Excimer ablation design and elliptical transition zones

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ABSTRACT

Purpose: To describe the rationale behind elliptical and other transition designs used with the excimer laser.

Setting: Casey Eye Institute, Oregon Health Sciences University, Portland, Oregon, USA.

Methods: Ablation zone designs were analyzed for the number of transition points for myopia and hyperopia. The advantages and disadvantages of elliptical transition zones are demonstrated graphically, with an emphasis on smooth ablation zone design to maximize the optics and biologic tolerance by the eye.

Results: The use of an individualized elliptical transition maximizes a circular effective optical zone and can enhance the smoothness of the transition zone while minimizing excessive tissue removal.

Conclusion: Elliptical transition zones may improve the optics and biologic tolerance of excimer laser treatments. *J Cataract Refract Surg 1999; 25:1191–1197 © 1999 ASCRS and ESCRS*

Several factors are important in the design of optimal excimer laser ablations. First, the design should maximize the optical effects of the ablation by creating (1) a smooth optical treatment zone, (2) a large effective optical zone (6.0 to 7.5 mm in diameter), and (3) an ablation pattern that accounts for the patient's pupil size in photopic and mesopic conditions.

The second factor in optimal ablation design is that it maximizes biologic acceptance. Smooth, regular posttreatment surfaces are important because the eye blinks over 10 000 times per day[1] at lid velocities[2] up to 30 cm/s with enough force to raise intraocular pressure 10 to 70 mm Hg with each blink.[3] Biologic acceptance can be maximized when (1) the ablation minimizes collateral tissue damage and does not stimulate epithelial hyperplasia or stromal scarring, (2) excessive epithelial and stromal tissue reaction is minimized by smooth transition zones and blending, and (3) the treatments minimize tissue removal (tissue conservation).

This article explores some concepts in transition zone and blend zone designs and suggests ways to improve ablation designs.

Background

The treatment of myopic with-the-rule (WTR) astigmatism with surface ablation differentially removes more tissue in the flat meridian (Figure 1B) than in the

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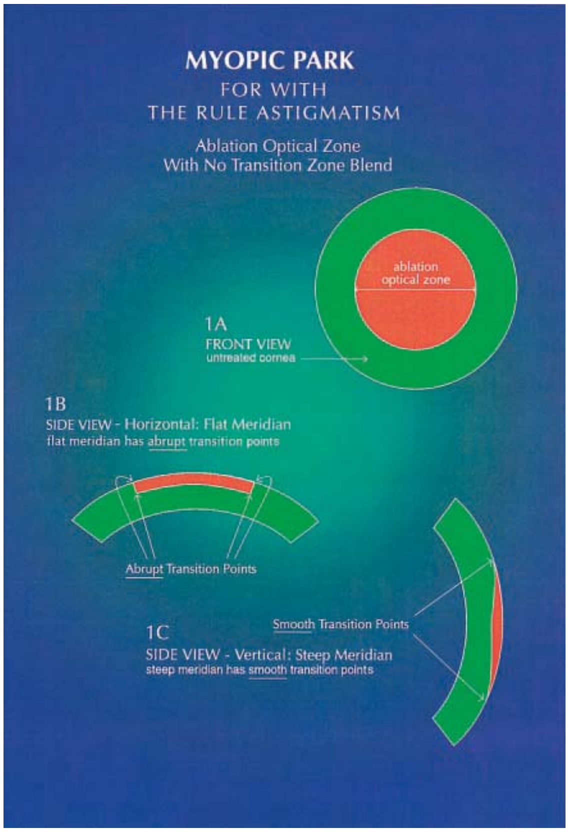

Figure 1. (MacRae) Photoastigmatic keratectomy (PARK) cylinder treatment for myopic astigmatism with no transition zone. 1A: Front view, treatment with a circular 6.0 mm ablation optical zone and no transition zone. Preoperatively, the patient has WTR astigmatism. 1B: Horizontal (flat) meridian, which is essentially a plano lenticule with abrupt transition points and no transition zone. 1C: Vertical (steep) meridian in which a plus lenticule of tissue is removed and the transition points are smooth.

steep meridian (Figure 1C).[4,5] This occurs by selectively flattening the steep meridian while removing an equal thickness of tissue centrally and peripherally in the flat meridian.

Treatment of hyperopic astigmatism requires removal of more tissue peripherally than centrally in the flat meridian to steepen the flat meridian. The steep meridian is left untreated. A combination strategy is used to treat mixed astigmatism. Chayet et al.[6] advocate treating both the steep and flat meridians for hyperopia and mixed astigmatism. More recently, Vinciguerra et al.[7] proposed treating myopic astigmatism with steep and flat meridian ablation.

Early treatments using myopic astigmatic ablations with abrupt transition points and no transition zone caused unacceptable scarring on the steep edges of the flat meridian when treating myopia (Figure 1B).[8] Because of the abrupt change at the transition points, epithelial hyperplasia and fibrous tissue reaction occurred at these junctures. Regression of astigmatic effect seemed to be associated with too steep an angle between the treated and untreated zones. The abrupt transition with no blending of the transition zone resulted in optical irregularity and regression of optical effect, which shrank the effective optical zone. Laser developers subsequently used an oval ablation optical zone to help blend the flat meridian.[9,10] These oval optical zones shrink the effective optical zone, especially in eyes with high astigmatism, which may cause optical aberration.

It is well documented that a larger ablation optical zone (greater than 5.0 mm) is highly desirable. Koch and coauthors[11] note that under mesopic conditions, mean pupil diameters are 5.4 to 5.2 mm in individuals in the 30 to 49 year age group. In a German study,[12] over 50% of patients treated with a 5.0 mm optical zone failed the German driving test for night driving because of reduced contrast sensitivity and glare difficulties. Thus, treatment with 4.5 mm oval optical zones creates aberrations, particularly in eyes with high astigmatism, especially when the pupil dilates at night. A larger ablation optical zone minimizes spherical aberration, which results in reduced glare and night-driving difficulties. In testing pupils dilated to 7.0 mm, Martinez et al.[13] found that coma and spherical-like aberrations increased significantly after photorefractive keratectomy with a 5.0 mm optical zone.

Elliptical Transition Zones

I propose the use of elliptical transition zones, which can be individualized based on the amount of cylinder, sphere, or both. These elliptical transition zones can be used for myopic, hyperopic, and mixed astigmatism.

Customized Myopic Transition Zones

Elliptical transition zones are noncircular transition zones that are elongated in the flat corneal meridian for myopia (or hyperopia) to allow more blending of the abrupt depression from the cylinder treatment. This is preferably an individualized or customized nonspherical transition zone with a maximal diameter based on the magnitude of cylinder. Thus, an astigmatic patient with −4.00 −2.00 × 180 (WTR astigmatism) may require a 1.5 mm transition zone to blend the sharp transition at

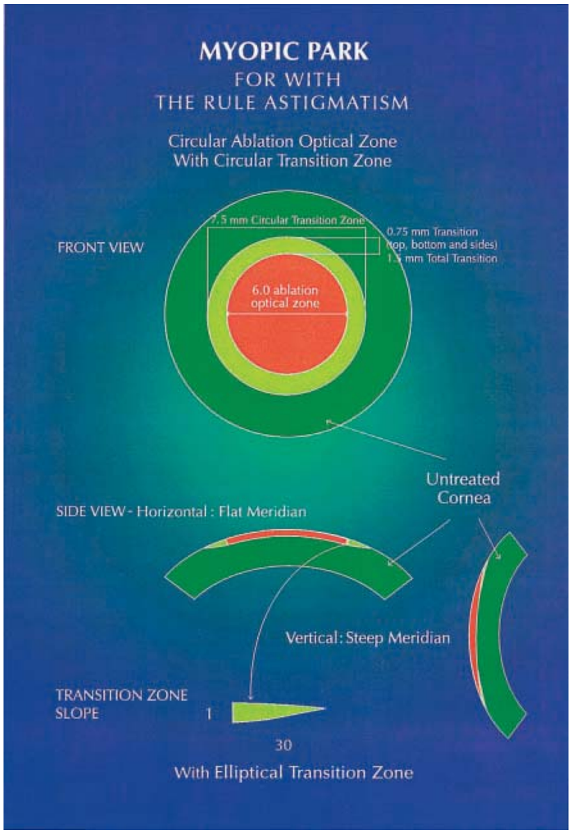

Figure 2. (MacRae) Myopic PARK treatment with 6.0 mm ablation optical zone and a 7.5 mm circular transition zone in an eye with a refraction of −4.00 −2.00 × 180. The slope of the transition zone is 1/30.

180 degrees, while an astigmatic patient with −4.00 −4.00 × 180 may require a larger 3.0 mm transition zone.

Consider the example of an eye in which the WTR astigmatism (−4.00 −2.00 × 180) is treated with a circular ablation optical zone of 6.0 mm (Figure 2). (In all examples, the eye has WTR astigmatism). The flat meridian has a crater at the horizontal (0 to 180 degrees) meridian that is 25 μm deep. The length of the circular transition zone is 0.75 mm (750 μm) on each side for a total of 1.5 mm. This transition zone smooths the crater. Thus, the slope height of the horizontal transition zone is 25 μm/75 μm = 1/30, which seems to be well tolerated by the overlying corneal epithelium. The steep meridian at 6 and 12 o'clock maintains a smooth transition similar to that shown in Figure 1C, with less need for a transition zone, as noted below. A 3-dimensional view is shown in Figure 3.

This ablation can become more efficient (removing less tissue) by using an elliptical transition zone (Figure 4). This is possible because the vertical 90 degree meridian is continuously blended from the center of the optical zone to the periphery. This occurs over the 3.0 mm (3000 μm) radius with a 6.0 mm diameter optical zone. The elliptical transition zone maintains a smooth transition while minimizing unnecessary tissue removal.

Consider a second example of an eye with −4.00 −4.00 × 180 using a 6.0 mm optical zone. Now the depth of the horizontal flat meridian crater is 50 μm. If this is treated with a 6.0 mm ablation optical zone and a 7.5 mm transition zone, the length of the transition zone is again 0.75 mm (750 μm) on each side. The slope of the transition zone would increase to 50 μm/750 μm = 6/100 = 1/15 (Figure 5). Since this is a steeper slope, it is likely that the epithelium will thicken to fill in the

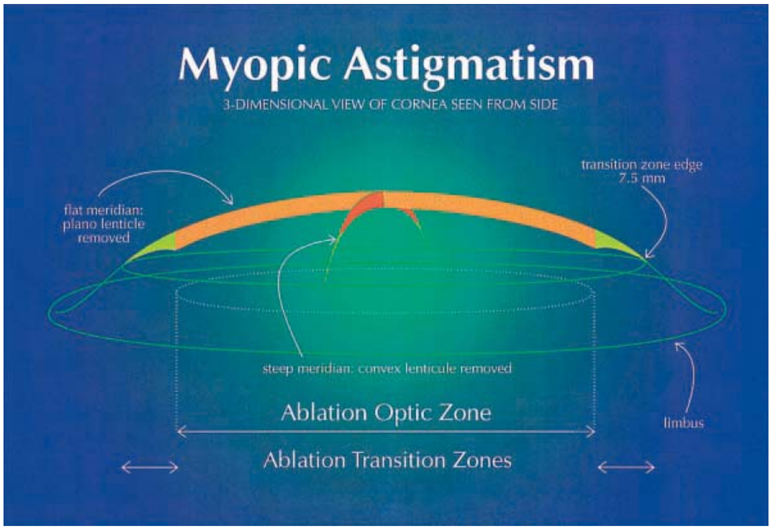

Figure 3. (MacRae) Three-dimensional view of PARK with a transition zone. In the flat meridian, a plano lenticule is removed. In the steep meridian, a convex lenticule is removed.

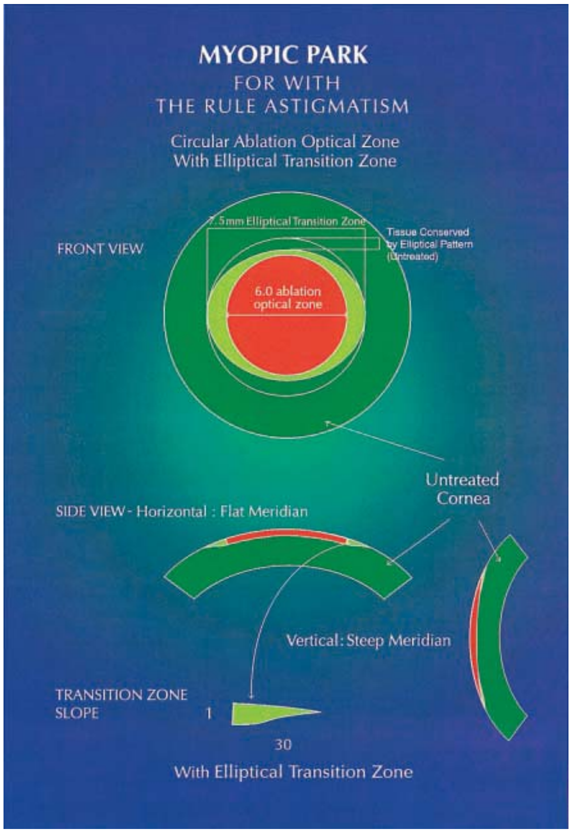

Figure 4. (MacRae) Myopic PARK treatment with elliptical 7.5 mm transition zone using same example of −4.00 −2.00 × 180. Note the conservation of tissue in the 6 and 12 o'clock meridians. The slope of the transition zone is again 1/30.

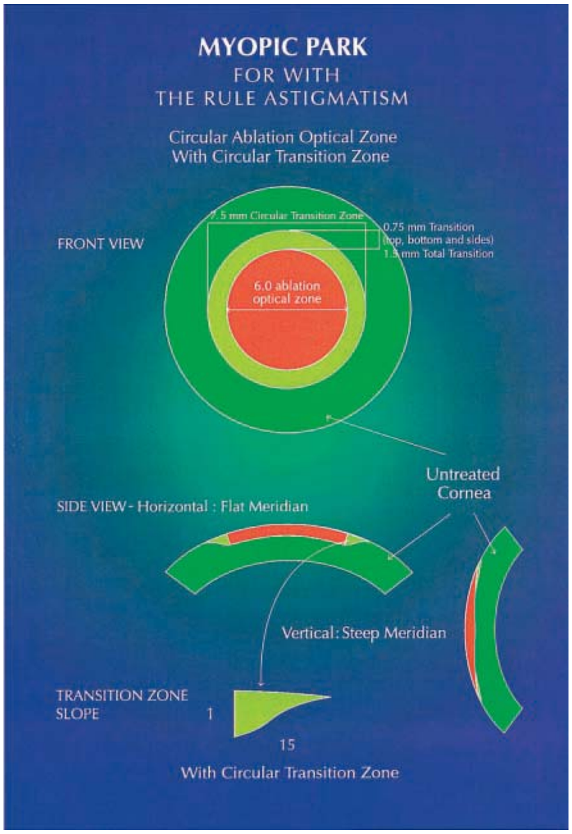

Figure 5. (MacRae) Higher astigmatism myopic PARK treatment with a 6.0 mm circular optical ablation zone and a 7.5 mm circular transition zone. The preoperative refraction in this eye is −4.00 −4.00 × 180. The slope of the transition zone is steeper at 1/15 than in Figure 2 or 3.

steep transition. To adjust for this steep slope, an elliptical 9.0 mm transition zone twice as long in the flat horizontal meridian, now 1.5 mm (1500 μm) on each side, will reduce the slope (Figure 6). The slope is now 50 μm/1500 μm = 1/30, which is the same as the slope in the first example, making excessive epithelial filling less likely.

The steep slope in which the epithelium or stroma begins to thicken excessively is called the "critical slope." When an ablation design exceeds the critical slope, there may be optical irregularity and shrinkage of the effective optical zone because of local excessive corneal thickening.

An elliptical transition zone allows the surgeon to maintain a large effective optical zone along with gradual transitions. The elliptical transition can be individualized or customized using the concept of the critical slope to minimize unnecessary tissue removal. Thus, an eye with a −4.00 −3.00 × 180 preoperative refraction would require a smaller elliptical transition zone than the eye in the second example.

Customized Hyperopic Transition Zones

The elliptical transition zone can also be used to treat hyperopic and mixed astigmatism. In these cases, the flat meridian is steepened centrally by removing more tissue in the midperiphery than in the center. During the astigmatic treatment, the steep meridian is untouched, which helps conserve tissue (Figure 7). Tissue removal can be minimized further by making the transition zone elliptical.

Transition Points

The epithelium is sensitive to abrupt or steeply sloped transitions and tends to thicken selectively to fill in sharp transitions.[5,8] When viewed in cross section, a myopic ablation without astigmatism has only 1 transition point on each side or semimeridian (Figure 8). This

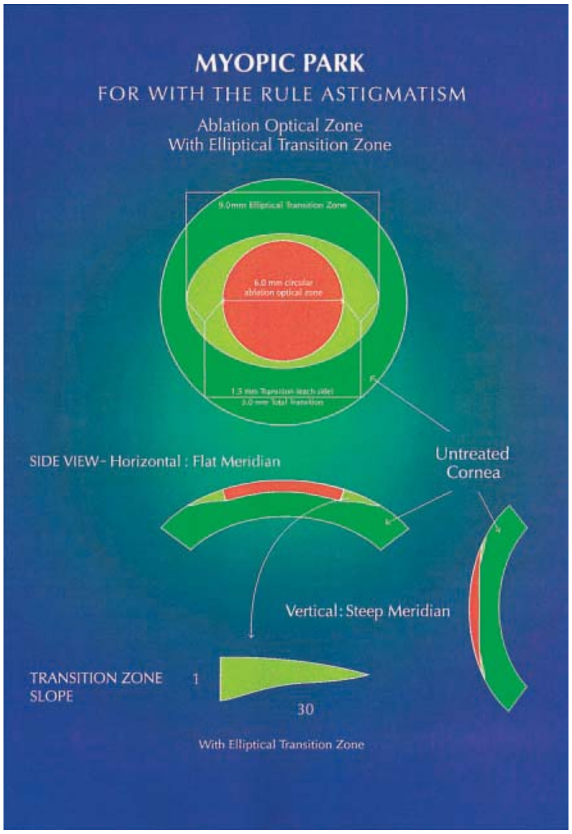

Figure 6. (MacRae) Higher astigmatism myopic PARK treatment with a 6.0 mm circular optical zone and a 9.0 mm elliptical transition zone. The slope of the transition zone is reduced to 1/30, which is similar to that noted in Figures 2 and 4.

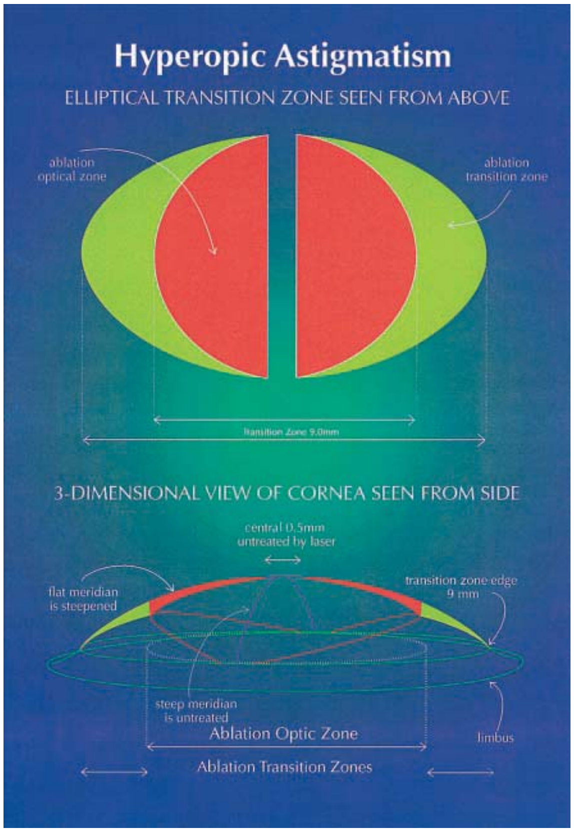

Figure 7. (MacRae) *Above*: Hyperopic PARK using elliptical transition zone. The steep vertical meridian at 90 and 270 degrees is untreated by the laser, while the flat meridian is steepened using the elliptical pattern. This same pattern can be used to treat mixed astigmatism. *Below*: Three-dimensional view of hyperopic astigmatism treatment.

is at the juncture of the treated and the untreated peripheral cornea. A myopic astigmatism ablation has only 1 transition point in the steep meridian but 2 transition points in the flat meridian on each side, including 1 where the ablation optical zone meets the transition zone and 1 where the transition zone meets the un-

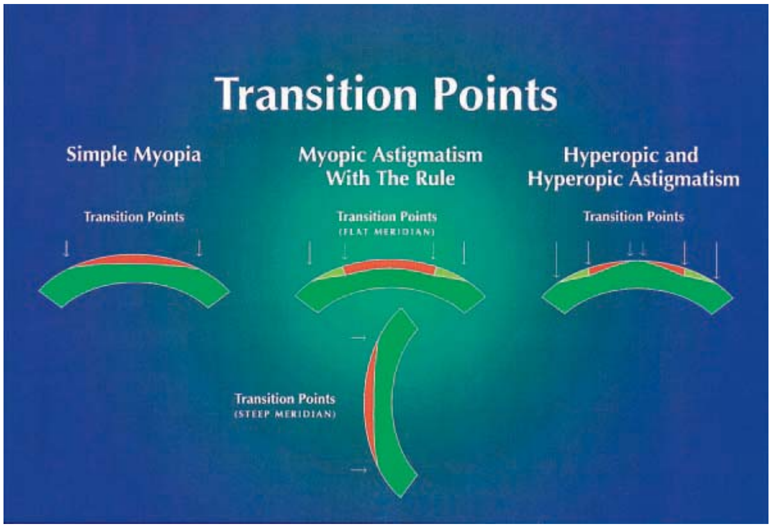

Figure 8. (MacRae) Transition points of cornea demonstrating corneal ablation for simple myopia, compound myopia, and hyperopia and hyperopic astigmatism. The simple myopic ablation has 1 transition point on each side (semimeridian). Compound myopic treatment has 2 transition points in the steep meridian and 1 in the flat meridian on each side. Hyperopic and hyperopic flat meridian ablations have 3 transition points on each side.

treated peripheral cornea. The ablation requires blending at these 2 transition points. If the transition is too abrupt, the blending is done over an area or zone that is commonly referred to as a transition zone. For elliptical ablations, the transition points will continuously vary in an elliptical fashion and the transition zones will be crescent-shaped as shown in Figures 3, 5, and 6.

In hyperopic and hyperopic astigmatism ablation, there are 3 transition points. The first is between the central cornea, which is untreated, and the adjacent treated tissue in the ablation optical zone. The second is where the ablation optical zone meets the transition zone. The third is where the transition zone meets the untreated peripheral cornea.

Chayet et al.[6] report on treating hyperopic and mixed astigmatism by treating both the steep and flat meridians. This is a complicated treatment pattern, and there may be as many as 5 transition points (per side) in the flat meridian and 4 (per side) in the steep meridian. Vinciguerra et al.[7] recently proposed treating myopic astigmatism with steep and flat meridian ablation. The treatment is also complicated but follows the tenets discussed in this paper.

In the cornea in which the limbal diameter remains constant, flattening or steepening 1 portion of the cornea tends to cause a reciprocal steepening or flattening in another part. In other words, curvature tends to be conserved. If 1 part of the cornea is steepened, there will be an adjacent area of flattening to compensate. Dierick and Missotten[14] reported this when they modeled hyperopic ablation. They noted that the transition zones for hyperopia may require marked midperipheral flattening to compensate for steepening of the central cornea. They also found that with 10 diopters (D) of hyperopic steepening of the central cornea, the midperipheral cornea had to be flattened 7 to 15 D. This may help us understand why hyperopic treatment with its 3 transition points is more challenging than the simple myopic ablation, which has only 1 transition point, and may explain why the upper limit for hyperopic ablation treatment (roughly 4 to 6 D) is approximately one-third that of myopic ablation treatment (roughly 12 to 18 D). Each of these transition points can be blended over an area or transition zone, if the edge is abrupt.

Because of the abrupt edge of the transition, the critical slope and blending become important. The transition zone slope starts at the transition point (Figure 1B) and extends to the edge of the zone. Further studies are warranted to determine how steep a transition zone slope can be before the critical slope is reached where there is variability of effect related to irregular tissue filling and regression. Conversely, a transition zone slope less than the critical slope may be well tolerated and result in a minimally variable effect. In addition, blending at the transition point is also important in helping to smooth the surface. Since the cornea cannot distinguish between hyperopic and myopic treatment but can distinguish when transition points are not smooth or when the slope is too steep, similar loss of predicted effect, undesirable tissue reaction, and optical aberrancy may occur with either myopic or hyperopic ablations.

Advantages of the Elliptical Transition Zone

The advantages of the noncircular or elliptical transition zone include the following:

1. There is better blending adjacent to the transition point.
2. A smoother transition zone slope (roughly less than 1/20) results in a smoother ocular surface. This minimizes local tissue hyperplasia, which probably occurs because of the repeated trauma of eye blinking. This results in less epithelial hyperplasia and scarring.
3. The effective optical zone is larger, and more regular, which allows the optical system to be fully utilized, particularly with pupil dilation at night. This also helps minimize spherical aberration.[13,15]
4. The noncircular or elliptical transition zone may minimize the transition zone in the steep meridian. This minimizes unnecessary removal of tissue.

Disadvantage of Elliptical or Nonspherical Transition Zones

The primary disadvantage of a noncircular or elliptical transition zone is the greater tissue removal needed than for an equivalent degree of astigmatism treated with an oval optical zone. Similarly, a larger diameter transition zone (7.0 to 9.0 mm) may be necessary, which means that a larger area of epithelial removal is required. This may slightly prolong healing times (with PARK) or require larger flap diameters with laser in situ keratomileusis.

These larger transition zones maybe more difficult to incorporate using first-generation broad-beam lasers.

The newer spot, slit, and segmental ablation systems can incorporate this type of change by simple software modifications. Nomograms may have to be modified to adjust for these changes.

Summary

An elliptical or noncircular transition zone may help reduce optical aberration by increasing the effective optical zone. This helps with nighttime glare when driving and enhances the quality of vision in patients treated with myopic, hyperopic, or mixed astigmatic ablation. Customization of the elliptical transition zone may also help minimize tissue removal. The use of blending techniques may be important to minimize epithelial hyperplasia and stromal fibrosis. Use of these blending techniques is a bit like creating aerodynamic designs for sports cars. The extent of blending is likely to be more critical as the amount of sphere and cylinder increases. It is hoped that elliptical transition zone patterns will further enhance the optical and biologic acceptance of laser refractive surgery.

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