Corneal Asphericity Following Excimer Laser Photorefractive Keratectomy

Peter S. Hersh, MD, FACS; Shetal I. Shah; Jack T. Holladay, MD, FACS;
*Summit PRK Topography Study Group**

■ **BACKGROUND AND OBJECTIVE:** To analyze corneal asphericity following excimer laser photorefractive keratectomy (PRK) and its influence on clinical outcomes.

■ **PATIENTS AND METHODS:** A computer program (Holladay Diagnostic Summary, EyeSys Laboratories, Houston, TX) was used to qualitatively and quantitatively analyze the corneal asphericity of 132 patients 1 year following PRK for correction of myopia. Color maps depicting actual corneal asphericity as compared to the normal expected asphericity were reviewed, and quantitative values of asphericity were evaluated for associations with clinical outcomes of uncorrected visual acuity and spectacle corrected visual acuity, achieved refractive correction, a subjective glare/halo index, and subjective patient satisfaction, as well as standard corneal topography patterns and optical zone decentration following PRK.

■ **RESULTS:** Following PRK, all corneas exhibited a positive central asphericity, changing from a prolate (negative asphericity) to an oblate optical contour. There was a trend toward higher positive asphericity measurements with improving spectacle corrected visual acuity which was not statistically significant; such a relationship was not found with uncorrected visual acuity. A significant association was found between greater achieved refractive correction and increased postoperative positive asphericity. No association was found between postoperative asphericity and the glare/halo index, subjective patient satisfaction, topography pattern, or optical zone decentration.

■ **CONCLUSION:** Asphericity may be a useful quantitative descriptor of corneal optical contour following PRK. Greater positive central corneal asphericity is found with greater degrees of refractive correction. Further understanding of both the pre- and postoperative corneal contour and the consequent optical effects should aid in a better understanding of the optical outcomes of PRK.

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From the Department of Ophthalmology, UMDNJ-New Jersey Medical School, Newark, NJ; the Cornea and Laser Institute at Hackensack University Medical Center, Hackensack, NJ; the Department of Ecology and Evolutionary Biology, Princeton University, Princeton, NJ; and the Department of Ophthalmology, University of Texas Medical School, Houston, TX.

**Summit PRK Topography Study Group:*
Daniel Durrie, MD, Timothy Cavanaugh, MD, John Hunkeler, MD, Kansas City, MI, Marc Michelson, MD, John Owen, MD, Birmingham, AL, Michael Gordon, MD, San Diego, CA, Roger Steinert, MD, Carmen Puliafito, MD, Michael Raizman, MD, Boston, MA, Jay Pepose, MD, St. Louis, MI.

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Request reprints from Peter S. Hersh, MD, Department of Ophthalmology, UMDNJ-New Jersey Medical School, 90 Bergen St., Newark, NJ 07103.

INTRODUCTION

Excimer laser photorefractive keratectomy (PRK) has recently been approved by the United States Food and Drug Administration after undergoing clinical trials for the treatment of mild to moderate myopia with encouraging results to date. Currently, computer-assisted videokeratoscopy is able to produce an analysis of corneal surface curvature, producing color maps of corneal power based on the radii of curvature of the cornea at points interpolated from reflected rings.[1-3] Quantitative descriptors of corneal topography, such as the surface regularity index and surface asymmetry index[4] and the potential corneal acuity measurement,[5] have attempted to provide insight into the corneal optical contour following PRK. Seiler and co-workers have demonstrated a measurement which they describe as the effective spherical aberration.[6]

Corneal asphericity and contour measurement began in the middle of the 19th century when it was believed that the cornea was a perfect sphere.[7] In 1860, the German optician Knapp postulated that the cornea was not a sphere, but rather was a perfect spherocylinder.[8] This picture of the corneal optical contour was again revised in 1929 when Berg noted the cornea to be aspheric, flattening peripherally in an attempt, teleologically, to reduce the spherical aberration of the eye.[9]

Aspheric surfaces can be described by the expression of a three-dimensional X, Y, Z coordinate system: $Z = cp2/\{1+1-(1+Q)c^2p^2\},^{-1/2}$ where Z is the axis perpendicular to the cornea, c is the vertex curvature of the system, $p^2 = X^2+Y^2$ where X and Y describe coordinates on the surface, and Q is the asphericity. If Q is negative, the surface is prolate, flattening toward the periphery of the surface; a positive value for Q indicates an oblate surface, steepening as you move away from the vertex toward the periphery.[10] Quantitative determination of the asphericity of the human cornea has been accomplished using theoretical eye models. Lotmar determined corneal asphericity to be -0.29.[11] Mandell and co-workers estimated corneal asphericity at -0.25 to -0.15,[12] and Kiely found it to be -0.26.[13] Other studies have found corneal asphericity to be between -0.18 and -0.30.[14-16] A corneal asphericity of -0.26, for instance, indicates a surface that flattens peripherally by about 7%, as compared to a sphere at a distance of 5 mm from the pupil center.

In this study, we have analyzed topography maps in patients following excimer laser PRK using a new quantitative descriptor of corneal asphericity, and have investigated the relationship of postoperative asphericity to clinical outcomes of PRK including uncorrected visual acuity, spectacle corrected visual acuity, achieved refractive correction, a subjective glare/halo index, and subjective patient satisfaction following PRK, as well as to standard qualitative topography patterns and optical zone decentration.

PATIENTS AND METHODS

Background

This study used a new quantitative descriptor of corneal asphericity (Holladay Diagnostic Summary [HDS] profile difference map, EyeSys Laboratories, Houston, TX). Using radius of curvature values from the videokeratographic data, the HDS graphically depicts deviations from the idealized normal asphericity as a color map known as the "profile difference map," and also calculates the average asphericity of the cornea for a 4.5 mm area overlying the entrance pupil. The profile difference map is generated by first determining the average refractive power of the cornea over a 3 mm pupil zone, weighted by the Stiles-Crawford effect. The computer algorithm then creates an idealized corneal surface based on this refractive power by assigning a "normal" corneal asphericity value (Q) of -0.26, using the equation described by Atchinson.[10] The powers on this generated ideal surface are then compared point for point along each of 360 semimeridians with the power of the actual patient's cornea. A color map is thus generated, graphically depicting the differences of the clinical cornea from the idealized aspheric model. Green is the defined zero value, indicating no discrepancy between that particular point on the corneal surface and the normal expected corneal asphericity. Warmer colors using 0.50 diopters (D) bins denote a steeper than expected cornea, while cooler colors indicated peripheral flattening, which is greater than that expected based on normal corneal asphericity. To obtain the overall asphericity value for the cornea, the average of the deviations at each semimeridian over the central 4.5 mm area is calculated and each semimeridian is fit with an aspheric curve to determine the asphericity value for that semimeridian. The weighted average of the Q values for all semimeridians is then calculated, giving an overall asphericity value to the cornea.

Study Design and Data Acquisition

Profile distortion maps and aphericity values for 132 patients who had undergone PRK for correction of myopia were derived from standard computer assisted videokeratography data. In this report, videokeratography data taken 1 year following PRK was used in all cases. All patients fit the criteria for the United States Food and Drug Administration-monitored Phase III clinical trials of the Summit Technology, Inc. Excimer Laser (Waltham, MA) and were enrolled in the national multicenter study of the Summit laser for correction of myopia. Approvals from appropriate institutional review boards and informed consents had been obtained in all cases. The PRK procedure and preoperative and postoperative management are described elsewhere.[17] All patients were treated with either a 4.5 mm or 5.0 mm beam diameter with attempted corrections ranging from 1.50 to 6.00 D.

Profile distortion maps were qualitatively reviewed and asphericity values were collected on all patients. Patients were excluded from a specific analysis if necessary clinical data were unavailable.

Clinical And Topography Pattern Correlations

Asphericity data was compared with the patient's uncorrected visual acuity and spectacle corrected visual acuity, as well as with procedure decentration with respect to the center of the entrance pupil. The methodology used for measuring optical zone decentration is detailed elsewhere.[18] The data were also compared to a patient index of glare and halo, as well as subjective patient satisfaction. These two numerical values were obtained by having each patient complete a questionnaire in which they categorized their overall satisfaction on a scale ranging from 0 to a maximum of 5. Glare/halo effects were measured individually on an identical scale, with the index measured by taking the higher of the two values.

We had previously analyzed the corneal topography maps on this patient group and had defined seven treatment zone topography patterns:[17]

1. Homogeneous — showing a uniform flattening;
2. Smooth toric bowtie with axis (WA) — showing a symmetric treatment zone with a greater induced flattening in the steep preoperative axis;
3. Smooth toric bowtie against axis (AA) — showing a symmetric treatment zone with a greater induced flattening in the flat preoperative axis;
4. Irregularly irregular — showing generalized irregularities over the treatment zone (defined as more than one area measuring >0.5 mm and >0.50 D in power from other areas at the same radius from the optical zone center, or one area measuring >1.0 mm in size and 1.00 D in power which does not conform to the specific criteria of any other patterns described;
5. Keyhole/semicircular — showing topographic regions, quantitatively measuring >1.0 mm in size and 1.00 D of relatively less flattening, extending in from the periphery of the ablation zone (keyhole), or a general foreshortening of the ablation zone effect in one meridian (semicircular);
6. Central island — showing a central area of relatively less flattening measuring >1.0 mm in size and >1.00 D in power; and
7. Focal topographic variants (FTV) — showing a generally homogeneous pattern with topographic irregularities measuring <1.0 mm in size or <1.00 D in power.

Asphericity data were compared to these stratified topography categories to determine if this quantitative measurement correlated with the defined qualitative patterns. In addition, two pooled groups were defined — a regular group including homogeneous, toric-with-axis, and toric-against-axis and a broader irregular group including irregular, keyhole/semicircular, and focal topographic variant — and also analyzed for correlations with asphericity values.

Data Analysis

For all analyses, true mean visual acuities and PCA values were calculated using the logarithmic transformation of the Snellen values.[19] Associations between asphericity values and clinical outcomes were tested using Student's unpaired t tests for comparison of means. A significance level of 0.05 was used for all tests.

RESULTS

General Findings

Corneas following PRK were characterized by a change from a prolate conformation (negative asphericity) to an oblate optical contour (positive asphericity) (Fig. 1). Mean asphericity for all patients postoperatively was +1.05.

Clinical Correlations

Visual Acuity. One hundred thirty-two patients had their spectacle corrected visual acuity compared with their asphericity values (Table 1). A general trend

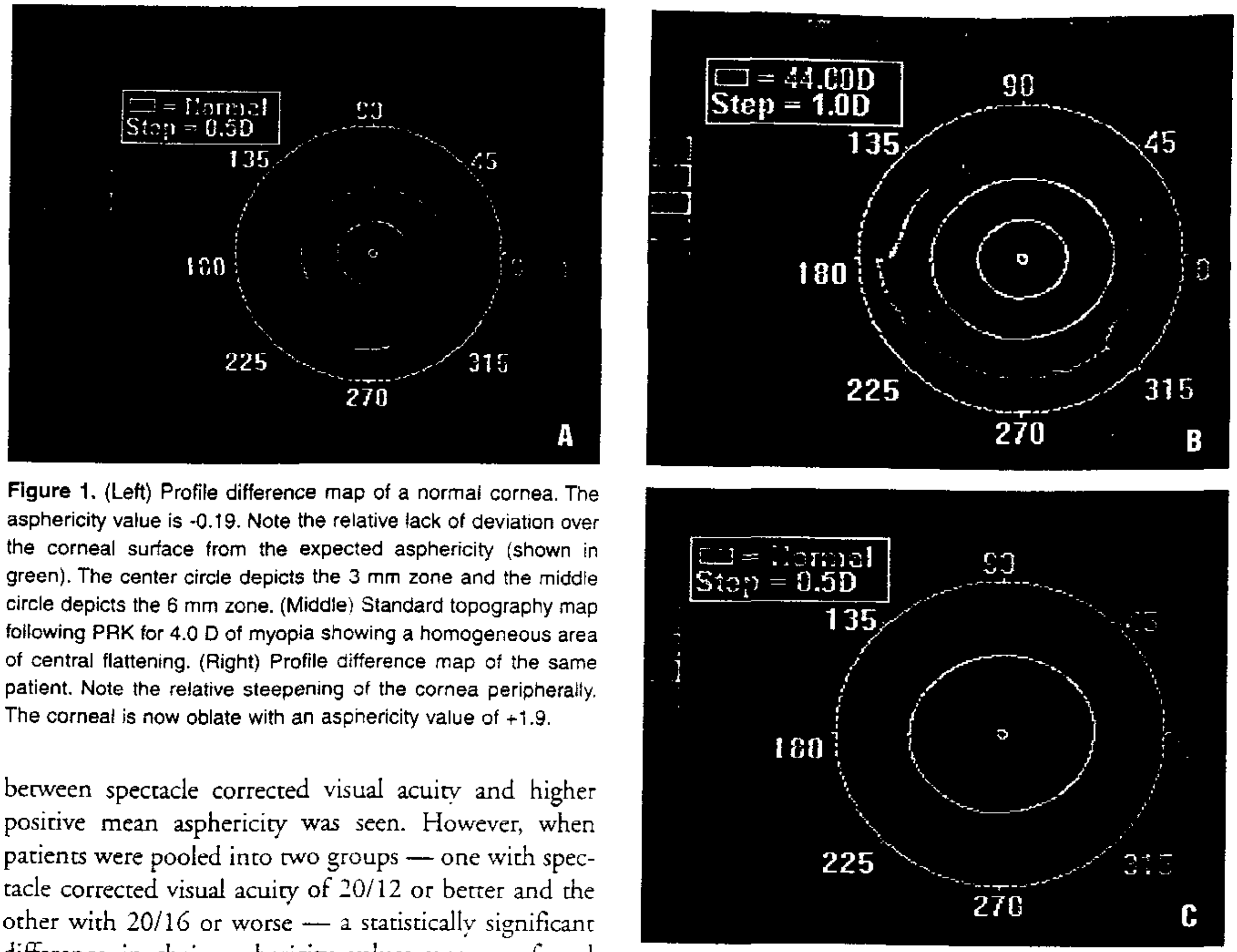

Figure 1. (Left) Profile difference map of a normal cornea. The asphericity value is -0.19. Note the relative lack of deviation over the corneal surface from the expected asphericity (shown in green). The center circle depicts the 3 mm zone and the middle circle depicts the 6 mm zone. (Middle) Standard topography map following PRK for 4.0 D of myopia showing a homogeneous area of central flattening. (Right) Profile difference map of the same patient. Note the relative steepening of the cornea peripherally. The corneal is now oblate with an asphericity value of +1.9.

between spectacle corrected visual acuity and higher positive mean asphericity was seen. However, when patients were pooled into two groups — one with spectacle corrected visual acuity of 20/12 or better and the other with 20/16 or worse — a statistically significant difference in their asphericity values was not found (P=0.35). No trend was seen for uncorrected visual acuity nor was there a statistically significant difference comparing asphericity values for those patients with uncorrected visual acuity of 20/20 or better and those with 20/25 or worse (Table 2).

Achieved Refractive Correction. Achieved refractive correction was available for 129 patients entered in the study. Corneal asphericity value was associated with achieved refractive correction. When patients were pooled into two groups — those with corrections between 0 and 4.00 D in one and those with corrections greater than 4.00 D in the other — a statistically significant difference was found, patients with higher corrections demonstrating greater positive corneal asphericity postoperatively (P=0.01) (Table 3).

Glare/Halo Index. The subjective reported glare and halo effects of 122 patients were analyzed for associations with asphericity measurements (Table 4). There was no association found either for the single indices or for patients stratified to either a glare/halo index of 0 to 2 or an index of 3 to 5 (P=0.11).

Subjective Patient Satisfaction. Table 5 shows the mean asphericity measurements stratified to subjective patient satisfaction with the results of the PRK procedure for 127 patients. There was no statistically significant association when looking at patients stratified to single satisfaction indices or pooled groups comprising satisfaction values of 0 to 3 or 4 to 5 (P=0.74).

Optical Zone Centration. Table 6 shows mean asphericity measurements stratified to 0.25 mm increments of optical zone decentration. Data were available on 123 patients for this analysis. There was no significant association between amount of decentration and mean asphericity measurement for either of these stratified subgroups or for two pooled groups comprising patients with either 0.50 mm or less of decentration or those with greater than 0.50 mm of decentration (P=0.21).

Qualitative Topography Patterns. Table 7 shows the mean PCA values for the different topography patterns for 114 patients. The homogeneous and toric-

TABLE 1

Spectacle Corrected Visual Acuity Versus Asphericity Value

SCVA	No. of Eyes	Mean Asphericity	SD
20/10	9	1.83	0.23
20/12	44	1.05	0.48
20/16	61	1.00	0.48
20/20	14	1.00	0.67
20/25	2	0.75	0.01
20/32	2	0.38	0.54

SCVA = spectacle corrected visual acuity

TABLE 2

Uncorrected Visual Acuity Versus Asphericity Value

UCVA	No. of Eyes	Mean Asphericity	SD
20/12	14	1.02	0.40
20/16	41	0.96	0.44
20/20	34	0.95	0.55
20/25	10	1.19	0.34
20/32	8	1.17	0.53
20/40	12	1.19	0.48
20/50	2	1.10	0.58
20/62.5	4	0.48	0.65
20/80	1	0.31	0.00
20/125	1	0.51	0.00
20/200	2	1.17	0.50
20/400	1	0.00	0.00

UCVA = uncorrected visual acuity

against-axis groups showed the greatest positive postoperative asphericity. However, when the variables were collapsed into two broader regular and irregular classifications, no statistically significant difference was found (*P*=0.16).

DISCUSSION

TABLE 3

Achieved Correction Versus Asphericity Value

Correction (D)	No. of Eyes	Mean Asphericity	SD
0 to 1.00	1	0.21	0.00
1.00 to 2.00	7	0.49	0.21
2.00 to 3.00	21	0.59	0.32
3.00 to 4.00	30	0.92	0.39
4.00 to 5.00	30	1.01	0.39
5.00 to 6.00	23	1.18	0.50
6.00 to 7.00	8	1.67	0.32
>7.00	7	1.64	0.26
Pooled 0 to 4.00 D	59	0.74	0.39
Pooled >4.00 D	70	1.20	0.48

The normal cornea is a prolate asphere. From a teleologic viewpoint, such negative asphericity partially ameliorates the spherical aberration of the eye's optical system. The normal corneal asphericity is dramatically changed by refractive surgical procedures.

Previous studies have shown that different patterns of corneal topography following PRK may affect both the objective and subjective visual outcomes of PRK.[3,17] In addition, various quantitative descriptors of corneal topography may also help explain outcomes of PRK.[3-5] Thus, an accurate measurement of the postoperative corneal contour may have importance in further elucidating the optical consequences of PRK. The current study uses a newly developed computer program to calculate the corneal asphericity and compare it graphically to a "normal" corneal contour.

As expected, the overall corneal shape following PRK changed from a prolate to an oblate configuration. Moreover, the degree of induced positive asphericity was associated with the achieved refractive correction. This was expected, because the central cornea is progressively flattened by higher corrections while leaving the periphery at its natural contour.

No other statistically significant associations with clinical outcomes were found in this study. This was somewhat surprising, because optical aborations secondary to altering this normal asphericity might be expected. Such effects would likely manifest in psychophysical symptoms, such as glare and halo symptoms. This was not found in the current study. One explanation may lie in the size of the pupil. Because most entrance pupil diameters are smaller than the diameter of the optical zone even in this study using

TABLE 4

Glare/Halo Index Versus Asphericity Value

Glare/Halo Index	No. of Eyes	Mean Asphericity	SD
0	20	0.85	0.62
1	35	1.04	0.44
2	24	0.88	0.43
3	26	1.13	0.48
4	9	1.14	0.52
5	8	0.94	0.48
Pooled 0 to 2	79	0.94	0.49
Pooled 3 to 5	43	1.09	0.48

TABLE 5

Subjective Patient Satisfaction Versus Asphericity Value

Satisfaction	No. of Eyes	Mean Asphericity	SD
0	4	0.62	0.56
1	7	1.23	0.62
2	8	1.18	0.45
3	14	0.93	0.52
4	27	1.03	0.51
5	67	0.96	0.48
Pooled 0 to 3	33	1.02	0.54
Pooled 4 to 5	94	0.98	0.49

beam diameters of 4.5 or 5.0 mm, the pencil of light rays external to the optical zone would not enter the eye and thus not have a profound influence on clinical optical outcomes.[20] Analyzing objective data, such as contrast sensitivity data, may reveal psychophysical effects of asphericity changes not uncovered in this study. In addition, further studies may assess the effect of pupil size on these outcomes. For instance, as the pupil dilates in low light situations bringing the junction of the optical zone and untreated cornea over the entrance pupil, increased optical aberration with defocused rays may reduce the contrast of retinal images similar to the experience with multifocal intraocular lenses.[21] While high contrast Snellen acuity may not be significantly affected, patients may notice glare and halo and low contrast acuity, theoretically, may be reduced.

TABLE 6

Optical Zone Decentration Versus Asphericity Value

Decentration (mm)	No. of Eyes	Mean Asphericity	SD
≤ 0.25	28	0.92	0.45
0.25 to 0.5	35	1.11	0.49
0.5 to 0.75	32	0.88	0.50
0.75 to 1.00	19	0.79	0.51
1.00 to 1.25	8	1.30	0.39
1.25 to 1.50	1	1.18	0.00
Pooled ≤ 0.50	63	1.02	0.47
Pooled > 0.50	60	0.92	0.51

In similar work, Seiler and co-workers have measured what they describe as the effective spherical aberration.[6] Using standard topography data based on axial radius of curvature and Snell's law, these investigators projected the refractive contribution of each point on the cornea onto the retina. Contributions were weighted by the Stiles-Crawford effect, so that those projections nearer the center of the pupil contributed more than those nearer the periphery. The resulting array of focal points were then analyzed to determine a weighted focal distribution and an effective spherical aberration index. Using this quantitative descriptor, these investigators did find an association of asphericity with patients experiencing glare following PRK. In other work, Seiler and co-workers suggested aspheric PRK to avoid such optical side effects.[22]

Asphericity was not associated with either procedure decentration or our qualitative characterization of topography patterns in this group of patients, suggesting that asphericity alone is not the cause of the different outcomes found in these various patient subsets.[17,18]

It should be stressed that this study involved the use of one manufacturer's excimer laser. The findings presented here, therefore, may be specific to this particular laser and not necessarily applicable to PRK in general. Moreover, idiosyncrasies of the topography instrumentation may also influence the results found in this study. Placido disc-based topography systems, such as the EyeSys unit, may have idiosyncrasies in the reconstruction algorithms used, which may affect the quantitative analysis of corneas following PRK.[23] For instance, in a previous study, we demonstrated quantitative cross-sectional power profiles of the optical zone following PRK that suggested a diminution in myopic correction as the periphery of the treatment zone was reached, thus increasing the measured magnitude of positive asphericity created by the treatment.[17] However, this might be in error. Assuming a relatively spherical surface, data from the current topography unit are averaged across meridians, thus tending to "smooth" the relatively sharp power transitions that would be expected to occur in the bispheric surface following PRK. Such averaging would artificially magnify our measurements of positive asphericity this finding because the higher midperipheral powers of the nontreated cornea would be averaged into the periphery of the treated zone, thus improperly increasing the actual power value.

The development of quantitative descriptors of corneal topography should greatly aid our general understanding of corneal topography following PRK. The influence of corneal topography characteristics as determined by carefully controlled clinical studies may then suggest changes in the laser ablation algorithm to give a postoperative corneal optical surface which affords both the best possible objective and subjective visual results for the patient. Further development of descriptors such as asphericity measurements thus should be of great use in defining the corneal surface and evaluating optical function following PRK.

TABLE 7

Topography Classification Versus Asphericity Value

Topography Pattern	No. of Eyes	Mean Asphericity	SD
Homogeneous	67	1.04	0.52
Toric-with-axis	16	0.85	0.46
Toric-against-axis	3	1.25	0.44
Irregular	19	0.87	0.49
Keyhole/semicircular	4	0.87	0.59
Focal topographic variant	5	0.87	0.26
Pooled regular groups	86	1.01	0.51
Pooled irregular groups	28	0.87	0.46

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