Optical Zone Diameters for Photorefractive Corneal Surgery

Calvin W. Roberts* and Charles J. Koester†

Purpose. To examine the physiological optics of photorefractive corneal surgery and to study the effect on glare production of the optical zone diameter.

Methods. An optical analysis computer program was used to generate rays that define the edge of the optical zone for any given pupil size and glare-free field.

Results. The optical zone diameter must be based on the postoperative corneal curvature because that determines magnification of the pupil. The minimal optical zone diameter of uniform optical power was determined both for myopic and hyperopic surgery and for two values of anterior chamber depth.

Conclusions. 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.


Excimer laser photorefractive keratectomy alters the refractive power of the cornea by ablating a central disc of the superficial stroma so as to induce a new corneal profile. The required depth of the keratectomy is a function of the amount of ametropia to be corrected and the diameter of the optical zone selected.1 Greater refractive errors or larger optical zones require deeper keratectomies. Recent studies have demonstrated better healing with less stromal haze when more superficial keratectomies are performed.2-5 Therefore, the smallest diameter optical zone should be used compatible with normal physiologic optics of the cornea.

One optical concern in photorefractive keratectomy is the glare induced by beams of light entering the pupil through the cornea outside the area of ablation. As the pupil dilates, more of these rays will reach the retina and degrade the image, either in the fovea or in the parafoveal region.

Glare, in the sense used here, can arise when light from a bright source is incident on an interface or irregularity that reflects, refracts, or scatters light to the fovea or the parafovea area of the retina. Such an interface or irregularity can, in principle, be on any surface or region between the object and the retina. In this study we consider just irregularities on the cornea. The type of glare arising from postoperative stromal haze in the optical zone is not within the scope of this study.

Uozato and Guyton6 were the first to calculate the optical zone area needed to obtain glare-free distance vision in emmetropia. 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 (apparent diameter of the pupil)." Not only must this optical zone be without scarring and irregularity, but it must also be of uniform refractive power.

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From *Cornell University Medical College, and †Columbia University College of Physicians and Surgeons, New York, New York. Supported by grants to Dr. Roberts from Michael and Gina Ricciardi Foundation, Debra and Leon Black, Leonard and Sylvia Marx, and the Leonard and Adele Block Foundation, and to The Department of Ophthalmology, Columbia University from Research to Prevent Blindness.

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Reprint requests: Calvin W. Roberts, Department of Ophthalmology, Cornell University Medical College, 520 E. 70th St., New York, NY 10021.
We extend their findings to include the effect of different anterior chamber depths and the effect of a postoperative corneal curvature that is (intentionally) different from the preoperative value.

In a related topic, Uozato et al. dealt with the required optical zone diameters of contact lenses for various glare-free field sizes.

Maloney described the consequences of a decentered optical zone and discussed methods to ensure centering.

**METHODS**

The edge of the optical zone was determined by exact ray tracing using the corneal model as given by Helmholtz:9 Radius of posterior surface, 6.8 mm; refractive index of cornea, 1.376; refractive index of aqueous humor, 1.336; thickness of cornea, 0.5 mm. Figure 1 illustrates the rays used to determine the diameter of the anatomic pupil and the diameter of the optical zone. For a given preoperative corneal power, K, the anterior corneal radius R1 was calculated using the keratometer equation:

$$R_1 = \frac{0.3375}{K}$$

where R1 is in meters, and K is the corneal power determined by an ophthalmometer. The corneal surfaces were assumed to be spherical.

The entrance pupil diameter was then selected, and a ray (LR1) parallel to the axis was traced to determine the diameter of the anatomic pupil (AP). The edge of the pupil is the point of intersection (AP) of the ray and the pupil plane, 3.6 mm posterior to the corneal surface.

Next, the postoperative corneal radius was calculated. We assume that only the anterior surface curvature is altered by the excimer laser procedure, so we first need to calculate the initial power, PS1, of the anterior corneal surface:

$$PS_1 = \frac{(1.376 - 1)}{R_1}$$

If the desired change in corneal power is $-\Delta P$, the postoperative anterior surface power is

$$PS_2 = PS_1 - \Delta P$$

and the post-op anterior surface radius is given by

$$R_2 = \frac{(1.376-1)}{PS_2}.$$ 

The anterior radius was next changed to R2, and in the case of myopic correction the thickness of the cornea was reduced to account for the tissue that was removed centrally, as described by Munnerlyn et al.1

The starting data were the power of the preoperative cornea, the anterior chamber depth, and the anticipated entrance pupil diameter. The latter is the maximum entrance pupil that is anticipated when the patient will be engaged in activities where glare-free vision is important. Because this is a clinical decision involving many factors, our calculations were done for the range of anticipated entrance pupil diameters from 2 to 8 mm. These entrance pupil diameters are based on the preoperative corneal curvature, because that curvature determines the pupil size seen during preoperative examination. The computer calculates the postoperative entrance pupil diameter based on the planned postoperative corneal curvature.

Optical design software (SuperOSLO, Sinclair Optics, Fairport, NY) was used to perform the following steps:

1. For the 43D (preoperative) cornea, a ray was traced parallel to the axis at a distance equal to the radius of the entrance pupil (EP) (Fig. 1). At the plane of the pupil the point of intersection, AP, was located.

2. The radius of the cornea was then changed to correspond to the postoperative dioptic power, based on the corneal index 1.376.

3. A "reference" ray was traced from infinity at the desired angle relative to the axis, aimed so it would pass through point P in the pupil plane (Fig. 2). (The reference ray tracing routine in the software program automatically finds the ray that passes through the specified point P.)

4. The intersection of this reference ray with the corneal surface was then determined (C in Fig.
Optical Zone for Photorefractive Corneal Surgery

FIGURE 2. Tracing the limiting ray at the angle $\theta$. Three rays are shown, all of which focus to point H on the retina. The ray that determines the radius of the optical zone is the uppermost ray, labeled LR, which just passes the edge of the pupil at P. The point C at which the ray intersects the cornea determines the radius R of the optical zone for the glare-free field of half-angle $\theta$.

2) The distance R from C to the axis is the radius of the optical zone.
5. Steps 3 and 4 were then repeated for each desired field angle, 0–60°.
6. Steps 1 through 5 were repeated for each entrance pupil diameter.

RESULTS

The minimum optical zones of uniform optical power necessary to preclude glare from the fovea and from the peripheral cornea are shown in Tables 1–5. Comparison of Tables 1 and 2 indicates that for a greater anterior chamber depth, a larger optical zone is required to protect the extrafoveal region from glare. For example, Table 1 shows that for an eye with 3.6 mm anterior chamber depth, a 4 mm round pupil will have no glare at 30° from the fovea with a 6.69 mm optical zone. As illustrated in Table 2, if the anterior chamber is increased to 4.1 mm (the long end of the distribution of anterior chamber depths, as reported by Sorsby[10]), a 4 mm round pupil will require a 7.13 mm optical zone at 30°.

In Tables 3, 4, and 5, the value in parenthesis below each optical zone diameter is the thickness of tissue removed by an ablation of that diameter. An asterisk denotes an ablation depth exceeding 0.5 mm.

FIGURE 4. Point A is at the edge of the optical zone. The solid ray starting at A just grazes the iris and is refracted by the lens to the fovea. Point B is outside the optical zone. No rays originating at B can arrive at the fovea, as denoted by the dashed lines.
TABLE 1. Optical Zone Diameters for a 43D Cornea, Anterior Chamber Depth of 3.6 mm

<table>
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<th>Glare-free Field (half angle, degrees)</th>
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<td>12.26</td>
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<tr>
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<td>9.54</td>
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<td>13.19</td>
<td>15.02</td>
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<td>10.43</td>
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<td>14.09</td>
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<td>7.71</td>
<td>9.54</td>
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<td>15.02</td>
<td>16.85</td>
<td>18.68</td>
</tr>
</tbody>
</table>

The second variable studied was the effect of flattening or steepening of the cornea on the requisite optical zone. Table 3 indicates that a myopic patient with a preoperative cornea of 43 diopters and a preoperative entrance pupil of 4 mm, whose cornea was to be flattened to 38 diopters, would require an optical zone of 3.59 mm to be glare-free at the fovea. Table 4 gives the corresponding optical zone diameters for a ten diopter myopia correction. In each case the required optical zone is slightly smaller than for the 5D myopic correction illustrated in Table 3. However, the ablation depths are approximately twice as great as for the 5D case, and in several situations would exceed the (assumed) corneal thickness, 0.5 mm.

In Table 5 it is seen that an aphakic patient with a preoperative entrance pupil of 4 mm whose cornea was to be steepened from 43 diopters to 59 diopters would require a 4.11 mm optical zone for glare-free vision at the fovea.

DISCUSSION

Irregularities on the cornea could be of two types: scattering and refractive. Scattering could occur, for example, from a radial keratotomy incision. A refractive glare source is one in which there is a local change of slope of the corneal surface, particularly if the change in slope is sufficient to refract light from a strong source so that it strikes the fovea (Figure 3).

Both the untreated cornea and the transition zone are sources of refractive glare, because they produce out-of-focus images on the retina.

For a given eye, and particularly for a given pupil diameter, there is an optical zone such that an irregularity outside this circular zone is incapable of scattering or refracting light to the fovea. This is illustrated in Figure 4. Point A is at the edge of the optical zone because there is one ray from A that can strike the fovea. Point B, located outside the optical zone, is incapable of scattering or refracting any ray to reach the fovea, as indicated by the fan of rays.

In surgery the optical zone should be centered on the line of sight, for reasons discussed by Walsh and Guyton, by Uozato and Guyton, and by Maloney. The principal reason is that the line of sight passes through the center of the entrance pupil, by definition. If the optical zone were centered at another point, say the corneal light reflex, then the optical zone would be off center with respect to the pupil and an optical zone of a given diameter would not produce as large a glare-free field in all directions as that shown in Tables 1–5.

We use the term “optical zone” to describe that part of the ablated central cornea that has the desired optical correction. After surgery there is also a transition zone, a small peripheral ring around the optical zone that connects the optical zone to the nonablated cornea. The optical zone therefore is generally smaller than the ablated area. The optical zone reported by

TABLE 2. Optical Zone Diameters for a 43D Cornea, Anterior Chamber Depth of 4.1 mm

<table>
<thead>
<tr>
<th>Glare-free Field (half angle, degrees)</th>
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<td>3.98</td>
<td>5.87</td>
<td>7.71</td>
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<tr>
<td>3</td>
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<td>10.43</td>
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<td>13.19</td>
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<td>13.19</td>
<td>15.02</td>
<td>16.85</td>
<td>18.68</td>
</tr>
</tbody>
</table>

Both the untreated cornea and the transition zone are sources of refractive glare, because they produce out-of-focus images on the retina.
TABLE 3. Optical Zone Diameters for a Postoperative Cornea power of 38D, Anterior Chamber Depth of 3.6 mm

<table>
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<th>Glare-free Field (half angle, degrees)</th>
<th>Anticipated Entrance Pupil Diameter (mm)</th>
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<td></td>
<td>(.045)</td>
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<td>40</td>
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<td>(.067)</td>
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<td>(.157)</td>
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</table>

Entrance pupil diameters are based on a preoperative corneal power of 43D. Central ablation depths (mm) are given in parentheses.

many investigators is really the ablation area and therefore overstates the true optical zone in their patients.

If the optical zone is smaller than the entrance pupil, there will be an out-of-focus image of the object formed on the retina in addition to the in-focus image, resulting in degradation of the in-focus image. The figures in the first rows of Table 3 and 4 indicate that for myopic correction the optical zone could in principle be slightly less than the diameter of the anticipated entrance pupil. However, it has been shown\textsuperscript{12} that the diameter of the optical zone should not be smaller than the entrance pupil as seen through the unoperated cornea. The reason is that light that passes through the annulus of untreated cornea will focus either in front of or behind the retina. If the subject is fixating on a bright object, the out-of-focus light will form a halo around the image of the object. In this case the cornea is functioning as a bifocal optical element.

If the optical zone diameter is larger than the entrance pupil then the fovea will receive only the in-focus image. In the latter case, the parafoveal region beyond a certain distance will receive both in-focus

TABLE 4. Optical Zone Diameters for a Postoperative Corneal Power of 33D, Anterior Chamber Depth, 3.6 mm

<table>
<thead>
<tr>
<th>Glare-free Field (half angle, degrees)</th>
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<td>(.270)</td>
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</table>

Entrance pupil diameters are based on a preoperative corneal power of 43D. Central ablation depths (mm) are given in parentheses.

* Indicates that this combination of field and pupil cannot be achieved because the ablation depth would exceed 0.5 mm.

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TABLE 5. Optical Zone Diameters and Edge Depths for a Postoperative Cornea Power of 59D, Anterior Chamber Depth of 3.6 mm

<p>| Glare-free | Anticipated Entrance Pupil, Diameter (mm) |</p>
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<td>(.451)</td>
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Entrance pupil diameters are based on a preoperative corneal power of 43D. Edge depths are shown in parentheses.

* Indicates that this combination of field and pupil cannot be achieved because the ablation depth would exceed 0.5 mm.

and out-of-focus images. The tables of optical zone diameter give the apparent angle at which the out-of-focus image will begin to overlap the in-focus image. In Table 1, for example, a central zone of 4.94 mm together with an entrance pupil diameter of 3 mm would give a field of 20° half-angle in which there is only one image.

It should be emphasized that while the decision on the optical zone diameter must be made preoperatively, the choice should be based on the best estimate of the postoperative entrance pupil. The latter should take account for both the anticipated change in corneal power (as has been done in the current calculations), and the expected postoperative pupil size of the patient.

The presence of an out-of-focus second image in the parafoveal region may or may not be a matter of concern, considering the rapid decrease in visual acuity at retinal points away from the fovea. However, in the parafoveal region where both images are present, there may be a sensation of diplopia or of image swimming whenever the eye moves to a new fixation point. This region will be annular in shape, and located just outside the visual field angle given by the table, ie, 20° in the example cited. It would appear desirable to keep this annular zone at as great a distance from central vision as is feasible.

A useful rule of thumb is that the optical zone of uniform optical power should never be less than the largest expected postoperative entrance pupil diameter. Care should be taken to allow for pupillary dilation in low light. If the pupil has an irregular shape, the optical zone should include the entire area of the entrance pupil.

In the correction of myopia by photorefractive keratectomy, a distinct trade-off exists for the surgeon. To prevent glare, high myopes require large optical zones, which means ablating deeper into the central stroma. Surgeons must weigh the disadvantages of deeper surgery with the advantage of glare prevention. In addition, careful preoperative evaluation requires an assessment of the anticipated variation in pupil size in differing ambient light. Those patients who do extensive night driving or who engage in other activities in which glare could be a problem should be considered for larger optical zones.

Key Words
refractive surgery, glare, optical zone, cornea, photorefractive keratectomy

Acknowledgment
The authors acknowledge numerous helpful discussions with Stephen Trokel.

References
Appendix

Details of the ray tracing are illustrated in Fig. 5. The iris is shown at I, and the axis of the cornea is at A. The following step numbers correspond to those in the Methods section.

1. First the entrance pupil diameter was selected. Ray 1 was then traced parallel to the axis, at a distance equal to the radius of the entrance pupil. The point, AP, where the ray crossed the plane of the iris was thereby located, and was used to determine the radius of the anatomic pupil for the selected entrance pupil diameter.

2. The radius of the anterior corneal surface was then changed in the program, using the equation for determining the postoperative anterior surface. For ease of illustration the anterior radius in Figure 5 is not changed. (This diagram corresponds to the ray tracing done for Tables 1 and 2, where the cornea was not changed.)

3. A “reference” ray (2) was traced from infinity at the desired angle, 30° in this figure. The program automatically finds the ray at 30° that passes through the designated point, which in this case is the point AP.

4. The intersection of the reference ray with the anterior corneal surface at point C was determined. The distance from C to the axis is then the radius of the optical zone.