Role of Spherical Aberration in Contrast Sensitivity Loss with Radial Keratotomy

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A technique is described to determine the change in image contrast as a result of the spherical aberration induced by the radial keratotomy procedure. The hypothesis that the loss in contrast sensitivity of the RK eye is due to the change in spherical aberration postsurgically, is found to be acceptable for some patients. However, this is not a sufficient explanation in all cases. This conclusion may be due to assumptions inherent in the technique derived for calculating spherical aberration or to other factors of importance in the post-RK eye. Invest Ophthalmol Vis Sci 30:1997–2001, 1989

It has been reported by several investigators1–9 that some subjects show a measurable change in contrast sensitivity (CS) following radial keratotomy (RK). In some cases the losses reported appear transitory.2,6–8 In a recent study by Tomlinson and Caroline1 CS was measured 1 year postoperatively on six subjects who had undergone RK on one eye only. In three of these subjects it was found that the CS of the maximally corrected, operated eye was significantly reduced compared to that of the maximally corrected, unoperated eye. Assuming that the CS of the unoperated eye is similar to the preoperative CS of the fellow eye this implies a reduction in visual performance as a consequence of RK.

The losses in contrast sensitivity noted in this study1 are not found in all patients undergoing the procedure. It is of interest to discover the source of the visual loss found in some patients since this might allow anticipation of such consequences of RK. Several possibilities have been considered including increased glare,3 changes in corneal thickness4 and change in retinal image size.5 Another possibility, the one to be considered in this paper, is the loss of retinal image quality as a result of the change in spherical aberration of the post-RK cornea.

Since we have pre- and 1 year postoperative photokeratoscopic data on each of the eyes which underwent RK in the previous study, it is possible to estimate the visual effects of increased spherical aberration resulting from change in corneal shape. We have carried out such a calculation and have compared our results to the measured differences in CS for each of the subjects.

Technique of Calculation of Spherical Aberration with the Post-RK Eye

Typical photokeratoscopic data are shown in Figure 1. In order to analyze such data we make the simplifying assumption that the cornea can be approximated by a surface of revolution with an axis of symmetry that passes through the center of the pupil. We therefore averaged the eight powers around each of the nine rings giving a total of nine data (powers) for each cornea. Each of these powers corresponds to a position along a typical meridian of the surface of revolution which will approximate the cornea. It is straightforward, using a recursion method,10 to find the position of each of these points in a coordinate system in which the x-axis corresponds to the axis of symmetry and the origin is located at the vertex of the cornea (see Fig. 2). It is convenient to express the sagittal depth (X) as a function of the semi-chord length (Y). We have taken this function to be a sixth order polynomial,

\[ X = aY^2 + bY^4 + cY^6 \]  

(1)

and have used a least squares method to find the “best” values for the coefficients in Equation (1) by fitting Equation (1) to the nine data points. Typical pre- and postoperative results are shown in Figure 3. Notice that the sagittal depth of a point 4 mm from the center of the postoperative cornea is about 0.1 mm less than that for the preoperative cornea. This is typical for the corneas in this study and agrees with that expected from geometrical considerations. The sagittal height, s, of a spherical surface is the square of

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Fig. 1. An example of photokeratoscopic output. Eighteen data (powers) are given along each of four meridians. In this example, data are shown for one meridian only.

Fig. 2. Typical corneal profiles calculated from photokeratoscopic data. The left-hand profile in each pair is preoperative and that on the right, postoperative. Notice that the center of the postoperative cornea is, in each case, flattened by about 0.1 mm relative to a point 4 mm from the center.

Fig. 3. Calculated longitudinal spherical aberrations in diopters for postoperative (asterisks) and preoperative (open circles) corneas expressed as a function of distance from the center of the cornea (semi-chord length). Notice that the corneal spherical aberration has increased for each subject in the study except AR. Results for a spherical cornea are included for comparisons.

the semi-chord length divided by twice the radius of curvature, that is, \( s = h^2/(2r) \). Since the power, \( D \), of a refracting surface of index, \( n \), is given by, \( D = (n - 1)/r \), one finds immediately that the change in sagittal height for a unit change in power (ie, the derivative of \( s \) with respect to \( D \)) is \( h^2/(2(n - 1)) \). Putting the semi-chord length, \( h = 4 \text{ mm} = 0.004 \text{ m} \), and \( n = 1.34 \), \( ds/dD = 0.024 \text{ mm/diopter} \). Thus, a change in corneal power of 4 diopters, typical of the corneas in this study, leads to a reduction in sagittal height of about 0.1 mm.

The central flattening of postoperative corneas is quite apparent in Figure 2. One expected consequence of this is an increased spherical aberration. Treating the cornea as a single surface separating air from the aqueous of refractive index \( n \), it is a simple matter to calculate spherical aberration. An incoming ray parallel to the optical axis (symmetry axis) of each cornea described by Equation (1) will cross this axis after refraction. The dioptric difference between this position and the paraxial focus is a measure of corneal spherical aberration. Figure 3 shows pre- and postoperative spherical aberrations as a function of
distance from the center of the pupil (Y-coordinate) for each subject in the study. It should be noted that this calculation shows substantial increased spherical aberration following RK in all except one subject (AR).

**The Calculated Change in Image Contrast (MTF) Induced by Change in Spherical Aberration**

We have calculated the modulation transfer function (MTF) for each cornea approximated by Equation (1). In fact the MTF is simply a measure of image contrast expressed as a function of spatial frequency of sine-wave grating targets. It is expected that, because of increased spherical aberration, the postoperative corneas will produce a lower MTF (ie, lower image contrast) for all spatial frequencies. This loss in image contrast is then to be identified with, and compared to, the measured reductions in CS.

The MTF for an axial target is expressible as an integral over the overlap of two circles of unit radius with centers displaced by an amount, $s_2$, which is proportional to the spatial frequency of the target (Fig. 4a). Specifically,

$$M(s) = \pi^{-1} \int dudv \int_{\text{overlap}} X \cos \{W(u + s, v) - W(u - s, v)\}$$

where the integral of the spatial frequency of the target,

$$w = 2Rs/(57.3\lambda) \text{ cycles/deg}$$

In all calculations we have taken the wavelength to be $0.55 \times 10^{-7}$ mm. In Equation (2) the quantity $W$ is a phase in radians given by

$$W(u, v) = (2\pi/\lambda)[X - nL]$$

where $X$ is the sagittal depth of a point on the corneal surface. $L$ is the separation between this point and the reference sphere. The reference sphere is centered at the receiving plane and passes through the corneal vertex.

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**Fig. 4.** A schematic illustrating the components in a calculation of the corneal MTF. The region of integration in Equation (2) is the overlap of two circles of unit radius as shown in part (a). The parameter, $s$, is proportional to spatial frequency [Eq. (3)]. Part (b) illustrates the definition of the distance, $L$, separating the reference sphere and the cornea. The reference sphere is centered at the receiving plane and passes through the corneal vertex.

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**Fig. 5.** Ratios of calculated contrasts before RK ($C_1$) to those after RK ($C_2$) for four of the subjects in the study as a function of spatial frequency in cycles per degree (filled circles). Pupil diameters in each case are taken to be 3 mm. Notice that for each subject except AR there is a reduction in calculated image contrast after RK at each spatial frequency. Included for comparison are the experimental ratios of CS of the unoperated eye to those of the operated eye (crosses).
Fig. 6. A comparison of calculated image contrasts before RK (C₁) and after RK (C₂) for one subject. Notice that the results for a pupil diameter of 4 mm (filled triangles) are significantly reduced compared to those for a 5 mm pupil (filled circles). The corresponding experimental ratios of CS of unoperated to operated eye (crosses) are included for comparison.

reference sphere along a refracted ray (Fig. 4b) so is expressible as a function of the semi-chord length, Y. The reference sphere is centered at the receiving plane (the position on the optical axis at which image contrast is determined) and passes through the corneal vertex. Finally, in Equation (4), the sagittal depth, X, is expressible in terms of the semi-chord length, Y, through Equation (1), while Y is related to the variables u, v by

\[ Y = \sqrt{(u^2 + v^2)}, \]

The above equations completely determine the MTF for corneas described by Equation (1) if the pupil radius, R, and the position of the receiving plane are specified.

Comparison of Calculated Change in Image Contrast (MTF) and Measured Change in CS

We have calculated the MTF for each of the subjects included in this study. The changes in MTF as a result of RK are shown in Figures 5 and 6. In these figures the measured changes in CS in each case are included for comparison. The pupil radius in each case in Figure 5 has been taken to be 2.5 mm (diameter = 5 mm) and the position of the receiving plane has been determined by requiring that the image contrast at 22.4 cycles/deg is maximum.

Discussion

Calculated and measured reductions in image contrast are compared in Figures 5 and 6. It will be noted that the agreement is excellent for subject PP, but the calculated change is significantly larger than that measured for subject LJ (for the 5 mm pupil). For subject LT the measured change in CS is significant while the calculated change in MTF is not, and neither calculated nor measured changes are significant for subjects SM and AR. Thus, while it is interesting that calculated changes in image contrast have the right magnitudes, detailed agreement with measurements is not always good. In this regard we point out the dependence of the results on parameters that are difficult or impossible to control. One such parameter is pupil diameter. A concrete example is shown in

Fig. 7. Calculated changes in image contrast resulting from a fixed change in longitudinal spherical aberration represented as a function of the total spherical aberration of a hypothetical eye.
Figure 6 where the loss of image contrast for subject LJ is calculated for a 4 mm pupil. It will be noted that the results are in much better agreement with measurements than those using a 5 mm pupil.

A parameter that is more difficult to deal with is the unknown spherical aberration of the crystalline lens, which, although unchanged by RK, does contribute to the total spherical aberration of the eye. Thus, a tribute to the total spherical aberration of the eye. 14 The MTF of the eye depends on the total spherical aberration in a highly nonlinear manner. 15 Thus, a change in the MTF after RK depends not only on the change in spherical aberration of the cornea but also depends on the total spherical aberration of the eye including that of the lens. The complicated dependence of the MTF on spherical aberration seems to be a consequence of variations in the optimal position of the receiving plane. Thus, for relatively low amounts of spherical aberration the optimum position of the receiving plane is one-half of the distance between the paraxial focus and the peripheral focus (ie, the position on the optical axis intersected by the ray that goes through the edge of the pupil). 15 On the other hand, for somewhat higher amounts of spherical aberration the optimum position is close to one-quarter of the distance from the paraxial to peripheral focus. 15 The change in MTF for a fixed change in spherical aberration is entirely different in these two cases, as illustrated in Figure 7. This figure shows that a change in image contrast depends not only on the amount of change in SA (due, eg, to RK) but also depends strongly on the total SA arising from both cornea and lens. This dependence on total SA results from a shift in the optimum position of the receiving plane from a position halfway between the paraxial and peripheral foci at low total SA (p = 1/2, open triangles) to a position one-quarter of the distance from paraxial to peripheral foci at higher total SA (p = 1/4, filled circles). These results suggest that image contrast loss with RK may be much greater for an eye with small total SA than for an eye with a large amount of SA.

There are possible parallels between the effect of corneal shape on contrast sensitivity in the post RK eyes considered in this study and the reduced contrast sensitivity noted by Mannis et al in preoperative keratoconus. He has reported a loss in contrast sensitivity in eyes with keratoconus and apparently normal Snellen visual acuity. This loss may be due to corneal opacification or distortion found in the condition. These workers found an improvement in contrast sensitivity following corneal grafting which may have been attributable to a clearer media and/or the return to normality of the corneal profile. It is possible that the spherical aberration induced by the change in corneal profile in keratoconus contributed to the loss in contrast sensitivity.

In conclusion, the hypothesis that the loss in contrast sensitivity of the RK eye is due to the change in spherical aberration of the postsurgical cornea, is acceptable for some patients. However, it is not a sufficient explanation in all cases. This may be due to assumptions inherent in the technique derived for calculating spherical aberration, or to factors other than spherical aberration, in the post-RK eye. At present, work is in progress to test the validity of the hypothesis on a larger, independent sample of patients.

Key words: spherical aberration, contrast sensitivity, radial keratotomy

References