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The Relationship of Visual Acuity, Refractive Error, and Pupil Size After Radial Keratotomy

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• To better define the relationship between residual refractive error, uncorrected visual acuity, and pupil diameter, we compared 42 eyes that had an eight-incision radial keratotomy according to the Prospective Evaluation of Radial Keratotomy Study protocol with 42 matched control eyes. The parameters measured were best corrected visual acuity, uncorrected visual acuity, and the change in cycloplegic refraction with enlarging pupil diameter. The best corrected visual acuity was 20/16 in both the radial keratotomy and control groups, but the variability (SD) was higher in the radial keratotomy group. The average uncorrected visual acuity was 0.35 (35%) better in the radial keratotomy group, but the variability was 1.77 times higher. Change in refraction with dilation occurred in 9% of the controls and 36% of the radial keratotomy patients, indicating a significant difference (*P*=.002). The change in refraction with dilation in the eyes with radial keratotomy was almost equally split between a hyperopic change (17%) and a myopic change (18%), which was much different than in the control eyes, only 2% of which changed in a hyperopic direction and 7% in a myopic direction. The radial keratotomy patients with a myopic change had the best uncorrected visual acuity, indicating that positive spherical aberration yielded the best aspherical surface for uncorrected visual acuity.

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The outcome following radial keratotomy is usually characterized by residual refractive error, uncorrected visual acuity, and best spectacle-corrected visual acuity. In a previous study[1] we demonstrated that for myopic refractive errors ranging from −2.00 to −2.50 diopters (D) the uncorrected visual acuity was better for eyes that had radial keratotomy than for eyes that were not operated on. In that study, visual acuity was measured with the pupil undilated and the refractive error was measured with the pupil dilated. This variation in pupil diameter could have been a significant factor in determining the results.[2-4]

A thorough assessment of refraction and visual acuity after radial keratotomy requires control of both accommodation and pupil diameter. This control is necessary because young patients tend to accommodate during refraction, leading to an overestimate of their myopia. Also, a dilated pupil allows the paracentral optics of the cornea to change the refractive error. In the present study we have evaluated the influence of pupil diameter on the uncorrected visual acuity and the cycloplegic refractive error by using a variable-diameter artificial circular aperture to simulate the "natural" pupil diameter during cycloplegia. These measurements were made in a series of 42 eyes after radial keratotomy in the Prospective Evaluation of Radial Keratotomy (PERK) Study and in a group of control eyes matched for age and refractive error.

PATIENTS AND METHODS

Patient Selection

Two groups of patients were selected for study: 25 patients who had an eight-incision radial keratotomy in the PERK study[5] and 21 control patients matched for age and cycloplegic refractive error. The radial keratotomy patients were chosen by asking each patient who returned for a regularly scheduled visit in the PERK study to participate in this substudy. The first 25 consecutive patients who agreed to participate were selected.

The 25 radial keratotomy patients (50 eyes) were examined using the standardized examination techniques outlined by the PERK protocol.[5] Of these 50 eyes, 42 qualified for the study. Eight eyes were excluded for the following reasons: five were not operated on, two had 16 incisions, and one had four incisions. The 25 radial keratotomy patients ranged in age from 32 to 53 years (mean, 41±6.2 years). The mean (±SD) spherical equivalent of the undilated manifest refraction was −0.15 (±1.09) D and ranged from −4.12 to +2.75 D.

The control group consisted of 21 volunteers selected from an outpatient clinic population and employees of the Emory Clinic, Atlanta, Ga, yielding 42 eyes that were not operated on that had no ocular pathology. We attempted to match the control group with the radial keratotomy group by age in decades and cycloplegic refractive error (±1.00 D). Recruiting young hyperopic controls was difficult because most young people with hyperopia are unaware of their refractive error. As a result, there were five cases in which the differences were outside these limits: four age differences of 11, 12, 16, and 23 years and one refractive difference of 1.38 D. The range of age for the control group was 26 to 57 years (mean±SD, 42±9.2 years). The mean spherical equivalent of the undilated manifest refraction was −0.25 (±1.02) D and ranged from −3.25 to +2.12 D.

Clinical Measurements

Measurements taken prior to dilation included the natural pupil diameter, uncorrected visual acuity, manifest refraction, and best spectacle-corrected visual acuity. The natural pupil diameter prior to dilation was measured with a ruler to the nearest half millimeter while the patient was fixating on the distance visual acuity chart, with trial frames in place under room illumination of approximately 10 foot-candles. Phenylephrine hydrochloride, 2.5%, and tropicamide, 1.0%, were then instilled, and, after a minimum of 20 minutes, a dilated (cycloplegic) manifest refraction was performed. The dilated refraction was repeated through a circular aperture in the trial frame; the diameter of the aperture was the same diameter as that of the patient's natural pupil prior to dilation.

Table 1.—Snellen Visual Acuity as a Function of Pupil Size and Defocus

Defocus, Diopters	Snellen Visual Acuity by Pupil Size, mm								
	0.5	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
TDL*	20/36	20/18	20/09	20/06	20/04	20/04	20/03	20/03	20/02
0.0	20/36	20/18	20/10	20/09	20/10	20/10	20/11	20/11	20/11
0.5	20/36	20/22	20/13	20/15	20/19	20/24	20/28	20/30	20/31
1.0	20/36	20/27	20/19	20/24	20/33	20/44	20/52	20/56	20/58
2.0	20/37	20/33	20/36	20/49	20/68	20/95	20/121	20/130	20/135
3.0	20/38	20/39	20/60	20/83	20/117	20/168	20/214	20/230	20/239
4.0	20/39	20/47	20/95	20/132	20/182	20/252	20/307	20/330	20/343
5.0	20/40	20/56	20/140	20/190	20/258	20/348	20/428	20/460	20/478

*TDL indicates theoretical diffraction limits.

Definition of Defocus Equivalent for Grouping Refractive Errors

Eyes were grouped by similar cycloplegic refractive errors to evaluate the uncorrected visual acuity for a given pupil diameter. These groupings were not based solely on the spheroequivalent of the refraction, because, in patients with astigmatism, the spheroequivalent does not provide sufficient information to predict its effect on visual acuity. For example, a patient with a refraction of $-1.00+2.00\times90°$ has a spheroequivalent of zero but certainly would not be expected to have the same visual acuity as a person with zero refractive error for the same pupil diameter, even though both have spheroequivalents of zero.

To eliminate this inequity, a value termed the *defocus equivalent* was calculated that is proportional to the area of the blur circle formed on the retina by various spherocylindric refractive errors. This method of grouping patients with differing spherocylindric refractive errors allows a correlation with Snellen visual acuity that has been described and verified clinically by previous investigators.[6-8] When the pupil is dilated and accommodation paralyzed, the defocus equivalent is equal to the sum of the absolute value of the spheroequivalent plus half the absolute value of the cylinder. In the previous example, the patient with a $-1.00+2.00\times90°$ refractive error would have a spheroequivalent of zero, and half of the cylinder is one, yielding a defocus equivalent of 1.00 D. For grouping purposes, this patient would be considered equivalent to someone with 1.00 D of simple myopia.

In the natural, undilated state, where accommodation is allowed, a patient with hyperopia accommodates to obtain the clearest retinal image, moving the circle of least confusion anteriorly onto the retina. As a result, in the undilated state, the defocus equivalent would simply equal half the absolute value of the cylinder; the spheroequivalent is zero.

Role of Pupil Diameter and Depth of Field

To determine the clarity of a defocused image in any optical system, the depth of field (sensitivity to defocus) or the f-number (relative aperture) of the system must be known. To estimate the visual acuity in a patient with a known refractive error, the f-number of the eye must be known. In any optical system, the f-number is the ratio of the effective focal length to the diameter of the clear aperture of the system.[9] In the eye, this would be the effective focal length of the eye divided by the diameter of the entrance pupil. The entrance pupil is the same as the apparent pupil but approximately 14% larger than the actual pupil.[9]

In the human eye, using the Gullstrand Model,[9] the effective focal length is approximately 22.8 mm. For pupil diameters from 1 to 8 mm, this would result in f-numbers ranging from 22.8 to 2.85, very close to the range of f-numbers found on a standard 35-mm camera. Since refractive errors in this study were moderate (+4 to −4), there was less than a 10% probability that the effective focal length would vary by more than 10% from the mean value of 22.8.[10] Thus, in our study the f-number of an eye can be estimated by using the pupil diameter alone. For extremely long or short eyes these estimates would be inaccurate by the percentage difference between the actual effective focal length of the eye compared with 22.8 mm.

Creation of Historical Reference Grid

Early studies relating visual acuity and refractive error rarely considered the f-number of the eyes and in some cases never mentioned the pupil diameter, resulting in a large amount of variability in their findings. Later studies,[6-8,11-16] however, reduced the variability by giving ambient light levels and patient age, for which an average pupil diameter could be determined.[17] More recent studies did record the pupil diameter, visual acuity, and refractive error[18-20] and found the most consistent relationship among these three parameters. We have taken the refractive errors, visual acuities, and pupil diameters reported in these 12 studies[6-8,11-16,18-20] from 1928 to 1990 and tabulated the results to create a "historical reference grid" (Table 1).

When differences in Snellen visual acuities existed for the same pupil size and refractive error, a simple average of the visual acuities from each study was used to compute the historical grid value. A weighted average was not used because some of the studies had over 10 000 patients and others had fewer than 10 patients, which would have resulted in a negligible effect of the smaller studies. Nevertheless, the correlation of values among the studies was always within two lines and usually within one line of the same Snellen visual acuity.

These historical reference grid values are plotted in Figures 1 through 3, illustrating the complex relationship of these three parameters over the normal physiologic range of the human eye. The historical reference grid provided Snellen visual acuity values with which both the radial keratotomy patients and controls could be compared.

Definition of Visual Acuity Ratio

The defocus equivalent (the magnitude of the spheroequivalent added to half of the magnitude of the cylinder) was calculated for all radial keratotomy and control eyes using the cycloplegic refraction through the circular aperture and compared with the corresponding values of the historical reference grid (Table 1). The comparison was made by establishing a visual acuity ratio obtained by dividing the denominator of the patient's uncorrected Snellen visual acuity for a given defocus and pupil diameter into the denominator of the corresponding value from the historical reference grid.

For example, one radial keratotomy patient with a pupil 4.0 mm in diameter and a defocus equivalent of 2 D had an uncorrected visual acuity of 20/50. The corresponding visual acuity in the historical reference grid is 20/68, so the visual acuity ratio would be 1.36 (68/50). The visual acuity ratio is therefore similar to the decimal notation for visual acuity; values less than 1 are worse than the expected normal values, and values greater than 1 are better than expected normal values. In the previous example, the visual acuity ratio of 1.36 indicates that the visual acuity is 0.36 (36%) better than the corresponding historical reference grid value. The visual acuity ratios in the radial keratotomy and control groups were compared using the Mann-Whitney U test.

RESULTS

Dilated Refraction With and Without Circular Aperture

We compared the spheroequivalent of the cycloplegic refractive error with the pupil dilated with and without the circular aperture of the same diameter as the natural pupil. In the control group only four (9%) of 42 eyes had a change in their dilated refractions with and without the circular aperture.

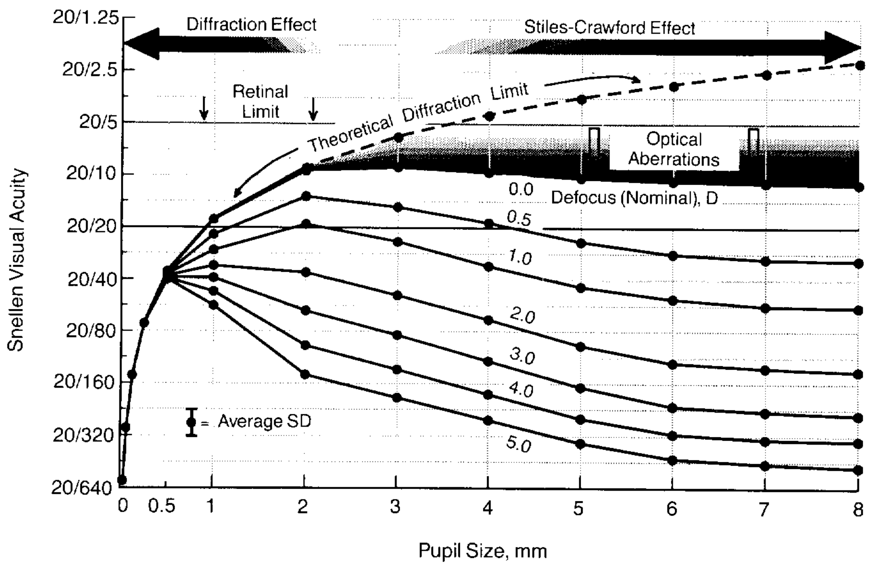

Fig 1.—The Snellen visual acuity vs pupil diameter as a function of diopters (D) of defocus in normal eyes. For pupil diameters less than 0.5 mm, the visual acuity is completely determined by the diffraction limit and is not affected by defocus up to 5 D. Between pupil diameters of 0.5 and 3.0 mm, the visual acuity is determined by a complex interplay among diffraction, defocus, and optical aberrations. For diameters above 3.0 mm, diffraction is no longer a factor but the Stiles-Crawford effect becomes a contributing factor. Above 5.4 mm, the additional pupil area has little effect on Snellen visual acuity due to the Stiles-Crawford effect.

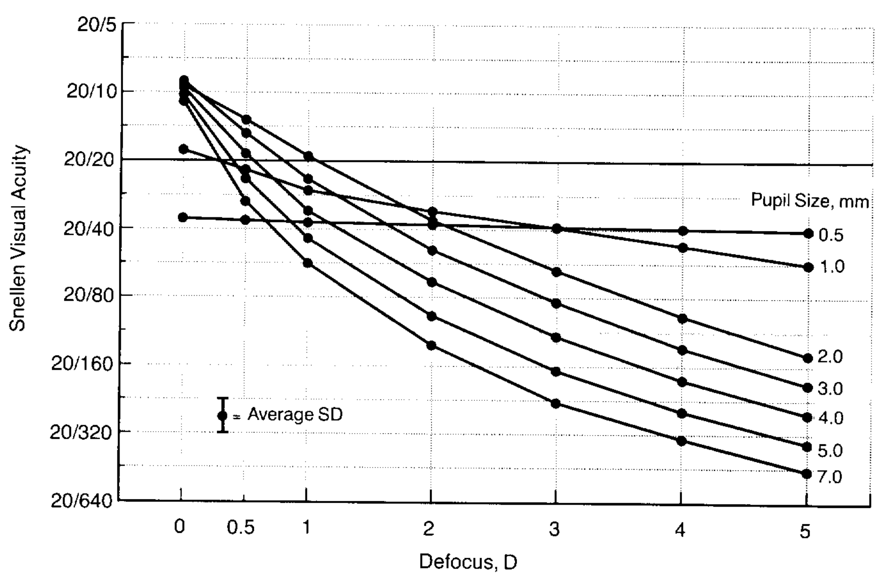

Fig 2.—The Snellen visual acuity vs diopters (D) of defocus as a function of pupil diameter in normal eyes. These are the same values used in Fig 1 replotted using defocus as the *x* axis, so that for a given pupil diameter the effect of defocus can be seen. The curves for 6- and 8-mm pupils have been omitted for clarity since they are so close to the curve for the 7-mm pupil.

Three of these eyes (7%) changed in the myopic direction and one (2%) changed in the hyperopic direction. In the radial keratotomy group, in contrast, 15 (36%) of 42 eyes had a change in the dilated refraction with and without the circular aperture. Eight eyes (19%) changed in the myopic direction and seven (17%) changed in the hyperopic direction.

Visual Acuity

The mean value of the uncorrected visual acuity ratio with the natural-diameter pupil was 0.95±0.39 for the control group and 1.30±0.67 for the radial keratotomy group, indicating that the control group had an average visual acuity that was 0.05 (5%) worse than the historical reference grid, and the radial keratotomy group had an average visual acuity that was 0.30 (30%) better than the historical reference grid. For reference, a one-line difference in Snellen visual acuity is approximately a 25% difference in visual acuity in the range between 20/20 and 20/100 on the standard Snellen visual acuity chart. The 5% difference between the control group and the historical reference grid shows excellent agreement, since this represents one fifth of a Snellen acuity line difference (approximately one letter).

The difference in the mean values of the visual acuity ratios for the two groups was 0.35, and the distribution of visual acuity ratios was significantly different between the two groups ($P=.002$). The 0.35 difference indicates that the radial keratotomy group had an average visual acuity that was 35% (approximately 1.4 Snellen lines) better than that of the control group for the same pupil diameter and defocus equivalent. The variability (SD) of the visual acuity ratio in the radial keratotomy group was 0.67, almost twice that of the control group (0.39) for the same pupil diameter and defocus equivalent.

In the seven radial keratotomy eyes (17%) that had a myopic change in their dilated refractions with and without the circular aperture, the mean value of the visual acuity ratio was 1.77 (±0.74). In the eight eyes (19%) with a hyperopic change, the mean value of the visual acuity ratio was 0.92 (±0.31). The 27 eyes (64%) with no change in refraction had a mean visual acuity ratio of 1.29±0.65. The only statistically significant difference among these three groups of radial keratotomy eyes was between those with a myopic change and those with a hyperopic change (1.77 vs 0.92, $P=.03$ by the Kruskal-Wallis test).

The mean best corrected visual acuity was 20/16 in both the control group and the radial keratotomy group, preoperatively and postoperatively, indicating that the radial keratotomy procedure did not lower the average best spectacle-corrected visual acuity in these eyes. In the PERK study, the average preoperative and postoperative best corrected visual acuity was also 20/16. In our study there was higher variability (SD) in the best spectacle-corrected visual acuity in the radial keratotomy group. This is similar to the findings in the PERK study after 1 and 3 years; 30% of the eyes had an improvement of one or more lines and 18% had a reduction of one or more lines best spectacle-corrected visual acuity.[21,22] Our results are summarized in Tables 2 and 3.

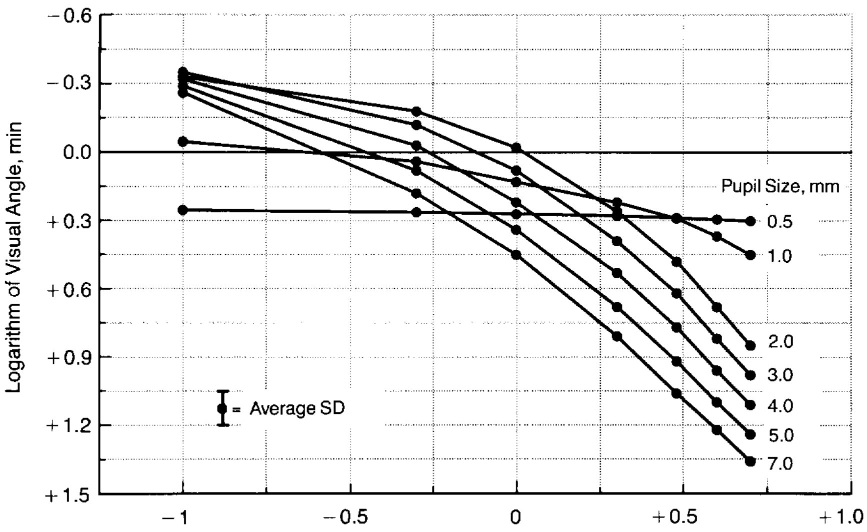

Fig 3.—The Snellen visual acuity vs the logarithm of defocus as a function of pupil diameter. This plot uses the same values as Figs 1 and 2, but the visual acuity values on the *y* axis have been converted to the logarithm of the visual angles, and the values for defocus on the *x* axis have been plotted on a logarithmic scale. This plot is comparable to those of previous investigators and emphasizes that the relationship between Snellen visual acuity and defocus for a given pupil diameter is not linear, even on a logarithm-logarithm scale, except for pupils less than 0.5 mm. The curves for 6- and 8-mm pupils have been omitted for clarity since they are so close to the curve for the 7-mm pupil.

Table 3.—Comparison of Uncorrected Visual Acuity Ratio in Eyes With Radial Keratotomy by Type of Spherical Aberration

Spherical Aberration	Uncorrected Visual Acuity Ratio (SD)*
Positive (myopic change in refraction)†	1.77 (0.74)
None (no change in refraction)†	1.29 (0.65)
Negative (hyperopic change in refraction)†	0.92 (0.31)

*The visual acuity ratio is the ratio of the actual Snellen visual acuity to the corresponding visual acuity for the same pupil size and defocus shown in Table 1. It is similar to the decimal notation of visual acuity; 1.77 would be 77% better than the value in Table 1 and 0.92 would be 8% worse.

†The change in refraction that occurred with cycloplegia through a circular aperture of the same size as the patient's predilated, natural pupil diameter to the cycloplegic refraction with no aperture. A myopic change is considered positive spherical aberration and a hyperopic change is considered negative spherical aberration (Fig 5).

Table 2.—Comparison Between Eyes With Radial Keratotomy and Control Eyes That Were Not Operated on

Parameter	Radial Keratotomy Group	Control Group
No. of eyes	42	42
Age, y*	41 ± 6.2	42 ± 9.2
Cycloplegic refractive error, diopters*	−0.15 ± 1.09	−0.25 ± 1.02
Best spectacle-corrected visual acuity*	20/16 (1.34 ± 0.24)	20/16 (1.22 ± 0.17)
Uncorrected visual acuity ratio*†	1.30 ± 0.67	0.95 ± 0.39
Positive spherical aberration, (myopic change in refraction), %‡	19	7
No spherical aberration (no change in refraction), %‡	64	91
Negative spherical aberration (hyperopic change in refraction), %‡	17	2

*Values are average ± SD.

†The visual acuity ratio is the ratio of the actual Snellen visual acuity to the corresponding visual acuity for the same pupil size and defocus shown in Table 1. It is similar to the decimal notation of visual acuity; 1.30 would be 30% better than the value in Table 1 and 0.95 would be 5% worse.

‡The change in refraction that occurred with cycloplegia through a circular aperture of the same size as the patient's predilated natural pupil diameter to the cycloplegic refraction with no aperture. A myopic change is considered positive spherical aberration and a hyperopic change is considered negative spherical aberration (Fig 5).

COMMENT

Historical Reference Grid: Normal Relationship of Refractive Error, Uncorrected Snellen Visual Acuity, and Pupil Diameter

Figures 1 through 3 plot values from the historical reference grid in Table 1.[6-8,11-16,18-20] These three figures illustrate the complex relationship among refractive error (defocus equivalent), pupil diameter, and uncorrected visual acuity over the physiologic range of the human pupil diameter. Figure 1 demonstrates that, for pupil diameters smaller than 0.5 mm, the visual acuity is solely determined by the pupil diameter.[18,20] Defocusing up to 5 D has no measurable effect on the visual acuity. This is true because diffraction is the primary factor limiting the visual acuity for pupil diameters less than 0.5 mm (pinhole effect).

Between pupil diameters of 0.5 and 3.0 mm, the visual acuity is a complex interplay among diffraction, defocus, and optical aberrations.[20,23,24] Between pupil diameters of 3.0 and 5.4 mm, diffraction is no longer a factor. Defocus and optical aberrations are joined by an additional factor, the Stiles-Crawford effect.[20,23,24] The Stiles-Crawford effect is a progressive reduction in the effectiveness of light rays as they pass farther from the center of the pupil due to the directional sensitivity of the retina. Increasing the pupil diameter above 5.4 mm has little effect on the visual acuity due to the Stiles-Crawford effect.[25-27] The actual relationship of visual acuity, defocus, and pupil diameter is nonlinear even on a logarithm-logarithm scale (Fig 3), except over a very short range or for pupil diameters less than 0.5 mm.

Uncorrected Visual Acuity

With the pupil undilated, the mean uncorrected visual acuity in the eyes with radial keratotomy was 35% (1.4 lines) better than in the control eyes for the same refractive error and pupil diameter ($P<.001$). These results confirm our previous findings.[1]

The better uncorrected visual acuity and the increase in the incidence of refractive change with a larger pupil indicate that the optical configuration

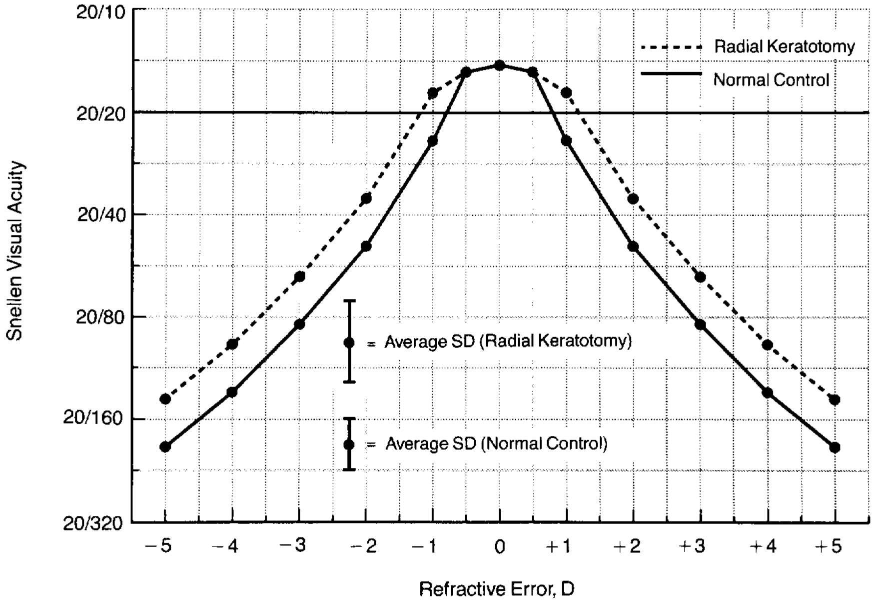

Fig 4.—Theoretical comparison of Snellen visual acuity vs refractive error (diopters [D] of defocus) for a 3-mm pupil in normal eyes and those with radial keratotomy. Each value for the radial keratotomy curve is theoretically 0.30 (30% or 1.2 lines) better than the historical reference grid values in Table 1, as found in our study. The curve for the control eyes is 0.05 (5% or 0.2 lines) lower than the historical reference grid. The best spectacle-corrected visual acuity (20/16) was the same for both groups. The variability (SD) was 1.77 times higher in the radial keratotomy group (0.67) than in the control group (0.39), as shown by the SD symbols.

of the cornea following radial keratotomy has been changed so that the best corrected visual acuity is no different but the uncorrected visual acuity is better. This relationship is illustrated in Fig 4 for a 3-mm pupil. This change in the optical configuration of the cornea creates a multifocal effect, as we postulated previously,[1] similar to that of the aspheric multifocal intraocular lenses presently under investigation by the Food and Drug Administration.[28]

With multifocal intraocular lenses, the twofold to threefold increase in the depth of field is accompanied by a best corrected visual acuity that is approximately one line lower than with monofocal lenses when the lens (ie, not the cornea or retina) is the limiting factor in the visual acuity. This one-line decrease in best corrected visual acuity is due to the 50% reduced contrast of the retinal image.[28] Previous studies have demonstrated the same relationship between decreased contrast and Snellen visual acuity.[29] In addition, there is a 0.20- to 0.30-log decrease in contrast sensitivity.[28,30]

Similarly, in our study, small changes in the configuration of the optical zone of the cornea produced by radial keratotomy increased the depth of field by 0.35 (35%), or six to 10 times less than that induced with multifocal intraocular lenses. Compared with the multifocal intraocular lens, the change in best corrected visual acuity induced by radial keratotomy would be expected to be negligible, as we found in our study. The decrease in contrast sensitivity following radial keratotomy also should be less than with multifocal intraocular lenses.[31-39]

In our study, the only correlation with better uncorrected visual acuity following radial keratotomy was in those eyes with a myopic change in the dilated refractions with and without the circular aperture. No other parameters (optical zone, residual refractive error, pupil size, or age) in the radial keratotomy eyes were correlated with better uncorrected visual acuity ($P<.05$). There was no correlation between the presence of positive or negative spherical aberration with the uncorrected visual acuity in the control group. We did not measure contrast sensitivity in this study.

Characterizing the Aspherical Optical Zone of the Cornea

The change in the dilated refraction with and without the circular aperture provides conclusive information as to the optical nature of the multifocal effect. In the control group, only 9% of the eyes had a change in their refraction with and without the aperture, and 7% were in a myopic direction. These results are consistent with previous measurements of the spherical aberration of the human eye.[40-45] In these previous studies, approximately 10% of the population had a myopic change at night, when the pupil dilated because the focus of the marginal rays of the eye was anterior to the focus of the paraxial rays. This phenomenon is known as positive spherical aberration (Fig 5). Ninety percent of humans have less than 0.50 D of refractive change with normal physiologic pupil dilation,[40-45] and a change in the hyperopic direction with dilation is extremely rare. These previous findings are comparable with those in our control group.

Change in refraction with the pupil dilated occurred in 9% of the controls and 36% of the radial keratotomy patients, indicating a significant difference ($P=.002$). The control group was similar to control groups in previously published studies of normal eyes.[40-45] These findings indicate that radial keratotomy increased the incidence of clinically significant (0.50 D) spherical aberration. Other investigators have reported cases with similar findings.[35,38,39] In our study, the change in refraction was almost equally split between the myopic (19%) and the hyperopic (17%) directions. The normal aspherical shape of the cornea has been clinically altered in these eyes (36%). Our study indicates that eyes with a myopic change (positive spherical aberration) had the best uncorrected visual acuity compared with control eyes and other radial keratotomy eyes. Better uncorrected vision with positive spherical aberration may be important in aspheric multifocal intraocular and contact lens design as well as anterior laser keratomileusis for determining the optimal shape of these aspheric surfaces.

Figure 5 demonstrates that the change in refraction with pupil dilation represents only a fraction of the total spherical aberration (difference in marginal and paraxial rays). The change in refraction with pupil dilation is from the focus of the paraxial rays to the circle of least confusion, not the focus of the marginal rays. Additionally, peripheral rays are not as effective as central rays in the human eye due to the Stiles-Crawford effect.[25-27] These studies show that corneal shape and power changes peripheral to 5.4 mm have very little effect on central vision.

Our method of measurement is what the patient experiences and the amount the clinician would correct with refraction (night myopia). Actual

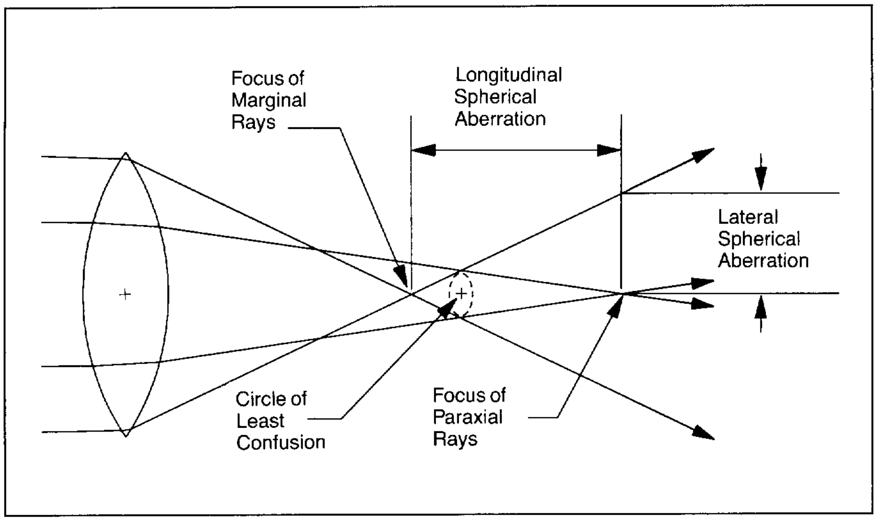

Fig 5.—Positive spherical aberration. In an optical system, if the marginal (peripheral) rays come into focus anterior to the paraxial (central) rays, the system exhibits positive spherical aberration. The clearest image is formed at the circle of least confusion, which is between the focus of the paraxial and marginal rays but is usually closer to the focus of the marginal rays. The change in refraction that occurs with pupil dilation is measured from the paraxial focus to the circle of least confusion, which is less than the total longitudinal spherical aberration. Negative spherical aberration also can occur if the marginal rays focus posterior to the paraxial rays; a hyperopic change in refraction would occur with pupil dilation in this condition.

spherical aberration measurements using an annular aperture or aberroscope[4] and peripheral keratometry measurements[46] confirm our results, but, as expected, the aberrations are of greater magnitude. Previous studies in normal patients comparing the change in refraction with dilation with the measured spherical aberration show that the measured spherical aberration may be two to six times greater than the change in refraction due to the location of the circle of least confusion and the Stiles-Crawford effect (Fig 5).[41]

Mechanism of Radial Keratotomy

Our findings contradict the traditional description of the corneal configuration following radial keratotomy, according to which the paracentral cornea flattens less than the central cornea, allegedly forming a relatively steeper "paracentral knee."[46] If this change occurred in the effective optical zone of the cornea (<5.4 mm), most patients who undergo radial keratotomy would have a myopic change with pupil dilation. If the knee formed at a diameter of 6 mm or greater, as one study has shown,[47] the knee would have a minimal effect on the refraction.

In fact, only eight radial keratotomy eyes (19%) had a myopic change with dilation. In eyes with a myopic change, an optical "paracentral knee" occurs within the effective optical zone of the cornea (<5.4 mm). All seven eyes (17%) that changed in the hyperopic direction with dilation would be considered to have changed as a result of radial keratotomy, since hyperopic changes rarely occur in the normal population. These eyes would be considered to have "paracentral flattening," with the knee outside the effective optical zone of the cornea.

In our study, 64% of the radial keratotomy eyes had no change in their dilated refraction as a function of pupil diameter. This indicates that, by clinical refraction, no significant change in the aspheric shape of the cornea occurred within the effective optical zone of their cornea. From physical considerations and corneal topographic studies,[46,47] there must be a "knee" present at some peripheral location in the cornea following a radial keratotomy, but our study demonstrates that this topographic change occurred outside the effective optical zone (>5.4 mm) of the cornea in at least 64% of our patients. Furthermore, the 36% whose refraction did change with the larger pupil diameter were almost equally split between positive and negative spherical aberration within the effective optical zone.

In conclusion, the radial keratotomy group maintained the same best spectacle-corrected visual acuity as the control group and the preoperative value, and radial keratotomy provided approximately a one-line improvement in uncorrected visual acuity for a given pupil diameter and refractive error compared with control eyes that were not operated on. The superior uncorrected visual acuity in radial keratotomy eyes was most apparent in individuals with a myopic change in their refraction (positive spherical aberration). Positive spherical aberration changed the asphericity of the cornea and was associated with the best uncorrected visual acuity. The increase in depth of field with the multifocal effect is also associated with a slight decrease in the contrast sensitivity,[31-39] which we did not measure. Additional studies clarifying the effects of radial keratotomy on contrast sensitivity and Snellen uncorrected visual acuity are still necessary to adequately characterize the effect of these changes on visual performance.

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