decreased in straylight when their values before capsulotomy were > 1.40 log(s) units. This could guide the clinician with the decision to treat PCO and avoid increased intraocular straylight after posterior capsulotomy. Although intraocular straylight decreased on average after capsulotomy, 4 eyes (8%) experienced an unexpected increase of more than 0.15 log(s) units. In terms of visual acuity, all eyes benefited from capsulotomy treatment.

To try to explain this phenomenon, we looked for features that were present only after capsulotomy was performed. Image analysis revealed that those eyes showed capsule remnants in a large percentage (mean 34%) of the photopic pupil area. The effect of light scattering from these remnants and from the capsulotomy border could probably explain this unexpected increase. This issue should be further studied. Our results confirm earlier findings that capsulotomy should be larger than the pupil diameter (Goble, 1994; Hayashi, 2010; Lohmann, 1994). A higher percentage of pupil area with capsule remnants induced more retinal straylight.

One limitation of this study is the lack of a baseline straylight value for each patient before PCO developed. It would be very useful to know the straylight value right after cataract surgery, so we could have a target value of straylight to achieve after capsulotomy.

A multiple regression analysis (table 4.3.2) was performed to understand the causes of the wide range of intraocular straylight values after capsulotomy. The analysis showed that age, IOL material, axial length, and percentage of pupil area with capsule remnants significantly contributed to intraocular straylight after capsulotomy.



Independent Variable	Std Coeff	*t*	Significance (*P*)
Age	0.319	2.323	.026
IOL material	−0.492	−4.082	.000
Axial length	0.472	3.270	.002
% of pupil area with capsule remnants	0.397	3.363	.002

IOL= intraocular lens; Std Coeff = standardized coefficient.

[a] Dependent variable = straylight after capsulotomy.

Table 4.3.2. Multiple regression analysis of the factors influencing straylight after Nd:YAG laser capsulotomy.

Lens opacification has been associated with increasing intraocular straylight with age (Michael, 2009). We found that this age dependent increase is also true in pseudophakic post capsulotomy eyes. Because these eyes do not have crystalline lenses, which are considered the main source for entoptic intraocular straylight, this effect might be associated with age-related changes in the cornea and/or retina. Studies suggest that the cornea might contribute to about 30%, and the retina up to 40% of entoptic straylight (Vos, 1963; Vos, 1964).

It has been shown that large axial length also causes more retinal straylight (Rozema, 2010). Here, it could only be speculated that the larger eye volume causes more straylight and/or that the retina in subjects with high myopia is a more important source of entopic light scatter. It is unclear why hydrophobic acrylic IOLs induce more straylight than hydrophilic acrylic ones.

Hydrophobic acrylic IOLs have largely been studied for their high incidence of glistenings (Colin, 2009; Dhaliwal, 1996; Gunenc, 2001). A recent study suggests that may IOL glistenings may increase intraocular straylight (Henriksen, 2015). Nonetheless, our patients didn't present glistenings.

In summary, our study suggests that several factors influence visual quality after capsulotomy: age, axial eye length, capsulotomy size, and IOL material. Most importantly, the influence of the IOL material is surprising and should be studied in more detail.

Additionally, we subjectively graded vitreous opacities visible in the reflected-light images and found that they don't relate to post-capsulotomy intraocular straylight. This might be because of the low number of cases (n = 10) and low scores (between 1 and 4 on the 0-10 scale) of these cases in our study population and/or possible overestimation of the reflected-light images with backward-scattered light, which was compared with the forward light scattering measured by the C-Quant meter.

4.4 Interrelation between visual acuity and intraocular straylight

A large multicenter study on European drivers reported that intraocular straylight increases with age in the normal population (van den Berg, 2007). Newly evaluated data from that study also showed that visual acuity decreases with age (figure 4.4.1). We can use this data as a baseline for the normal values of intraocular straylight and visual acuity and compare it with the values observed in our studies.

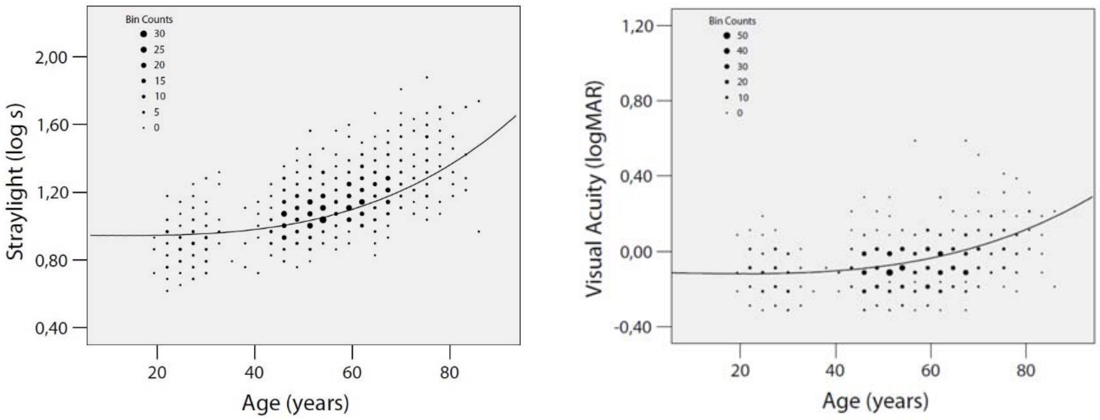


Figure 4.4.1. In phakic eyes without cataract (n = 3182), straylight increased with age (left), according to the formula: $\log(s) = 0.87+\log(1+(age/65)^{4})$ (Data obtained from [van den Berg, 2007]); whereas visual acuity decreased with age (right), according to the formula: $\text{logMAR} = -0.1116+\log(1+(age/90.38)^{5.4739})$.

Visual acuity and intraocular straylight didn't show a significant correlation after LASIK (figure 4.4.2a). Both visual acuity and intraocular straylight values were close to normal for the mean age of 30 years. Mean BCVA was 0.041 logMAR (0.91 decimal) and mean intraocular straylight was 0.96 log(s) after LASIK.

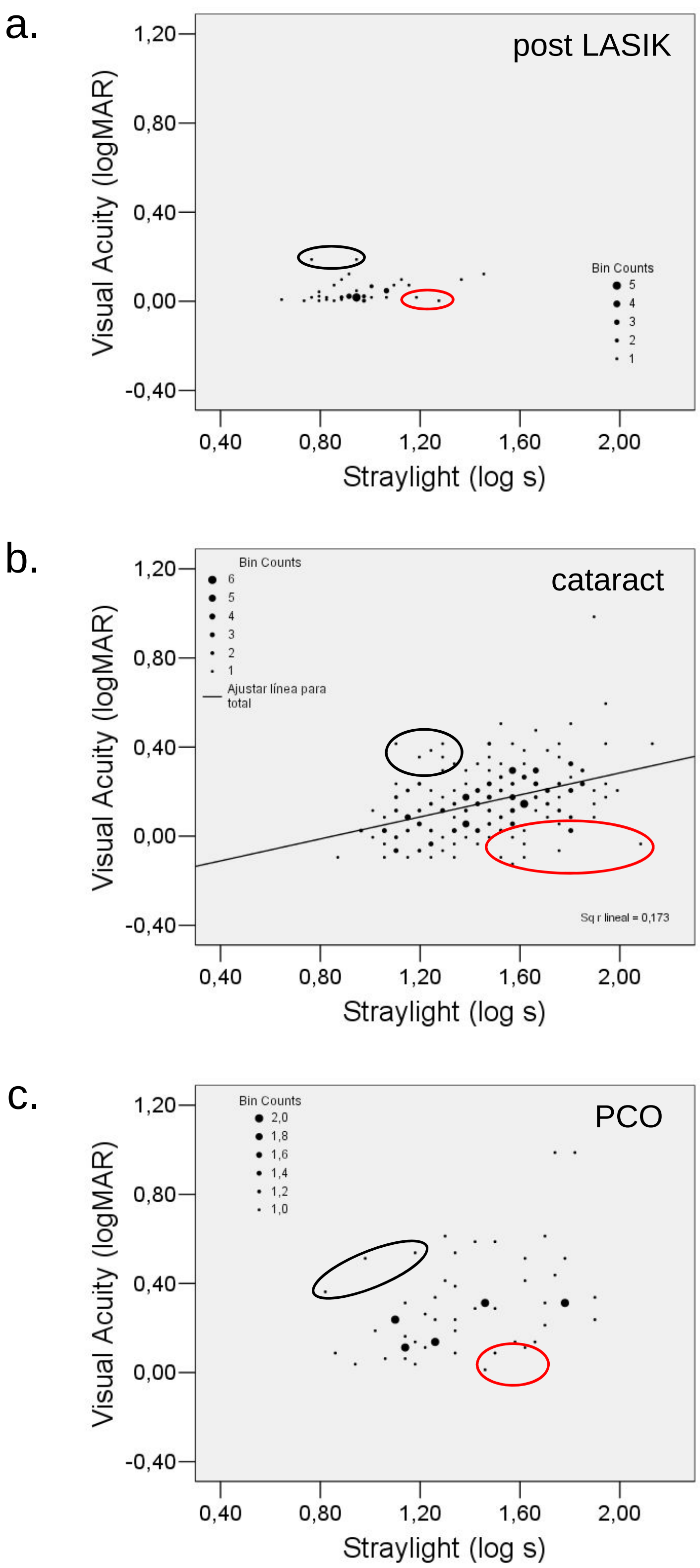


Figure 4.4.2. Visual acuity and intraocular straylight were only weakly correlated in patients with cataract (b), and did not show correlation after LASIK (a) nor before posterior capsulotomy (c). Black circles indicate higher than normal visual acuity with normal straylight values. Red circles indicate higher than normal straylight values with normal visual acuity values.

In the presence of cataract, mean BCVA was 0.13 logMAR (0.74 decimal), which is lower than normal for mean age of 65 years, and mean intraocular straylight was higher than normal, presenting a value of 1.45 log(s). Our study showed a statistically significant relationship between visual acuity and intraocular straylight, however, this correlation was weak (r2 =0.173) (figure 4.2.4b). Similarly, Van der Meulen et al (van der Meulen, 2012), also found a weak correlation between both parameters (r2 = 0.080). On the other hand, Bal et al. and Peng et al. (Bal, 2011; Peng, 2011) showed no correlation between visual acuity and intraocular straylight in the presence of cataract.

PCO also affected both visual acuity and intraocular straylight, but these parameters were not correlated (figure 4.4.2c). Visual acuity was lower than normal, with a mean value of 0.298 logMAR (0.5 decimal). Intraocular straylight was 1.38 log(s), which is above normal values for mean age of 67 years.

It can be seen that visual acuity and intraocular straylight behave differently in various clinical situations. After LASIK, both BCVA and intraocular straylight stay close to normal values. It has to be noted that LASIK improves UCVA, thus, it really changes visual acuity without affecting intraocular straylight.

Media opacities, such as cataracts and PCO, affect both, visual acuity and intraocular straylight, but not to the same extent. Visual acuity decreases more with PCO than with cataracts, whereas intraocular straylight is higher with cataracts than with PCO.

The different behavior of visual acuity and intraocular straylight in the three clinical situations can be observed in figure 4.4.2, which shows that there can be some patients with close to normal visual acuity values (red circles) that have increased intraocular straylight values and, especially in the case of PCO, there can be patients with normal intraocular straylight values with decreased visual acuity (black circles).

These results indicate that visual quality can be independently affected by a decrease in visual acuity or an increase in intraocular straylight, and thus both parameters should be considered when assessing visual quality.

5. Conclusions

- Intraocular straylight did not increase after uneventful refractive surgery. Nonetheless, some cases of temporarily increase have been reported on the literature, returning to normal levels after up to 6 months. In cases of postoperative complications straylight may also increase.

- There was a variable increase in intraocular straylight in the presence of cataract and posterior capsule opacification. Nevertheless, there was only a weak correlation between measured straylight and opacity severity grading. This could be explained by the fact that straylight measurement considers the forward-scattered light, whereas opacity grading considers backward-scattered light.

- When intraocular straylight was elevated due to PCO, larger than pupil size capsulotomies decreased it. Smaller than pupil size capsulotomies, on the other hand, further increased intraocular straylight.

- In general there was only a weak correlation between intraocular straylight and visual acuity. These parameters didn´t show a correlation after LASIK nor in the presence of PCO, and they were only weakly correlated in the presence of cataract. Intraocular straylight affects visual quality independently of visual acuity, thus acting as an additional descriptor of visual quality and helping on its evaluation.

6. Acknowledgements

I would personally like to thank:

My family, my parents Richard and Ana María for your unconditional love and support and all that you have taught me. My brothers Juan Carlos and Richard A. for always worrying about me and being there for me.

Professor Joaquín Barraquer Moner, my thesis director, for your support and for being an inspiration for the way you love your profession, and the way you care for your patients.

Doctor Ralph Michael, my thesis director and mentor, for being always there pushing me, guiding me and helping me throughout the long way that took me to get to the culmination of my doctoral formation.

My tutor Doctor José García Arumí, for having the time to and the patience to review my work and providing me with valuable input.

Doctor Rafael I. Barraquer, for all the help you have given me during my time in this Center, all the knowledge shared and the insight in the publications included in this thesis, all of them you have coauthored.

Doctors María Isabel Canut and Andrés Picó, for agreeing to coauthor in one publication and allowing me to use your patients for the study.

Doctors Günther Grabner, Patrick Marvan, and Alois Dexl, for your willingness to collaborate in one study and letting me use the results to include them in this thesis.

Doctor Tom J. van den Berg, developer of the C-Quant straylight meter, for your support and stimulus, and for allowing me to use your data for the elaboration of this thesis.

Joaquín Gioino, Alexander Ospino, Alejandro Recancof, Kattia Llanos Rota and Yolanda Chahua Torres, for performing some of the C-Quant measurements.

Juan Carlos Reyes, Conrad Latoche and Lourdes Ruiz for your help collecting patient data.

Dimas Abello, Jordi Navazo, Jordi Carcelero, Emilio Hernández, Federico Martínez from the photographic department, for your help and your great work.

My previous and current co-workers and friends, Marek, Jurja, Paola, María, Víctor, Lourdes, Ruth, Kelma, Laura, and Justin, for all your help and all the good moments.

All the workers from the Centro de Oftalmología Barraquer and the Institut Universitari Barraquer, for making it work.

My friends, for all your support and for being my friends. Thank you so much.

7. References

Alio, J.L., Muftuoglu, O., Ortiz, D., Perez-Santonja, J.J., Artola, A., Ayala, M.J., Garcia, M.J., & de Luna, G.C. 2008. Ten-year follow-up of laser in situ keratomileusis for high myopia. *Am.J.Ophthalmol.*, 145, (1) 55-64

Bal, T., Coeckelbergh, T., Van, L.J., Rozema, J.J., & Tassignon, M.J. 2011. Influence of cataract morphology on straylight and contrast sensitivity and its relevance to fitness to drive. *Ophthalmologica*, 225, (2) 105-111

Beerthuizen, J.J., Franssen, L., Landesz, M., & van den Berg, T.J. 2007. Straylight values 1 month after laser in situ keratomileusis and photorefractive keratectomy. *J.Cataract Refract.Surg.*, 33, (5) 779-783

Bender, L., Spalton, D.J., Uyanonvara, B., Boyce, J., Heatley, C., Jose, R., & Khan, J. 2004. POCOman: new system for quantifying posterior capsule opacification. *J.Cataract Refract.Surg.*, 30, (10) 2058-2063

Cervino, A., Montes-Mico, R., & Hosking, S.L. 2008. Performance of the compensation comparison method for retinal straylight measurement: effect of patient's age on repeatability. *Br.J.Ophthalmol.*, 92, (6) 788-791

Chylack, L.T., Jr., Wolfe, J.K., Singer, D.M., Leske, M.C., Bullimore, M.A., Bailey, I.L., Friend, J., McCarthy, D., & Wu, S.Y. 1993. The Lens Opacities Classification System III. The Longitudinal Study of Cataract Study Group. *Arch.Ophthalmol.*, 111, (6) 831-836

Cobb, P.W. 1911. The influence of illumination of the eye on visual acuity. *American Journal of Physiology -- Legacy Content*, 29, (1) 76-99 available from: http://ajplegacy.physiology.org/content/29/1/76.abstract

Colin, J., Orignac, I., & Touboul, D. 2009. Glistenings in a large series of hydrophobic acrylic intraocular lenses. *J.Cataract Refract.Surg.*, 35, (12) 2121-2126

Delori, F.C. & Pflibsen, K.P. 1989. Spectral reflectance of the human ocular fundus. *Appl.Opt.*, 28, (6) 1061-1077

Dhaliwal, D.K., Mamalis, N., Olson, R.J., Crandall, A.S., Zimmerman, P., Alldredge, O.C., Durcan, F.J., & Omar, O. 1996. Visual significance of glistenings seen in the AcrySof intraocular lens. *J.Cataract Refract.Surg.*, 22, (4) 452-457

Donate, D., Denis, P., & Burillon, C. 2005. [Prospective study of contrast sensitivity and visual effects after LASIK]. *J.Fr.Ophtalmol.*, 28, (10) 1070-1075

Elliott, D.B. & Bullimore, M.A. 1993. Assessing the reliability, discriminative ability, and validity of disability glare tests. *Invest Ophthalmol.Vis.Sci.*, 34, (1) 108-119 available from: PM:8425818

Elliott, D.B., Fonn, D., Flanagan, J., & Doughty, M. 1993. Relative sensitivity of clinical tests to hydrophilic lens-induced corneal thickness changes. *Optom.Vis.Sci.*, 70, (12) 1044-1048

Fares, U., Suleman, H., Al-Aqaba, M.A., Otri, A.M., Said, D.G., & Dua, H.S. 2011. Efficacy, predictability, and safety of wavefront-guided refractive laser treatment: metaanalysis. *J.Cataract Refract.Surg.*, 37, (8) 1465-1475

Franssen, L. & Coppens, J.E. 2007. Straylight at the retina: scattered papers. *Doctoral thesis.*

Franssen, L., Coppens, J.E., & van den Berg, T.J. 2006. Compensation comparison method for assessment of retinal straylight. *Invest Ophthalmol.Vis.Sci.*, 47, (2) 768-776

Franssen, L., Tabernero, J., Coppens, J.E., & van den Berg, T.J. 2007. Pupil size and retinal straylight in the normal eye. *Invest Ophthalmol.Vis.Sci.*, 48, (5) 2375-2382

Ginis, H., Sahin, O., Pennos, A., & Artal, P. 2014. Compact optical integration instrument to measure intraocular straylight. *Biomed.Opt.Express*, 5, (9) 3036-3041

Goble, R.R., O'Brart, D.P., Lohmann, C.P., Fitzke, F., & Marshall, J. 1994. The role of light scatter in the degradation of visual performance before and after Nd:YAG capsulotomy. *Eye (Lond)*, 8 (Pt 5), 530-534

Gunenc, U., Oner, F.H., Tongal, S., & Ferliel, M. 2001. Effects on visual function of glistenings and folding marks in AcrySof intraocular lenses. *J.Cataract Refract.Surg.*, 27, (10) 1611-1614

Guo, Y.W., Li, J., Song, H., & Tang, X. 2014. Comparison of the Retinal Straylight in Pseudophakic Eyes with PMMA, Hydrophobic Acrylic, and Hydrophilic Acrylic Spherical Intraocular Lens. *J.Ophthalmol.*, 2014, 340759

Hayashi, K., Nakao, F., & Hayashi, H. 2010. Influence of size of neodymium:yttrium-aluminium-garnet laser posterior capsulotomy on visual function. *Eye (Lond)*, 24, (1) 101-106

Henriksen, B.S., Kinard, K., & Olson, R.J. 2015. Effect of intraocular lens glistening size on visual quality. *J.Cataract Refract.Surg.*, 41, (6) 1190-1198

Heys, K.R., Friedrich, M.G., & Truscott, R.J. 2008. Free and bound water in normal and cataractous human lenses. *Invest Ophthalmol.Vis.Sci.*, 49, (5) 1991-1997

Holladay, L.L. 1926. The fundamentals of glare and visibility. *J.Opt.Soc.Am.*, 12, (4) 271-319

Iijima, A., Shimizu, K., Kobashi, H., Saito, A., & Kamiya, K. 2015. Repeatability, Reproducibility, and Comparability of Subjective and Objective Measurements of Intraocular Forward Scattering in Healthy Subjects. *Biomed.Res.Int.*, 2015, 925217

Kaminski, S. & Lukas, J. 1997. [Refractive laser surgery of the cornea]. *Wien.Med.Wochenschr.*, 147, (12-13) 302-307

Kim, T.W., Wee, W.R., Lee, J.H., & Kim, M.K. 2007. Contrast sensitivity after LASIK, LASEK, and wavefront-guided LASEK with the VISX S4 laser. *J.Refract.Surg.*, 23, (4) 355-361

Knorz, M.C., Jendritza, B., Liermann, A., Hugger, P., & Liesenhoff, H. 1998. [LASIK for myopia correction. 2-year follow-up]. *Ophthalmologe*, 95, (7) 494-498

Lapid-Gortzak, R., van der Linden, J.W., van, d.M., I, Nieuwendaal, C., & van den Berg, T. 2010. Straylight measurements in laser in situ keratomileusis and laser-assisted subepithelial keratectomy for myopia. *J.Cataract Refract.Surg.*, 36, (3) 465-471

Lee, H.K., Choe, C.M., Ma, K.T., & Kim, E.K. 2006. Measurement of contrast sensitivity and glare under mesopic and photopic conditions following wavefront-guided and conventional LASIK surgery. *J.Refract.Surg.*, 22, (7) 647-655

Li, J. & Wang, Y. 2011. Characteristics of straylight in normal young myopic eyes and changes before and after LASIK. *Invest Ophthalmol.Vis.Sci.*, 52, (6) 3069-3073

Lohmann, C.P., Goble, R., O'Brart, D., Fitzke, F., Marshall, J., & Gabel, V.P. 1994. [Sensitivity to glare before and after Nd:YAG capsulotomy. Comparison between small and large capsulotomy]. *Klin.Monbl.Augenheilkd.*, 205, (2) 65-69

Lorente-Velazquez, A., Nieto-Bona, A., Collar, C.V., & Gutierrez Ortega, A.R. 2010. Intraocular straylight and contrast sensitivity (1/2) and 6 months after laser in situ keratomileusis. *Eye Contact Lens*, 36, (3) 152-155

Marcos, S. 2001. Aberrations and visual performance following standard laser vision correction. *J.Refract.Surg.*, 17, (5) S596-S601

Michael, R., van Rijn, L.J., van den Berg, T.J., Barraquer, R.I., Grabner, G., Wilhelm, H., Coeckelbergh, T., Emesz, M., Marvan, P., & Nischler, C. 2009. Association of lens opacities, intraocular straylight, contrast sensitivity and visual acuity in European drivers. *Acta Ophthalmol.*, 87, (6) 666-671

Montenegro, G.A., Michael, R., & van den Berg, T.J. 2012. Variation of straylight between contra lateral eyes - results from 1017 healthy subjects. *Acta Ophthalmol.*, 90, (4) e332-e333

Mrochen, M., Kaemmerer, M., & Seiler, T. 2001. Clinical results of wavefront-guided laser in situ keratomileusis 3 months after surgery. *J.Cataract Refract.Surg.*, 27, (2) 201-207

Neeracher, B., Senn, P., & Schipper, I. 2004. Glare sensitivity and optical side effects 1 year after photorefractive keratectomy and laser in situ keratomileusis. *J.Cataract Refract.Surg.*, 30, (8) 1696-1701

Nieto-Bona, A., Lorente-Velazquez, A., Collar, C.V., Nieto-Bona, P., & Mesa, A.G. 2010. Intraocular straylight and corneal morphology six months after LASIK. *Curr.Eye Res.*, 35, (3) 212-219

Nischler, C., Michael, R., Wintersteller, C., Marvan, P., Emesz, M., van Rijn, L.J., van den Berg, T.J., Wilhelm, H., Coeckelbergh, T., Barraquer, R.I., Grabner, G., & Hitzl, W. 2010. Cataract and pseudophakia in elderly European drivers. *Eur.J.Ophthalmol.*, 20, (5) 892-901

O'Doherty, M., O'Keeffe, M., & Kelleher, C. 2006. Five year follow up of laser in situ keratomileusis for all levels of myopia. *Br.J.Ophthalmol.*, 90, (1) 20-23

Peng, C., Zhao, J.Y., Ma, L.W., Qu, B., & Zhang, J.S. 2011. [Clinical evaluation of quality of vision with age-related cataract of different morphologies]. *Zhonghua Yan.Ke.Za Zhi.*, 47, (11) 1001-1006

Puell, M.C., Palomo, C., Sanchez-Ramos, C., & Villena, C. 2004. Mesopic contrast sensitivity in the presence or absence of glare in a large driver population. *Graefes Arch.Clin.Exp.Ophthalmol.*, 242, (9) 755-761

Rozema, J.J., van den Berg, T.J., & Tassignon, M.J. 2010. Retinal straylight as a function of age and ocular biometry in healthy eyes. *Invest Ophthalmol.Vis.Sci.*, 51, (5) 2795-2799

Salchow, D.J., Zirm, M.E., Stieldorf, C., & Parisi, A. 1998. [Laser in situ keratomileusis (LASIK) for correction of myopia and astigmatism]. *Ophthalmologe*, 95, (3) 142-147

Shaheen, M.S., Massoud, T.H., Ezzeldin, H., & Khalifa, M.A. 2013. Four-year visual, refractive, and contrast sensitivity outcomes after wavefront-guided myopic LASIK using an advanced excimer laser platform. *J.Refract.Surg.*, 29, (12) 816-822

Stiles, W.S. 1929. The Effect of Glare on the Brightness Difference Threshold. *Proceedings of the Royal Society of London B: Biological Sciences*, 104, (731) 322-351 available from: http://rspb.royalsocietypublishing.org/content/104/731/322.abstract

Tahzib, N.G., Bootsma, S.J., Eggink, F.A., Nabar, V.A., & Nuijts, R.M. 2005. Functional outcomes and patient satisfaction after laser in situ keratomileusis for correction of myopia. *J.Cataract Refract.Surg.*, 31, (10) 1943-1951

Tuan, K.M. & Liang, J. 2006. Improved contrast sensitivity and visual acuity after wavefront-guided laser in situ keratomileusis: in-depth statistical analysis. *J.Cataract Refract.Surg.*, 32, (2) 215-220

van Bree, M.C., Zijlmans, B.L., & van den Berg, T.J. 2008. Effect of neodymium:YAG laser capsulotomy on retinal straylight values in patients with posterior capsule opacification. *J.Cataract Refract.Surg.*, 34, (10) 1681-1686

van den Berg, T.J. 2011. Problem of double pass recording using infrared light. *Clin.Exp.Optom.*, 94, (4) 393-395

van den Berg, T. J., Franssen, L., & Coppens, J. E. 2010, "Ocular media clarity and straylight," *In Encyclopedia of the Eye*, vol. 3 A. D. Dart, J. C. Besharse, & R. Dana, eds., Oxford: Academic Press, pp. 173-183.

van den Berg, T.J., Ijspeert, J.K., & de Waard, P.W. 1991. Dependence of intraocular straylight on pigmentation and light transmission through the ocular wall. *Vision Res.*, 31, (7-8) 1361-1367

van den Berg, T.J. & Spekreijse, H. 1999. Light scattering model for donor lenses as a function of depth. *Vision Res.*, 39, (8) 1437-1445

van den Berg, T.J., van Rijn, L.J., Michael, R., Heine, C., Coeckelbergh, T., Nischler, C., Wilhelm, H., Grabner, G., Emesz, M., Barraquer, R.I., Coppens, J.E., & Franssen, L. 2007. Straylight effects with aging and lens extraction. *Am.J.Ophthalmol.*, 144, (3) 358-363

van der Meulen, I.J., Engelbrecht, L.A., van Vliet, J.M., Lapid-Gortzak, R., Nieuwendaal, C.P., Mourits, M.P., Schlingemann, R.O., & van den Berg, T.J. 2010. Straylight measurements in contact lens wear. *Cornea*, 29, (5) 516-522

van der Meulen, I.J., Gjertsen, J., Kruijt, B., Witmer, J.P., Rulo, A., Schlingemann, R.O., & van den Berg, T.J. 2012. Straylight measurements as an indication for cataract surgery. *J.Cataract Refract.Surg.*, 38, (5) 840-848

van Gaalen, K.W., Koopmans, S.A., Hooymans, J.M., Jansonius, N.M., & Kooijman, A.C. 2010. Straylight measurements in pseudophakic eyes with natural and dilated pupils: one-year follow-up. *J.Cataract Refract.Surg.*, 36, (6) 923-928

van Rijn, L.J., Nischler, C., Gamer, D., Franssen, L., de, W.G., Kaper, R., Vonhoff, D., Grabner, G., Wilhelm, H., Volker-Dieben, H.J., & van den Berg, T.J. 2005. Measurement of stray light and glare: comparison of Nyktotest, Mesotest, stray light meter, and computer implemented stray light meter. *Br.J.Ophthalmol.*, 89, (3) 345-351

Veraart, H.G., van den Berg, T.J., Hennekes, R., & Adank, A.M. 1995. Stray light in photorefractive keratectomy for myopia. *Doc.Ophthalmol.*, 90, (1) 35-42

Veraart, H.G., van den Berg, T.J., Ijspeert, J.K., & Cardozo, O.L. 1992. Stray light in radial keratotomy and the influence of pupil size and straylight angle. *Am.J.Ophthalmol.*, 114, (4) 424-428

Vos, J.J. & Boogaard, J. 1963. Contribution of the cornea to entoptic scatter. *J.Opt.Soc.Am.*, 53, 869-873

Vos, J.J. & Bouman, M.A. 1964. Contribution of the retina to entoptic scatter. *J.Opt.Soc.Am.*, 54, 95-100

Yamane, N., Miyata, K., Samejima, T., Hiraoka, T., Kiuchi, T., Okamoto, F., Hirohara, Y., Mihashi, T., & Oshika, T. 2004. Ocular higher-order aberrations and contrast sensitivity after conventional laser in situ keratomileusis. *Invest Ophthalmol.Vis.Sci.*, 45, (11) 3986-3990

8. Appendix A

Intraocular straylight and contrast sensitivity two months after LASIK

Ralph Michael, PhD[1]; Gustavo A. Montenegro, MD[1]; Rafael I. Barraquer, MD, PhD[1]

PURPOSE: To study the effect of Laser in-Situ Keratomileusis on intraocular straylight and contrast sensitivity.

METHODS: Altogether 46 eyes of 28 patients (mean age 30 years; refractive error range 3.5 to -8.0 D) were treated for LASIK with Bausch & Lomb Technolas Z100 and studied pre-op and two-month post-op. Intraocular straylight was measured with the Oculus C-Quant and contrast sensitivity with the CSV-1000 (at 3, 6, 12, 18 cycles/degree).

RESULTS: Pre-op mean straylight parameter did not change at two months post-op. Only one eye out of 46 had straylight values increased by more than 0.25 log units. There was no significant change in contrast sensitivity at all four spatial frequencies. We found a significant improvement of post-op contrast sensitivity when we excluded 10 eyes that presented variations of two or more positions in contrast sensitivity.

CONCLUSION: Mean straylight and contrast sensitivity did not change two months after LASIK. Both visual quality measures worsened in a few cases but remained constant or improved slightly in the majority of the cases.

SYNOPSIS: Mean C-Quant measurements of intraocular straylight, and contrast sensitivity at 3, 6, 12, 18 cycles/degree did not change significantly two months after LASIK.

J Emmetropia 2010; 1: 59-63

INTRODUCTION

Laser in-Situ Keratomileusis (LASIK) is currently one of the most widely used laser refractive surgeries. Over the years it has been continuously improving and refining its outcome. A successful procedure is commonly judged on visual acuity only. However, patients with an excellent visual acuity may sometimes complain of bad vision. Contrast sensitivity and intraocular straylight are known to have an impact on visual performance[1,2] and could explain some of the patients' complaints. Therefore the purpose of this study is to quantify the variation, if any, in the level of intraocular straylight and contrast sensitivity in patients who underwent LASIK surgery.

There is no agreement on the effects of LASIK on contrast sensitivity. Some authors suggest that there is a decrease in contrast sensitivity after LASIK[3-5], whereas others believe there is no change or even an improvement, depending on the technique[6,7].

Considering straylight, there are only a few studies. Lee et al. found a post-op increase of straylight[6] in LASIK patients and Kim et al. reported no change[7] post-op. Both used the subjective ALC Glare test where the patient looked at the white spot (316 pixels) displayed on a 17-inch TFT LCD monitor (1024x768 resolution) positioned 50 cm from the patient. The patient had to draw the boundary of the halo he or she saw on a graphics tablet. The area of the halo was then automatically calculated in pixels or square millimeters. Beerthuizen et al., using the C-Quant, found no variation in intraocular straylight[8] one month after LASIK.

We measured contrast sensitivity at four different spatial frequencies using the CSV-1000 (Vector Vision;

Submitted: 5/23/2010
Revised: 6/7/2010
Accepted: 6/13/2010

[1] Institut Universitari Barraquer, Universitat Autònoma de Barcelona, Barcelona, Spain.

Financial support: This study has been supported in part by a grant of the Spanish Ministry of Health, Instituto Carlos III, Red Temática de Investigación Cooperativa en Salud «Patología ocular del envejecimiento, calidad visual y calidad de vida», Subproyecto de Calidad Visual (RD07/0062).

Proprietary and financial interest: None.

Corresponding author: Dr. Ralph Michael. Institut Universitari Barraquer. Laforja 88 - E-08021 Barcelona. Tel: (+34) 93 200 6311 Ext 2406 / 2402. Fax: (+34) 93 414 1228. E-mail: ralphm@barraquer.com

ISSN: 2171-4703

Haag Streit, Harlow, UK). The C-Quant straylight meter[2] was employed to measure intraocular straylight.

METHODS

Study Population

This prospective study includes 46 eyes of 28 patients from the *Centro de Oftalmología Barraquer,* Barcelona, who were eligible for LASIK surgery, after excluding lens opacities, macular lesions, or any other anatomic anomaly of the eye globe. All the subjects in the study were treated for LASIK with Bausch & Lomb Technolas Z100. We included conventional ablation profiles (Planoscan and Cross Cylinder, n = 23) and wavefront-guided ablation profiles (Zyoptx, n = 23). One day prior surgery patients went through a full ophthalmologic examination with registration of uncorrected visual acuity (UCVA), best spectacle-corrected visual acuity (BSCVA), contrast sensitivity and straylight measurements. Preoperative spherical error ranged from -8.0 to +3.5 diopters, with 39 miopes (mean -4.0 diopters) and 7 hyperopes (mean 2.1 diopters). The age of the patients ranged from 22 to 50 years, with an average of 30 years. Two months after surgery a full evaluation was performed again.

Straylight Measurements

Values for intraocular straylight were obtained using the C-Quant (Oculus GmbH, Wetzlar, Germany). This is a commercial version of the third generation straylight meter, implemented on a personal computer. The C-Quant measures intraocular straylight based on the Compensation Comparison method[9]. The test field is divided in two half rings that flicker at 8 Hz. One side has the counter-phase compensation light. The patient must choose the side that seems to flicker more strongly. To assure the quality of the measurements, the test was repeated up to three times in case the computer software indicated low reliability. If the result was still unreliable, the subject was excluded from the study. Values were expressed[10] as log[straylight parameter] (log[s]). Higher straylight values indicate a higher sensitivity to glare and thus a more compromised visual function.

Contrast Sensitivity Measurements

Contrast sensitivity was measured using the CSV-1000 (Vector Vision; Haag Streit, Harlow, UK) at 3, 6, 12 and 18 cycles/degree. The CSV-1000 consists of a backlighted chart that presents sine wave gratings with four different special frequencies. Each frequency is presented on a separate row on the chart. There are 17 patches for each row. The first patch has a high contrast grating and identifies the spatial frequency for that row. The remaining 16 are paired in eight columns across the row. For each pair, one patch presents the grating, whereas the other is blank but of the same luminance. The patches decrease 40% in contrast across the row from left to right. The patient must choose which patch has the grating for that column. The contrast threshold is measured from the last correct response. The contrast sensitivity levels in each row range from 0.7 to 2.08; 0.91 to 2.29; 0.61 to 1.99; and 0.17 to 1.55 log units for 3, 6, 12, and 18 cycles/degree respectively (User manual CSV-1000).

Statistical Analysis

Mean and 95% confidence interval is given and the Students t-test was used to compare straylight and contrast sensitivity values; $p < 0.05$ was considered significant. The computer based statistical software SPSS 13.0 for Windows (SPSS, Chicago, Ill.) was used for the analysis of the data.

Table 1: Mean individual differences (2 months post minus pre LASIK) of best spectacle corrected visual acuity (BSCVA), straylight and contrast sensitivity (CS); considering all eyes together, a group of cases without 10 eyes that presented variations of two or more positions in CS and for the 10 excluded eyes alone. A negative BSCVA difference, a negative straylight difference or a positive CS difference reveals a post operative improvement

	All eyes (n = 46)		Without extreme CS cases (n = 36)		Extreme CS cases (n = 10)	
Difference (post - pre)	**Mean ± CI**	**p**	**Mean ± CI**	**p**	**Mean ± CI**	**p**
BSCVA (logMAR)	0.01±0.01	0.09	0.01±0.01	0.06	0.00±0.04	0.84
Straylight (log [s])	-0.02±0.05	0.43	-0.05±0.06	0.07	0.09±0.09	0.05
CS at 3 cyc/deg (log [c])	0.01±0.03	0.44	0.03±0.04	0.08	-0.06±0.08	0.10
CS at 6 cyc/deg (log [c])	-0.01±0.06	0.69	0.05±0.05	0.03	-0.25±0.18	0.01
CS at 12 cyc/deg (log [c])	-0.05±0.09	0.26	0.05±0.05	0.03	-0.43±0.03	0.01
CS at 18 cyc/deg (log [c])	-0.05±0.10	0.30	0.07±0.05	0.01	-0.49±0.31	0.01

CI = confidence interval; p = significance coefficient obtained using the paired Students *t* test.

RESULTS

Pre operative best spectacle-corrected visual acuity (BSCVA) was 0.029 ± 0.011 logMAR [mean ± (confidence interval (CI)], which corresponds to a mean of 0.93 on a decimal scale. Post-operative (2 month) BSCVA was 0.041 ± 0.014 logMAR (0.91 decimal). There was no significant change in the mean of the individual post minus pre operative differences, considering the BSCVA for all patients together (Table 1). One eye (2 %) lost 2 lines of BSCVA. Post-operative UCVA was 0.091 ± 0.041 logMAR (0.81 decimal). The mean safety index (BSCVA post / BSCVA pre) was 0.98 and the mean efficacy index (UCVA post/ BSCVA pre) was 0.90. Except for two eyes (4%), there were no clinically significant complications post-operatively. One case showed a diffuse lamellar keratitis (DLK) and an increased optical density within the flap-cornea interface and the other a light paracentral superficial punctate keratitis (SPK). The DLK patient was 50 years old, was corrected for +1 diopter and had a pre-op decimal BSCVA of 0.90 and post-op of 0.75. The SPK patient was 29 years old, was corrected for -5.25 diopters and had a pre-op decimal BSCVA of 0.95 and post-op of 0.85. Figure 1 and 2 show the clinical appearance of both cases.

We found a straylight value of 0.98 ± 0.04 log(s) (mean ± CI) pre operatively and 0.96 ± 0.05 log(s) post operatively. There was no statistically significant variation in post-operative straylight values compared to those pre operatively (Table 1). Only one eye had an increase of more than 0.25 log units in straylight post operatively (Figure 3). This was the patient with diffuse lamellar keratitis. Straylight increased from 1.03 to 1.46 log(s). The patient with superficial punctuate keratitis did not have a significant change in his straylight values [pre-op 1.07 and post-op 1.02 log(s)].

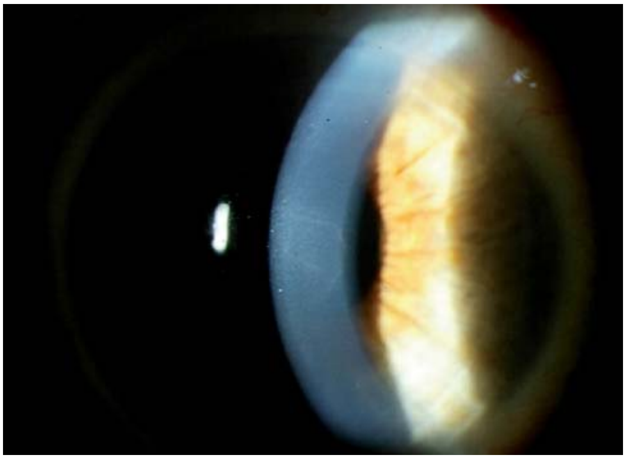


Figure 1. Slit lamp view of the eye with diffuse lamellar keratitis and an increased optical density within the flap-cornea interface.

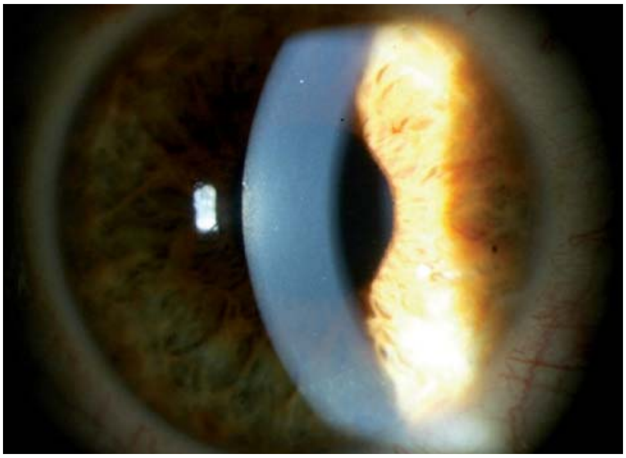


Figure 2. Slit lamp view of the eye with light paracentral superficial punctate keratitis.

A few eyes had already pre operative contrast sensitivity values below the normal range for their age (as defined by the CSV-1000 manual); 4 eyes at 18 cyc/deg and 1 eye at 12 cyc/deg. They remained there stable post operatively (Figure 4).

On average, contrast sensitivity values did not change significantly (Table 1). However, important individual variations were observed in 10 eyes (22%). Nine eyes presented a decline of two or more positions in the CSV-1000 log scale at one or more spatial frequencies and one eye an increase of three lines. Only two of those eyes had a clinical explanation for the decrease, one presented the light paracentral superficial punctuate keratitis and the other case was the patient with the diffuse lamellar keratitis (Figure 4).

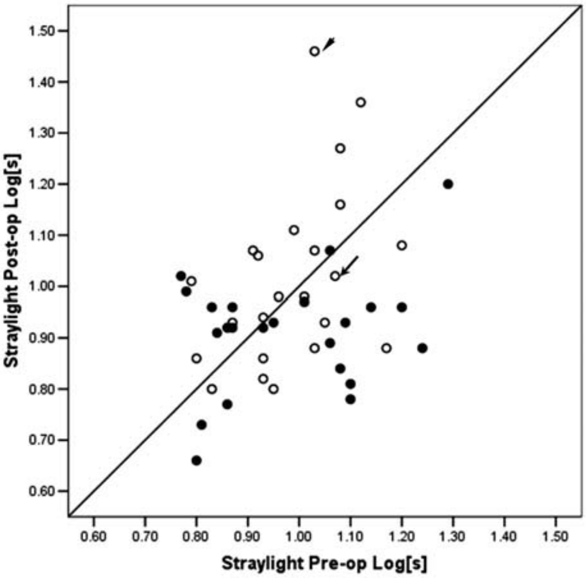


Figure 3. Straylight values before and 2 months after LASIK measured with the C-Quant. Data points below the solid line reveal improved straylight values post operatively. Full circles denote conventional ablation profiles and open circles wavefront-guided ablation. The small arrow indicates a patient with light superficial punctate keratitis and the arrow head a patient with diffuse lamellar keratitis post operatively.

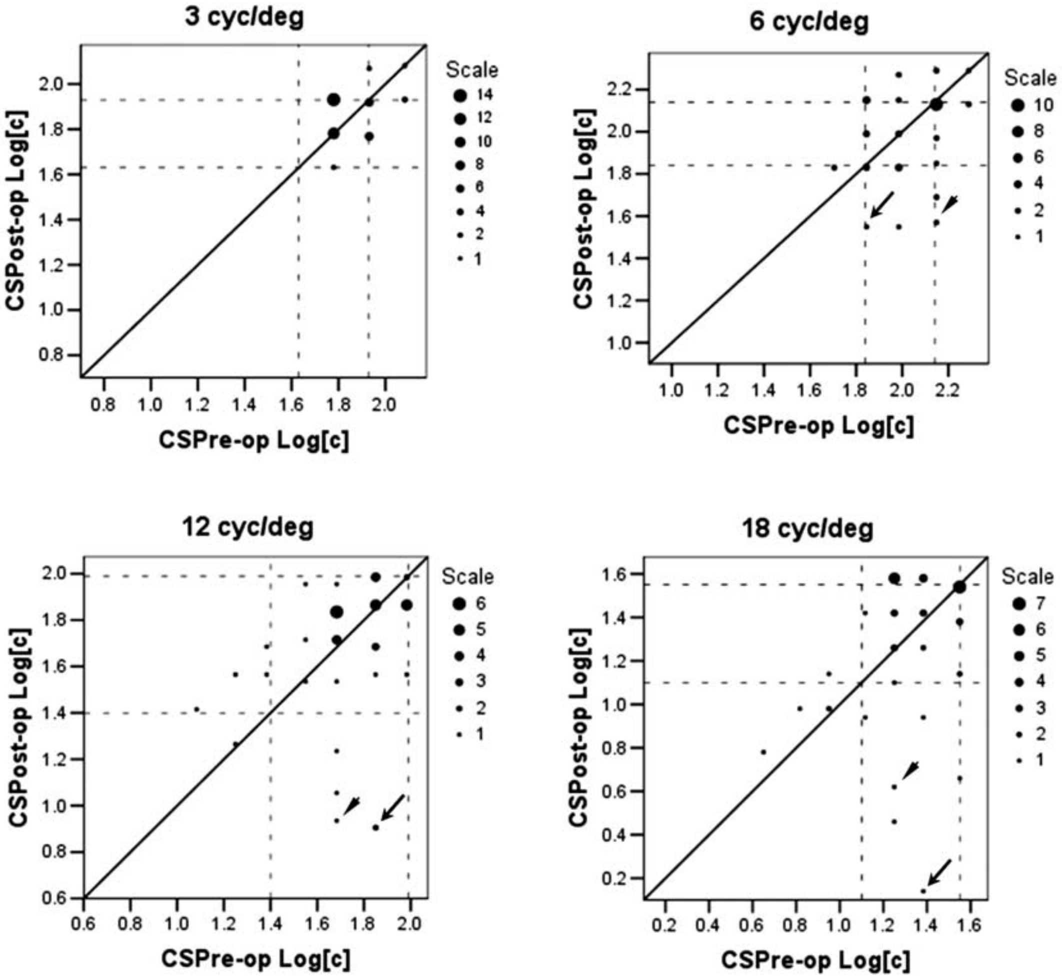


Figure 4. Contrast sensitivity logarithmic values before and 2 months after LASIK for each spatial frequency measured with the CSV-1000. Data points above the solid line reveal improved contrast sensitivity post operatively. For each spatial frequency, the dashed lines indicate the normal range from the CSV-1000 for ages 20 to 59 years. The small arrow indicates a patient with light superficial punctate keratitis and the arrow head a patient with diffuse lamellar keratitis post operatively.

Of the cases that presented an unexplained postoperative decrease in the contrast sensitivity values, only some fell below the normal range for their age; 2 eyes at 6 cyc/deg, 3 eyes at 12 cyc/deg and 4 eyes at 18 cyc/deg (Figure 4). When we excluded the 10 eyes that presented variations of two or more positions in the contrast sensitivity readings, the analysis yielded a slight improvement of the contrast sensitivity values post operatively that was significant for the 6, 12 and 18 cyc/deg spatial frequencies (Table 1). The post-pre operative differences of BSCVA were not significant in both groups (Table 1). However, straylight seemed to be worse in the 10 eyes excluded [0.09 log (s) ($p = 0.05$)] and improved in the main group [-0.05 log(s) ($p = 0.06$)], but these differences were not statistically significant.

The wavefront-guided group regained their pre-op BSCVA whereas the conventional group had a minor decrease. The ablation technique had no significant influence on post-pre operative straylight or contrast sensitivity changes.

DISCUSSION

The study population consisted of normal subjects with a good BSCVA and without lenticular or retinal lesions who were eligible for LASIK surgery. Post-operative results for UCVA and BSCVA were normal as well. We had two cases (4%) with clinically significant complications; one patient with diffuse lamellar keratitis (DLK) and another one with light paracentral superficial punctate keratitis (SPK).

DLK is an inflammatory response to multiple stimuli, but it is mostly associated to sterilizers with reservoirs, and it can occur in 0.4% of the LASIK patients[11,12]. A meta-analysis for worst case economic impact showed an incidence of 6.5% of inflammatory complications after LASIK, where DLK was included[13]. SPK is a corneal defect that presents usually as central doted ulcerations of the epithelium and may course with a slight decrease of visual acuity. It is associated with a variety of conditions such as dry eye, immune reactions, denervation and abrasions, among others. The DLK explains the important increase in straylight and the decrease in contrast sensitivity for this patient. The SPK case was described as light and paracentral inferior by the physician and showed only a decrease in contrast sensitivity, but not an increase in straylight.

On average, there was no significant change in straylight at 2 month after LASIK. This is in accordance with an earlier study by Beerthuizen et al[8]. He observed no significant increase in straylight one month after LASIK, but three cases with an increase of more than 0.2 log(s). Clinically, 2 eyes had microstriae in the flap and 1 eye had a significant amount of debris under the flap. Two other studies by Lee et al[6]. and Kim et al[7]. applied the subjective ALC Glare test (described in the introduction). Lee found some increase in glare sensitivity at 6 months post LASIK under photopic and a more pronounced increase under mesopic conditions. Kim did not found a significant variation in glare sensitivity at 2 and 6 months post LASIK.

Our present study showed, on average, no statistically significant decrease in contrast sensitivity 2 months after LASIK surgery. When we excluded the cases that presented variations of two or more positions in contrast sensitivity (10 eyes or 22%) we obtained a significant improvement in contrast sensitivity (6, 12 and 18 c/d). In the literature, there is no general consensus of the effect of LASIK on contrast sensitivity. Studies from 2001 and 2003 revealed a decrease in contrast sensitivity at 1, 2 or 6 months post operatively[3-5]. More recent studies suggest that contrast sensitivity can return to baseline values or even improve depending on the surgical technique[6,7]. Lee found a decrease in contrast sensitivity at 1, 3 and 6 months post-op conventional LASIK and no change at 6 months after wavefront-guided LASIK. One year later, Kim found no change after 2 and 6 month post conventional LASIK and an improvement after wavefront-guided LASIK. We found no significant change of contrast sensitivity post minus pre operative differences between the wavefront-guided and the conventional ablation group. The wavefront-guided group regained their pre-op BSCVA whereas there was a minor decrease in the conventional group.

In summary, LASIK patients seem to fall in three groups; one group, the vast majority (in our study 78%) has no complications and maintains their visual quality as judged by visual acuity, contrast sensitivity and intraocular straylight. With advanced ablation techniques, there seem to be even a potential to have improved visual quality post operatively. A few patients (in our study 18%) have no clinical significant complications but a slightly decreased visual quality. Very few (in our study 4%) have clinical complications with decreased visual quality.

ACKNOWLEDGEMENTS

The authors would like to thank Joaquin Gioino, Alexander Ospino, Alejandro Recancof, Kattia Llanos Rotta and Yolanda Chahua Torres for performing the C-Quant measurements. This study has been supported in part by a grant of the Spanish Ministry of Health, Instituto Carlos III, Red Temática de Investigación Cooperativa en Salud «Patología ocular del envejecimiento, calidad visual y calidad de vida», Subproyecto de Calidad Visual (RD07/0062).

REFERENCES

1. Packer M, Fine IH, Hoffman RS. Functional vision, contrast sensitivity, and optical aberrations. Int Ophthalmol Clin. 2003; 43: 1-3.
2. Van den Berg TJTP, Van Rijn LJ, Michael R et al. Straylight effects with aging and lens extraction. Am J Ophthalmol 2007; 144: 358-363.
3. Marcos S. Aberrations and visual performance following standard laser vision correction. J Refract Surg 2001; 17: S596-S601.
4. Nayort Y, Kazunort M, Tomokazu S et al. Ocular higher-order aberrations and contrast sensitivity after laser in situ keratomileusis. Invest Ophthal Vis Sci. 2004; 45: 3986-3990.
5. Donate D, Denis P, Burillon C. Prospective study of contrast sensitivity and visual effects after LASIK. J Fr Ophtalmol. 2005; 28: 1070-1075.
6. Hyung Keun L, Cul Myung C, Kyoung T, Eung Kweon K. Measurement of contrast sensitivity and glare under mesopic and photopic conditions following wavefront-guided and conventional LASIK surgery. J Refract Surg. 2006; 22: 647-655.
7. Tae Wan K, Won Ryang W, Kin Hak L, Mee Kum K. Contrast sensitivity after LASIK, LASEK and wavefront-guided LASEK with the VISX S4 laser. J Refract Surg 2007; 23: 355-361.
8. Beerthuizen J., Franssen L, Landesz M, van den Berg TJTP. Straylight values 1 month after laser in situ keratomileusis and photorefractive keratectomy. J Cataract Refract Surg. 2007; 33: 779-783.
9. Franssen L, Coppens JE, van den Berg TJ. Compensation comparison method for assessment of retinal straylight. Invest Ophthalmol Vis Sci 2006; 47: 768-776.
10. Van den Berg TJTP. Analysis of intraocular straylight, especially in relation to age. Optom Vis Sci. 1995; 72: 52-59.
11. Stulting RD, Randleman JB, Couser JM, Thompson KP. The epidemiology of diffuse lamellar keratitis. Cornea. 2004; 23: 680-688.
12. Villarrubia A., Palacín E., Gómez del Río M., Martínez P. Description, etiology, and prevention of an outbreak of diffuse lamellar keratitis after LASIK. J Refract Surg. 2007; 23: 482-486.
13. Lamparter J., Dick H.B., Krummenauer F. Complications after Laser in Situ Keratomileusis (LASIK): Results of a meta-analysis of incidences and expectable costs. Klin Monatsbl Augenheilkd 2007; 224: 627-635.

First author:
Ralph Michael, PhD

Institut Universitari Barraquer,
Universitat Autònoma de Barcelona,
Barcelona, Spain

9. Appendix B

Posterior Capsule Opacification Assessment and Factors That Influence Visual Quality After Posterior Capsulotomy

GUSTAVO A. MONTENEGRO, PATRICK MARVAN, ALOIS DEXL, ANDRÉS PICÓ, MARÍA ISABEL CANUT, GÜNTHER GRABNER, RAFAEL I. BARRAQUER, AND RALPH MICHAEL

- **PURPOSE: To study the correlation between posterior capsule opacification (PCO) and intraocular straylight and visual acuity.**
- **DESIGN: Prospective noninterventional study.**
- **METHODS: We measured visual acuity (VA), logarithm of minimal angle of resolution (logMAR) and intraocular straylight (C-Quant straylight parameter log[s]) under photopic conditions before and 2 weeks after YAG capsulotomy in 41 patients (53 eyes) from the Centro de Oftalmología Barraquer in Barcelona and the University Eye Clinic, Paracelsus Medical University in Salzburg. Photopic pupil diameter was also measured. To document the level of opacification, pupils were dilated and photographs were taken with a slit lamp, using retroillumination and the reflected light of a wide slit beam at an angle of 45 degrees. PCO was subjectively graded on a scale of 0 to 10 and using the POCOman system. A multiple regression analysis was performed to evaluate factors that influence straylight after capsulotomy.**
- **RESULTS: Straylight correlated well with retroillumination and reflected-light PCO scores, whereas VA only correlated with retroillumination. Both VA and straylight improved after capsulotomy. Straylight values varied widely after capsulotomy. Multiple regression analysis showed that older age, large ocular axial length, hydrophobic acrylic intraocular lenses (IOLs), and small capsulotomies are factors that increased intraocular straylight.**
- **CONCLUSION: Intraocular straylight is a useful tool in the assessment of PCO. It correlates well with PCO severity scoring methods. When performing a posterior capsulotomy, factors such as age, IOL material, axial length, and capsulotomy size must be taken into consideration, as they influence intraocular straylight. (Am J Ophthalmol 2010;150:248–253. © 2010 by Elsevier Inc. All rights reserved.)**

POSTERIOR CAPSULAR OPACIFICATION (PCO) IS STILL the most frequent long-term complication after extracapsular cataract extraction surgery. The decision to perform a posterior capsulotomy is usually based on decreased visual acuity and patients' general complaints about glare phenomena and reduced contrast. Different tests such as low-contrast acuity and acuity under glare have been used to assess glare sensitivity, but they are still not widely accepted and their validity and sensitivity are debated.[1,2] Recently, intraocular straylight has been found to have added value in describing visual function, given that it is affected independently of visual acuity and contrast sensitivity.[3,4] Straylight causes a veiling luminance on the retina, which can be perceived as halos, glare, hazy vision, and blinding at night while driving. The C-Quant instrument (Oculus GmbH, Wetzlar, Germany) has been demonstrated to be reliable in measuring intraocular straylight.[5,6]

In an earlier study, Hayashi and associates found that visual acuity correlates more significantly with PCO than contrast sensitivity and glare sensitivity, measured with a contrast glare tester.[7] By contrast, Meacock and associates reached the conclusion that straylight is the most sensitive test for assessing PCO severity compared with high- and low-contrast visual acuity and contrast sensitivity.[8] A later study in European drivers showed large variations in straylight values in pseudophakic eyes,[9] ranging from values below the normal noncataract phakic eyes to values well above. This study raised the question of whether PCO severity explains this phenomenon. Van Bree and associates found that some patients had little or no improvement in straylight after performing a posterior capsulotomy for PCO.[10] The authors of the study suggested that PCO morphology and unknown factors other than PCO might influence retinal straylight.

The effects of pearl-type and fibrosis-type capsular opacification on visual acuity and contrast sensitivity have been studied,[11,12] but there are limited data on the effect of PCO morphology on straylight. Hull and associates (Hull CC, et al. IOVS 2009;50:ARVO E-Abstract 6128) found no correlation between straylight values and PCO severity scores obtained with POCOman computer software from an in vitro PCO culture. POCOman uses retroillumination images to determine severity scores. A group of investiga-

Accepted for publication Feb 28, 2010.

From the Institut Universitari Barraquer, Universitat Autònoma de Barcelona (G.A.M., R.I.B., R.M.), and the Centro de Oftalmología Barraquer (A.P., M.I.C., R.I.B.), Barcelona, Spain; and the University Eye Clinic (P.M., A.D., G.G.), Paracelsus Medical University, Salzburg, Austria.

Inquiries to Ralph Michael, Institut Universitari Barraquer, Laforja, 88, 08021 Barcelona, Spain; e-mail: ralphm@co-barraquer.es

0002-9394/$36.00
doi:10.1016/j.ajo.2010.02.026

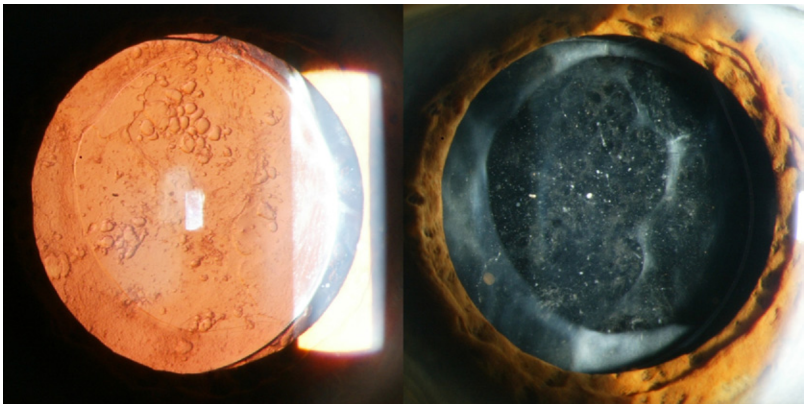


FIGURE 1. Retroillumination (Left) and slit-lamp-derived, reflected-light (Right) images of posterior capsule opacification (PCO) in the same eye. Different aspects of PCO morphology are observed in each image.

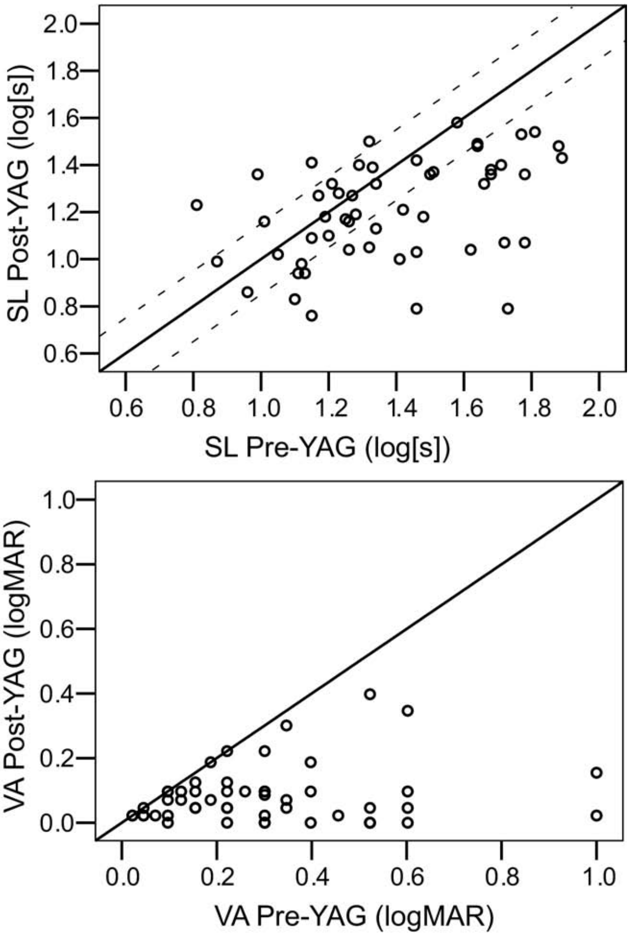


FIGURE 2. >Straylight (SL) and visual acuity (VA) before and after capsulotomy (YAG). Both straylight and visual acuity show postoperative improvement in the majority of cases. Straylight difference of ± 0.15 log[s] (dashed lines) is considered treatment effect. logMAR = logarithm of minimal angle of resolution; log[s] = log straylight parameter.

tors found that retroillumination images might lead to underestimation of PCO, compared with slit-lamp-derived, reflected-light images.[13] However, retroilluminated PCO images analyzed with POCOman have been compared with other computer software used to calculate PCO severity, and they proved to correlate well with high- and low-contrast acuity tests and straylight measurements.[14]

Capsulotomy size has been associated with visual performance outcome after posterior capsulotomy. Studies have found that capsulotomies smaller than pupil size induce more sensitivity glare than larger capsulotomies.[15–18] Data on the effects of monofocal and multifocal intraocular lenses (IOLs) and IOL glistenings on straylight are inconclusive.[19–23]

This study compares retroillumination and reflected-light images with POCOman software for PCO assessment and evaluates their relationship with visual quality as a function of visual acuity and retinal straylight. We tried to determine the influence of various factors on straylight measurements after posterior capsulotomy.

PATIENTS AND METHODS

- **PATIENTS:** Fifty-three eyes in 41 patients of the Centro de Oftalmología Barraquer in Barcelona (26 patients) and the University Eye Clinic, Paracelsus Medical University in Salzburg (15 patients), who were scheduled for neodymium–yttrium-aluminum-garnet (Nd:YAG) laser posterior capsulotomy from January 1, 2008 to May 31, 2009, were included in this prospective study. The mean age was 67 (range: 44 to 82).

Exclusion criteria were diabetes mellitus, glaucoma, clinical retinal or macular pathologies, optic nerve atrophy, astigmatism greater than 4 diopters, any kind of keratoplasty, and corneal opacities. Best-corrected visual acuity (VA) and straylight were measured, and photographs were taken before surgery and 2 weeks later. Pupil size was measured 2 weeks after performing the capsulotomy with the Procyon P3000 or P2000 infrared pupillometer (Procyon Instruments Ltd, London, United Kingdom).

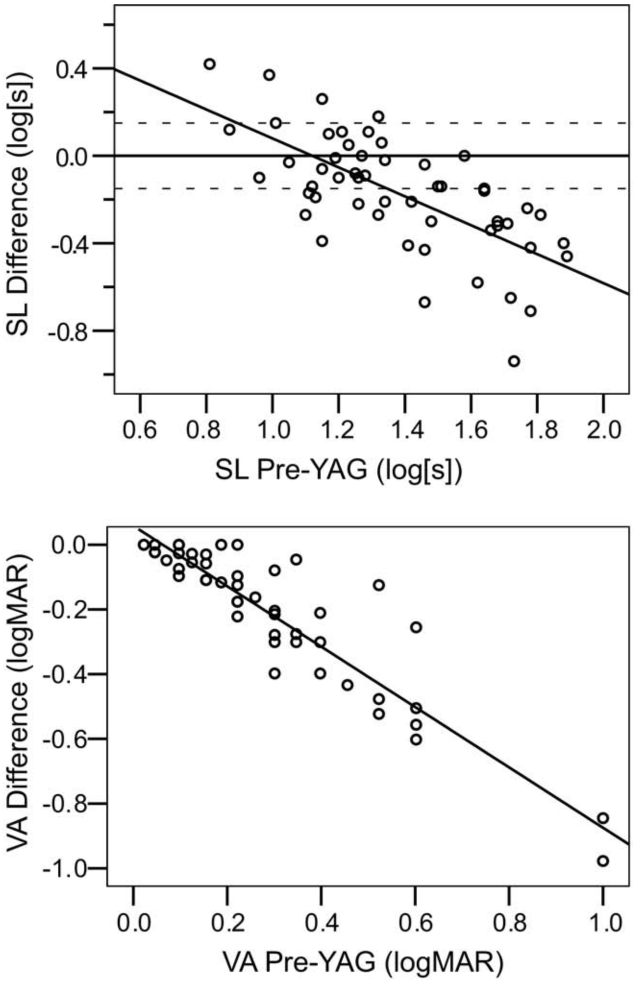


FIGURE 3. Before- and after-capsulotomy differences in straylight (SL) and visual acuity (VA) compared with the precapsulotomy (YAG) value. For both straylight and visual acuity, we observe a tendency for larger improvement as the precapsulotomy value is more impaired. Straylight difference of ± 0.15 log[s] (dashed lines) is considered treatment effect. logMAR = logarithm of minimal angle of resolution; log[s] = log straylight parameter.

• **STRAYLIGHT MEASUREMENT:** The C-Quant straylight meter (Oculus GmbH, Wetzlar, Germany) was used to measure retinal straylight. The measurement is based on the compensation comparison method.[24] In short, the test field consists of a dark circle divided into 2 halves (left and right) and is surrounded by a ring-shaped flickering light, which serves as the glare source. Light emitted from the ring is scattered in the eye, resulting in the perception that the test field is flickering. A counterphase compensation light is then presented in 1 of the semicircles, reducing the flicker perception on that side. Then the patient is asked to choose the side without the compensation light (ie, the side that flickers more intensely). To obtain the straylight value, this process is repeated a set number of times with different levels of compensation light.

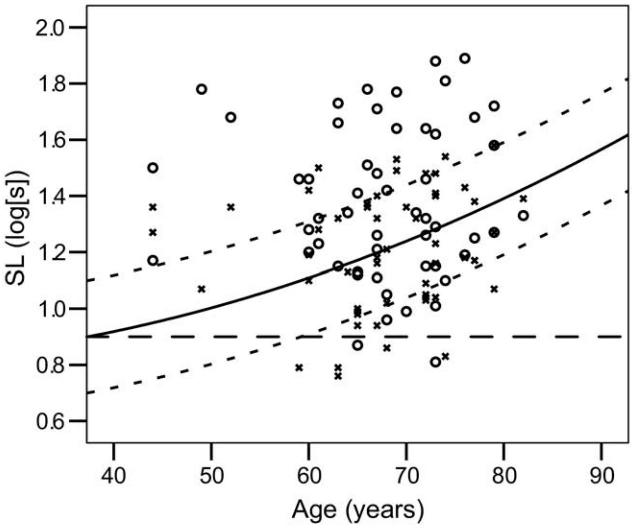


FIGURE 4. Straylight values (SL) before and after capsulotomy, as a function of age, precapsulotomy (circle) and postcapsulotomy (crosses). The 95% confidence interval for noncataract phakic eyes (dotted lines) and the normal baseline value in young eyes (dashed line) from the literature is provided for comparison.[9]

To ensure measurement quality, the test was repeated up to 3 times in case the computer software indicated low reliability. If the results remained unreliable, the subject was excluded from the study (n = 14). Values were expressed as log [straylight parameter] (log[s]). Higher straylight values indicate higher sensitivity to glare and thus more compromised visual function. The average normal baseline value for 20- to 30-year-old subjects is 0.90 log[s].[3,9]

We considered a log[s] of 0.15 units as intrapatient variance for straylight measurements.[6] When the difference of the straylight value after capsulotomy was > 0.15 log[s] compared with the straylight value before capsulotomy, it was considered a significant treatment effect.

• **POSTERIOR CAPSULE OPACITIES IMAGES:** Pupils were pharmacologically dilated using a combination of tropicamide 0.5% and phenylephrine 2.5% topically; when fully dilated, the posterior capsule was photographed using a digital camera attached to a slit lamp. Two different images were obtained from each eye, 1 of retroillumination and 1 of the light reflected from the posterior capsule (Figure 1). To obtain the reflected-light images, we used a wide slit beam at an angle of 45 degrees focused on the posterior capsule.

The corresponding photopic pupil diameter was delimited on each reflected-light and retroillumination image, and PCO inside that area was then subjectively graded on a scale of 0 to 10. Retroillumination images were also analyzed using POCOman computer software.[25] The photopic pupil diameter was used to calculate the percentage of pupil area containing capsule remnants left from the posterior capsulot-

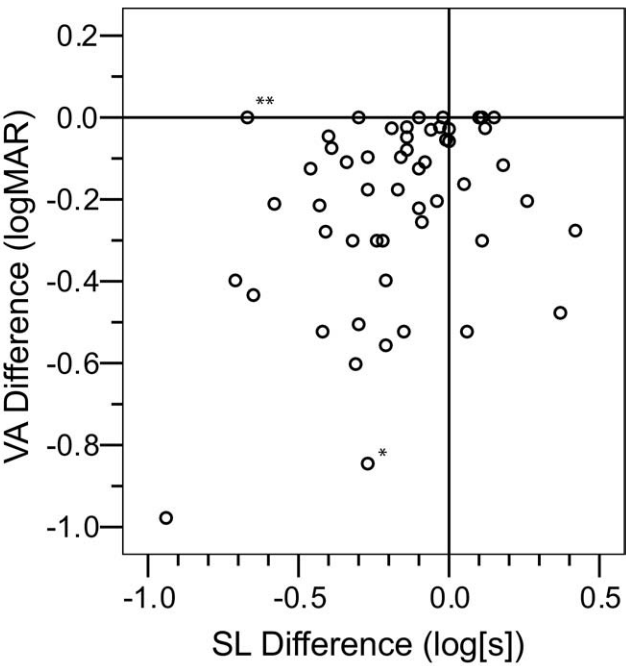


FIGURE 5. Before- and after-capsulotomy difference in straylight (SL) compared with before and after difference in visual acuity (VA). Some eyes gained very much in VA, but little in straylight (*); others gained in straylight, but not in VA (**). logMAR = logarithm of minimal angle of resolution; log[s] = log straylight parameter.

TABLE 1. Visual Acuity and Straylight and Their Relation With Posterior Capsule Opacification Severity Scores

	VA (logMAR) Post minus Pre YAG Difference		Straylight (Log[s]) Post minus Pre YAG Difference	
PCO Grading	Std. Regression Coefficient (*r*)	Significance (*P*)	Std. Regression Coefficient (*r*)	Significance (*P*)
Reflected-light	0.257	.089	0.403	.006[a]
Retroillumination	0.375	.007[a]	0.414	.003[a]
POCOman	0.460	.001[a]	0.340	.013[a]

logMAR = logarithm of minimal angle of resolution; PCO = posterior capsule opacification; VA = visual acuity; YAG= yttrium-aluminum-garnet (laser capsulotomy).

[a] Statistically significant.

TABLE 2. Multiple Regression Analysis of Factors Influencing Straylight Values After Capsulotomy[a]

Independent Variable	Std Coeff	*t*	Significance (*P*)
Age	0.319	2.323	.026
IOL material	−0.492	−4.082	.000
Axial length	0.472	3.270	.002
% of pupil area with capsule remnants	0.397	3.363	.002

IOL= intraocular lens; Std Coeff = standardized coefficient.

[a] Dependent variable = straylight after capsulotomy.

omy. Vitreous opacities visible in the reflected-light images were graded on a subjective scale of 0 to 10.

• STATISTICAL ANALYSIS: For statistical analysis, the visual acuity decimal scale was converted into a logMAR scale. A paired *t* test was used to compare VA and straylight measurements before and after capsulotomy. Pearson correlation and regression coefficients (r) were calculated. A multiple regression analysis was performed. A *P* value of $< .05$ was considered statistically significant for all tests.

RESULTS

MEAN PREOPERATIVE STRAYLIGHT MEASURED 1.38 LOG[S]. It decreased on average by 0.17 log[s] units, resulting in a mean of 1.21 log[s] postoperatively. This decrease was statistically significant ($P < .001$); however, 4 eyes (8%) showed an increase of more than 0.15 log[s] units (Figures 2 and 3). Postoperative straylight values varied widely; a few were above noncataract phakic eyes (9 eyes; 17%) but the majority were similar to noncataract phakic eyes (32 eyes; 60%), or similar to the normal baseline value for young subjects (12 eyes; 23%) (Figure 4).

Visual acuity significantly improved ($P < .001$). Mean precapsulotomy VA was 0.298 logMAR (20/40) compared with postoperative 0.078 logMAR (20/25), with a mean difference of 0.219 logMAR units. No eye lost VA after posterior capsulotomy (Figures 2 and 3). Visual acuity and retinal straylight were slightly correlated prior to surgery (r = 0.399; $P = .003$). Two weeks after capsulotomy, these visual quality parameters had no correlation ($P = .354$). Figure 5 illustrates that a gain in VA can be quite independent of straylight improvement.

When analyzing PCO images, retroillumination scoring (0-10 scale and POCOman) correlated with both VA and straylight. Reflected-light scoring (0-10 scale) correlated with straylight but not with VA (Table 1).

Multiple regression analysis revealed a statistically significant relationship between post-capsulotomy straylight values and patient age, IOL material, axial length, and the amount of remnant capsule area (Table 2). Straylight increased proportionally to age and axial length. A higher percentage of pupil area with capsule remnants caused higher postoperative straylight values. Hydrophobic and hydrophilic acrylic IOLs had different effects on light scattering. Mean postoperative straylight in the hydrophobic acrylic group (n = 23) was significantly higher ($P = .005$), measuring 1.28 log[s], than in the hydrophilic acrylic group (n = 20 and 1.10 log[s]). Subjectively graded vitreous opacities visible in the reflected light images did not relate to post-capsulotomy straylight.

DISCUSSION

PCO ASSESSMENT VARIES WITH THE ILLUMINATION TECHnique. With retroillumination we can observe Elschnig's pearls and wrinkles in the posterior capsule in great detail (Figure 1). Fibrosis of the capsule scatters light backward when using the reflected-light technique. The fibrosis appears as a white, hazy layer, giving the impression of having a greater impact on visual performance. These different aspects of PCO morphology may explain the different results correlating visual acuity and straylight (Table 1). The reflected-light images might relate more to straylight than to visual acuity because they consider the backward-scattered light at a 45-degree angle, while retroillumination is reflected at a very small angle, usually not more than 1 degree.

Retroillumination and reflected-light images (Figure 1) may overestimate the real influence of PCO on visual quality. Both images capture backward-scattered light, whereas the C-Quant meter measures forward-scattered light. For vision, forward light scattering is relevant because it is superimposed with the focused light on the retina. There is some correlation between forward and backward light scattering, but they are of different morphologic origins.[26] This may explain the only moderate correlation between the measured (forward) straylight and the subjective PCO severity scoring based on backward-scattered light (Table 1). Similar results are reported in the literature (Hull CC, et al. IOVS 2009;50: ARVO E-Abstract 6128).

As in earlier studies,[3,9] we also found that visual acuity and straylight are independent descriptors of visual quality. Van den Berg[27] has suggested that intraocular straylight comprises visual angles from 1 to 30 degrees of the point spread function, whereas visual acuity encompasses only the central 0.02 degrees. The C-Quant meter measures forward light scattering at a visual angle from 5 to 10 degrees. After capsulotomy, there was no correlation between the 2, and the change in straylight after capsulotomy was independent of the gain in visual acuity (Figure 5).

Considering a change in straylight of more than 0.15 log[s] units as treatment effect, our results showed that patients improved in straylight when their values before capsulotomy were $>$ 1.40 log[s] units (Figure 3). This could guide the clinician with the decision to treat PCO and avoid increased straylight after posterior capsulotomy. In terms of visual acuity, all eyes benefited from capsulotomy treatment (Figure 3). Although straylight decreased on average after capsulotomy, 4 eyes (8%) experienced increase (Figures 2 and 3). To try to explain this phenomenon, we looked for features that were present only after capsulotomy was performed. Image analysis revealed that those eyes presented with capsule remnants in a large percentage (mean 34%) of the photopic pupil area. The effect of light scattering from these remnants and from the capsulotomy border probably explains this unexpected increase. This issue should be further studied. Our results confirm earlier findings that capsulotomy should be larger than the pupil diameter.[16–18] A higher percentage of pupil area with capsule remnants induced more retinal straylight. One limitation of this study is the lack of a baseline straylight value for each patient before PCO developed. It would be very useful to know the straylight value right after cataract surgery, so we could have a target straylight to achieve after capsulotomy.

A multiple regression analysis (Table 2) was performed to understand the wide range of straylight values after capsulotomy (crosses in Figure 4). It showed that age, IOL material, axial length, and percentage of pupil area with capsule remnants significantly contributed to straylight after capsulotomy. Subjectively scored vitreous opacities visible in the reflected-light images were found not to relate to post-capsulotomy straylight. This might be because of the low number of cases (n = 10) and low scores (between 1 and 4 on the 0-10 scale) of these cases in our study population and/or possible overestimation of the reflected-light images with backward-scattered light, which was compared with the forward light scattering measured by the C-Quant meter.

Lens opacification has been associated with increasing straylight with age.[3] We found that this increase is also true in pseudophakic eyes. Because these eyes do not have crystalline lenses, which are considered the main source for entoptic straylight, this effect might be associated with age-related changes in the cornea and/or retina. Studies suggest that the cornea might contribute to about 30%, and the retina up to 40%, of entoptic straylight.[28,29] Large axial eye length also causes more retinal straylight.[30] Here, it could only be speculated that the larger eye volume causes more straylight and/or that the retina in subjects with high myopia is a more important source of entopic light scatter. It is unclear why hydrophobic acrylic IOLs induce more straylight than hydrophilic acrylic ones. Hydrophobic acrylic IOLs have largely been studied for their high incidence of glistenings.[21,22,31] IOL glistenings could cause increased straylight, but we are unaware of studies confirming this.

In summary, our study suggests that several factors influence visual quality after capsulotomy: age, axial eye length, capsulotomy size, and IOL material. Most importantly, the influence of the IOL material is surprising and should be studied in more detail.

THE AUTHORS INDICATE NO FINANCIAL SUPPORT OR FINANCIAL CONFLICT OF INTEREST. INVOLVED IN DESIGN OF STUDY (G.A.M., P.M., A.D., G.G., A.P., R.I.B., R.M.); analysis and interpretation of data (G.A.M., P.M., A.D., G.G., A.P., R.I.B., R.M.); writing of manuscript (G.A.M., R.M.); critical revision (G.A.M., P.M., A.D., G.G., A.P., M.I.C., R.I.B., R.M.); final approval (G.A.M., P.M., A.D., G.G., A.P., M.I.C., R.I.B., R.M.); data collection (G.A.M., P.M., A.D., R.M.); provision of patients (P.M., A.D., A.P., M.I.C.); statistical expertise (G.A.M., R.M.); literature search (R.M., G.A.M.); and logistic support (G.A.M., P.M., A.D., R.M.). This study was approved by the Comité Ético de Investigación Clínica of the

Centro de Oftalmología Barraquer and the Ethikkommission des Landes Salzburg in conformity with the tenets of the Declaration of Helsinki. The authors thank Juan Carlos Reyes, Conrad Latoche, and Lourdes Ruiz for their help collecting patient data. We also thank Dimas Abello, Jordi Navazo, Jordi Carcelero, Emilio Hernández, and Federico Martínez of the department of photography.

REFERENCES

1. Elliott DB, Bullimore MA. Assessing the reliability, discriminative ability, and validity of disability glare tests. Invest Ophthalmol Vis Sci 1993;34:108–119.
2. Aslam TM, Haider D, Murray IJ. Principles of disability glare measurement: an ophthalmological perspective. Acta Ophthalmol Scand 2007;85:354–360.
3. Michael R, Van Rijn LJ, van den Berg TJ, et al. Association of lens opacities, intraocular straylight, contrast sensitivity and visual acuity in European drivers. Acta Ophthalmol 2009;87:666–671.
4. Van Rijn LJ, Wilhelm H, Emesz M, et al. Relation between perceived driving disability and scores of vision screening tests. Br J Ophthalmol 2002;86:1262–1264.
5. Cervino A, Montes-Mico R, Hosking SL. Performance of the compensation comparison method for retinal straylight measurement: effect of patient's age on repeatability. Br J Ophthalmol 2008;92:788–791.
6. van den Berg TJ, Franssen L, Coppens JE. Straylight in the human eye: testing objectivity and optical character of the psychophysical measurement. Ophthalmic Physiol Opt 2009;29:345–350.
7. Hayashi K, Hayashi H, Nakao F, Hayashi F. Correlation between posterior capsule opacification and visual function before and after Neodymium: YAG laser posterior capsulotomy. Am J Ophthalmol 2003;136:720–726.
8. Meacock WR, Spalton DJ, Boyce J, Marshall J. The effect of posterior capsule opacification on visual function. Invest Ophthalmol Vis Sci 2003;44:4665–4669.
9. van den Berg TJ, Van Rijn LJ, Michael R, et al. Straylight effects with aging and lens extraction. Am J Ophthalmol 2007;144:358–363.
10. van Bree MC, Zijlmans BL, van den Berg TJ. Effect of neodymium:YAG laser capsulotomy on retinal straylight values in patients with posterior capsule opacification. J Cataract Refract Surg 2008;34:1681–1686.
11. Aslam TM, Aspinall P, Dhillon B. Posterior capsule morphology determinants of visual function. Graefes Arch Clin Exp Ophthalmol 2003;241:208–212.
12. Cheng CY, Yen MY, Chen SJ, Kao SC, Hsu WM, Liu JH. Visual acuity and contrast sensitivity in different types of posterior capsule opacification. J Cataract Refract Surg 2001; 27:1055–1060.
13. Camparini M, Macaluso C, Reggiani L, Maraini G. Retroillumination versus reflected-light images in the photographic assessment of posterior capsule opacification. Invest Ophthalmol Vis Sci 2000;41:3074–3079.
14. Jose RM, Bender LE, Boyce JF, Heatley C. Correlation between the measurement of posterior capsule opacification severity and visual function testing. J Cataract Refract Surg 2005;31:534–542.
15. Claesson M, Klaren L, Beckman C, Sjostrand J. Glare and contrast sensitivity before and after Nd:YAG laser capsulotomy. Acta Ophthalmol (Copenh) 1994;72:27–32.
16. Goble RR, O'Brart DP, Lohmann CP, Fitzke F, Marshall J. The role of light scatter in the degradation of visual performance before and after Nd:YAG capsulotomy. Eye (Lond) 1994;8(Pt 5):530–534.
17. Hayashi K, Nakao F, Hayashi H. Influence of size of neodymium:yttrium-aluminium-garnet laser posterior capsulotomy on visual function. Eye 2009. Forthcoming.
18. Lohmann CP, Goble R, O'Brart D, Fitzke F, Marshall J, Gabel VP. [Sensitivity to glare before and after Nd:YAG capsulotomy. Comparison between small and large capsulotomy]. Klin Monatsbl Augenheilkd 1994;205:65–69.
19. Cervino A, Hosking SL, Montes-Mico R, Alio JL. Retinal straylight in patients with monofocal and multifocal intraocular lenses. J Cataract Refract Surg 2008;34:441–446.
20. de Vries NE, Franssen L, Webers CA, et al. Intraocular straylight after implantation of the multifocal AcrySof ReSTOR SA60D3 diffractive intraocular lens. J Cataract Refract Surg 2008;34:957–962.
21. Dhaliwal DK, Mamalis N, Olson RJ, et al. Visual significance of glistenings seen in the AcrySof intraocular lens. J Cataract Refract Surg 1996;22:452–457.
22. Gunenc U, Oner FH, Tongal S, Ferliel M. Effects on visual function of glistenings and folding marks in AcrySof intraocular lenses. J Cataract Refract Surg 2001;27:1611–1614.
23. Hofmann T, Zuberbuhler B, Cervino A, Montes-Mico R, Haefliger E. Retinal straylight and complaint scores 18 months after implantation of the AcrySof monofocal and ReSTOR diffractive intraocular lenses. J Refract Surg 2009; 25:485–492.
24. Franssen L, Coppens JE, van den Berg TJ. Compensation comparison method for assessment of retinal straylight. Invest Ophthalmol Vis Sci 2006;47:768–776.
25. Bender L, Spalton DJ, Uyanonvara B, et al. POCOman: new system for quantifying posterior capsule opacification. J Cataract Refract Surg 2004;30:2058–2063.
26. van den Berg TJ, Spekreijse H. Light scattering model for donor lenses as a function of depth. Vision Res 1999;39: 1437–1445.
27. van den Berg TJ, Franssen L, Coppens JE. Straylight in the human eye: testing objectivity and optical character of the psychophysical measurement. Ophthalmic Physiol Opt 2009; 29:345–350.
28. Vos JJ, Boogaard J. Contribution of the cornea to entoptic scatter. J Opt Soc Am 1963;53:869–873.
29. Vos JJ, Bouman MA. Contribution of the retina to entoptic scatter. J Opt Soc Am 1964;54:95–100.
30. Rozema JJ, van den Berg TJ, Tassignon MJ. Retinal straylight as a function of age and ocular biometry in healthy eyes. Invest Ophthalmol Vis Sci 2009. Forthcoming.
31. Colin J, Orignac I, Touboul D. Glistenings in a large series of hydrophobic acrylic intraocular lenses. J Cataract Refract Surg 2009;35:2121–2126.

10. Appendix C

Métodos Diagnósticos en Segmento Anterior

Alfredo Castillo Gómez

Barraquer, Rafael I.; Montenegro, Gustavo; Michael, Ralph.
Medición de la luz dispersa (straylight) como nuevo parámetro de calidad visual.
In: Castillo Gómez, Alfredo, editor. Métodos diagnósticos en segmento anterior.
Madrid: Sociedad Española de Cirugía Ocular Implanto-Refractiva, 2011:337-351.
ISBN 978-84-933144-9-1

30. Medición de la luz dispersa (*straylight*) como parámetro de calidad visual

Rafael I. Barraquer, Gustavo Montenegro, Ralph Michael

INTRODUCCIÓN: CALIDAD VISUAL, DESLUMBRAMIENTO Y LUZ DISPERSA

Cuando se habla de calidad visual, desde hace tiempo se ha caído en la cuenta de que no basta con la agudeza visual (AV). Una medida más fina puede obtenerse con la función de sensibilidad al contraste (CSF), pero siguen habiendo problemas como el del deslumbramiento o luz dispersa que ni la AV ni la CSF miden bien.

¿Qué es el deslumbramiento? ¿Qué impacto tiene sobre la visión? ¿Cómo y cuándo medirlo? Según la RAE, deslumbramiento es la acción y efecto de deslumbrar, es decir, «ofuscar la vista o confundirla con el exceso de luz». María Moliner añade: «impedir momentáneamente a alguien el exceso de luz que vea bien», e «incapacitar el exceso de luz en un sitio para que se vean las cosas que están menos iluminadas». Corresponde al término inglés *glare* el cual hace, de hecho, referencia tanto al propio deslumbramiento como a la luz o resplandor que lo causa (entre otras acepciones; p. ej., *glare* también puede significar «una mirada feroz»). Los ejemplos clásicos incluyen la conducción en dirección hacia un sol poniente o los faros de otros coches por la noche, pero el concepto se hace extensivo a cualquier otra situación de contraluz (fig. 1) (1). Pese al evidente impacto sobre la calidad visual, sólo recientemente se han desarrollado instrumentos fiables para su estudio clínico como el C-Quant (Oculus GmbH, Wetzlar, Alemania). Sigue siendo un campo escasamente divulgado que merece una revisión desde los conceptos básicos a las principales aplicaciones prácticas.

En principio, el deslumbramiento se debe a cierta relación desfavorable de las luminancias entre la zona de interés (la tarea que se está mirando) y la fuente de luz, influyendo también su ángulo relativo y el estado de adaptación del ojo, entre otros factores. Una luz brillante puede reducir el brillo (luminancia aparente subjetiva) del resto de la escena a consecuencia de la miosis y adaptación que induce. Sin embargo, el deslumbramiento consiste sobre todo en una pérdida o reducción del contraste en la imagen retiniana. Esta reducción puede deberse, a su vez, a efectos por reflexión de la luz o bien por dispersión de la misma. Ejemplos de lo primero serían el velamiento del texto por reflejo excesivo de la luz en un papel cuché, o el de la carrete-

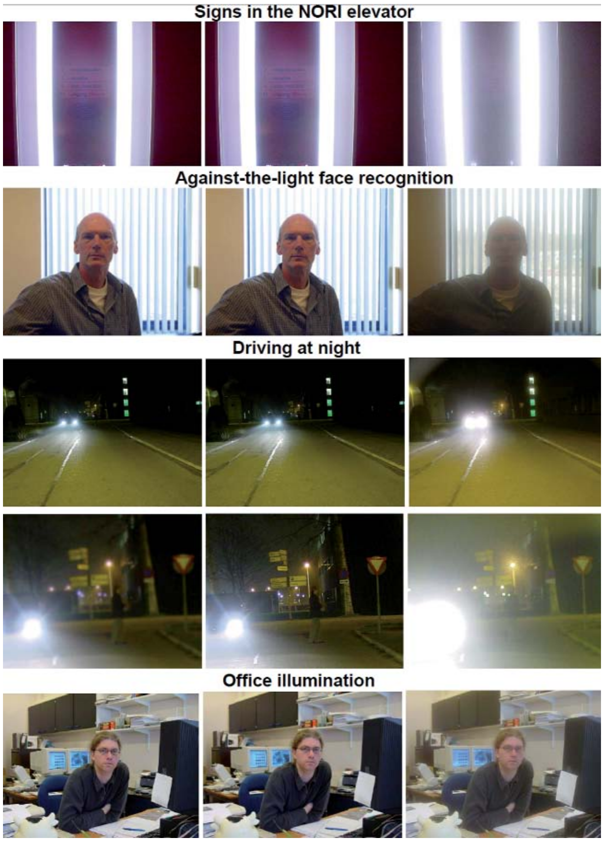


Fig. 1: Ejemplos de situaciones cotidianas que pueden inducir deslumbramiento. Comparación entre los efectos del desenfoque refractivo (columna izquierda, equivalente a una AV ≈ 0,4) y el de un aumento de la luz dispersa (columna derecha, log(s) ≈ 1,47). La columna central corresponde a un ojo normal (tomado de ref [6], con permiso).

ra por el reflejo del sol en el cristal del parabrisas. La dispersión de la luz (*scattering*) puede originarse en el exterior, por partículas en el aire (como la «barrera» visual que se crea al iluminar una niebla densa con los faros del coche) o bien internamente, por las estructuras intraoculares. Este último mecanismo es el que nos interesa como causa del deslumbramiento por luz dispersa o *straylight* (STL) intraocular o retiniana.

Los términos «scattering» y «stray light» (literalmente, «luz extraviada») son sinónimos, si bien el primero hace referencia al proceso de dispersión del haz de luz y el segundo a la propia luz dispersa que aparece dentro de un sistema óptico de forma no intencionada en su diseño. En términos de óptica, la STL limita el rango dinámico de un sistema pues impide que la oscuridad dentro del mismo pueda ser total, lo que a su vez limita las razones de contraste y de señal-ruido.

A principios del siglo pasado Cobb (2) introdujo el concepto de «luminancia veladora equivalente» (L_{eq}) para definir el deslumbramiento como STL retiniana, lo que más tarde utilizaron Holladay y Stiles en su fórmula de la *disability glare* (deslumbramiento o resplandor que incapacita) (3). El «velo de luz» que produce la fuente deslumbrante sobre la imagen retiniana se debe ante todo a la dispersión de la luz en los medios oculares, es decir, a la STL (fig. 2) (4). Siguiendo esta concepción, la Commision Internationale de l'Eclairage (CIE) definió el *disability glare* como sinónimo de STL retiniana y en términos de L_{eq} (5).

Por otra parte, se habla a veces de *discomfort glare* (resplandor molesto, el que induce a desviar instintivamente la mirada de la fuente de luz brillante) cuya naturaleza es esencialmente subjetiva, a diferencia de *disability glare*/STL que representa la definición física de una condición funcional del ojo.

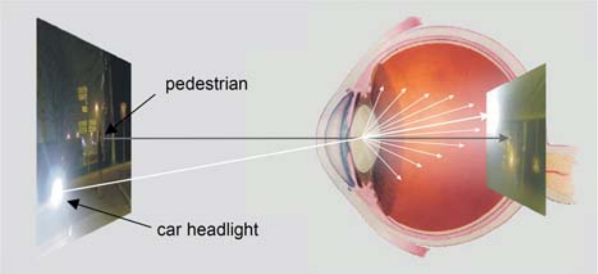


*Fig. 2: Dispersión intraocular de la luz (*straylight*) a partir de una luz brillante externa, lo que provoca un «velo de luz» que degrada la imagen retiniana. Las fotos corresponden al ejemplo en la 4.ª fila de la fig. 1, una calle de noche con peatón cruzando y los faros de un coche de cara (tomado de ref [6], con permiso).*

Los efectos deletéreos de la STL en la calidad visual pueden apreciarse de forma variable, como una visión velada o neblinosa, aumento del deslumbramiento, pérdida de contraste y de color, dificultad para reconocer caras o detalles a contraluz, halos en las luces y otros síntomas que en su conjunto vienen a relatar un impedimento a la visión necesaria para realizar una tarea. Ahora bien, no siempre habrá una correspondencia exacta entre determinado síntoma y la STL medida. Un cierto grado de STL se encuentra presente en el ojo humano normal, ya que sus medios no son ópticamente ideales. Sin embargo, diversas condiciones pueden afectarlos aumentándola (véase la sección 4). Obviamente tales efectos se verán acentuados si existen condiciones adversas como un ambiente oscuro o bien una alteración previa en la función retiniana, p.ej., una degeneración macular o un glaucoma (1,6).

LUZ DISPERSA Y OTRAS MEDIDAS DE LA CALIDAD VISUAL

AGUDEZA VISUAL, SENSIBILIDAD AL CONTRASTE Y LUZ DISPERSA

Un aumento de la STL provoca una pérdida de calidad visual relacionada ante todo con la disminución del contraste de la imagen retiniana. Es importante comprender que este efecto es totalmente diferente de los que se asocian a una reducción de la AV e incluso con la CSF. En tanto que parámetros de calidad visual, AV, CSF y STL se afectan de forma independiente; por tanto, la discapacidad a que puedan dar lugar será distinta en tipo y grado. Las fotos de la figura 1 muestran cómo, en diversas situaciones cotidianas, un aumento de la STL puede tener un impacto en la calidad visual mucho mayor que una cierta reducción de la AV.

La AV mide la capacidad del ojo para resolver detalles finos, que corresponden a deflexiones de la luz sobre la retina en pequeños ángulos visuales, típicamente del orden de 1 minuto de arco (0,02°) como los que subtienden los trazos de los optotipos. Por ello la AV se afecta sobre todo por las imperfecciones ópticas en esa escala, es decir, las aberraciones, de las que el desenfoque es usualmente la más importante. En términos de calidad óptica, la AV representa solamente el pico más central de la función de dispersión de un punto (PSF) del ojo (fig. 3)

La STL viene determinada, en cambio, por la dispersión de la luz en ángulos mayores, entre 1° y al menos 90° alrededor del punto de fijación, alcan-

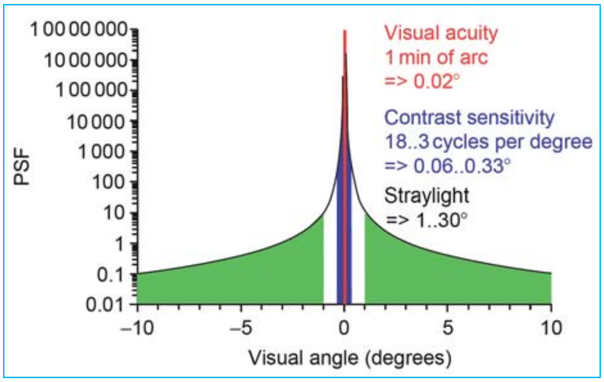


*Fig. 3: Relación de la agudeza visual, sensibilidad al contraste y luz dispersa (*straylight*) con el ángulo visual y las distintas porciones de la PSF (según el estándar humano normal CIE 1999). En rojo, el dominio de la AV; en azul el de la CSF, en verde el de la STL. Las tres zonas tienen importancia en la calidad de visión (tomado de ref [1], con permiso).*

zando de hecho toda la retina, lo que corresponde a las «faldas» de la PSF. Además, los procesos físicos que causan tales deflexiones de la luz son diferentes para los respectivos dominios angulares. En consecuencia, STL y AV tienen solamente una muy débil correlación (1,6). Por ejemplo, si ponemos una lente de +3 dioptrías (D) en una montura de pruebas delante del ojo de un sujeto emétrope, su AV obviamente disminuirá, mientras la STL permanecerá exactamente la misma (excepto por la suciedad que la lente pueda tener o reflejos en sus superficies ópticas). Por otro lado, al poner un filtro neblinoso delante del mismo ojo el valor de la STL aumentará drásticamente mientras la AV sufrirá como mucho una leve reducción.

Aunque la STL reduce el contraste de la imagen retiniana, su relación con la CSF es también muy débil. Así, un incremento de cinco veces en la STL reducirá la función de CSF en un 20% solamente, un efecto muy discreto en comparación con la reducción de que produce, especialmente a frecuencias altas de la CSF, un desenfoque (menor AV) o incluso una LIO bifocal (o lentilla de contacto) (fig. 4) (1,7). Como corolario se deduce que la CSF no sirve como medida de la STL.

Como ocurre con la AV, la CSF pertenece a un dominio espacial mucho más restringido que el de la STL. Se extiende en un ángulo visual entre 3 y 20 minutos de arco (0,06° a 0,33°), respectivamente para los valores de CSF entre 18 y 3 ciclos/grado (fig. 3), es decir, un dominio intermedio entre los de AV y STL. Dado que la STL influye sobre ángulos visuales mayores de 1°, su impacto sobre el contraste es de tipo más difuso, es decir, equivaldría a frecuencias espaciales inferiores a 1 ciclo/grado.

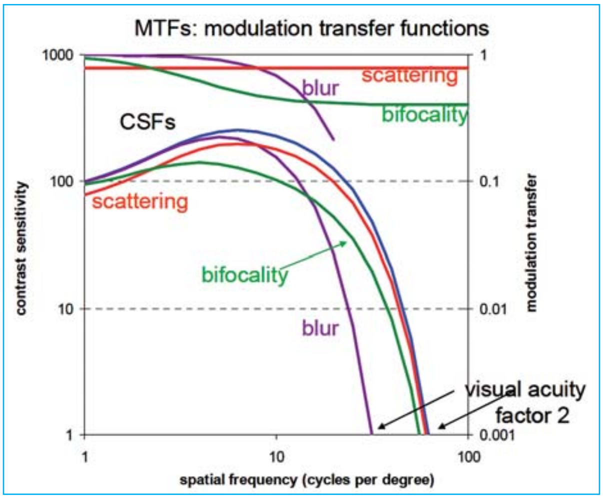


*Fig. 4: Efectos de distintos cambios ópticos en las funciones de sensibilidad al contraste (CSF) y de transferencia de modulación (MTF). En azul, la CSF de un ojo normal joven. En rojo, efecto de aumentar 5 veces la dispersión de luz (*scattering*). En verde, efecto de una óptica bifocal. En morado, efecto de reducir por desenfoque (*blur*) la AV en un factor de 2 (tomado de ref [6], con permiso).*

FRECUENCIAS ESPACIALES Y CALIDAD VISUAL

Una forma de comprender el papel de la STL en la calidad visual es por extensión de los efectos sobre ésta de las diferentes frecuencias espaciales que toma en consideración la CSF. Una determinada imagen puede entenderse como un conjunto de formas definidas por el contraste entre áreas de diferentes luminancias (más o menos claras u oscuras). A medida que nos fijamos en detalles más finos, estamos resolviendo regiones con cambios en el contraste con frecuencias espaciales cada vez más altas. La imagen está, efectivamente, compuesta por elementos con diferentes frecuencias espaciales (fig. 5).

Ahora bien, si quitamos de la imagen las frecuencias espaciales altas (como ocurre al desenfocar), el efecto es el de una pérdida de detalle (fig. 6). Por eso la porción de la función CSF en frecuencias altas se correlaciona bastante bien con la AV. En cambio, si quitamos de la imagen sólo las frecuencias espaciales bajas (p.ej., empleando un filtro de «paso alto»), el efecto equivaldrá a «aplanar la dinámica» de la imagen (fig. 7).

El efecto de una STL aumentada, es decir, lo que habitualmente describimos como «neblina» o «velamiento», correspondería también a un aplanamiento de la dinámica por reducción del contraste en frecuencias espaciales aún más bajas que en el

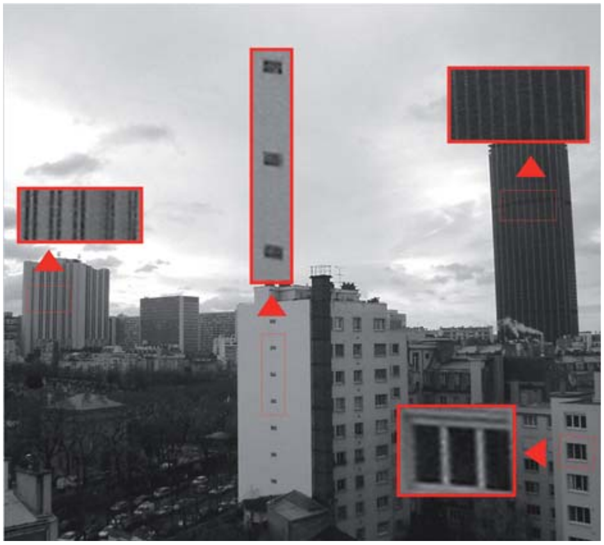


Fig. 5: Distintas frecuencias espaciales en los componentes de una imagen (foto cortesía de Zeiss).

Fig. 6: Efecto de eliminar las frecuencias espaciales altas (desenfoque), con pérdida de detalle (foto cortesía de Zeiss).

ejemplo anterior, pero en forma localizada en ciertas áreas de la imagen en relación con las fuentes de deslumbramiento.

ANALOGÍA PERCEPTIVA ENTRE LUZ DISPERSA Y ATMÓSFERA NEBLINOSA

En la teoría de la percepción visual, los efectos atmosféricos como la transparencia, la neblina o el *glare* también corresponden a una «luz añadida» a la luminancia de los objetos. En un primer esquema, más sencillo, la cantidad de luz que llega de un objeto a la retina o *luminancia* (L), para cada punto o píxel definido por sus coordenadas (x,y) en la imagen, equivale al producto de la *iluminancia* (i) o cantidad de luz que incide sobre la superficie del objeto observado, por la *reflectancia* (R) o proporción de la luz incidente reflejada por dicha superficie (fig. 8), según la expresión:

$$L_{(x,y)} = i_{(x,y)} * R_{(x,y)}$$

Fig. 7: Efecto de eliminar las frecuencias espaciales bajas (filtro de paso alto), con aplanamiento de la dinámica de la imagen (foto cortesía de Zeiss).

El problema para la percepción visual estriba en que, a partir sólo de la luminancia (la única información que capta la retina), hemos de adivinar la naturaleza de los objetos (su reflectancia o «pintura»), independientemente de la luz que reciben. Extraer dos factores desconocidos a partir sólo de su producto resultaría una tarea matemáticamente insoluble (las posibles combinaciones de i y R para dar una determinada L serían teóricamente infini-

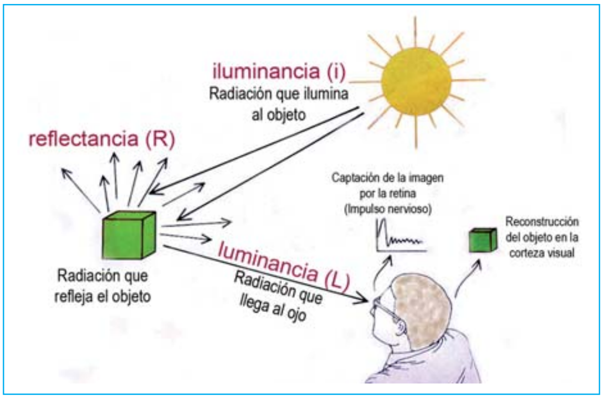


Fig. 8: Esquema general de la visión, que ilustra los conceptos de iluminancia, reflectancia y luminancia.

tas) si no fuera porque la evolución y la experiencia nos han enseñado que no son funciones arbitrarias sino limitadas por las propiedades estadísticas del mundo real. Desde el punto de vista subjetivo, se añaden los conceptos de *luminosidad* y *brillo*, que corresponden respectivamente a la reflectancia y la luminancia *aparentes* de un objeto, según se las atribuye nuestro sistema perceptivo.

Como los objetos de nuestro mundo real no están en el vacío, debemos considerar además los posibles efectos atmosféricos, sean de absorción o de dispersión de la luz, con lo cual la anterior fórmula queda modificada como sigue:

$$L = m^*R + e$$

en la que (m) da cuenta tanto de la iluminancia como de la proporción de luz absorbida por los medios entre el objeto y el ojo, mientras que la constante (e) es una fuente aditiva de luz que representa la neblina (fig. 9). De forma análoga, la STL actuaría sobre la imagen retiniana como una luz añadida dentro del ojo, y su efecto también sería el de crear un velamiento o neblina, con «compresión» del rango dinámico del sistema (8).

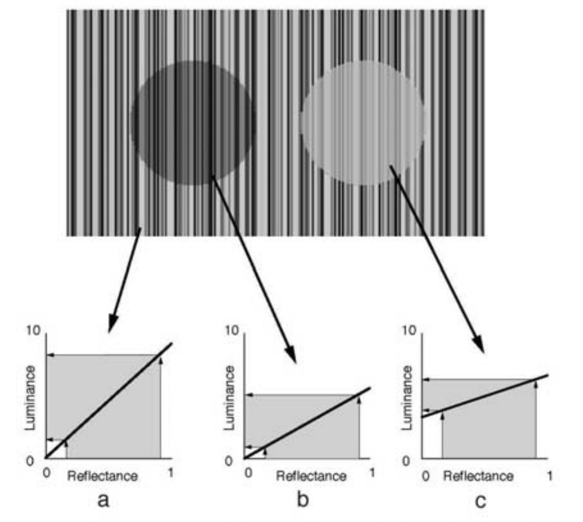


Fig. 9: Efectos atmosféricos sobre la percepción de la luminosidad (reflectancia aparente subjetiva). Este conjunto de líneas de gris aleatorio, visto en una atmósfera de referencia (por fuera de los círculos grises), presenta (a) una relación luminancia-reflectancia lineal y que parte del origen (0,0) con determinada pendiente (parámetro «m»). En una atmósfera que oscurece (círculo de la izquierda) la pendiente de la función (b) disminuye pero el origen se mantiene en 0,0. Si la atmósfera es neblinosa (círculo de la derecha), la función (c) queda comprimida y además el origen ya no es 0,0 pues hay una luminancia mínima causada por la luz añadida (parámetro «e») (según Adelson, ref [8]).

MEDICIÓN CLÍNICA DE LA LUZ DISPERSA RETINIANA

MÉTODOS INDIRECTOS PARA ESTIMAR LA LUZ DISPERSA RETINIANA

La STL se produce de hecho por las enormes diferencias de luz que se dan en el mundo real. Las áreas de alta intensidad luminosa reducen así la visibilidad (la sensibilidad al contraste efectiva) dentro de las zonas poco iluminadas adyacentes (fig. 1). Aparte de ocupar distintos dominios angulares, la falta de correlación entre CSF y STL se debería a que la primera se estudia normalmente en condiciones de iluminación homogénea. Aparatos como el Nyktotest (Rodenstock GmbH, Ottobrunn, Alemania) o el Mesotest II (Oculus) miden la CSF en condiciones mesópicas y en presencia de una fuente de luz deslumbrante, lo que ha sido denominado *glare sensitivity* (sensibilidad al deslumbramiento). Poner una fuente deslumbrante junto a la tabla de CSF permite una mejor correlación entre ésta y la STL. Sin embargo, las diferencias entre sujetos dependerán también de las diferencias previas de la CSF (en ausencia de deslumbramiento). Si se mide la CSF sin y con deslumbramiento, la diferencia viene a ser, en teoría, una forma indirecta y aproximada de medir la STL. Sin embargo, los resultados han sido poco fiables y escasamente relacionados con las molestias de los pacientes (9-11).

Otra posible forma de valorar la dispersión de luz en el ojo sería por el examen biomicroscópico de las opacidades en los medios oculares, lo cual puede hacerse de forma objetiva, p. ej., mediante densitometría basada en imágenes Scheimpflug de lámpara de hendidura o una clasificación del grado de las cataratas. Sin embargo, tales mediciones tampoco se correlacionan biunívocamente con la STL. En primer lugar porque la STL se produce a partir de toda la luz que entra en el ojo, no sólo por la pupila (la que podría interferir con opacidades en córnea o cristalino), sino también través del iris según sea su pigmentación o incluso de la esclerótica y la úvea, así como la luz reflejada por el fondo. Además, la biomicroscopía sólo puede estimar la dispersión de luz hacia atrás (*backward scatter*), mientras que la STL retiniana corresponde a la dispersión hacia adelante (*forward scatter*). Ambos tipos de dispersión no se correlacionan (1,6).

Por último, el Optical Quality Analysis System (OQAS^{TM}, Visiometrics S.L., Terrassa) utiliza una técnica de doble paso a partir de una fuente de luz puntual, analizando la imagen retiniana; algo parecido a visualizar directamente la PSF. El sistema se presenta como capaz de calcular la MTF a partir de dicha imagen, tomando en consideración tanto las aberraciones de alto orden como la luz dispersa (*scattered light*). Esto permitiría una medición de la MTF más exacta que con aberrómetros tipo Hartmann-Shack, pues éstos recogen la información sólo en el trayecto de salida del ojo ignorando la dispersión de luz y por ello sobreestimarían la calidad óptica en condiciones de alta STL. El OQAS produce además un «índice objetivo de scatter» (OSI), basándose en un campo entre 12 y 20 minutos de arco (12). Sin embargo, esto resulta claramente insuficiente para abarcar el dominio angular, mucho más amplio (1° a 90°), en que actúa la STL retiniana. Además, el empleo de luz infrarroja (780 nm) por el OQAS lo aleja de las condiciones normales de creación de STL (con luz visible), ya que la transmisión y reflexión de la luz por los medios y capas oculares (en especial por la coroides) dependen en gran medida de la longitud de onda. Todo ello ha llevado a cuestionar la validez de parámetros como el OSI (13).

MEDICIÓN PSICOFÍSICA DE LA LUZ DISPERSA RETINIANA: MÉTODO DE LA COMPENSACIÓN DIRECTA

Desde las últimas décadas del siglo pasado, un grupo de investigadores del Netherlands Institute for Neuroscience (NIN) liderado por Tom van den Berg han venido desarrollando métodos *psicofísicos* para medir objetivamente la STL retiniana. La psicofísica investiga cuantitativamente la relación entre estímulos físicos y las sensaciones y percepciones que afectan, empleando la *teoría de la detección de señales*. Debido a su punto de vista «desde el fondo del sistema» (la percepción visual), los métodos psicofísicos serían (quizá los únicos) capaces de medir la *forward scatter* (STL *hacia* la retina), teniendo en cuenta la totalidad de fuentes que pueden contribuir a la misma.

El llamado método de la *compensación directa* se propuso en primer lugar (14). Consiste en observar un campo gris uniforme (que no cambia) donde hay dos zonas de prueba: un disco central inicialmente negro y un anillo periférico a una distancia angular de 7° del centro. El anillo se ilumina de forma rápidamente intermitente creando así la fuente de STL. Cuando el anillo está encendido (fase *on*), se proyecta sobre la retina pericentral mientras una parte de su luz se dispersa y también cae sobre la fóvea, con lo que el disco central ya no se ve negro sino algo gris. Al apagarse el anillo (fase *off*), tanto éste como el disco central se ven negros. Al alternarse el encendido y apagado del anillo, al observador también le parece que el disco central parpadea de negro a gris. Se añade entonces una cierta cantidad de luz en el centro durante la fase de apagado del anillo. Ésta es la luz de compensación y se va variando hasta que desaparece el parpadeo aparente del disco central, momento en que la luz añadida equivaldrá a la STL (fig. 10).

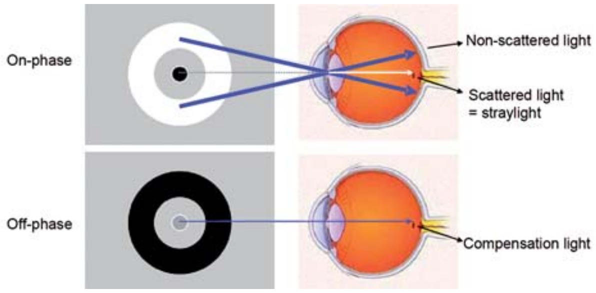


Fig. 10: Medición de la STL por el método de la compensación directa. Arriba, en la fase on la luz dispersa generada por el anillo de luz hace que el disco central no se vea totalmente negro (y «parpadee» con el anillo al apagarse éste). Abajo, al añadir luz compensatoria en el centro durante la fase off, *el parpadeo central llegará a desaparecer (tomado de ref. [6], con permiso).*

MÉTODO DE COMPARACIÓN DE LA COMPENSACIÓN (C-QUANT)

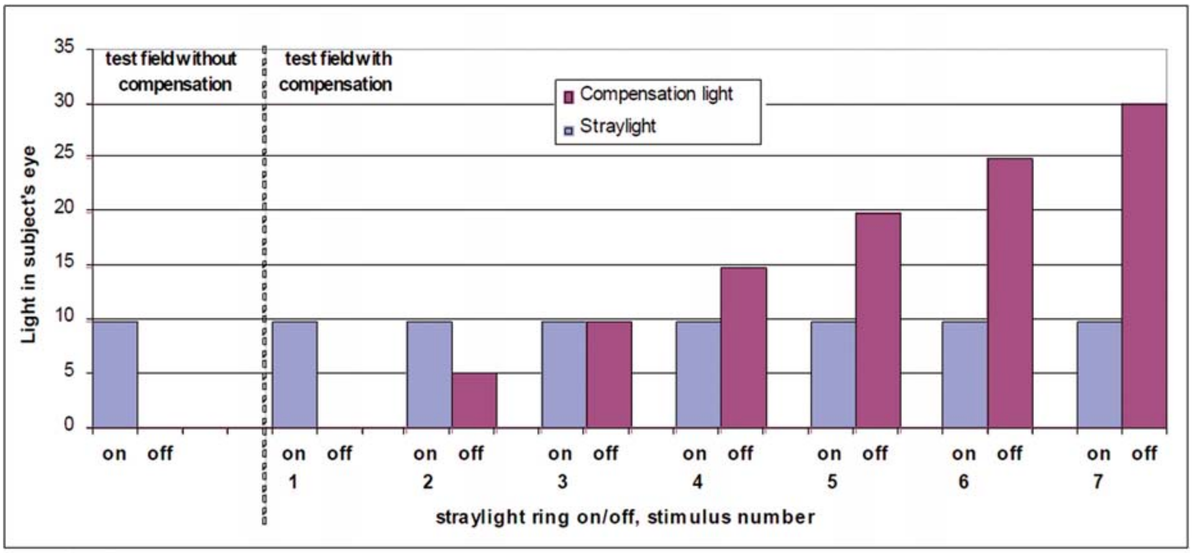
Con el método de compensación directa, muchos sujetos encontraban difícil discernir cuándo el disco central dejaba de parpadear en presencia de los continuos destellos del anillo. Se pasó por ello al método de la *comparación de la compensación*, variante que se ha implementado para la práctica clínica en forma de un dispositivo portátil denominado C-Quant Straylight Meter (Oculus) (fig. 11). La

Fig. 11: El dispositivo C-Quant (Oculus), con el instrumento estimulador y un ordenador con el programa de control. A la derecha, el campo de prueba con el anillo que origina la STL (aquí apagado) y el disco central dividido en dos mitades. El sujeto escoge un lado pulsando unos botones.

principal diferencia estriba en que el círculo central queda dividido en dos mitades; una de ellas recibe la iluminación compensatoria mientras la otra mitad permanece siempre apagada (15).

El anillo centelleante se presenta no de forma continuada como en el método directo sino en breves series de centelleos, siempre de la misma intensidad. Para cada serie o «estímulo», aleatoriamente en una de las mitades del disco central se presenta cierto nivel de luz compensatoria durante la fase *off*, mientras la otra permanece negra (y aparece gris durante la fase *on,* debido a la STL generada por el anillo). El sujeto debe *comparar* ambos lados y obligatoriamente decidir para cada estímulo cuál es el lado que parpadea más fuerte (derecha o izquierda). Si escoge el lado con compensación se considera, por convención, puntuación o *score* «1»; si elige el lado sin compensación la puntuación es «0». Hay que explicarle al sujeto que a veces no verá claramente de qué lado se trata y tendrá que «adivinar»; en algún caso esto puede requerir una cierta persuasión. Este tipo de prueba se conoce en psicofísica como de «Elección Forzada entre Dos Alternativas» (2AFC) y permite procedimientos de análisis estadístico bien establecidos que le dan características de objetividad.

En un ejemplo teórico en el que se supone que ya sabemos el valor de la STL, en el primer estímulo (n.º 1 en la fig. 12) no se presenta ninguna luz compensatoria y ambas mitades aparecen idénticas; el sujeto escogerá un lado u otro (*sco-*



stimulus number	compensation light	modulation no comp field	modulation comp field	modulation difference	average score
1	0	10	10	0	0.5
2	5	10	5	-5	0.1
3	10	10	0	-10	0
4	15	10	5	-5	0.1
5	20	10	10	0	0.5
6	25	10	15	5	0.85
7	30	10	20	10	1

Fig. 12: Ejemplo de prueba (ideal) con C-Quant. Arriba, niveles de luz (en unidades arbitrarias) que aparecen en el ojo del sujeto durante las fases on *y* off *en ambos lados del disco central. En un lado sólo se verá la* straylight*, que permanece constante en todos los estímulos. En el otro se añade la luz compensatoria en la fase* off*, la cual varía en cada estímulo e influencia la percepción del parpadeo que el sujeto debe juzgar. Abajo, tabla con los valores de luz de compensación, modulación en ambos campos (compensado y no compensado), diferencia de modulación entre ambos y puntuación media resultante para cada estímulo (tomado de ref. [6], con permiso).*

re 1 ó 0) en un 50% de los casos y por tanto en promedio obtendrá una puntuación de 0,5. A continuación se empieza a añadir luz compensatoria en un lado; cuando la intensidad de ésta es la mitad de la STL (estímulo n.º 2), la modulación o parpadeo entre *on* y *off* será la mitad en el lado compensado que en el otro sin compensar. Si el sujeto escoge éste, la puntuación será 0, pero como la diferencia es pequeña (de la mitad del valor de la STL), en la práctica al repetirlo se equivocará algunas veces, pongamos un 10%, y el *score* promedio será de 0,1.

Cuando la luz compensatoria es igual a la STL (estímulo n.º 3), la modulación en el lado compensado será nula (es el punto que se buscaba en la prueba de compensación directa) y la diferencia de parpadeo entre ambos lados será muy clara. El sujeto acertará (casi) siempre, con un *score* promedio de 0. En el estímulo n.º 4, la luz compensatoria aumenta hasta una vez y media la STL. De nuevo la modulación en el lado compensado baja a la mitad (como con el estímulo n.º 2, esta vez a favor de la mayor luz compensatoria), con lo que el *score* volverá a ser de 0,1.

Cuando llegamos al estímulo n.º 5, la luz compensatoria es justo el doble que la STL. Por lo tanto, la modulación entre *on* y *off* será de la misma magnitud que en el lado sin compensación, y en consecuencia el acierto promedio volverá a ser, como en el estímulo n.º 1, del 50% (*score* medio = 0,5). A partir de aquí, al aumentar más la compensación, el sujeto verá cada vez más parpadeo en el lado compensado. En el estímulo n.º 6, la luz compensatoria es 2 veces y media el valor de la STL, con lo que la modulación en ese lado es de una vez y media de la intensidad de la STL y el sujeto tenderá a escoger ese lado (*score* = 1). Sin embargo, la diferencia de modulación entre ambos lados vuelve a ser de una mitad del valor de la STL (como en los estímulos n.º 2 y 4), por lo que el sujeto se equivocará algunas veces y el *score* medio será, pongamos, de 0,85.

En el estímulo n.º 7 la luz compensatoria es tres veces la STL, con lo que la modulación es el doble que en lado no compensado, muy fácil de reconocer. y el *score* medio alcanza 1. Cualquier incremento ulterior de la luz compensatoria también aumentará la modulación haciendo la comparación del parpadeo cada vez más fácil, de forma que la puntuación se mantendrá a partir de aquí en 1 para todos esos estímulos.

Podemos preguntarnos para qué sirven todos estos estímulos si el punto de compensación directa ya se alcanzó con el n.º 3. Pero esto era sólo un ejemplo (con una STL teórica conocida, con valor arbitrario = 10) y en la práctica la STL, que desconocemos, puede variar en un factor de hasta 10 veces. Un sujeto que tuviese, p. ej., una STL = 15, se compensaría con el estímulo n.º 4, pero para abarcar todos los posibles valores de STL es preciso realizar muchos estímulos. Por otro lado, la medición de múltiples puntos más allá del de compensación directa permite estimar estadísticamente la fiabilidad del método.

LA FUNCIÓN PSICOMÉTRICA Y LA UTILIDAD DE LA ESCALA LOGARÍTMICA

Si representamos el grado de modulación retiniana o percibida (diferencia entre *on* y *off* o intensidad del «parpadeo» en los campos centrales del C-Quant), en función del grado de luz compensatoria (fig. 13, arriba, 2 ejemplos), obtendremos una línea horizontal (rosa) para el campo sin compensación, pues aquí la modulación es constante; en el campo compensado, la línea (azul) baja hasta el punto de compensación y luego va subiendo. Hay dos puntos en donde la modulación es igual en ambos campos, lo que da una puntuación media de 0,5. Si en lugar de la modulación ponemos en ordenadas la puntuación media (*score*) de la prueba para cada estímulo, obtendremos la denominada *función psicométrica* de la tarea de comparación (fig. 13, abajo). En general, esto representa la probabilidad de una determinada respuesta (aquí derecha o izquierda del campo de prueba) en función del valor del estímulo (la luz compensatoria).

Mientras el punto de compensación directa (*score* 0) tiene poca pendiente y por tanto no queda muy bien definido, la máxima pendiente (y por tanto máxima definición) se produce en el punto del 50%, en especial el de la derecha (fig. 13, b y d). Esto permite ajustar una función psicométrica a estos puntos para hallar el del 50%, según el procedimiento de la máxima probabilidad (*likelihood*), usual en psicofísica. Ahora bien, si representamos dicha función en una escala logarítmica para las abscisas (fig. 14), su forma y pendiente se vuelven independientes del valor de STL, y la única diferencia será la posición del punto de 50%. Esto hace en la práctica preferible el uso de la escala logarítmica para las funciones psicométricas. El parámetro de la STL resultante (parámetro «s« o su logaritmo, log(s)) corresponde a la mitad del valor del punto de 50%, y quedaría por tanto 0,3 unidades logarítmicas por debajo de dicho punto.

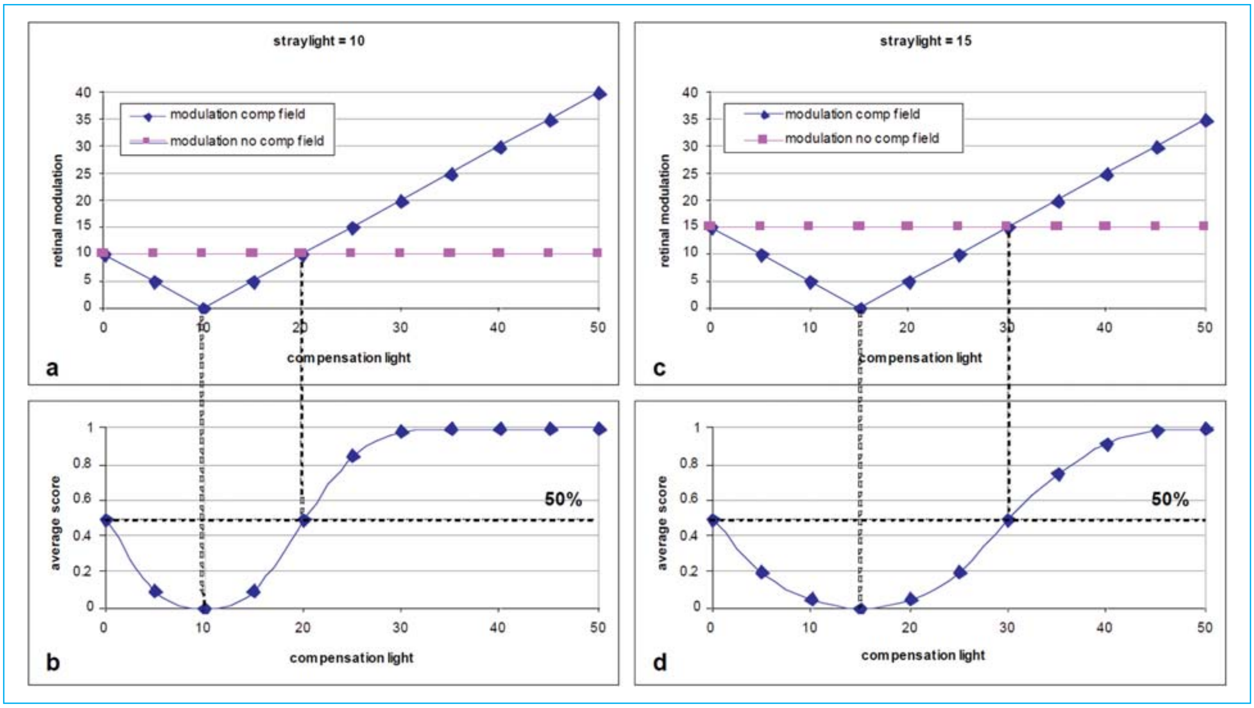


Fig. 13: Dos ejemplos de las funciones de modulación-compensación y psicométrica. (a): Modulación percibida en los campos de prueba con y sin compensación, en función de la cantidad de luz compensatoria en uno de los campos (según el ejemplo de la fig. 12, STL = 10). (b): Puntuación media en función de la luz compensatoria, que corresponde a la función psicométrica para este sujeto. Las gráficas de la derecha (c y d) son las mismas para otro caso con STL = 15, que sólo alcanzará la compensación con el estímulo n.º 4, es decir, más a la derecha. El punto del 50% también se ha desplazado hacia el mismo lado, todo lo cual «estira» la curva psicométrica (tomado de ref. [6], con permiso).

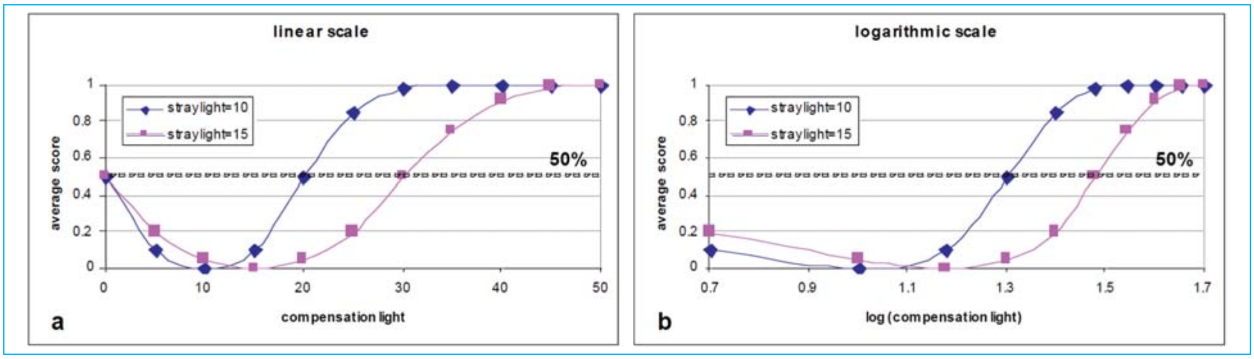
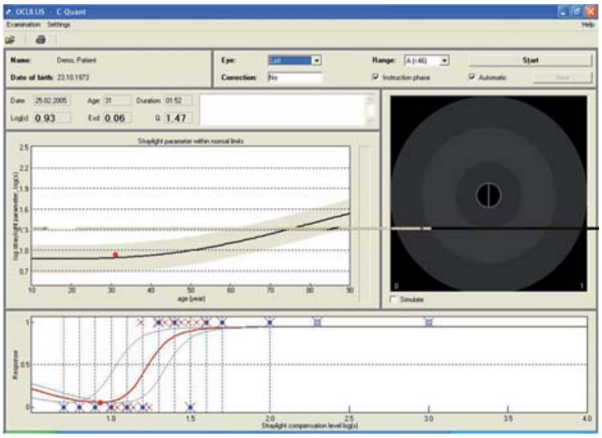


Fig. 14: Curvas psicométricas de las figuras 13b y 13d, combinadas en una única gráfica, sea con escala lineal (a) o bien logarítmica (b) para la luz compensatoria. Nótese como en ésta, la forma y pendiente de la curva se hace independiente del valor de STL, sólo se desplazan los puntos de score 0 y 0,5. El punto inicial de la gráfica (a), con luz compensatoria = 0, no puede representarse en (b) ya que log(0) = -∞ (tomado de ref. [6], con permiso).

MEDICIÓN DE LA LUZ DISPERSA CON EL C-QUANT

El funcionamiento del C-Quant, aunque se basa en el método de comparación de la compensación, es en realidad algo más complejo que el descrito con los anteriores ejemplos. Los valores de la fuente de STL y de luz compensatoria no son absolutos y de hecho varían, pero esto es irrelevante dado que el parámetro log(s) viene definido como *razón* entre la intensidad de la STL y la intensidad de la fuente que la causa. Es decir, log(s) caracteriza una *propiedad física* del ojo y como tal es independiente de la intensidad de la fuente de STL.

También hay aspectos prácticos como la ecualización de las luminancias, rangos de medición según la edad y patología, o las fases del procedimiento, cuyos detalles se describen en los manuales y literatura que acompaña al aparato. Resumiendo, tras una serie previa de estímulos «de instrucción», la prueba consta de dos fases. En total se presentan unos 25 estímulos en 1,5 a 2 minutos. En la fase inicial u «oscura» se emplean estímulos equidistantes en la escala logarítmica. La modulación se obtiene en este caso modificando la intensidad de la luz del anillo de menos a más, lo que en términos relativos es como si se fuese reduciendo la luz compensatoria (que de hecho se mantiene constante). De esta fase se obtiene una primera estimación del punto de 50%, que se emplea para situar a su alrededor los estímulos de la fase final o «luminosa». En ésta la intensidad del anillo es constante y se varía la luz compensatoria, como en los anteriores ejemplos, pero en orden aleatorio. Se logra así precisar mejor el punto de 50% y por tanto el valor de [log(s)] (0,3 unidades log por debajo del de 50%) (fig. 15). También se generan parámetros que permiten estimar la fiabilidad de la medición: «Esd», que debe ser menor de 0,08 y «Q», que debe ser mayor de 1,0; en los casos más severos pueden, no obstante, relajarse algo estos criterios.



Name: Demo, Patient
Date of birth: 23.10.1973
Eye: Left
Correction: No
Range: A (<46)
Date: 25.02.2005
Age: 31
Duration: 01:52
Log(s): 0.93
Esd: 0.06
Q: 1.47

Fig. 15: Pantalla del operador del C-Quant tras una medición. La gráfica de abajo muestra las respuestas del sujeto a los dos últimos de los cinco estímulos de instrucción (puntos azules huecos), a la fase inicial (puntos azules sólidos) y la fase final (cruces rojas), así como la función psicométrica ajustada a todas las respuestas (curva roja). El punto rojo indica el valor de la STL (en este caso 0,93), situado 0,3 unidades logarítmicas por debajo del punto de 50% en la curva roja. Las curvas grises representan los límites superior e inferior del rango de la función psicométrica para la edad del sujeto. En la gráfica de la parte media izquierda de la pantalla se indica la STL hallada [log(s)], en comparación con el rango normal para ojos sanos en función de la edad.

CAUSAS DE LA LUZ DISPERSA EN EL OJO

Las fuentes de STL en un aparato óptico son normalmente múltiples, desde las partículas en el camino óptico, pasando por reflejos desde las superficies de las lentes o espejos, hasta la luz reflejada por superficies de las estructuras de soporte de los elementos ópticos o incluso imágenes fantasma por efectos de difracción. En un ojo normal sin alteraciones de los medios, cada componente óptico puede causar cierta dispersión de la luz que se dirige a la retina, contribuyendo en un cierto porcentaje de la STL retiniana. Esto incluye desde lentes como la córnea y el cristalino, medios de paso como el vítreo y estructuras «de soporte» como la esclerótica o el iris. Incluso la reflexión en el fondo de ojo genera una parte de la STL. Todo ello variará con la edad, pigmentación, patologías asociadas o como efecto colateral de una cirugía ocular (1,6).

Estudios de población amplios usando el método de comparación de la compensación han determinado que los ojos jóvenes sanos tienen una STL media de cercana a log(s) = 0,87. Esto permanecería más o menos estable hasta la edad de 40 años, momento en que empieza a aumentar progresivamente, alcanzando log(s) = 1,20 hacia los 70 años y log(s) = 1,40 hacia los 80 años (fig. 16). Cuando la STL alcanza un valor de log(s) = 1,47 significa que la STL se ha cuadruplicado, lo cual se considera claramente discapacitante. Por tratarse de una escala logarítmica, cada incremento de log(s) en 0,3 unidades supone el doble de STL; un aumento en 1 unidad supone multiplicarla por 10. Un ojo joven y sano con pigmentación elevada (no Caucasiano) puede tener una STL tan baja como log(s) =

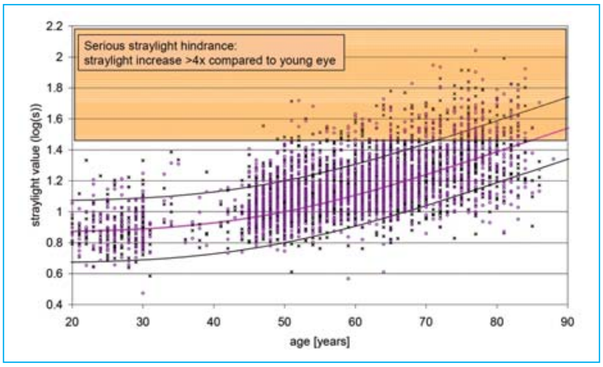


Fig. 16: Distribución de la luz dispersa en función de la edad en una población europea de conductores. Cada incremento en 0,3 unidades representa el doble de STL. La zona superior en color ocre corresponde a niveles de STL discapacitantes, con log(s) > 1,47 (ref. [17]).

0,6, mientras que valores de log(s) = 2,0 (25 veces lo normal) o superiores son comunes en presencia de cataratas (16,17).

CÓRNEA Y SUPERFICIE OCULAR

En un ojo normal sano la córnea es responsable de cerca de un tercio de la STL retiniana total, debido a dispersión tipo Rayleigh (por partículas menores a la longitud de onda de la luz, p.ej., la que da color azul al cielo). Esta proporción permanece aproximadamente constante con la edad, si bien ciertas patologías corneales pueden incrementarla, como la presencia de opacidades o edema (fig. 17a), de forma mucho más acusada que el efecto sobre la AV, en especial en algunas distrofias (fig. 17b) (18).

También aumenta la STL con el simple uso de lentes de contacto, especialmente si están sucias, rayadas o con depósitos. En el caso de las lentes rígidas, el aumento puede persistir tras retirarlasP (19). La inducción experimental de edema mediante lente de contacto dio lugar a un aumento del 50% de la STL por cada 10% de engrosamiento corneal (1).

La STL aumenta de forma transitoria tras la cirugía refractiva corneal, sea de tipo fotoqueratectomía refractiva (PRK) (20) o bien LASIK (21). Aunque en la mayoría de los casos la STL regresa a valores normales, en un 5% a 20% según los estudios persistió elevada, a menudo en ausencia de signos clínicos (1) En presencia de complicaciones como una queratitis laminar difusa (fig. 17c) el aumento de STL será marcado e incluso puede hacerse permanente, tal como se ha documentado en casos de queratotomía radial (22) o de *haze* persistente tras PRK (20).

CRISTALINO Y LENTES INTRAOCULARES

Otra tercera parte de la STL en un ojo normal se debe al cristalino. Esta componente aumenta, por otra parte, con la edad debido al proceso de la esclerosis nuclear y el desarrollo de las cataratas, correlacionándose con su grado (fig. 18) (23-26). La STL media para el grado mínimo de catarata (LOCS = 0,1) es de aproximadamente 1,0 log(s) y con el grado correspondiente a una catarata leve (LOCS > 0,75) alcanza 1,4 log(s), lo que supone un incremento de más del triple de STL.

La severidad de la catarata se correlaciona mucho mejor con la STL que con la AV o la CSF (17). Asimismo se ha encontrado una baja correlación entre los grados de catarata individuales y el Cuestionario de Función Visual VF-14, con la sola excepción de los casos con opacidad subcapsular posterior (27). Mediante filtros neblinosos comerciales (Tiffen Black Pro Mist 2) se ha logrado simular los efectos de las cataratas sobre la STL (28). Dentro de un grado leve a moderado de cataratas, las nucleares puras presentan una AV significativamente mejor y con menores valores de STL que las cataratas mixtas. Mientras en éstas se han medido valores de STL promedio de ≈ 1,30 log(s) en las córtico-nucleares, alcanzando una media de ≈ 1,35 log(s) si a éstas se añade una componente subcapsular posterior. En contraste, los valores medios de STL son más bajos para las formas puras, sean de catarata nuclear ≈ 1,19 log(s), corticales puras ≈ 1,20 log(s) o las únicamente subcapsulares posteriores ≈ 1,23 log(s). Con la progresión de las cataratas, se alcanzan valores de log(s) = 2,0 o superiores (17).

Aunque la cirugía de la catarata soluciona en principio en problema de la STL aumentada por

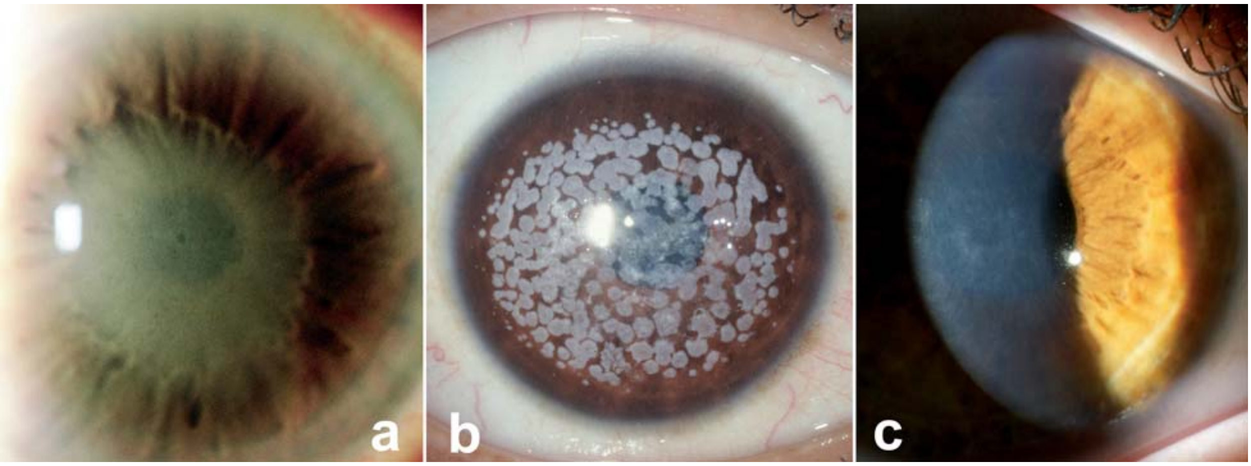


Fig. 17: Condiciones corneales que afectan la STL más que la AV. (a) Edema central en una distrofia de Fuchs. (b) Distrofia granular tipo II (homozigoto). (c) Cicatrización de la entrecara tras una queratitis laminar difusa post-LASIK.

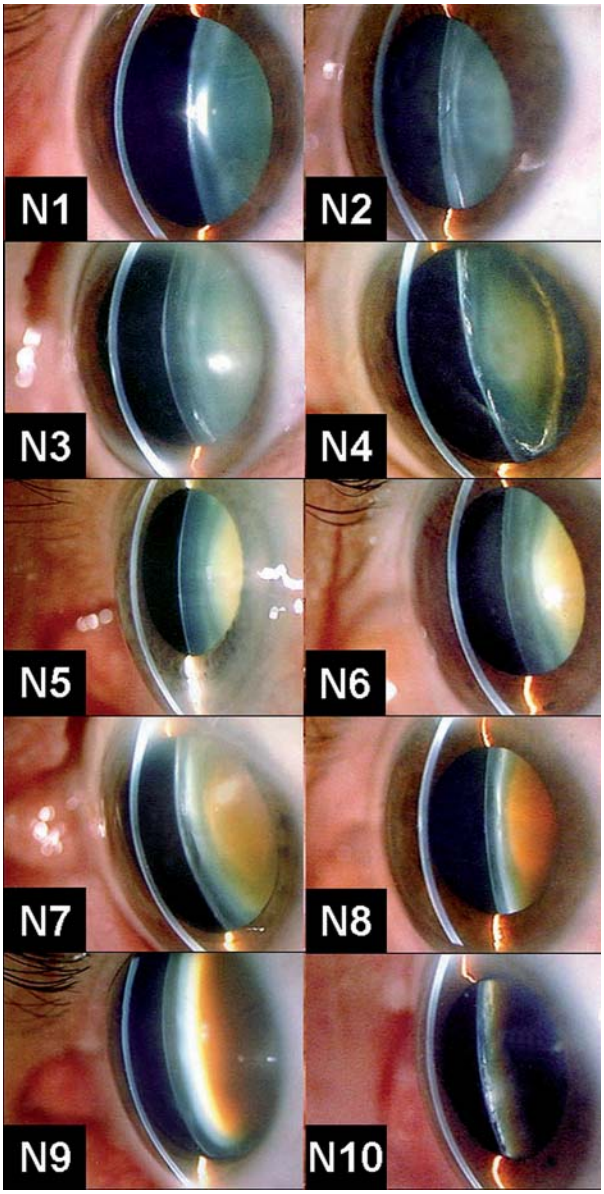


Fig. 18: La esclerosis nuclear del cristalino con la edad y el grado de catarata (según la clasificación BCN-10) provocan un aumento progresivo de la STL.

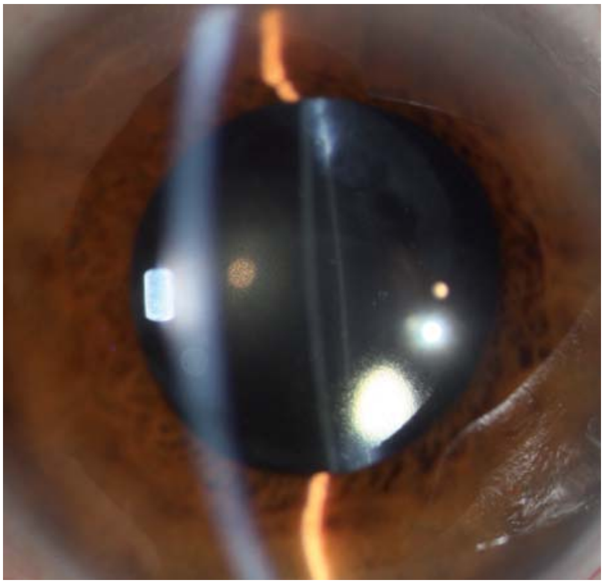


Fig. 19: Un caso de opacificación de LIO acrílica hidrófila, que resultó en un importante aumento de la STL retiniana asociado a visión neblinosa.

este concepto (de hecho la mejora en un factor 3 veces, en promedio superior al de la mejoría en AV), pueden darse nuevas condiciones que vuelvan a elevarla. Inclusive el tipo de material de la lente intraocular (LIO) influencia el grado de STL, siendo ésta en promedio mayor para las acrílicas hidrófobas que para las hidrófilas (29). Aunque la presencia de brillos internos (*glistenings*), un hallazgo frecuente en algunos tipos de LIO acrílicas hidrófobas, podría causar un aumento de la STL, no se han publicado por ahora datos que lo confirmen. En los casos de verdadera opacificación del material de la LIO, el cuadro viene dominado por síntomas de tipo visión neblinosa, lo cual se asocia a un aumento de la STL, típicamente de forma mucho más acusada que la reducción en la AV (fig. 19).

La opacificación de la cápsula posterior (OCP) es la complicación con impacto visual más frecuente tras la cirugía de la catarata (fig. 20a). Esto produce, como era de esperar, un aumento significativo de la STL que se correlaciona con la severidad de la OCP. Al realizar una capsulotomía con láser (Nd:YAG) se produce en promedio una mejoría de la STL (fig. 20b). Sin embargo, los valores individuales de STL tras capsulotomía son muy variables y en casos con orificio capsular de tamaño pequeño o en presencia de restos capsulares en el área pupilar (fig. 20c) pueden asociarse a una STL que persiste elevada o incluso aumenta tras la capsulotomía (29,30).

IRIS, ESCLERÓTICA, ÚVEA Y FONDO DE OJO

La parte de la restante de la STL retiniana se origina principalmente por vías ajenas al eje visual, en función del grado de pigmentación de los tejidos oculares. Especialmente en ojos poco pigmentados (Caucasianos de iris azules), esta vía origina normalmente otro tercio de la STL. Una parte de la luz que alcanza el diafragma iridiano (por fuera de la pupila) se transmite hacia la retina y lo mismo ocurre con la luz que atraviesa la esclerótica, en fun-

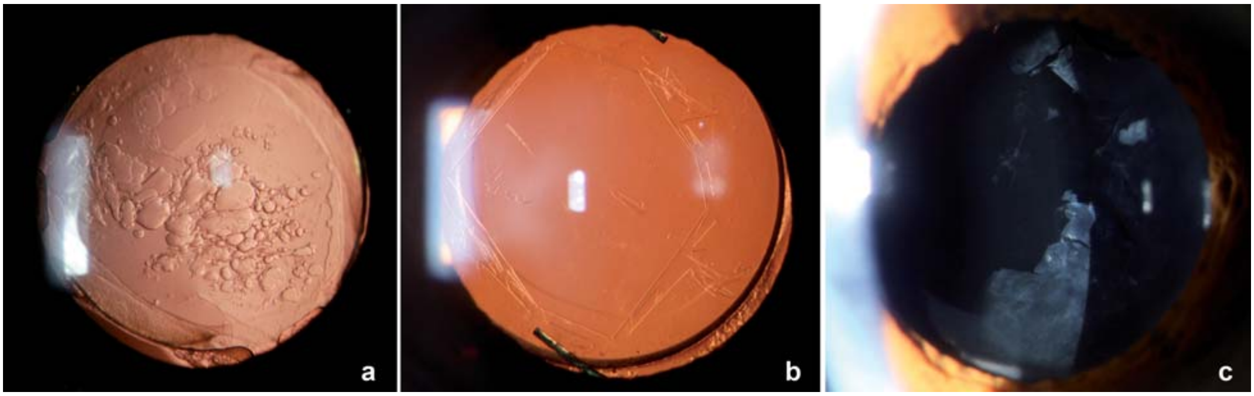


Fig. 20: (a) La opacificación de la cápsula posterior causa un marcado aumento de la STL, lo cual mejora con la capsulotomía (b), aunque de forma variable, según su tamaño y restos capsulares en el eje visual (c).

ción de la pigmentación uveal (31). Por otra parte, tampoco la luz que cae sobre la retina es absorbida completamente y será por ello difundida hacia atrás, contribuyendo a la STL que alcanza otras partes de la retina. Esto último dependerá sobre todo del grado de pigmentación del epitelio pigmentado de la retina y de la coroides (32).

A pesar de que el deslumbramiento es más frecuente de noche, el tamaño pupilar influye en general poco en el valor de STL. Aunque la dispersión de luz aumente con una pupila grande, también lo hará en la misma medida la luz no dispersa que alcanza la retina, con lo cual la razón permanecerá la misma. Esto puede variar según el caso, p. ej., en presencia de una opacidad central en el cristalino, el parámetro de STL puede ser menor en midriasis. En todo caso, no es preciso dilatar la pupila para medir la STL de un paciente con deslumbramiento nocturno (33).

HUMOR ACUOSO Y VÍTREO

El humor acuoso normal no contribuye a la STL pero puede hacerlo en caso de turbidez del mismo (Tyndall). Tampoco lo hace el vítreo normal, pero sus alteraciones como cuerpos flotantes, una hialosis asteroide u otras opacidades pueden aumentar mucho la STL, a menudo sin afectar a la AV (fig. 21).

APLICACIONES CLÍNICAS DE LA MEDICIÓN DE LA LUZ DISPERSA MEDIANTE C-QUANT

A lo largo del último cuarto del siglo pasado se realizaron diversos intentos de cuantificar el deslumbramiento y la cantidad de luz dispersa en el ojo. A partir de la introducción del método de comparación de la compensación, implementado en el dispositivo C-Quant, numerosos estudios han demostrado la independencia de la STL y la AV (1,6). Por este motivo el parámetro de STL puede usarse como descriptor adicional de la calidad visual.

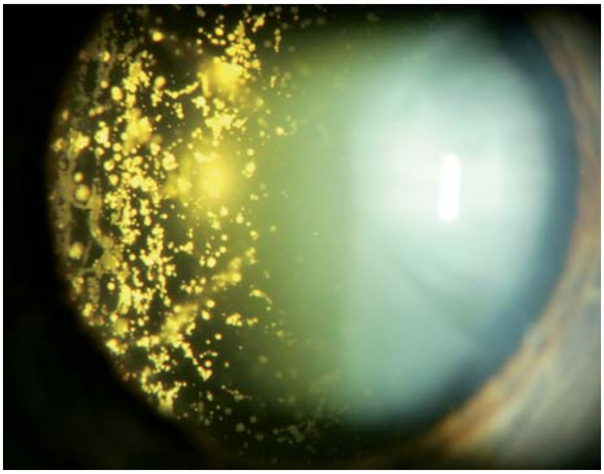


Fig. 21: Las condensaciones en el vítreo pueden elevar la STL sin apenas afectar la AV, como en este caso de hialosis asteroide.

A este respecto, uno de los conjuntos de datos de mayor calado ha sido el recogido por un estudio multicéntrico europeo sobre la función visual y su impacto sobre la conducción. Dicho estudio incluyó más de 2.400 conductores activos en 5 centros de diversos países de Europa en el periodo 2003-2004, los cuales se sometieron a una batería de pruebas de función visual, haciendo hincapié en el impacto visual causado por niveles elevados de STL (fig. 16) (16,17). Se constató que la STL aumenta con frecuencia en la población, lo cual no es detectado por la AV u otras mediciones (fig. 22). A partir del mismo se sugirió un valor de log(s) = 1,45 (4 ve-

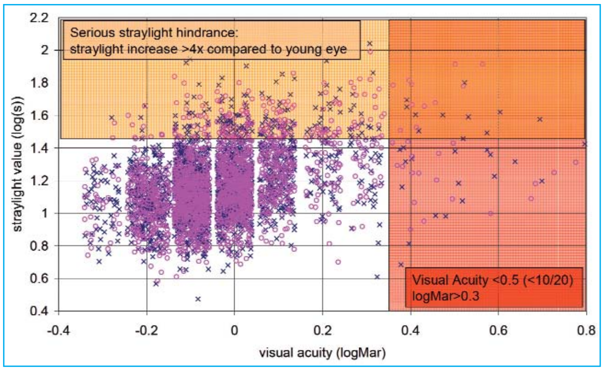


Fig. 22: Valores de STL en función de la AV en una población de conductores europeos. Si consideramos como defecto visual importante una AV < 0,5 (logMAR > 0,3) o una STL de log(s) > 1,45, existen muchos más individuos con discapacidad por STL aumentada (zona amarilla arriba izquierda) que por AV baja (zona naranja a la derecha abajo). Sólo unos pocos sufren ambos tipos de defecto (esquina arriba derecha)(de ref [17]).

ces el normal) como límite (*cut-off*) para una conducción segura. De este modo, la STL podría incluirse como criterio legal para la conducción (34,35). Está claro que si el deslumbramiento es un problema ya en los jóvenes, se convierte en un serio *handicap* al multiplicarse por 4. También pudo medirse la prevalencia de cataratas entre los conductores mayores de 65 años, que es frecuente pero no tan alta como en la población general de estas edades. La menor prevalencia de cataratas bilaterales severas entre los conductores de países con pruebas de función visual obligatorias indican que tal filtro es adecuado para reducir el número de conductores con ese tipo de limitación visualP (36). Sabemos, no obstante, que ciertos tipos de cataratas afectan mucho más a la STL que a la AV.

Estudios más recientes concuerdan con la potencial utilidad de la STL como criterio legal para la conducción, así como prueba complementaria para la indicación de cirugía de la catarata (37). Una STL alta podría justificar una extracción de catarata (o de cristalino más o menos transparente) en presencia de una AV normal. También se ha propuesto como método de evaluación de la idoneidad (*fitness*) ocular para el desempeño de profesiones visualmente exigentes como militares o pilotos, y en especial en sujetos que se han sometido a cirugía refractiva, entre los que se dan (aun de forma variable) valores elevados de STL más a menudo que en la población normal (38).

Las aplicaciones clínicas de la medición de la STL, como método de evaluación de la calidad visual complementaria de la AV y la CSF, pueden resumirse como sigue:

1. Evaluación de la idoneidad ocular para la práctica de actividades visualmente exigentes como la conducción de automóviles o el pilotaje de aeronaves, en particular en condiciones de desempeño profesional o tras cirugía refractiva.
2. Evaluación de la calidad visual de forma más fina que con los métodos usuales (básicamente la AV), en particular tras intervenciones en las que se esperan resultados visuales excelentes, como la cirugía refractiva y, cada vez más, la de la catarata (p. ej., LIO multifocales), las queratoplastias laminares, etc.
3. Evaluación de las indicaciones quirúrgicas en situaciones donde los síntomas de deslumbramiento o déficit visual no se correlacionan bien con la AV, como en ciertos tipos de cataratas, opacidades corneales, capsulares o vítreas, entre otras.
4. Ante una posible extracción de cristalino «transparente» con finalidad refractiva, la presencia de una STL preoperatoria alta será un factor favorable (y viceversa, si es muy baja podría aumentar tras la cirugía y causar descontento).

La medición de la STL mediante el C-Quant es ya una realidad que hace posible un estudio más profundo de la calidad visual, aplicable en muchos campos de la clínica oftalmológica. Se trata de una prueba psicofísica, que aunque depende de las respuestas del sujeto, en realidad no es «subjetiva», sino que mide de forma muy objetiva una propiedad física del ojo (el parámetro *s*), a través de una *función* del ojo que no puede ser influenciada por artefactos como los que a menudo limitan la fiabilidad de métodos ópticos supuestamente «objetivos».

Agradecimiento: Los autores agradecen muy especialmente al Dr. Tom van den Berg, inventor del C-Quant y alma del proyecto *glare* (www.glare.be), por su constante apoyo y estímulo. Además de permitirnos publicar sus figuras, es responsable de mucha de la información aquí contenida, de la que este capítulo es en buena parte resumen y versión al español.

BIBLIOGRAFÍA

1. van den Berg TJTP, Franssen L, Coppens JE. Ocular media clarity and straylight. En: Dart AD, Besharse JC, Dana R, eds., Encyclopedia of the Eye, Vol 3. Oxford: Academic Press, 2010. pp. 173-183.
2. Cobb PW. The influence of illumination of the eye on visual acuity. Am J Physiol 1911; 29: 76-99.
3. Holladay LL. The fundamentals of glare and visibility. J Opt Soc Am. 1926; 12: 271-319.
4. van den Berg TJTP. Importance of pathological intraocular light scatter for visual disability. Doc Ophthalmol 1986; 61: 327-333.

5. Vos JJ, van den Berg TJTP. Report on disability glare. CIE collection 1999; 135: 1-9. (véase www.cie.co.at).
6. Franssen L, Coppens J. Straylight at the retina, scatter papers. Doctoral thesis. Universiteit van Amsterdam, 2007.
7. van den Berg TJTP. On the relation between intraocular straylight and visual function parameters. Invest Ophthalmol Vis Sci 1994; 35: 2659-2661.
8. Adelson EH. Lightness perception and lightness illusions. En: M. Gazzaniga, ed., The New Cognitive Neurosciences, 2nd ed. Cambridge, MA. MIT Press, 2000. pp. 339-351. (Disponible en: http://web.mit.edu/persci/people/adelson/pub_pdfs/gazzan.pdf).
9. Elliott DB, Bullimore MA. Assessing the reliability, discriminative ability, and validity of disability glare tests. Invest Ophthalmol Vis Sci 1993; 34: 108-119.
10. Puell MC, Palomo C, Sánchez-Ramos C, Villena C. Mesopic contrast sensitivity in the presence or absence of glare in a large driver population. Graefe's Arch Clin Exp Ophthalmol 2004; 242: 755-761.
11. van Rijn LJ, Nischler C, Gamer D, Franssen L, de Wit G, Kaper R, Vonhoff D, Grabner G, Wilhelm H, Völker-Dieben HJ, van den Berg TJ. Measurement of stray light and glare: comparison of Nyktotest, Mesotest, stray light meter, and computer implemented stray light meter. Br J Ophthalmol 2005; 89: 345-351.
12. Vilaseca M, Peris E, Pujol J, Borras R, Arjona M. Intra- and intersession repeatability of a double-pass instrument. Optom Vis Sci 2010; 87: 675-681.
13. van den Berg TJTP. To the editor: Intra- and intersession repeatability of a double-pass instrument. Optom Vis Sci 2010; 87: 920-921.
14. van den Berg TJTP, IJspeert JK. Clinical assessment of intraocular straylight. Applied Optics 1992; 31: 3694-3696.
15. Franssen L, Coppens JE, van den Berg TJ. Compensation comparison method for assessment of retinal straylight. Invest Ophthalmol Vis Sci 2006; 47: 768-776.
16. van den Berg TJ, van Rijn LJ, Michael R, Heine C, Coeckelbergh T, Nischler C, Wilhelm H, Grabner G, Emesz M, Barraquer RI, Coppens JE, Franssen L. Straylight effects with aging and lens extraction. Am J Ophthalmol 2007; 144: 358-363.
17. Michael R, van Rijn LJ, van den Berg TJ, Barraquer RI, Grabner G, Wilhelm H, Coeckelbergh T, Emesz M, Marvan P, Nischler C. Association of lens opacities, intraocular straylight, contrast sensitivity and visual acuity in European drivers. Acta Ophthalmol 2009; 87: 666-671.
18. van den Berg TJTP, Hwan BS, Delleman JW. The intraocular straylight function in some hereditary corneal dystrophies. Doc Ophthalmol 1993; 85: 13-19.
19. van der Meulen IJ, Engelbrecht LA, van Vliet JM, Lapid-Gortzak R, Nieuwendaal CP, Mourits MP, Schlingemann RO, van den Berg TJ. Straylight measurements in contact lens wear. Cornea 2010; 29: 516-522.
20. Veraart HG, van den Berg TJ, Hennekes R, Adank AM. Stray light in photorefractive keratectomy for myopia. Doc Ophthalmol 1995; 90: 35-42.
21. Michael R, Montenegro GA, Barraquer RI. Intraocular straylight and contrast sensitivity two months after LASIK. J Emmetropia 2010; 1: 59-63.
22. Veraart HG, van den Berg TJ, IJspeert JK, Cardozo OL. Stray light in radial keratotomy and the influence of pupil size and straylight angle. Am J Ophthalmol 1992; 114: 424-428.
23. van den Berg TJTP, IJspeert JK. Light scattering in donor lenses. Vision Res 1995; 35: 169-177.
24. van den Berg TJTP. Depth-dependent forward light scattering by donor lenses. Invest Ophthalmol Vis Sci 1996; 37: 1157-1166.
25. van den Berg TJTP. Light scattering by donor lenses as a function of depth and wavelength. Invest Ophthalmol Vis Sci 1997; 38: 1321-1332.
26. van den Berg TJTP, Spekreijse H. Light scattering model for donor lenses as a function of depth. Vision Res 1999; 39: 1437-1445.
27. Heys KR, Friedrich MG, Truscott RJW. Free and bound water in normal and cataractous human lenses. Invest Ophthalmol Vis Sci 2008; 49: 1991-1997.
28. de Wit GC, Franssen L, Coppens JE, van den Berg TJ. Simulating the straylight effects of cataracts. J Cataract Refract Surg 2006; 32: 294-300.
29. Montenegro GA, Marvan P, Dexl A, Picó A, Canut MI, Grabner G, Barraquer RI, Michael R. Posterior capsule opacification assessment and factors that influence visual quality after posterior capsulotomy. Am J Ophthalmol 2010; 150: 248-253.
30. van Bree MC, Zijlmans BL, van den Berg TJ. Effect of neodymium:YAG laser capsulotomy on retinal straylight values in patients with posterior capsule opacification. J Cataract Refract Surg 2008; 34: 1681-1686.
31. van den Berg TJTP, IJspeert JK, de Waard PW. Dependence of intraocular straylight on pigmentation and light transmission through the ocular wall. Vision Res 1991; 31: 1361-1367.
32. Delori FC, Pflibsen KP. Spectral reflectance of the human ocular fundus. Appl Opt 1989; 28: 1061-1077.
33. Franssen L, Tabernero J, Coppens JE, van den Berg TJ. Pupil size and retinal straylight in the normal eye. Invest Ophthalmol Vis Sci 2007; 48: 2375-2382.
34. van den Berg TJTP, et al. Disability glare in the aging eye. Assessment and impact on driving. J Optom 2009; 2: 112-118.
35. van Rijn LJ, Nischler C, Michael R, Heine C, Coeckelbergh T, Wilhelm H, Grabner G, Barraquer RI, van den Berg TJ. Prevalence of impairment of visual function in European drivers. Acta Ophthalmol 2011; 89: 124-131.
36. Nischler C, Michael R, Wintersteller C, Marvan P, Emesz M, Van Rijn LJ, van den Berg TJ, Wilhelm H, Coeckelbergh T, Barraquer RI, Grabner G, Hitzl W. Cataract and pseudophakia in elderly European drivers. Eur J Ophthalmol 2010; 20: 892-901.
37. Bal T, Coeckelbergh T, Van Looveren J, Rozema JJ, Tassignon MJ. Influence of cataract morphology on straylight and contrast sensitivity and its relevance to fitness to drive. Ophthalmologica 2011; 225: 105-111.
38. van Bree MC, van Verre HP, Devreese MT, Larminier F, van den Berg TJ. Straylight values after refractive surgery: screening for ocular fitness in demanding professions. Ophthalmology 2011; Jan 12. [Epub ahead of print].