SURVEY OF OPHTHALMOLOGY VOLUME 47 • NUMBER 6 • NOVEMBER–DECEMBER 2002

ELSEVIER

MAJOR REVIEW

Night Vision Disturbances After Corneal Refractive Surgery

Nancy I. Fan-Paul, MD, MPH, Joan Li, MD, Julia Sullivan Miller, MD, PhD, and George J. Florakis, MD

Edward S. Harkness Eye Institute, Columbia Presbyterian Medical Center, New York, New York, USA

Abstract. A certain percentage of patients complain of "glare" at night after undergoing a refractive surgical procedure. When patients speak of glare they are, technically, describing a decrease in quality of vision secondary to glare disability, decreased contrast sensitivity, and image degradations, or more succinctly, "night vision disturbances." The definitions, differences, and methods of measurement of such vision disturbances after refractive surgery are described in our article. In most cases of corneal refractive surgery, there is a significant increase in vision disturbances immediately following the procedure. The majority of patients improve between 6 months to 1 year post-surgery. The relation between pupil size and the optical clear zone are most important in minimizing these disturbances in RK. In PRK and LASIK, pupil size and the ablation diameter size and location are the major factors involved. Treatment options for disabling glare are also discussed. With the exponential increase of patients having refractive surgery, the increase of patients complaining of scotopic or mesopic vision disturbances may become a major public health issue in the near future. Currently, however, there are no gold-standard clinical tests available to measure glare disability, contrast sensitivity, or image degradations. Standardization is essential for objective measurement and follow-up to further our understanding of the effects of these surgeries on the optical system and thus, hopefully, allow for modification of our techniques to decrease or eliminate post-refractive vision disturbances. **Surv Ophthalmol 47:**533–546, 2002. © 2002 by Elsevier Science Inc. All rights reserved.)

Key words. contrast sensitivity • glare • glare disability • image degradation • night vision disturbances • refractive surgery

I. Introduction

Glare disability, image degradation, and loss of contrast sensitivity under scotopic or mesopic lighting conditions are problems that may occur in patients who have otherwise excellent vision during the day. The incidence of night vision complaints may increase after refractive surgical procedures and represents a major clinical problem for a patient who has had a successful refractive procedure and is otherwise comfortable and asymptomatic.

The number of patients with complaints of glare at night (i.e., "difficulty with driving at night") has increased with the increasing population of ametropic patients who have undergone refractive surgical procedures. The public health implications of disabling glare are potentially great. Most of the patients seeking refractive surgery now are young to middle-aged, and in 30 to 40 years a certain percentage can be anticipated to develop cataracts or age-related macular changes.[93] The combined effects of vision disturbances from a cornea permanently altered by refractive surgery, cataract, or age-related macular degeneration on visual performance are currently unknown. With the population over age 55 expected to

© 2002 by Elsevier Science Inc.
All rights reserved.

0039-6257/02/$–see front matter
PII S0039-6257(02)00350-8

increase by 82% between 1980 and 2030,[177] and over 1 million refractive surgical procedures currently performed each year in the United States, keratorefractive surgery may become an important public health issue. Although there is significant confusion in the literature with respect to the definition of such vision disturbances, we attempt to review the reported incidence with the advent of refractive surgery and describe the current pre- and postoperative testing methods available to assess and understand these disturbances.

II. Defining the Terms

The human eye is a very versatile and accomplished image processor, and it is theoretically capable of seeing 20/5–20/10.[7,147] However, such good visual acuity is rarely achieved because two optical phenomena may reduce visual acuity: 1) diffraction originating from the entrance pupil, and 2) spherical aberrations of the eye. The limitation on visual acuity by diffraction decreases with increasing pupil diameter. The optical errors induced by spherical aberration, however, increase with larger pupil diameters. The shape of the cornea and the structure of the lens are designed in a way to minimize these optical degradations.

The cornea contributes 60–70% of the optical power of the human eye. Most of the total corneal power occurs at the air-tear film interface. The two main parameters affecting the optical quality of the cornea are its transparency, maintained by the regular microscopic structure of the fibrils, and its shape, which tends to be aspheric. Because the cornea is accessible and so important to the refractive state of the eye, most forms of refractive surgery achieve their goals by attempting to change the shape of the cornea. Many techniques have been developed to correct the refractive errors of the eye, and they can be grouped into several categories: incisional, thermal, lamellar, intracorneal, and intraocular. The underlying theme of all these techniques (except for intraocular techniques) is a change in corneal curvature. Specifically, myopia can be treated by decreasing central corneal steepness, thereby reducing the optical power of the cornea; hyperopia can be treated by increasing central corneal steepness, thus adding optical power to the cornea; and astigmatic correction addresses the corneal curvature in a specific axis. These changes in shape induce an increase in optical aberrations and may lead to image degradations that are detected under low lighting conditions in which the pupils are larger, despite elimination of sphero-cylindrical errors.[117] Furthermore, opacification of ocular media, such as from corneal scars or haze, which can result after refractive surgery, can also cause intraocular light scattering, which can lead to an increased amount of glare disability or decreased contrast sensitivity.

The terms most often confused both by patients and ophthalmologists (as seen anecdotally as well as in research for this article) are *glare*, *glare disability*, and *contrast sensitivity* (Table 1). To patients, glare is an encompassing term that fully explains their night vision difficulties. Technically, glare is only a physical term that refers to a light source. Glare disability and decreased contrast sensitivity are actually what patients are describing and what we measure in the office.

Glare disability is the term that has been adapted to describe any subjective reduction of visual performance due to a glare source. This disability occurs when the luminance within the visual field is sufficiently greater than the luminance to which the eyes are adapted. This can cause annoyance, discomfort, or, rarely, loss in visual performance or visibility.[1] Some light-induced disturbances may be less annoying than others; they may simply be noticeable and at times not even perceived by a patient unless specifically queried. Subjective assessment is usually done by way of a patient questionnaire, most commonly asking patients to grade the amount of glare as minimal, mild, moderate, or severe. More formal methods of subjective testing, such as psychometric questionnaires, have a broader scale for the severity of glare symptoms. More objective glare testers have been developed to have a light source of different luminances (i.e., different levels of glare) to test glare disability. These tests are described in the following section.

Optically, glare disability occurs when light from a source is scattered by the ocular media resulting in an image degradation. The scattering light forms a veiling luminance that reduces the overall contrast

TABLE 1

Definitions

Term	Definition
Glare	Physical term referring to a light source
Glare disability	Subjective reduction of visual performance due to a glare source
Contrast sensitivity	Comparison in which differences are demonstrated or enhanced
Image degradations	Altered object shape or size (halos, starbursts)
Night vision disturbances	Glare disability, contrast sensitivity and image degradations

of all objects, which ultimately decreases the visibility of the original intended target. Thus, in order to fully understand glare and its effects on vision, one must comprehend contrast.

A common definition of contrast in vision research uses the Michelson contrast equation:

$$\text{Contrast} = (\text{Lmax} - \text{Lmin})/(\text{Lmax} + \text{Lmin})$$

Where luminance (i.e., brightness) units = candelas per square meter (cd/m^2) or "nits" and Lmax = maximum luminance and Lmin = minimum luminance. According to this equation, contrast can be 0% to 100% with best visual discernment at 100% contrast. The Snellen chart is a prime example of items pictured at 100% contrast. Objects in the real world are rarely at such a high contrast level, thus accounting for the subjective complaints of poor vision despite good vision testing in the office. Tests developed to measure contrast sensitivity are designed to determine the threshold of contrast required to identify a target. Some tests combine contrast sensitivity tests and glare sources in an attempt to imitate true life situations, such as a bright sunny day or headlights from an oncoming car. Contrast sensitivity is altered since the glare source decreases overall contrast.

Glare disability and decreased contrast sensitivity have been grouped into the adapted term *night vision disturbances* (NVD). It is an appropriate term because most complaints of image degradations occur under scotopic or mesopic conditions when the pupil is physiologically dilated, most often in conditions such as night driving. Night vision disturbances can be defined based on the shape or size of image degradation that a source luminance produces subjectively. The most common descriptions of such image degradation are starbursts or streaks of aberrant light perceived as eminating from a light (Fig. 1). Such starbursts are a common phenomenon even described by nonsurgical patients who wear glasses or contact lenses, especially when they are undercorrected.[77] This form of image degradation, in its mildest form, rarely causes intolerable visual complaints. Another configuration that is often described are halos (Fig. 2). Halos can occur with or without starbursts. Halos may be attributed to a pupil diameter that is greater than the optical zone diameter after refractive surgery and was especially an issue with radial keratotomy and early small ablation zone photorefractive procedures. Furthermore, halos may be eccentric and may be the result of difficulties with the placement of an ablation zone and they may vary with a particular patient because the center of the pupil may vary with its diameter.[47]

There have been multiple studies on the complications after refractive surgery. The review of such studies demonstrates significant confusion in the literature as it pertains to scotopic or mesopic vision disturbances. Part of the problem is that the terms glare, glare disability, and contrast sensitivity have been used very loosely, meaning different things often not well defined by various authors. Discerning between a patient's subjective observation and an objective measureable image degradation in conditions which mimic real life situations, most notably while driving at night, has been difficult to sort out.

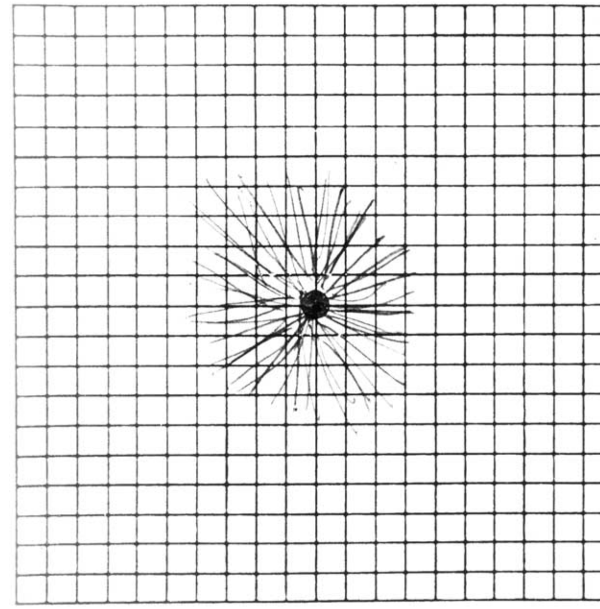

Fig. 1. Starburst as measured by the Night Vision Recording Chart.

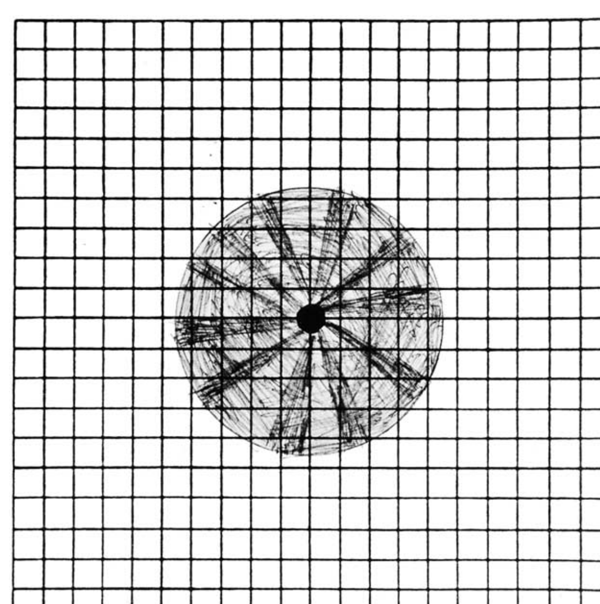

Fig. 2. Halo as measured by the Night Vision Recording Chart.

The goal of our review is to present the current findings in the literature. Articles relating to the correction of myopia are most widely available and these are the ones discussed in this review.

III. Testing Methods

In order to objectively assess and understand the subjective complaints of pre- and post-operative vision disturbances, several tests have been developed. The common goal of these tests has been to attempt to quantify a subjective phenomenon in order that it could be measured, followed, and, hopefully in the future, corrected or avoided.

Because such image degradations involve a subjective interpretation of an image projected by the eye to the visual cortex, testing to objectively characterize the type and level of disturbance initially relied on subjective surveys and questionnaires.[15] More formal methods with detailed questionnaires (psychometric testing) and broader grading scales were slightly more rigorous.[26] Since then, psychometric testing has been developed to be more reliable.[28]

Objective tests which involve or attempt to measure contrast sensitivity include the Snellen chart, Bailey-Lovie chart, Pelli Robson letter sensitivity chart, Regan chart, Small Letter Contrast Test, (Ginsberg-)Vistech MCT 8000, Vistech chart 6500, and the CSV 1000. Tests which involve or attempt to measure glare disability include the Berkeley glare test, Miller Nadler Glare Tester, Brightness Acuity Tester, Van den Berg Straylightmeter, and the Night Vision Recording Chart. These tests can be further categorized by their use of either letters, contrast gratings, or the Landolt C ring. Some tests can be combined to test contrast sensitivity with a glare source causing glare disability (Table 2). The advantages and disadvantages of some of the more common tests are discussed briefly following a description of the test itself.

A. TESTS FOR CONTRAST SENSITIVITY USING LETTERS

There are several tests that employ letters to assess contrast sensitivity. These include the Snellen chart, Bailey-Lovie chart, Pelli Robson letter sensitivity chart, Regan chart, and Small Letter Contrast Test. The routine Snellen chart has several disadvantages, including different charts having different number of letters per line, no logical progression of letter size with each line, and letters on the same line with different ease of recognition. In terms of testing post-refractive patients, the greatest disadvantage is the chart's limitation of functioning only at 100% contrast. The Bailey-Lovie chart[20] corrects some of earlier mentioned problems—it has 1) letters of equal legibility; 2) same number of letters on each row; 3) uniform between-letter and between-row spacing; and 4) a logarithmic progression of letter size—but again only functions at 100% contrast.

The Pelli-Robson letter sensitivity chart[122] is another commercially available test that provides a global measure of contrast sensitivity using letters. The letters are of constant size and grouped in triplets of decreasing contrast by a factor of 0.15 log units.[44] The test is helpful because it has been found to be reliable for patients with a visual acuity as low as 20/400. The Regan charts[136] are logMAR acuity charts of varying contrast which also use letters. Both of these charts, Pelli-Robson and Regan, can be helpful in evaluating glare disability with variable contrast objects since they can be used in combination with the Brightness Acuity Tester (BAT) (described below) which allows for testing at different luminances.

The Small Letter Contrast Test was described by Rabin and Wicks in 1996[130] with earlier prototypes

TABLE 2

Tests for Vision Disturbances

Name of Test	Contrast Sensitivity (CS) or Glare Disability (GD)	Form
Snellen chart	CS	letters
Bailey-Lovie chart	CS	letters
Pelli-Robson letter sensitivity chart	CS (and GD if used with BAT)	letters
Regan chart	CS (and GD if used with BAT)	letters
Small letter contrast test	CS	letters
(Ginsberg-) Vistech MCT 8000	CS and GD	contrast gratings
Vistech chart 6500	CS	contrast gratings
CSV 1000	CS	contrast gratings
Berkeley glare test	GD	letters
Miller-Nadler Glare Tester	GD	Landolt C
Brightness Acuity Tester (BAT)	GD	—
Van den Berg Straylightmeter	GD	—
Night Vision Recording Chart	GD	modified Amsler

tried in 1993[135] and 1990.[64] The letters are the same size but lines vary in contrast by 0.1 log steps. The test is conducted under normal illumination (i.e., does not cause pupil constriction) but was shown in one study to be a more sensitive index of optical defocus rather than visual acuity.[129]

There have been conflicting studies on the reliability of the Pelli-Robson Chart, Regan Chart, and Small Letter Contrast Test. Mantyjarvi and Laitinene found the Pelli-Robson chart to be reliable and easy to administer in the clinical setting.[95] In contrast, Reeves et al found the Pelli-Robson Chart, Regan Chart, and Small Letter Contrast Test to have poor reliability, thus limiting the effectiveness of the tests in finding small changes in visual performance.[133] Such conflicting arguments further emphasize the lack of a good clinical test that can be the standard measurement of contrast sensitivity.

B. TESTS FOR CONTRAST SENSITIVITY USING CONTRAST GRATINGS

Contrast gratings are another method used to test contrast sensitivity. The gratings are based on sinusoidal waves of light. Medium width bars are easier to see than thin or broad bars. The (Ginsberg-)Vistech MCT8000[118] allows contrast sensitivity measurements under low (3 cd/m^2) and high (125 cd/m^2) luminance(Vistech Consultants Inc., Multivision Contrast Tester [MCT8000]; Instruction manual). The ability to vary luminances has been helpful to test for glare disability post-RK.[25] Similar tests include the Vistech chart 6500[134] and the CSV 1000.[56]

C. TESTS FOR GLARE DISABILITY USING LETTERS OR CONTRAST GRATINGS

Testing for glare disability using letters couples some of the above described tests with glare sources. The Berkeley glare test[19] consists of a low contrast reduced Bailey-Lovie letter chart (described above) surrounded by a white background Plexiglas panel. The chart is front illuminated to 80 cd/m^2. The opaque panel may be transilluminated to serve as a glare source at luminances of 300, 800, and 3,000 cd/m^2. Other tests in this category include the Pelli-Robson letter sensitivity chart or the Regan chart combined with the Brightness Acuity Tester (described below). And lastly, using contrast gratings, the (Ginsberg-)Vistech MCT 8000 has, as mentioned above, the benefit of assessing contrast under different luminance conditions.

D. TESTS FOR GLARE DISABILITY USING THE LANDOLT C RING

The Miller-Nadler Glare Tester, introduced by Miller[102] and later modified by Le Claire,[85] utilizes constant-sized Landolt C rings in four different orientations and varying contrasts (2–92%). The rings are surrounded by a broad glare source of constant luminance. The final glare disability score, based on the last correctly identified ring orientation, can be converted to a Snellen equivalent based on a table of conversion provided by the manufacturer. The sensitivity of this test after refractive surgery has been questioned, however, with certain studies showing no difference in patient reported glare between RK patients and normals even though other tests show otherwise and RK patients report appreciable subjective glare.[14,182] The test is also very sensitive to patient positioning with a movement of 10 cm off-line, resulting in a 50% reduction in the effective intensity of the glare source.[173]

E. OTHER TESTERS

The Brightness Acuity Tester (BAT)[74] was introduced by Holladay in 1987. The instrument has been described as an ice cream scooper 60 mm in diameter with a hole (12 mm) in the center. The patient holds the device over the eye and a visual acuity chart is viewed through the aperture. A uniform luminance at three different settings, high (white sand beach), medium (clear day) and low (overhead lighting) is used to induce contrast settings. The BAT has been found to be a reliable predictor of outdoor visual acuity.[106] It has been used in conjunction with the Pelli-Robson chart as well as the Regan charts as described above.

The Van den Berg Straylightmeter[172] is another glare disability tester which by varying luminances can determine the amount of intraocular forward light scatter. The resultant test values have been used as references in assessing the validity of various glare testers.[45]

The Night Vision Recording Chart[50] (NVRC) as described by Florakis et al operates under natural scotopic conditions, allowing testing with a physiologically dilated pupil, which is when image degradation most often occurs. This is important, because as Wachler suggested, testing glare sources can often constrict the pupil leading to unnatural test results.[27] The NVRC test consists of projecting a small circle from a standard projector onto a screen in a darkened room. Patients are asked to reproduce what they see (starbursts, halos, or other image degradations) onto a chart that has been adapted from an Amsler grid. A similar apparatus to the NRVC consists of a computer and high-resolution monitor under scotopic conditions.[160] This test, however, was designed to map the size of halos only (i.e., not starbursts).

IV. Testing Results

Factors contributing to an increased risk for post-refractive night vision disturbances include the patient's own predisposing factors—large pupils, large refractive error, thin corneas (limiting the optical zone size), and low neural ability of adaptation—and factors specific to each method of refractive surgery as described in this section (Table 3).

A. RADIAL KERATOTOMY (RK)

The basis of most subjective complaints affecting the success of RK depend on the relation between pupil size[9,131] and the optical clear zone size.[131,141] These complaints include subjective glare disability[25,38,70,182,183] as well as measurable decreased contrast sensitivity[18,26,56,100,103,124,169] and image degradations.[180]

Overall, the reported incidence of moderate to severe glare disability after RK in the first 3 to 6 months ranges from 50% to 60%[35,71,141] when using questionnaires. This incidence falls to 0–5%[17,83,110,111,131] after 1 year and even further after 2 years.[16,144,181] Jory correctly classified the incidence as "common" at 2 weeks post RK, "uncommon" at 3 months, and "occasional" at 12 months.[78] Neumann further divided these complaints of glare disturbances into "night glare"(30%) and "day glare" (0.7%) after 12 months post RK.[107] Interestingly, the PERK studies found that although 16.9% of patients complained of significant glare disability 12 months post RK, 16.9% of patients also complained of significant glare disability pre RK.[26] Using the glare tester MCT 8000, Ghaith et al attempted to objectively measure glare disability post RK. They found a lower incidence of disability than found by subjective questionnaires.[25]

Changes in contrast sensitivity after RK have also been extensively studied. Similar to complaints of glare disabiltiy, decreases in contrast sensitivity were greatest immediately after RK[168] but showed rapid improvement between 6 months to 1 year after surgery. By 1 year, most studies showed no difference in contrast sensitivity from preoperative measurements.[58,82,131]

As described above, the etiology of these vision disturbances often includes pupil or optical zone size issues. For the typical eye, when the pupil size is smaller than 2.5–3 mm, the eye is diffraction limited. This means that as long as the residual refractive error is minimal and the surgery is well centered on the eye's entrance pupil, most patients will be happy with their outcomes under bright light conditions when their pupil is small. For pupil sizes larger than 3 mm, higher order aberrations have a greater effect on visual performance. Larger pupils are seen in scotopic conditions and in younger patients, and play an important role in causing night vision disturbances in such circumstances.[12]

As a demonstration of the above concept, it has been shown that under small pupil photopic conditions, post-RK eyes show a similar contrast sensitivity to normal unoperated eyes.[58] Alternatively, with naturally dilated scotopic pupils or pharmacologically dilated pupils, post-RK patients have increased glare complaints or decreased contrast sensitivity testing when matched with normal controls.[10,13,18,73] Using ray tracing techniques, Schwiegerling found that the peak loss of contrast sensitivity occurred for a pupil size of approximately 4 mm for a given optical zone size in RK, and that the contrast sensitivity loss is larger for smaller optical zone sizes.[148]

Similarly, the size of the optical clear zone in RK is

TABLE 3

Reported Factors Leading to Vision Disturbances

Patient Factors	Large pupil size Large refractive error Thin cornea (limiting optical zone size) Low neural ability of adaptation
Radial Keratotomy	Large pupil size Small optical clear zone Variable corneal steepening Inadvertent stray incisions Extensive scarring Debris within the incision Irregular astigmatism
Photorefractive Keratectomy	Large pupil size Small ablation diameter Decentration of ablation zone Corneal asphericity changes Microscopic changes
Laser-Assisted In Situ Keratomileusis	Large pupil size Small ablation diameter Decentration of ablation zone Corneal asphericity changes Flap striae Flap misalignment Epithelial ingrowth

a determining factor in the degree of visual aberrations after surgery. In fact, in 1982, Rowsey concluded that the only consistent variable in predicting the post-operative result after RK was the size of the optical clear zone.[141] He observed that a 3.0-mm optical clear zone produced a higher incidence of glare disturbances (79%) compared to a 4.0-mm optical zone (20%). Grimmett and Holland studied the complications in 31 eyes of 16 patients that had RK with a clear zone of less than 2.25 mm.[59] One hundred percent of their patients had unsolicited complaints of severe glare disability. All patients noted that their glare disturbances worsened in situations of low-level illumination. Sixty-nine percent of the 16 patients were unable to drive at night and 4% lost employment due to visual difficulty. Applegate attempted to explain this phenomenon by demonstrating a degradation of paracentral and peripheral corneal optics that may contribute to the increase of optical aberration post-RK, especially in smaller optical clear zones.[8]

Uozato and Guyton were the first to calculate the optical clear zone area needed to obtain glare-free disturbance distance vision in emmetropia.[171] They stated that, "for a patient to have a zone of glare-free vision centered on the point of fixation, the optical zone of the cornea must be larger than the entrance pupil." Thus, theoretically, the surgeon can decrease the risk of glare disability by increasing the optical clear zone size. However, this limits the corrective ability of RK since there is a necessary decrease in clear zone size with increasing refractive error corrected.[10]

Variable corneal steepening post RK can also lead to a persistent diurnal variation in refractive error and thus subjective image degradation.[23,31] The PERK study showed shifts in refraction of −0.42 D at 1 year and −0.27 D at 2.5–4 years.[143] Proposed mechanisms for nocturnal flattening of the cornea during sleep leading to variable corneal steepening in the morning include mild epithelial and stromal edema, constant pressure of the eyelids, and early morning diurnal upswing of intraocular pressure.

Other sources of increased glare or decreased contrast sensitivity after RK include inadvertent stray incisions, extensive scarring, debris within the incision, and irregular astigmatism. Interestingly, Veraart found that there was no correlation between the number of incisions and the incidence of glare disability.[174]

B. PHOTOREFRACTIVE KERATECTOMY (PRK)

In most studies, there was a substantial incidence of vision disturbances—most reports dealt with contrast sensitivity not glare disability—immediately following PRK.[40,56,108,150] In fact, Quah has reported that up to 9.8% of his patients refused PRK and that 12% of his patients had delayed PRK in their fellow eye a full year secondary to vision disturbances.[128] After 6 months to 1 year, most patients had a significant decrease in their complaints.[5,48,69,80,109,114,153,160,165,176,184] or even returned to their baseline pre-operative condition.[42,56,65,104,112,119,120,156,175,186] Some researchers, however, have found vision disturbances to persist in some patients even after 2 years,[29,87,145] especially if the myopia correction was large.[176] Interestingly, Shimizu et al also suggest that different races may have different outcomes status post successful PRK secondary to different levels of resultant corneal haze.[157]

Similar to RK, pupil size is an important factor in determining the end result of subjective visual success post PRK.[30,98,112,114,155] Using ray-tracing techniques, Seiler showed that there was a substantial increase in the effective spherical aberration in post-PRK eyes which was highly correlated with measured glare visual acuity. The effective spherical aberration increased with increasing pupil size, indicating an increase in blurring of the retinal image with the larger pupil at night.[152]

Of equal importance is the ablation diameter of treatment in PRK.[114] It has been shown that smaller ablation zones cause an increase in glare disability and image degradations (i.e., starburst and halos),[21,46,54,55,57,68,80,92,94,113,116,125] and decrease in contrast sensitivity.[178] Using ray-tracing techniques, Roberts and Koester concluded that optical zone diameters must be at least as large as the entrance pupil diameter to preclude glare at the fovea, and larger than the entrance pupil to preclude parafoveal glare. They also found that a larger optical zone was required to protect the extrafoveal region from glare for a greater anterior chamber depth.[138]

Decentration of the ablation zone is another factor important in the subjective result post-PRK.[105,146,159,175] Maloney showed that a 1-mm decentration can result in monocular diplopia with a defocused secondary ghost image.[94] Doane et al confirmed Maloney's findings showing that decentrations less than 0.89 mm do not necessarily cause vision disturbances.[39] To make matters more interesting, Fay and Trokel[47] demonstrated that the pupil did not dilate concentrically and its geometric center moved as much as 0.7 mm with full dilation. To reduce unwanted secondary optical effects from degraded vision, they recommended centering the optical zone around the line of sight and to superimpose the zone on the entrance pupil to avoid extension of the edge of the large pupil beyond the ablated zone. Dietz et al, however, disagrees with the importance that has been placed on ablation zone centration. They have shown that there is no difference in contrast sensitivity, glare disability or image degradation between cases with less than 0.5 mm of decentration and those cases with 0.5 mm or more decentration.[37]

Corneal asphericity and its correlation with subjective vision disturbance complaints after PRK was studied by Hersh et al.[66] In their study they used a computer program (Holladay Diagnostic Summary, EyeSys Laboratories, Houston, TX) to qualitatively and quantitatively analyze the corneal asphericity. Following PRK, all corneas showed a positive central asphericity (the physiologic cornea is a prolate asphere with negative asphericity) and there was no association between post-operative asphericity and, what they called, the glare/halo index.

Butuner et al addressed other possible causes of visual complaints post PRK at the microscopic level. He suggests that there is an alteration in normal physiologic cell structure or extracellular matrix after laser ablation.[32] Animal studies have shown deficient fibrils as long as 18 months post surgery[161] and cellular structure abnormalities up to 15 months post PRK.[52,63] In rabbits, chronic vacuoles and lakes of water imbibition did not heal by 45 weeks post ablation.[132] It has been suggested that these lakes can induce a refraction of light rays causing visual dysfunction. Corbet et al showed that in the early postoperative period, keratocyte disturbances were the most important factor in increasing vision disturbances. With time, persistent subepithelial deposits appeared to play a larger role.[33] Long-term effects of altered structural changes are unknown and may lead to premature expression of age-related corneal conditions.

Finally, studies have shown that the amount of correction correlated with reported incidences of complaints, with, as expected, a higher correction lending to a higher incidence of problems.[3,36,61,62,112,151] This correlation is secondary to resultant larger refractive differentials between the ablated and untouched cornea.[101]

C. LASER-ASSISTED IN SITU KERATOMILEUSIS (LASIK)

Because LASIK techniques are relatively new and essentially similar to PRK, most studies on the visual complaints post LASIK involve a comparison of post PRK vs. post LASIK patients. Similar to PRK, the etiology of most visual problems are pupil size, ablation zone size,[43] decentration, and corneal asphericity. Specific to LASIK, striae in the flap, epithelial ingrowth or misalignment of the flap may be associated with increased problems.

Fortunately, similar to RK and PRK, most complaints spontaneously improved or resolved with time.[60,72,123] Some studies have shown a quicker improvement with LASIK or lesser incidence of vision disturbances,[67,179] although others have recorded a 2-fold increased frequency of halos post-LASIK versus post-PRK.[126]

V. Treatment (Table 4)

Management of patients complaining of glare disability, decreased contrast sensitivity, or image degradations can be frustrating in the early postoperative period. Patience is usually the best healer to eliminate early symptoms, as the patient's own neural adaptive mechanisms come into play. The brain has an amazing ability to adapt to changing stimuli, ocular or otherwise, even in the later stages of life. The use of high-quality sunglasses with ultraviolet and infrared filters or polarized lenses may or may not helpful in daytime conditions,[34,131,158] and it leaves the more prevalent night-time vision disturbances unaltered.[93,140,164] In addition, Shadenkov et al describe the positive effect of photofilters on contrast sensitivity post PRK.[154] The Night Vision Spectacles (NiViS) were developed to assist post-refractive patients suffering from impaired night vision.[53] The spectacles consist of input and output mechanisms connected to a portable computer that can enlarge contrast sensitivity. Initial studies have been promising.

More involved treatment of vision disturbances requires the identification of the source. Most vision disturbances are secondary to lower order aberrations (i.e., sphere, cylinder, and axis), therefore, a careful refraction is essential for treatment. The impact of proper refractive correction on decreasing image degradations in non-refractive surgery patients has been shown,[51,77] and the authors' own unpublished data show similar pre- and post-operative image degradations after correction of residual refractive errors post-LASIK. If irregular astigmatism is the primary source of vision disturbances, sometimes rigid gas permeable lenses can provide a smooth optical surface to lessen light scattering.[88,185,190]

TABLE 4

Treatment Options

Observation
Sunglasses with filters and polarized lenses
Refractive correction
Spectacles
RGP contact lenses
Constrict pupil
Weak negative lenses
Weak miotics
Surgical correction
Scar removal (RK)
Tattooing (RK)
Removal of hyperplastic epithelium (PRK)
Increase optical zone diameter (PRK)
Retreat to reduce residual myopia and astigmatism (PRK/LASIK)
Interface Scraping (LASIK)
Flap realignment (LASIK)
Penetrating keratoplasty (RK, PRK, LASIK)

Another method of conservative treatment includes constricting the pupil.[4] O'Brart has recommended prescribing weak over-corrective negative contact lenses for night driving or weak miotics 30 minutes before night traveling for some patients[115] in order to increase the effective optical zone size. Anecdotal evidence has also shown some miotic effect of topical brinmonidine. Another suggestion has been to leave the car's dome light on while driving at night to allow for pupillary constriction.[101]

If careful refraction does not sufficiently eliminate vision disturbances or pharmacologically constricted pupils are not desired, a slit-lamp examination and corneal topography[79] may reveal other sources including higher order aberrations such as decentered ablation, flap irregularity, interface opacities, or surface irregularities. If needed, minor surgical procedures such as scar removal or tattooing post RK,[49,97] removal of hyperplastic epithelium post PRK,[89] or flap realignment or interface scraping post LASIK can be considered. Retreatments of PRK eyes for symptomatic image degradations have also been relatively successful. In most cases, the cause of visual complaints were secondary to small ablation zones (associated with large pupils or decentrations). Undercorrected eyes can be retreated to reduce residual myopia as well as increase the ablation zone[41] or near plano eyes after initial PRK can be retreated just to enlarge the ablation zone without a change in refraction.[84] Retreatments of RK eyes with PRK has shown to have an increased risk of night vision difficulties.[127] Lastly, if the vision disturbances are intolerable, corneal transplantation may be necessary, with, fortunately, good results.[24,121]

VI. Discussion

The terms *good vision, good visual acuity,* or *best corrected visual acuity* have often only been previously assessed by Snellen visual acuity. Since the advent of refractive surgery, it has become apparent that other, often difficult to describe, vision disturbances may interfere with an otherwise excellent refractive surgical result. These vision disturbances often occur at night and may affect such functions as night driving. Perhaps the more appropriate term to consider is *quality of vision* because this includes glare disability, contrast sensitivity, and image degradation as well as other aspects of both the objective and subjective modifiers of vision. However, just as in mathematics, the greater the number of modifiers, the more complicated the definition; especially when the modifiers themselves have not been clearly defined. Ophthalmologists have not, as yet, fully agreed on a standard definition or even whether scotopic or mesopic conditions are the proper conditions to study. This confusion leads to an inability to develop a precise and accurate clinical test to objectively verify post-refractive "quality of vision." We agree with Van den Berg when he stated that "the reliability of glare testing seems to be questionable . . . [the] problem is the absence of a generally accepted reference, a golden standard for glare."[172] Some of the complaints with current glare disability and contrast sensitivity testing methods include: lack of standardization, lack of scientific validity, hard to interpret by physician, time to administer test, hard to interpret by patient, cost, lack of correlation with symptoms, lack of familiarity with test, and superfluous.[81]

Furthermore, most of our existing testing methods either involve a constricted pupil as a result of the "glare" producing light source[90,91] or a pharmacologically dilated pupil. Even testing methods with a natural nonpharmacologically dilated pupil, still depend on subjective drawings or interpretations by the patient. This makes patient to patient differences and visit to visit differences in the same patient difficult to compare. Although this subjective component is difficult to quantify, it is nevertheless an integral part in the development of an ideal tester because, for example, what might be simply noticeable to one patient might be disabling to another. At present, it is difficult to separate out the objective versus the subjective component of this equation, although some of the new technology such as wave front analyses might be helpful.

The need for standardization in measuring quality of vision post-refractive surgery has not gone unnoticed. The United States Department of Treasury and United States Customs Service currently has a vision testing protocol for all applicants to federal agencies (e.g., the FBI) who have had refractive surgery. Visual acuity, contrast sensitivity, and glare disability (undilated and dilated), are tested using the ETDRS acuity chart, Pelli-Robson CS tester, and BAT. Whether these tests are the most reliable and sensitive may be questioned. However, the attempt at standardization is appreciated and perhaps should be incorporated both pre- and post-operatively into all practices dealing with refractive surgery patients.

In conclusion, glare disability, contrast sensitivity, and other night vision disturbances are terms that the general public is becoming more familiar with as the number of post-refractive patients exponentially increases. The importance of these issues is evidenced by the increasing number of Internet Web sites developed by patients with quality of vision problems after refractive surgery. Our review shows that, fortunately, most disturbances decrease with time and that at 1 year follow-up, only a low percentage of patients are actually prevented from driving at night. At this time, it can only be speculated of how much of this improvement is due to a subjective acceptance of the disturbances (by neural adaptation) or an actual physical–optical improvement (e.g., decreased corneal scarring or corneal remodeling).

However, despite these encouraging reports, an aging population with preexisting night vision impairments such as developing cataracts, dry eyes, or age-related macular degeneration may have worsening problems which may have a significant impact on public health and safety. The impact of cataracts on increasing vision disturbances has been known for a long time before the advent of refractive surgery.[2,74,76,142,162,163,166] Severe dry eyes are another age-dependent factor leading to decreased contrast sensitivity. Besides the physical symptoms of dry eyes, such as pain, it has been shown that optical aberrations created by increased tear break-up time contribute to the decline in image quality observed.[137,139,170] Several reports have linked refractive surgery with the exacerbation of dry eye symptoms.[6,22,101,167,189] These symptoms tend to be transient, resolving by approximately six months after surgery,[188] and more common in patients with pre-existing dry eye disease. Some report more prolonged and severe dry eye symptoms after PRK than LASIK;[75] some report the opposite.[86] The pathophysiology of this exacerbation of dry eyes may be secondary to the creation of a negative feedback loop to the lacrimal gland created by decreased corneal sensation after refractive surgery.[6,99]

Therefore, although the majority of patients after refractive surgery are highly satisfied with their present vision, it is of utmost importance to be able to understand, characterize, prevent, and treat the possible exponential complaints of vision disturbances as our post-refractive population ages. Our understanding of the altered corneal shape, corneal healing process, and the delicate interaction between all ocular structures post-refractive surgery has increased dramatically in an attempt to answer the public's questions. Our review suggests, however, that this increased knowledge is not sufficient without standard quality of vision definitions and gold-standard clinical tests which have yet to be incorporated into this quickly expanding field.

To help reach the goal of perfect refractive surgery we must first standardize our terms, develop a reproducible clinical test which can accurately and objectively measure subjective complaints, and develop means to prevent or surgically correct higher order aberrations (Table 5). We suggest that future researchers be more rigorous when describing night vision disturbances instead of simply using the word *glare*. Our definitions in Table 1 may be a starting point. Secondly, we hope that this review has encouraged the interest in developing an accurate clinical test that can be the standard test for pre- and post-refractive patients. In our opinion, such a test should include a physiologically dilated pupil, a pinpoint light source (versus a broad fully lit acuity chart) and varying contrast objects. Lastly, with the development of wave front technology, our need to understand higher order aberrations may not be so far off. This new technology will hopefully allow customized ablations to decrease optical abberations.[11,96,187] In addition, Schwiegerling and Synder describe possible modifications of existing ablation algorithms to decrease the introduction of spherical aberration produced by current laser systems. According to their research, the ideal ablation pattern would require additional flattening of the ablation periphery.[149] Until all three conditions are met, the burden is on ophthalmologists to carefully screen for poor refractive candidates (i.e., patient's with a large pupil size, thin corneas, or large refractive errors) and to fully explain what night vision disturbances are and what difficulties they may pose before proceeding with surgery.

TABLE 5

Future Considerations

1. Standardize terms
2. Develop a reproducible accurate clinical test
3. Prevent or be able to correct higher order aberrations

VII. Method of Literature Search

Pertinent articles addressing post-refractive surgery glare or night vision disturbances were identified through a multistaged systematic approach. In the first stage, a computerized search of Medline was performed to obtain all articles describing NVD. The last search was done on 15 October 2001. Text words and terms searched included: *refractive surgery, glare, glare disability, contrast sensitivity, and night vision disturbances.* In the second stage, all abstracts were scanned and relevant articles obtained in whole copies. Bibliographies of the selected articles were also reviewed for additional sources. In the third stage, the complete articles were reviewed and grouped according to the disturbance term used and the technique of refractive surgery employed. Only English articles on refractive surgery for myopia were used.

References

1. __: Radial keratotomy for myopia. American Academy of Ophthalmology. Ophthalmology 100:1103–15, 1993
2. Adamsons IA, Vitale S, Stark WJ, Rubin GS: The association of postoperative subjective visual function with acuity, glare, and contrast sensitivity in patients with early cataract. Arch Ophthalmol 114:529–36, 1996
3. Alio JL, Artola A, Claramonte PJ, et al: Complications of

photorefractive keratectomy for myopia: two year follow-up of 3000 cases. J Cataract Refract Surg 24:619–26, 1998
4. Alster Y, Loewenstein A, Baumwald T, et al: Dapiprazole for patients with night haloes after excimer keratectomy. Graefes Arch Clin Exp Ophthalmol 234(Suppl 1):S139–41, 1996
5. Ambrosio G, Cennamo G, De Marco R, et al: Visual function before and after photorefractive keratectomy for myopia. J Refract corneal Surg 10:126–36, 1994
6. Ang RT, Dartt DA, Tsubota K: Dry eye after refractive surgery. Curr Opin Ophthalmol 12:318–22, 2001
7. Applegate RA: Limits to vision: can we do better than nature? J Refract Surg 16(Suppl):S547–S551, 2000
8. Applegate RA: Acuities through annular and central pupils after radial keratotomy. Optom Vis Sci 68:584–90, 1991
9. Applegate RA, Gansel KA: The importance of pupil size in optical quality measurements following radial keratotomy. Refract Corneal Surg 6:47–54, 1990
10. Applegate RA, Hilmantel G, Howland HC: Corneal aberrations increase with the magnitude of radial keratotomy refractive correction. Optom Vis Sci 73:585–9, 1996
11. Applegate RA, Hilmantel G, Howland HC, et al: Corneal first surface optical aberrations and visual performance. J Refract Surg 16:507–14, 2000
12. Applegate RA, Howland HC: Refractive surgery, optical aberrations, and visual performance. J Refract Surg 13:295–9, 1997
13. Applegate RA, Howland HC, Sharp RP, et al: Corneal aberrations and visual performance after radial keratotomy. J Refract Surg 14:397–407, 1998
14. Applegate RA, Trick LR, Meade DL, Hartstein J: Radial keratotomy increases the effects of disability glare: initial results. Ann Ophthalmol 19:293–7, 1987
15. Arrowsmith PN, Marks RG: Visual, refractive, and keratometric results of radial keratotomy. Five-year follow-up. Arch Ophthalmol 107:506–11, 1989
16. Arrowsmith PN, Marks RG: Visual, refractive, and keratometric results of radial keratotomy. A two-year follow-up. Arch Ophthalmol 105:76–80, 1987
17. Arrowsmith PN, Marks RG: Visual, refractive, and keratometric results of radial keratotomy. One-year follow-up. Arch Ophthalmol 102:1612–7, 1984
18. Atkin A, Asbell P, Justin N, et al: Radial keratotomy and glare effects on contrast sensitivity. Doc Ophthalmol 62: 129–48, 1986
19. Bailey IL, Bullimore MA: A new test for the evaluation of disability glare. Optom Vis Sci 68:911–7, 1991
20. Bailey IL, Lovie JE: New design principles for visual acuity letter charts. Am J Optom Physiol Opt 53:740–5, 1976
21. Baron WS, Munnerlyn C: Predicting visual performance following excimer photorefractive keratectomy. Refract Corneal Surg 8:355–62, 1992
22. Battat L, Macri A, Dursun D, Pflugfelder SC: Effects of laser in situ keratomileusis on tear production, clearance, and the ocular surface. Ophthalmology 108:1230–5, 2001
23. Binder PS: Optical problems following refractive surgery. Ophthalmology 93:739–45, 1986
24. Binder PS, Charlton KH: Surgical procedures performed after refractive surgery. Refract Corneal Surg 8:61–74, 1992
25. Bores LD: Historical review and clinical results of radial keratotomy. Int Ophthalmol Clin 23:93–118, 1983
26. Bourque LB, Cosand BB, Drews C, et al: Reported satisfaction, fluctuation of vision, and glare among patients one year after surgery in the Prospective Evaluation of Radial Keratotomy (PERK) Study. Arch Ophthalmol 104:356–63, 1986
27. Boxer Wachler BS, Durrie DS, Assil KK, Krueger RR: Improvement of visual function with glare testing after photorefractive keratectomy and radial keratotomy. Am J Ophthalmol 128:582–7, 1999
28. Brunette I, Gresset J, Boivin JF, et al: Functional outcome and satisfaction after photorefractive keratectomy. Part 1: development and validation of a survey questionnaire. Ophthalmology 107:1783–9, 2000
29. Brunette I, Gresset J, Boivin JF, et al: Functional outcome and satisfaction after photorefractive keratectomy. Part 2: survey of 690 patients. Ophthalmology 107:1790–6, 2000
30. Bullimore MA, Olson MD, Maloney RK: Visual performance after photorefractive keratectomy with a 6-mm ablation zone. Am J Ophthalmol 128:1–7, 1999
31. Bullimore MA, Sheedy JE, Owen D: Diurnal visual changes in radial keratotomy: implications for visual standards. Refractive Surgery Study Group. Optom Vis Sci 71:516–21, 1994
32. Butuner Z, Elliott DB, Gimbel HV, Slimmon S: Visual function one year after excimer laser photorefractive keratectomy. J Refract Corneal Surg 10:625–30, 1994
33. Corbett MC, Prydal JI, Verma S, et al: An in vivo investigation of the structures responsible for corneal haze after photorefractive keratectomy and their effect on visual function. Ophthalmology 103:1366–80, 1996
34. Coupland SG, Kirkham TH: Improved contrast sensitivity with antireflective coated lenses in the presence of glare. Can J Ophthalmol 16:136–40, 1981
35. Cowden JW, Bores LD: A clinical investigation of the surgical correction of myopia by the method of Fyodorov. Ophthalmology 88:737–41, 1981
36. Danjoux JP, Kalski RS, Cohen P, et al: Excimer laser photorefractive keratectomy for hyperopia. J Refract Surg 13: 349–55, 1997
37. Deitz MR, Piebenga LW, Matta CS, et al: Ablation zone centration after photorefractive keratectomy and its effect on visual outcome. J Cataract Refract Surg 22:696–701, 1996
38. Deitz MR, Sanders DR, Marks RG: Radial keratotomy: an overview of the Kansas City study. Ophthalmology 91:467–78, 1984
39. Doane JF, Cavanaugh TB, Durrie DS, Hassanein KM: Relation of visual symptoms to topographic ablation zone decentration after excimer laser photorefractive keratectomy. Ophthalmology 102:42–7, 1995
40. Dutt S, Steinert RF, Raizman MB, Puliafito CA: One-year results of excimer laser photorefractive keratectomy for low to moderate myopia. Arch Ophthalmol 112:1427–36, 1994
41. Eggink FA, Houdijn Beekhuis W, Trokel SL, den Boon JM: Enlargement of the photorefractive keratectomy optical zone. J Cataract Refract Surg 22:1159–64, 1996
42. Eiferman RA, ONeill KP, Forgey DR, Cook YD: Excimer laser photorefractive keratectomy for myopia: six-month results. Refract Corneal Surg 7:344–7, 1991
43. el Danasoury MA: Prospective bilateral study of night glare after laser in situ keratomileusis with single zone and transition zone ablation. J Refract Surg 14:512–6, 1998
44. Elliot DB, Sanderson K, Conkey A: The reliability of the Pelli-Robson contrast sensitivity chart. Ophthalmic Physiol Opt 10:21–4, 1990
45. Elliott DB, Bullimore MA: Assessing the reliability, discriminative ability, and validity of disability glare tests. Invest Ophthalmol Vis Sci 34:108–19, 1993
46. Endl MJ, Martinez CE, Klyce SD, et al: Effect of larger ablation zone and transition zone on corneal optical aberrations after photorefractive keratectomy. Arch Ophthalmol 119:1159–64, 2001
47. Fay AM, Trokel SL, Myers JA: Pupil diameter and the principal ray. J Cataract Refract Surg 18:348–51, 1992
48. Ficker LA, Bates AK, Steele AD McG, et al: Excimer laser photorefractive keratectomy for myopia: 12 month follow-up. Eye 7:617–24, 1993
49. Florakis GJ, Fay AM, Darrell RW, Srinivasan BD: Corneal tattooing to treat glare symptoms following radial keratotomy, in Lass J (ed): Advances in Cornea Research: Selected Transactions of the World Congress on the Cornea. New York, Plenum Publishing, 1997, pp 293–7
50. Florakis GJ, Jewelewicz DA, Michelsen HE, Trokel SL: Evaluation of night vision disturbances. J Refract Corneal Surg 10:333–8, 1994
51. Florakis GJ, Jewelewicz DA, Fan NI, Trokel SL: Night vision testing in unoperated eyes. J Refract Surg 12:S311–2, 1996
52. Fountain TR, de la Cruz Z, Green WR, et al: Reassembly of corneal epithelial adhesion structures after excimer laser keratectomy in humans. Arch Ophthalmol 112:967–72, 1994
53. Friedburg C, Serey L, Sharpe LT, et al: Evaluation of the Night Vision Spectacles on patients with impaired night vision. Graefes Arch Clin Exp Ophthalmol 237:125–36, 1999

54. Gartry DS, Kerr Muir MG, Marshall J: Excimer laser photorefractive keratectomy. 18-month follow-up. Ophthalmology 99:1209–19, 1992
55. Gartry DS, Kerr Muir MG, Marshall J: Photorefractive keratectomy with an argon fluoride excimer laser: a clinical study. Refract Corneal Surg 7:420–35, 1991
56. Ghaith AA, Daniel J, Stulting RD, et al: Contrast sensitivity and glare disability after radial keratotomy and photorefractive keratectomy. Arch Ophthalmol 116:12–8, 1998
57. Gimbel HV, Van Westenbrugge JA, Johnson WH, et al: Visual, refractive, and patient satisfaction results following bilateral photorefractive keratectomy for myopia. Refract Corneal Surg 9:S5–10, 1993
58. Ginsburg AP, Waring GO 3rd, Steinberg EB, et al: Contrast sensitivity under photopic conditions in the Prospective Evaluation of Radial Keratotomy (PERK) Study. Refract Corneal Surg 6:82–91, 1990
59. Grimmett MR, Holland EJ: Complications of small clearzone radial keratotomy. Ophthalmology 103:1348–56, 1996
60. Guell JL, Vazquez M, Gris O, et al: Combined surgery to correct high myopia: iris claw phakic intraocular lens and laser in situ keratomileusis. J Refract Surg 15:529–37, 1999
61. Hadden OB, Ring CP, Morris AT, Elder MJ: Visual, refractive, and subjective outcomes after photorefractive keratectomy for myopia of 6 to 10 diopters using the Nidek laser. J Cataract Refract Surg 25:936–42, 1999
62. Halliday BL: Refractive and visual results and patient satisfaction after excimer laser photorefractive keratectomy for myopia. Br J Ophthalmol 79:881–7, 1995
63. Hanna KD, Pouliquen YM, Waring GO 3rd, et al: Corneal wound healing in monkeys after repeated excimer laser photorefractive keratectomy. Arch Ophthalmol 110:1286–91, 1992
64. Hard AL, Abrahamsson M, Sjostrand J: A new glare test based on low contrast letters—evaluation in cataract patients. Acta Ophthalmol (Copenh) 68:145–50, 1990
65. Heitzmann J, Binder PS, Kassar BS, Nordan LT: The correction of high myopia using the excimer laser. Arch Ophthalmol 111:1627–34, 1993
66. Hersh PS, Shah SI, Holladay JT: Corneal asphericity following excimer laser photorefractive keratectomy. Summit PRK Topography Study Group. Ophthalmic Surg Lasers 27:S421–8, 1996
67. Hersh PS, Steinert RF, Brint SF: Photorefractive keratectomy versus laser in situ keratomileusis: comparison of optical side effects. Summit PRK-LASIK Study Group. Ophthalmology 107:925–33, 2000
68. Hersh PS, Stulting RD, Steinert RF, et al: Results of phase III excimer laser photorefractive keratectomy for myopia. The Summit PRK Study Group. Ophthalmology 104:1535–53, 1997
69. Hodkin MJ, Lemos MM, McDonald MB, et al: Near vision contrast sensitivity after photorefractive keratectomy. J Cataract Refract Surg 23:192–5, 1997
70. Hoffer KJ, Darin JJ, Pettit TH, et al: Three years experience with radial keratotomy. The UCLA study. Ophthalmology 90:627–36, 1983
71. Hoffer KJ, Darin JJ, Pettit TH, et al: UCLA clinical trial of radial keratotomy. Preliminary report. Ophthalmology 88: 729–36, 1981
72. Holladay JT, Dudeja DR, Chang J: Functional vision and corneal changes after laser in situ keratomileusis determined by contrast sensitivity, glare testing, and corneal topography. J Cataract Refract Surg 25:663–9, 1999
73. Holladay JT, Lynn MJ, Waring GO 3rd, et al: The relationship of visual acuity, refractive error, and pupil size after radial keratotomy. Arch Ophthalmol 109:70–6, 1991
74. Holladay JT, Prager TC, Trujillo J, Ruiz RS: Brightness acuity test and outdoor visual acuity in cataract patients. J Cataract Refract Surg 13:67–9, 1987
75. Hovanesian JA, Shah SS, Maloney RK: Symptoms of dry eye and recurrent erosion syndrome after refractive surgery. J Cataract Refract Surg 27:577–84, 2001
76. Jaffe NS: Glare and contrast: indications for cataract surgery. J Cataract Refract Surg 12:372–5, 1986
77. Jewelewicz DA, Evans R, Chen R, et al: Evaluation of night vision disturbances in contact lens wearers. CLAO J 24: 107–10, 1998
78. Jory WJ: Radial keratotomy: 500 consecutive cases. Eye 3: 663–71, 1989
79. Kampmeier J, Tanzer DJ, Er H, et al: Significance of corneal topography in predicting patient complaints after photorefractive keratectomy. J Cataract Refract Surg 25: 492–9, 1999
80. Kim JH, Hahn TW, Lee YC, et al: Photorefractive keratectomy in 202 myopic eyes: one year results. Refract Corneal Surg 9:S11–6, 1993
81. Koch DD, Liu JF: Survey of the clinical use of glare and contrast sensitivity testing. J Cataract Refract Surg 16:707–11, 1990
82. Krasnov MM, Avetisov SE, Makashova NV, Mamikonian VR: The effect of radial keratotomy on contrast sensitivity. Am J Ophthalmol 105:651–4, 1988
83. Kremer FB, Marks RG: Radial keratotomy: prospective evaluation of safety and efficacy. Ophthalmic Surg 14:925–30, 1983
84. Lafond G: Treatment of halos after photorefractive keratectomy. J Refract Surg 13:83–8, 1997
85. LeClaire J, Nadler MP, Weiss S, Miller D: A new glare tester for clinical testing. Results comparing normal subjects and variously corrected aphakic patients. Arch Ophthalmol 100:153–8, 1982
86. Lee JB, Ryu CH, Kim J, et al: Comparison of tear secretion and tear film instability after photorefractive keratectomy and laser in situ keratomileusis. J Cataract Refract Surg 26: 1326–31, 2000
87. Lee YC, Park CK, Sah WJ, et al: Photorefractive keratectomy for undercorrected myopia after radial keratotomy: two year follow-up. J Refract Surg 11S:274–9, 1985
88. Lim L, Siow KL, Sakamoto R, et al: Reverse geometry contact lens wear after photorefractive keratectomy, radial keratotomy, or penetrating keratoplasty. Cornea 19:320–4, 2000
89. Loewenstein A, Lipshitz I, Lazar M: Scraping of epithelium for treatment of undercorrection and haze after photorefractive keratectomy. J Refract Corneal Surg 10:S274–6, 1994
90. Lohmann CP, Fitzke F, OBrart D, et al: Corneal light scattering and visual performance in myopic individuals with spectacles, contact lenses, or excimer laser photorefractive keratectomy. Am J Ophthalmol 115:444–53, 1993
91. Lohmann CP, Timberlake GT, Fitzke FW, et al: Corneal light scattering after excimer laser photorefractive keratectomy: the objective measurements of haze. Refract Corneal Surg 8:114–21, 1992
92. Machat JJ, Tayfour F: Photorefractive keratectomy for myopia: preliminary results in 147 eyes. Refract Corneal Surg 9: S16–9, 1993
93. Maguire LJ: Keratorefractive surgery, success, and the public health. Am J Ophthalmol 117:394–8, 1994
94. Maloney RK: Corneal topography and optical zone location in photorefractive keratectomy. Refract Corneal Surg 6:363–71, 1990
95. Mantyjarvi M, Laitinen T: Normal values for the Pelli-Robson contrast sensitivity test. J Cataract Refract Surg 27:261–6, 2001
96. Marcos S: Aberrations and visual performance following standard laser vision correction. J Refract Surg 17:S596–601, 2001
97. Marmer RH: Radial keratotomy complications. Ann Ophthalmol 19:409–11, 1987
98. Martinez CE, Applegate RA, Klyce SD, et al: Effect of pupillary dilation on corneal optical aberrations after photorefractive keratectomy. Arch Ophthalmol 116:1053–62, 1998
99. Mathers WD: Why the eye becomes dry: a cornea and lacrimal gland feedback model. CLAO J 26:118, 2000
100. McDonald MB, Haik M, Kaufman HE: Color vision and contrast sensitivity testing after radial keratotomy. Am J Ophthalmol 103:468, 1987
101. Melki SA, Azar DT: LASIK complications: etiology, management, and prevention. Surv Ophthalmol 46:95–116, 2001
102. Miller D, Jernigan ME, Molnar S, et al: Laboratory evaluation of a clinical glare tester. Arch Ophthalmol 87:324–32, 1972
103. Miller D, Miller R: Glare sensitivity in simulated radial keratotomy. Arch Ophthalmol 99:1961–2, 1981

104. Moilanen JA, Vesaluoma MH, Vesti ET, et al: Photorefractive keratectomy in ophthalmic residents. J Refract Surg 16: 731–8, 2000
105. Mrochen M, Kaemmerer M, Mierdel P, Seiler T: Increased higher-order optical aberrations after laser refractive surgery. J Cataract Refract Surg 27:362–9, 2001
106. Neumann AC, McCarty GR, Locke J, Cobb B: Glare disability devices for cataractous eyes: a consumers guide. J Cataract Refract Surg 14:212–6, 1988
107. Neumann AC, Osher RH, Fenzl RE: Radial keratotomy: a comprehensive evaluation. Doc Ophthalmol 56:275–301, 1984
108. Niesen U, Businger U, Hartmann P, et al: Glare sensitivity and visual acuity after excimer laser photorefractive keratectomy for myopia. Br J Ophthalmol 81:136–40, 1997
109. Niesen UM, Businger U, Schipper I: Disability glare after excimer laser photorefractive keratectomy for myopia. J Refract Surg 12:S267–8, 1996
110. Nirankari VS, Katzen LE, Karesh JW, et al: Ongoing prospective clinical study of radial keratotomy. Ophthalmology 90:637–41, 1983
111. Nirankari VS, Katzen LE, Richards RD, et al: Prospective clinical study of radial keratotomy. Ophthalmology 89:677–83, 1982
112. O'Brart DP, Corbett MC, Lohmann CP, et al: The effects of ablation diameter on the outcome of excimer laser photorefractive keratectomy. A prospective, randomized, double-blind study. Arch Ophthalmol 113:438–43, 1995
113. O'Brart DP, Corbett MC, Verma S, et al: Effects of ablation diameter, depth, and edge contour on the outcome of photorefractive keratectomy. J Refract Surg 12:50–60, 1996
114. O'Brart DP, Lohmann CP, Fitzke FW, et al: Disturbances in night vision after excimer laser photorefractive keratectomy. Eye 8:46–51, 1994
115. O'Brart DP, Lohmann CP, Fitzke FW, et al: Night vision after excimer laser photorefractive keratectomy: haze and halos. Eur J Ophthalmol 4:43–51, 1994
116. O'Brart DPS, Lohmann CP, Fitzke FW: Discrimination between the origins and functional implications of haze and halo at night after photorefractive keratectomy. J Refract Surg 10:S281, 1994
117. Oliver KM, Hemenger RP, Corbett MC, et al: Corneal optical aberrations induced by photorefractive keratectomy. J Refract Surg 13:246–54, 1997
118. Olsen H, Andersen J: Contrast sensitivity in radial keratotomy. Acta Ophthalmol (Copenh) 69:654–8, 1991
119. Pallikaris I, McDonald MB, Siganos D, et al: Tracker-assisted photorefractive keratectomy for myopia of −1 to −6 diopters. J Refract Surg 12:240–7, 1996
120. Pallikaris IG, Koufala KI, Siganos DS, et al: Photorefractive keratectomy with a small spot laser and tracker. J Refract Surg 15:137–44, 1999
121. Parmley V, Ng J, Gee B, et al: Penetrating keratoplasty after radial keratotomy. A report of six patients. Ophthalmology 102:947–50, 1995
122. Pelli DG, Robson JG, Wilkins AJ: The design of a new letter chart for measuring contrast sensitivity. Clin Vis Sci 2:187–9, 1988
123. Perez-Santonja JJ, Sakla HF, Alio JL: Contrast sensitivity after laser in situ keratomileusis. J Cataract Refract Surg 24: 183–9, 1998
124. Peyman GA, Spigelman AV: Reduction of glare after radial keratotomy: an experimental study. Ophthalmic Surg 12: 727–30, 1981
125. Piebenga LW, Matta CS, Deitz MR, et al: Excimer photorefractive keratectomy for myopia. Ophthalmology 100: 1335–45, 1993
126. Pop M, Payette Y: Photorefractive keratectomy versus laser in situ keratomileusis: a control-matched study. Ophthalmology 107:251–7, 2000
127. Probst LE, Machat JJ: Conservative photorefractive keratectomy for residual myopia following radial keratotomy. Can J Ophthalmol 33:20–7, 1998
128. Quah BL, Wong EY, Tseng PS, et al: Analysis of photorefractive keratectomy patients who have not had PRK in their second eye. Ophthalmic Surg Lasers 27:S429–34, 1996
129. Rabin J: Optical defocus: differential effects on size and contrast letter recognition thresholds. Invest Ophthalmol Vis Sci 35:646–8, 1994
130. Rabin J, Wicks J: Measuring resolution in the contrast domain: the small letter contrast test. Optom Vis Sci 73:398–403, 1996
131. Rashid ER, Waring GO 3rd: Complications of radial and transverse keratotomy. Surv Ophthalmol 34:73–106, 1989
132. Rawe IM, Zabel RW, Tuft SJ, et al: A morphological study of rabbit corneas after laser keratectomy. Eye 6:637–42, 1992
133. Reeves BC, Wood JM, Hill AR: Reliability of high- and low-contrast letter charts. Ophthalmic Physiol Opt 13:17–26, 1993
134. Reeves BC, Wood JM, Hill AR: Vistech VCTS 6500 charts—within- and between-session reliability. Optom Vis Sci 68: 728–37, 1991
135. Regan D, Giaschi DE, Fresco BB: Measurement of glare susceptibility using low-contrast letter charts. Optom Vis Sci 70:969–75, 1993
136. Regan D, Giaschi DE, Resco BB: Measurement of glare sensitivity in cataract patients using low-contrast letter charts. Ophthalmic Phsiol Opt 13:115–23, 1993
137. Rieger G: Contrast sensitivity in patients with keratoconjunctivitis sicca before and after artificial tear application. Graefes Arch Clin Exp Ophthalmol 231:577–9, 1993
138. Roberts CW, Koester CJ: Optical zone diameters for photorefractive corneal surgery. Invest Ophthalmol Vis Sci 34: 2275–81, 1993
139. Rolando M, Iester M, Macri A, Calabria G: Low spatial-contrast sensitivity in dry eyes. Cornea 17:376–9, 1998
140. Rowsey JJ, Balyeat HD: Radial keratotomy: preliminary report of complications. Ophthalmic Surg 13:27–35, 1982
141. Rowsey JJ, Balyeat HD: Preliminary results and complications of radial keratotomy. Am J Ophthalmol 93:437–55, 1982
142. Rubin GS, Adamsons IA, Stark WJ: Comparison of acuity, contrast sensitivity and disability glare before and after cataract surgery. Arch Ophthalmol 111:56–61, 1993
143. Santos VR, Waring GO 3rd, Lynn MJ, et al: Morning-to-evening change in refraction, corneal curvature, and visual acuity 2 to 4 years after radial keratotomy in the PERK Study. Ophthalmology 95:1487–93, 1988
144. Sawelson H, Marks RG: Two-year results of radial keratotomy. Arch Ophthalmol 103:505–10, 1985
145. Schlote T, Kriegerowski M, Bende T, et al: Mesopic vision in myopia corrected by photorefractive keratectomy, soft contact lenses, and spectacles. J Cataract Refract Surg 23: 718–25, 1997
146. Schwartz-Goldstein BH, Hersh PS: Corneal topography of phase III excimer laser photorefractive keratectomy. Optical zone centration analysis. Summit Photorefractive Keratectomy Topography Study Group. Ophthalmology 102: 951–62, 1995
147. Schwiegerling J: Theoretical limits to visual performance. Surv Ophthalmol 45:139–46, 2000
148. Schwiegerling J, Greivenkamp JE, Miller JM, et al: Optical modeling of radial keratotomy incision patterns. Am J Ophthalmol 122:808–17, 1996
149. Schwiegerling J, Snyder RW: Corneal ablation patterns to correct for spherical aberration in photorefractive keratectomy. J Cataract Refract Surg 26:214–21, 2000
150. Seiler T, Holschbach A, Derse M, et al: Complications of myopic photorefractive keratectomy with the excimer laser. Ophthalmology 101:153–60, 1994
151. Seiler T, Kaemmerer M, Mierdel P, Krinke HE: Ocular optical aberrations after photorefractive keratectomy for myopia and myopic astigmatism. Arch Ophthalmol 118:17–21, 2000
152. Seiler T, Reckmann W, Maloney RK: Effective spherical aberration of the cornea as a quantitative descriptor in corneal topography. J Cataract Refract Surg 19(Suppl):155–65, 1993
153. Seiler T, Wollensak J: Myopic photorefractive keratectomy with the excimer laser. One-year follow-up. Ophthalmology 98:1156–63, 1991
154. Shadenkov D, Cheloudchenko V, Kourenkov V: Photofil-

ters for dimensional contrast sensitivity improvement in patients with corneal haze after photrefractive keratectomy. J Refract Surg 15:S263–4, 1999
155. Sher NA, Barak M, Daya S, et al: Excimer laser photorefractive keratectomy in high myopia. A multicenter study. Arch Ophthalmol 110:935–43, 1992
156. Sher NA, Chen V, Bowers RA, et al: The use of the 193-nm excimer laser for myopic photorefractive keratectomy in sighted eyes. A multicenter study. Arch Ophthalmol 109: 1525–30, 1991
157. Shimizu K, Amano S, Tanaka S: Photorefractive keratectomy for myopia: one-year follow-up in 97 eyes. J Refract Corneal Surg 10:S178–87, 1994
158. Steen R, Whitaker D, Elliott DB, Wild JM: Effect of filters on disability glare. Ophthalmic Physiol Opt 13:371–6, 1993
159. Stein R: Photorefractive keratectomy. Int Ophthalmol Clin 40:35–56, 2000
160. Stephenson CG, Gartry DS, OBrart DP, et al: Photorefractive keratectomy. A 6-year follow-up study. Ophthalmology 105:273–81, 1998
161. SundarRaj N, Geiss MJ 3rd, Fantes F, et al: Healing of excimer laser ablated monkey corneas. An immunohistochemical evaluation. Arch Ophthalmol 108:1604–10, 1990
162. Superstein R, Boyaner D, Overbury O: Functional complaints, visual acuity, spatial contrast sensitivity, and glare disability in preoperative and postoperative cataract patients. J Cataract Refract Surg 25:575–81, 1999
163. Superstein R, Boyaner D, Overbury O, Collin C: Gare disability and contrast sensitivity before and after cataract surgery. J Cataract Refract Surg 23:248–53, 1997
164. Swinger CA: Postoperative astigmatism. Surv Ophthalmol 31:219–48, 1987
165. Tengroth B, Epstein D, Fagerholm P, et al: Excimer laser photorefractive keratectomy for myopia. Clinical results in sighted eyes. Ophthalmology 100:739–45, 1993
166. Terry CM, Brown PK: Clinical measurement of glare effect in cataract patients. Ann Ophthalmol 21:183–7, 1989
167. Toda I, Asano-Kato N, Komai-Hori Y, Tsubota K: Dry eye after laser in situ keratomileusis. Am J Ophthalmol 132:1–7, 2001
168. Tomlinson A, Caroline P: Effect of radial keratotomy on the contrast sensitivity function. Am J Optom Physiol Opt 65:803–8, 1988
169. Trick LR, Hartstein J: Investigation of contrast sensitivity following radial keratotomy. Ann Ophthalmol 19:251–4, 1987
170. Tutt R, Bradley A, Begley C, Thibos LN: Optical and visual impact of tear break-up in human eyes. Invest Ophthalmol Vis Sci 41:4117–23, 2000
171. Uozato H, Guyton DL: Centering corneal surgical procedures. Am J Ophthalmol 103:264–75, 1987
172. van den Berg TJTP: On the relation between glare and straylight. Doc Ophthalomol 78:177–81, 1991
173. van der Heijde GL, Weber J, Boukes R: Effects of straylight on visual acuity in pseudophakia. Doc Ophthalmol 59:81–4, 1985
174. 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 114:424–8, 1992
175. Verdon W, Bullimore M, Maloney RK: Visual performance after photorefractive keratectomy. A prospective study. Arch Ophthalmol 114:1465–72, 1996
176. Vetrugno M, Quaranta GM, Maino A, et al: Contrast sensitivity measured by 2 methods after photorefractive keratectomy. J Cataract Refract Surg 26:847–52, 2000
177. Vision Research. A National Plan 1992–1996. Volume, Section C, p 6
178. Wachler BS, Durrie DS, Assil KK, Krueger RR: Role of clearance and treatment zones in contrast sensitivity: significance in refractive surgery. J Cataract Refract Surg 25:16–23, 1999
179. Wang Z, Chen J, Yang B: Comparison of laser in situ keratomileusis and photorefractive keratectomy to correct myopia from −1.25 to −6.00 diopters. J Refract Surg 13:528–34, 1997
180. Waring GO 3rd, Casebeer JC, Dru RM: One-year results of a prospective multicenter study of the Casebeer system of refractive keratotomy. Casebeer Chiron Study Group. Ophthalmology 103:1337–47, 1996
181. Waring GO 3rd, Lynn MJ, Culbertson W, et al: Three-year results of the Prospective Evaluation of Radial Keratotomy (PERK) Study. Ophthalmology 94:1339–54, 1987
182. Waring GO 3rd, Lynn MJ, Gelender H, et al: Results of the prospective evaluation of radial keratotomy (PERK) study one year after surgery. Ophthalmology 92:177–98, 307, 1985
183. Waring GO 3rd, Lynn MJ, Nizam A, et al: Results of the Prospective Evaluation of Radial Keratotomy (PERK) Study five years after surgery. The PERK Study Group. Ophthalmology 98:1164–76, 1991
184. Waring GO 3rd, OConnell MA, Maloney RK, et al: Photorefractive keratectomy for myopia using a 4.5-millimeter ablation zone. J Refract Surg 11:170–80, 1995
185. Waring GO 3rd, Steinberg EB, Wilson LA: Slit-lamp microscopic appearance of corneal wound healing after radial keratotomy. Am J Ophthalmol 100:218–24, 1985
186. Weinstock SJ, Machat JJ: Excimer laser keratectomy for the correction of myopia. CLAO J 19:133–6, 1993
187. Williams D, Yoon GY, Porter J, et al: Visual benefit of correcting higher order aberrations of the eye. J Refract Surg 16:S554–9, 2000
188. Wilson SE, Ambrosio R: Laser in situ keratomileusis-induced neurotrophic epitheliopathy. Am J Ophthalmol 132:405–6, 2001
189. Yu EY, Leung A, Rao S, Lam DS: Effect of laser in situ keratomileusis on tear stability. Ophthalmology 107:2131–5, 2000
190. Zadnik K: Contract lens management of patients who have had unsuccessful refractive surgery. Curr Opin Ophthalmol 10:260–3, 1999

The authors reported no proprietary or commercial interest in any product mentioned or concept discussed in this article. The authors would like to thank Dr. Stephen Trokel for his suggestions and review of the early versions of our manuscript.

Reprint address: George J. Florakis, MD, Edward S. Harkness Eye Institute, Columbia Presbyterian Medical Center, 635 West 165th Street, Suite 303, New York, NY 10032 USA.

Outline