

Figure 1: Schematic of the simple "shape-subtraction" paradigm for correction of myopia. R_1 and R_2 are initial and final radii of curvature; t_0 is the maximum depth of the laser cut; S is the diameter of the optical zone. Reprinted from Munnerlyn et al.

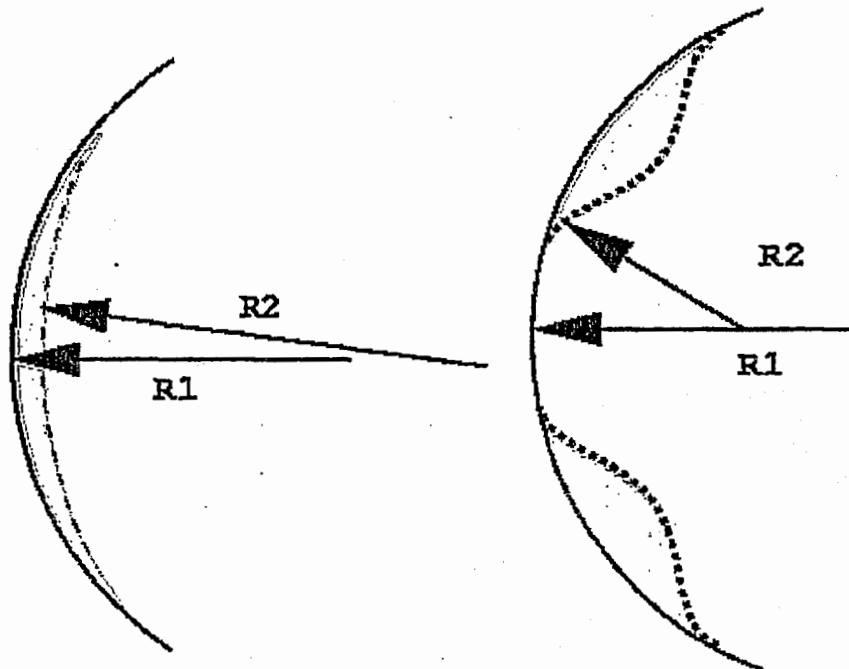


Figure 2: Schematic diagram of shape-subtraction model of refractive surgery for a myopic ablation (left) and hyperopic ablation (right). The pre-operative radius of curvature is R_1 and the desired post-operative curvature is R_2 . The maximum ablation depth is determined by the ablation zone size. The intervening tissue, shown in red, between the pre-operative curve (solid) and post-operative curve (dashed/dotted) is "subtracted" with an excimer laser to produce the desired result.

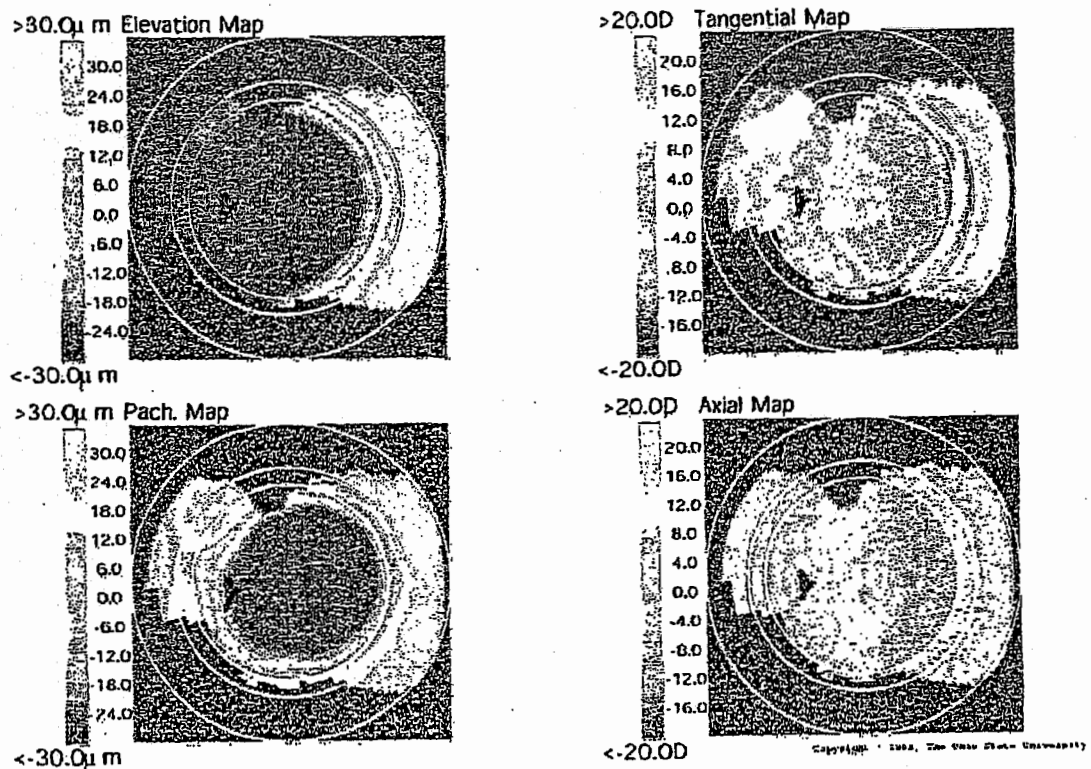
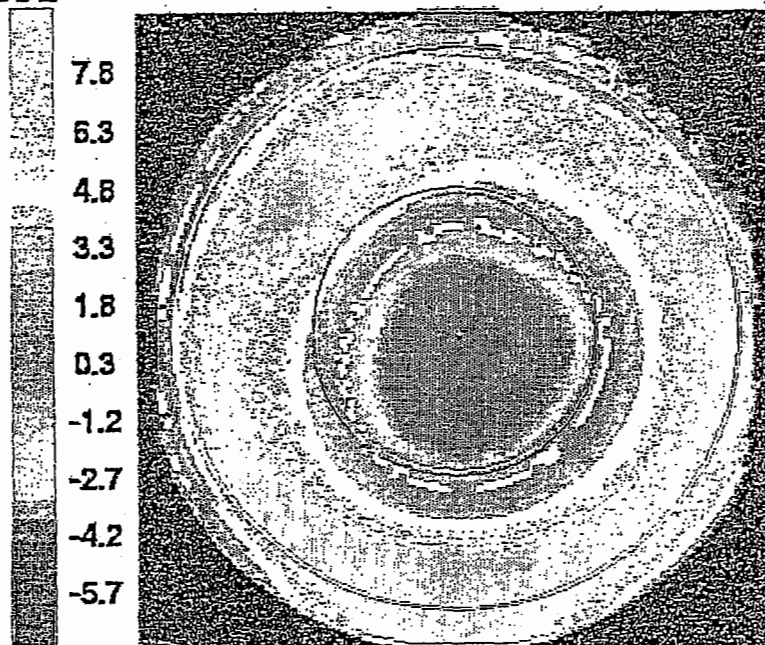


Figure 3: Post-operative minus pre-operative elevation (upper left), pachymetric (lower left), tangential curvature (upper right) and axial (lower right) *difference* maps, measured with an Orbscan II for a patient with a 6mm ablation zone. The white circles define three corneal regions. The central region has radius 2.75mm, the middle region has radius 2.75 to 3.25mm and the outer region has radius 3.25 to 4.5mm. Elevation (upper left) differences were calculated by fitting the two surfaces in the middle region. Note the increases in elevation, pachymetry and tangential curvature in the region *outside* the ablation zone.

Tangential Map >7.8D



<-7.2D

Figure 4: Tangential curvature difference map (post-op minus pre-op) after a -12.5 diopter LASIK procedure with a 5.5mm diameter ablation zone. White pixels indicate zero difference. Central red circle is at 4mm diameter and outer white circle is at 8mm diameter. Note the increased curvature outside the ablation zone.

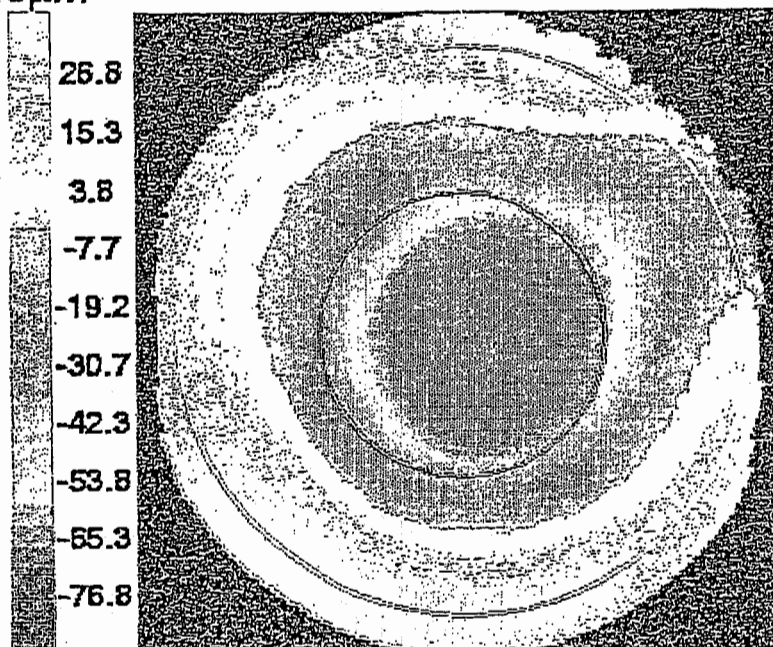
Pachymetry Map**>26.8 μ m****<-88.3 μ m**

Figure 5: Pachymetry difference map (post-op minus pre-op) after a -12.5 diopter myopic LASIK procedure with a 5.5mm diameter ablation zone. White pixels indicate zero difference. Central red circle is at 4mm diameter and outer white circle is at 8mm diameter. Note the increased pachymetry outside the ablation zone.

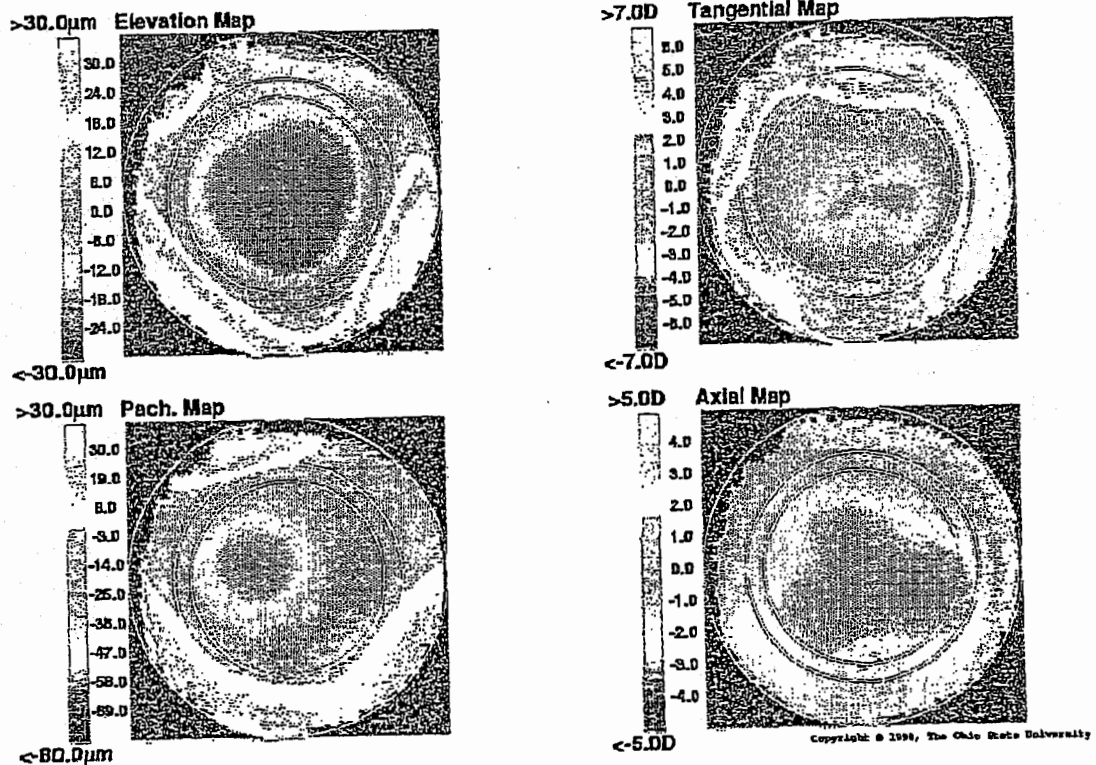


Figure 6: Post-op minus pre-op difference maps from a -2.25 diopter LASIK correction with a 6mm diameter ablation zone. Topography was acquired using Orbscan and exported for analysis using custom software. The inner, middle and outer white circles have radii of 2.75mm, 3.25mm and 4.5mm, respectively. The central zone within the inner circle lies within the ablation zone. The edge of the ablation zone is contained within the annulus between the center and middle circle. Expected central decreases in elevation, pachymetry, and curvature are seen as negative differences on the respective maps. However, unexpected increases in elevation, pachymetry and curvature have occurred outside the ablation zone, due to the biomechanical response of the cornea to a change in its structure. This is seen within the annulus between the middle and outer circles, where the redder colors represent increases.

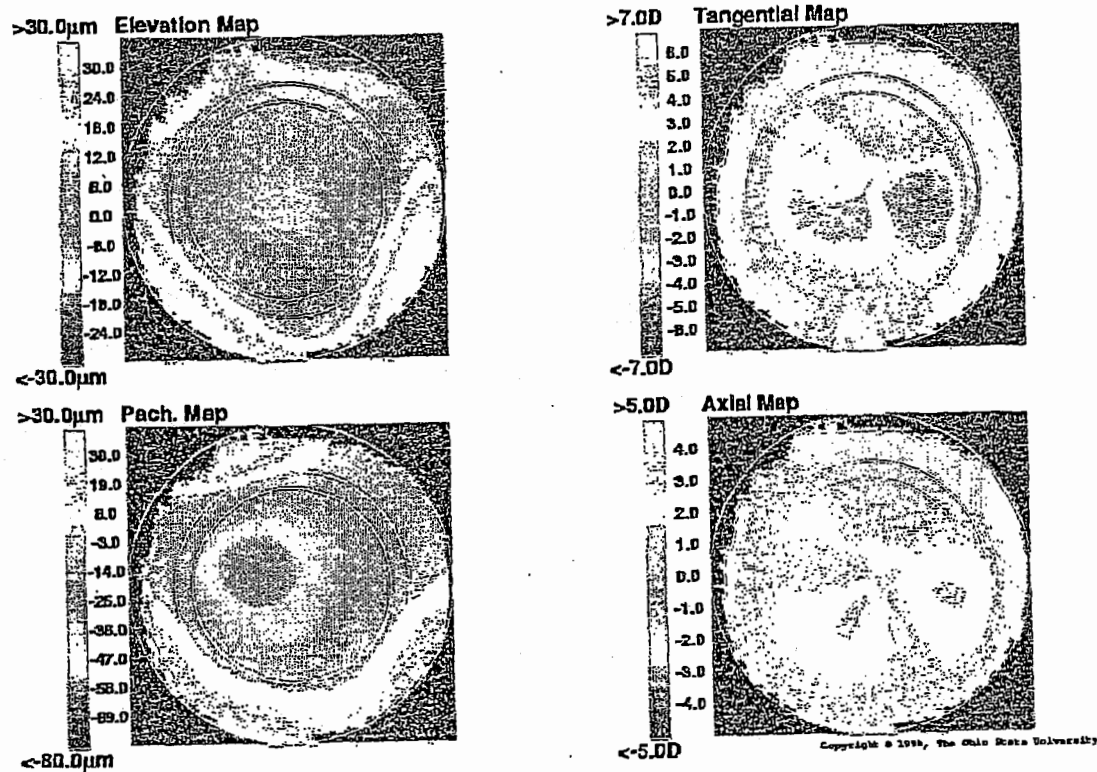


Figure 7: Error maps of actual minus predicted post-op topography for the same subject as Figure 6. Predicted post-op topography was generated by calculating an estimated ablation profile using Munnerlyn's formulas and subtracting it from the pre-operative raw elevation. Predicted curvature was then calculated along corneal meridians. Note that both the elevation and pachymetry error maps demonstrate less than predicted central values (or greater than expected ablation depth), as indicated by negative numbers and blue color. However, both maps also paradoxically show greater than predicted differences outside the ablation zone. The tangential curvature error map also shows greater than expected curvature change outside the ablation zone. Centrally, the values range from less than predicted to greater than predicted, with overall less error than outside the ablation zone. These errors are consistent with the biomechanical model proposed herein.

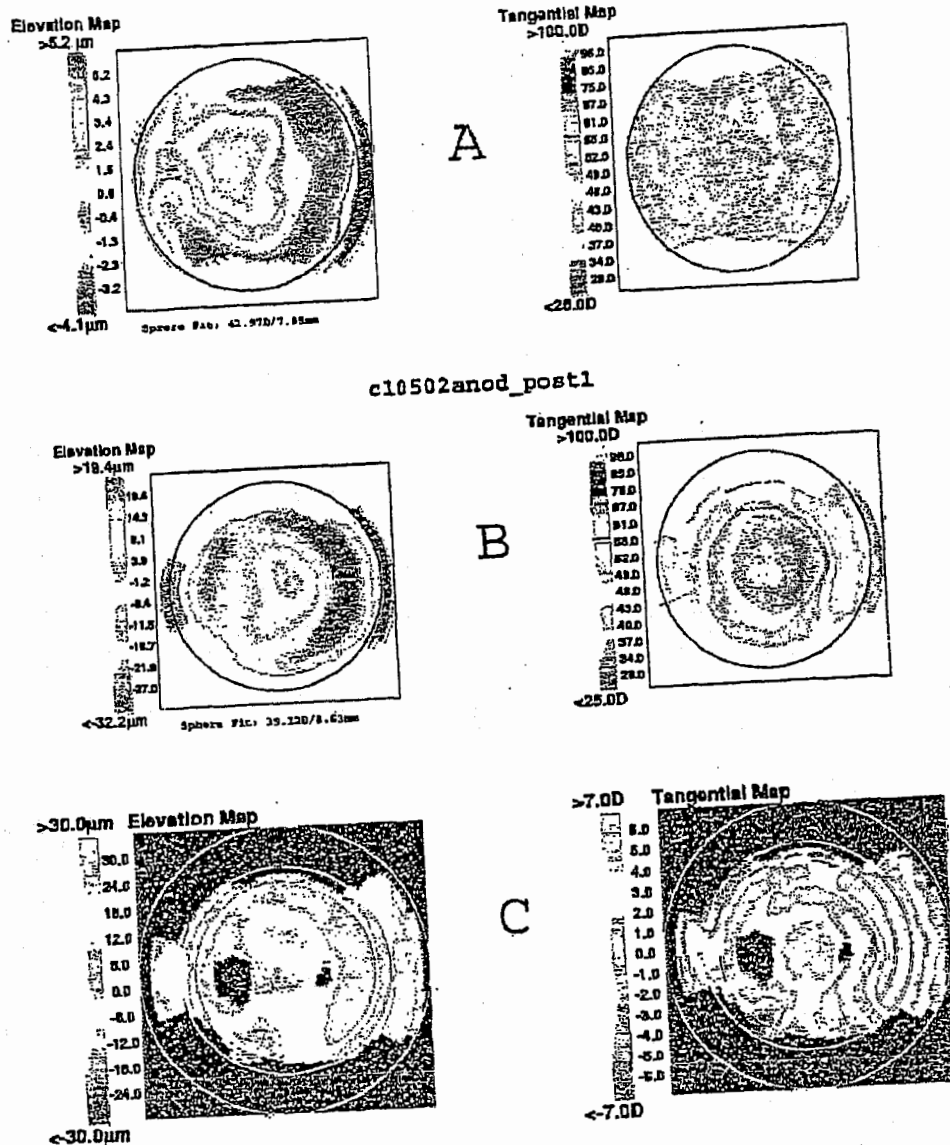


Figure 8: A) Pre-operative elevation (left) and tangential curvature (right). B) Post-operative elevation (left) and tangential curvature (right) after a -7.63 diopter LASIK procedure. C) Elevation error map (left) and tangential curvature error map (right) generated by subtracting known ablation algorithms (supplied by Summit Technologies) from the pre-operative topography (A) and generating a predicted post-operative topography, which was subtracted from the measured topography (B) to create the difference maps shown in (C). The red area in the center of the tangential error map represents the central island pre-treatment and the outer red area represents the biomechanical response of the cornea.

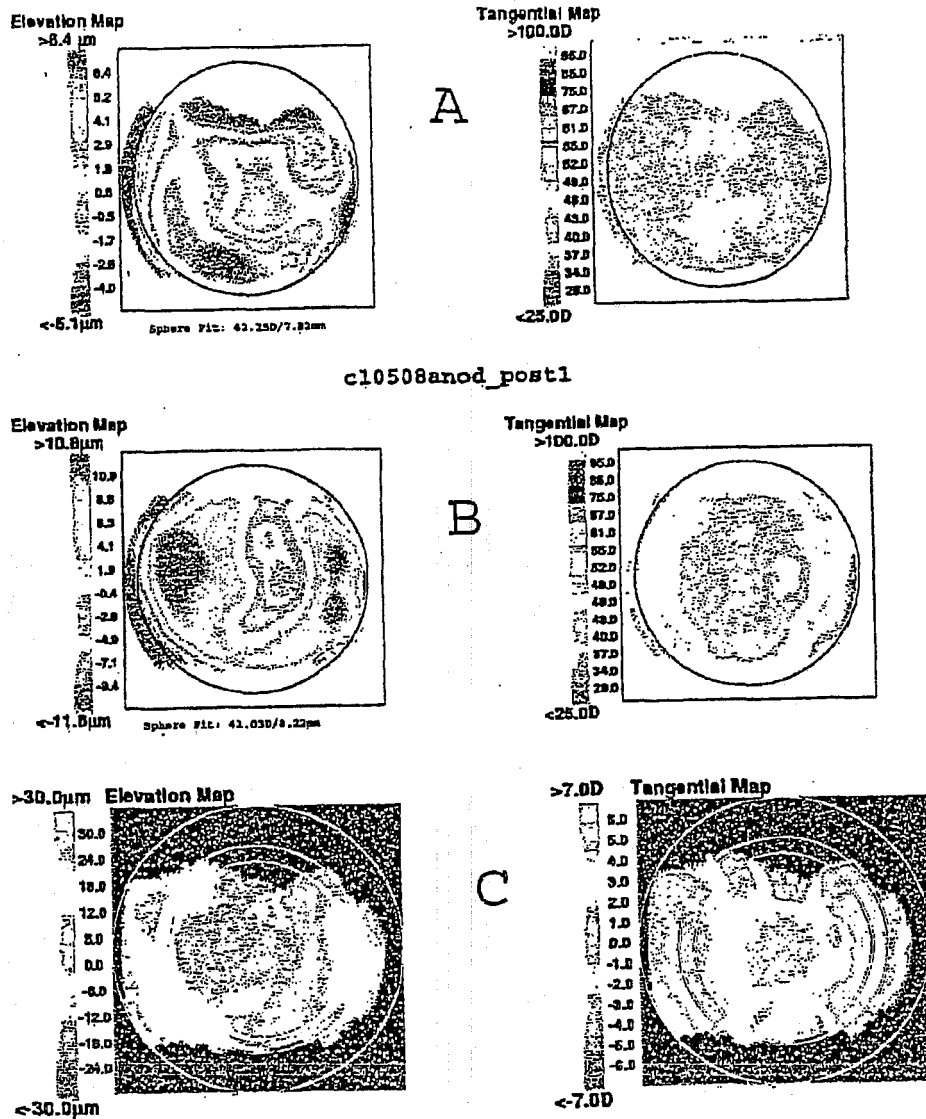
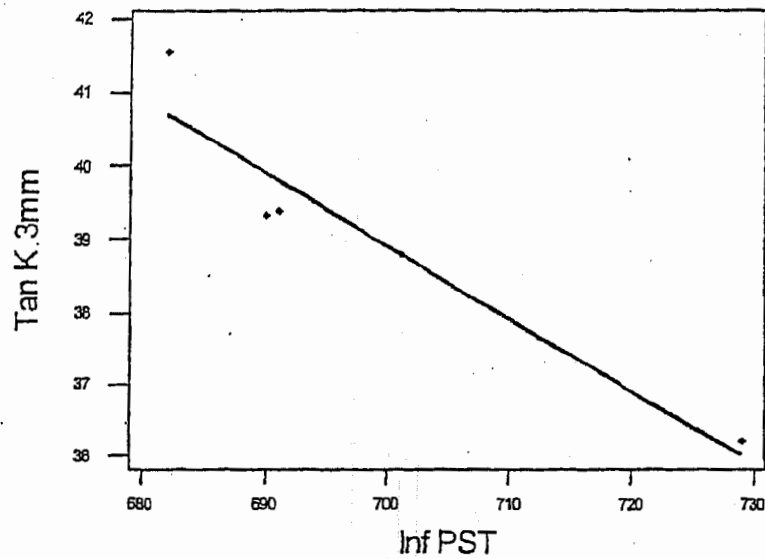


Figure 9: A) Pre-operative elevation (left) and tangential curvature (right). B) Post-operative elevation (left) and tangential curvature (right) after a -3.82 diopter LASIK procedure. C) Elevation error map (left) and tangential curvature error map (right) generated by subtracting known ablation algorithms (supplied by Summit Technologies) from the pre-operative topography (A) and generating a predicted post-operative topography, which was subtracted from the measured topography (B) to create the difference maps shown in (C). The red area in the center of the tangential error map represents the central island pre-treatment and the outer red area represents the biomechanical response of the cornea.

9/28

Regression Plot

$$Y = 108.863 - 9.99E-02X$$
$$R-Sq = 91.3 \%$$



Regression Plot

$$Y = 99.1080 - 8.16E-02X$$
$$R-Sq = 88.3 \%$$

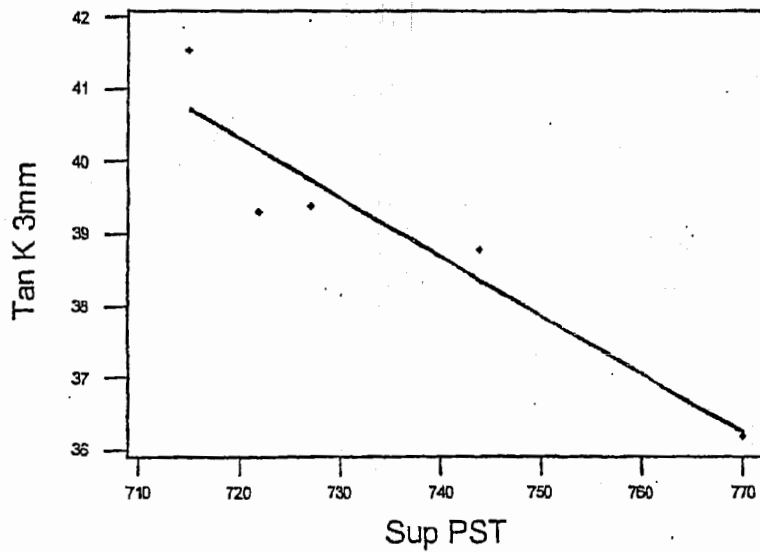


Figure 10: Regression analysis of peripheral stromal thickness of the superior region (upper plot) and inferior region (lower plot) against curvature in the central 3 mm region, pre-operatively and at 4 time points post-operatively after PRK in one patient. This demonstrates how central curvature for this patient closely tracked peripheral stromal thickness over time.

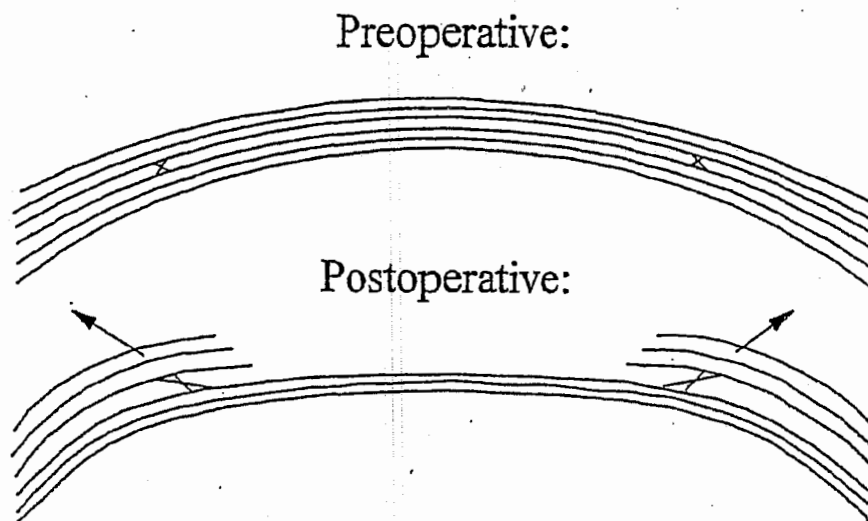


Figure 11: A conceptual model that predicts biomechanical central *flattening* as a direct consequence of severed corneal lamellae. (A- TOP) The pre-operative cornea may be conceived as a series of stacked rubber bands (lamellae) with sponges between each layer (interlamellar spaces filled with ground substance or matrix). The rubber bands are in tension, since there is a force pushing on them from underneath (intraocular pressure), and the ends are held tightly by the limbus. (B- BOTTOM) After myopic laser refractive surgery, a series of lamellae are severed and obliterated centrally. The remaining peripheral segments relax, just like the taut rubber bands would relax once cut. With the reduction of tension in the peripheral lamellae, the squeezing force on the matrix is reduced and the distance between lamellae expands, analogous to the sponges taking up water if the rubber bands are cut. This allows the periphery of the cornea to thicken. Due to the crosslinking between lamellar layers, the expansion force pulls on the underlying intact lamellae, as indicated by the arrows pointing radially outward. An outward force in the periphery pulls laterally on the center and flattens it. Thus, the cornea will flatten centrally with any procedure that circumferentially severs lamellae. This includes myopic profiles, hyperopic profiles, constant depth-PTK profiles, as well as the simple cutting of a LASIK flap.

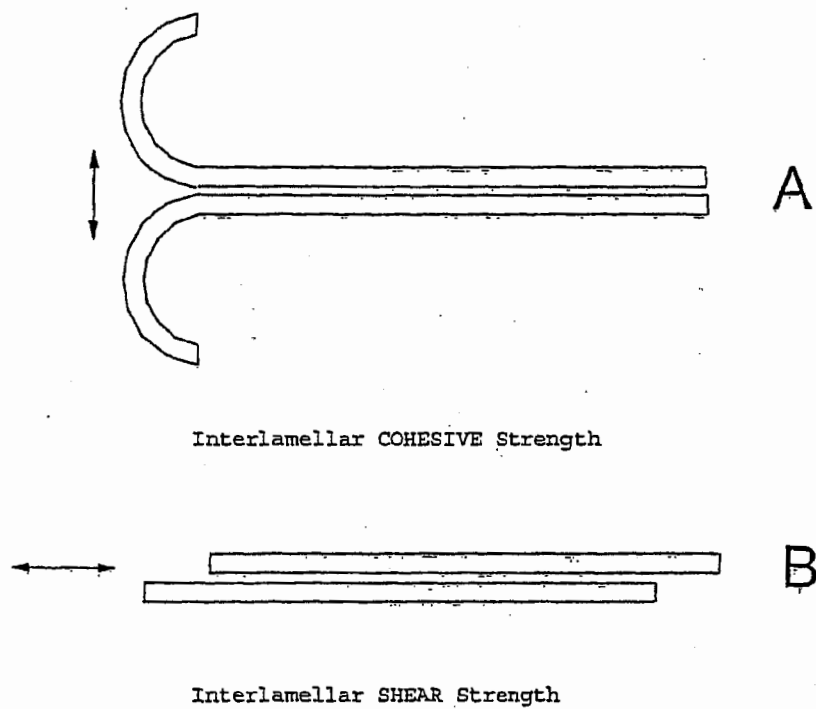


Figure 12: A schematic diagram of the forces described by A) the interlamellar cohesive strength and B) the interlamellar shear strength.

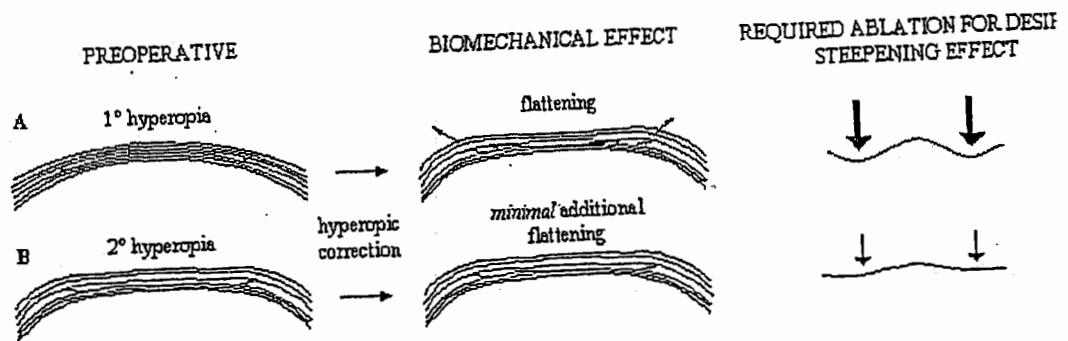


Figure 13: Proposed impact of biomechanics on LASIK nomograms for primary and secondary hyperopia. Biomechanical flattening opposes corneal steepening in attempted corrections of hyperopia. This effect is more pronounced in previously untreated corneas (1° hyperopia, A) and requires compensatory enhancement of the ablation profile to achieve the desired steepening effect. Corneas of eyes that are hyperopic after previous surgical overcorrection (B) are less "loaded" biomechanically; i.e., peripheral expansion (blue x's) and associated central flattening have already occurred. Accordingly, profile effects are opposed to a lesser degree and little or no enhancement of the ablation profile is required. Corneal geometry is exaggerated for illustrative purposes.

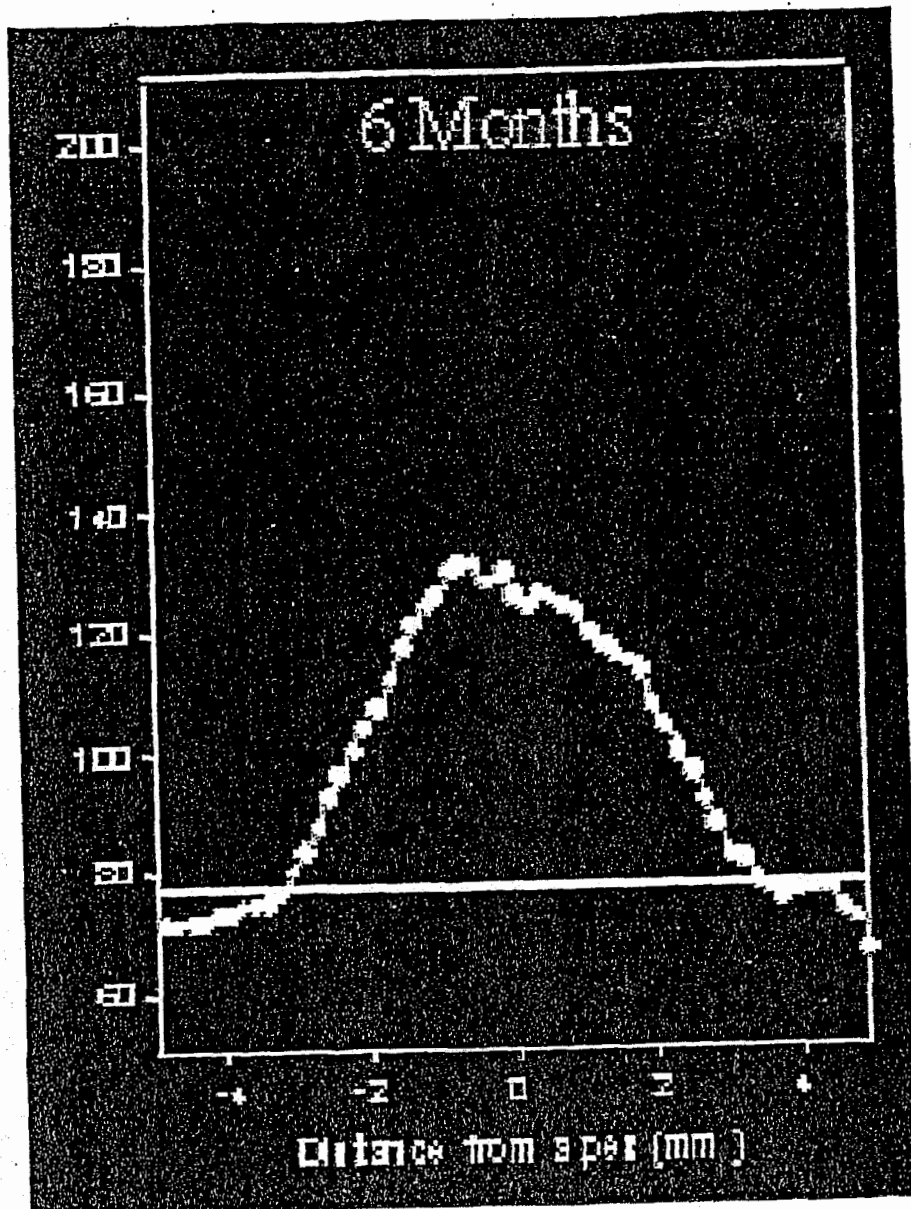
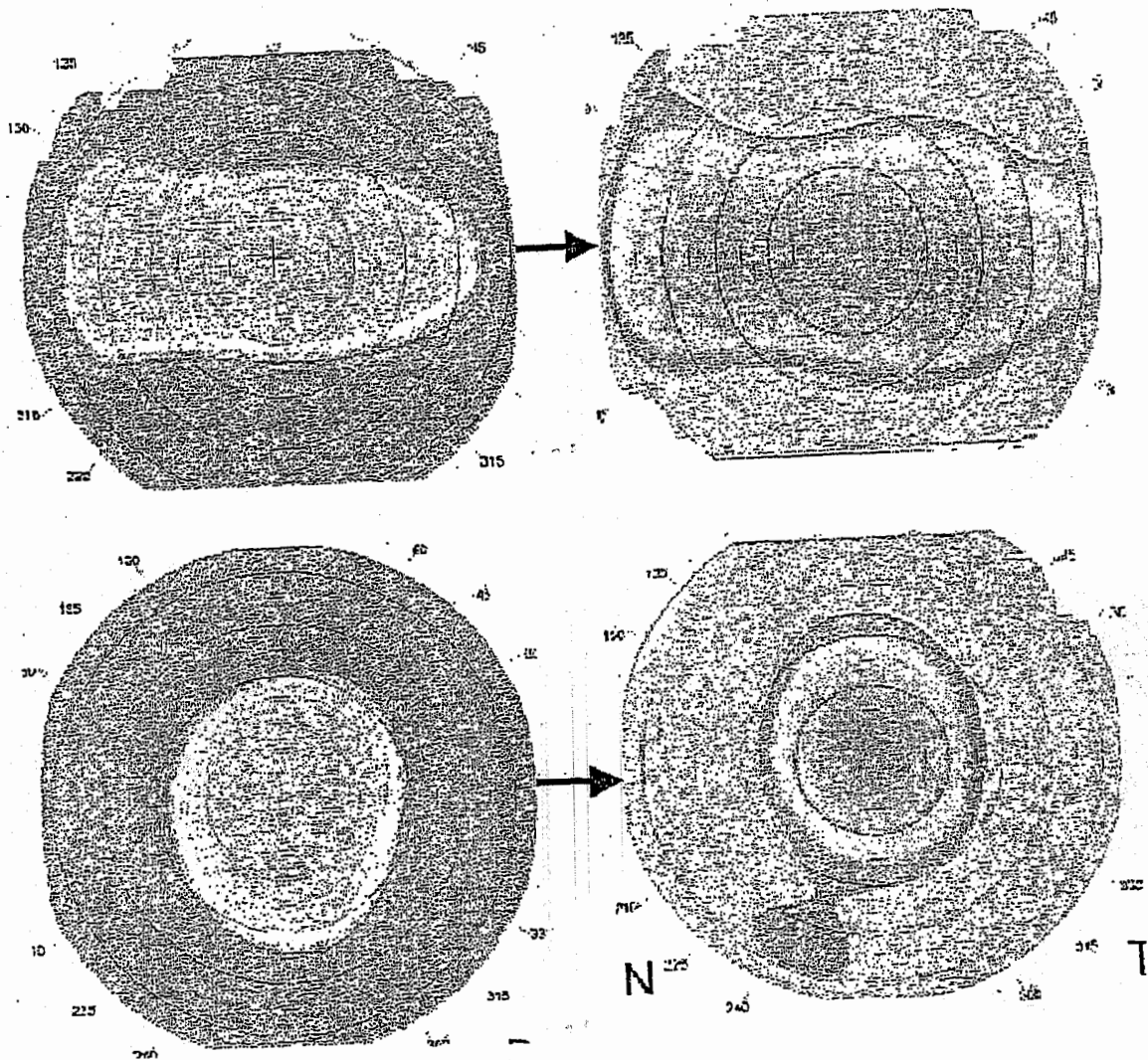


Figure 14: Sample ablation depth profile calculated at 6 months after PRK by subtracting pre-op minus post-op height with an offset, measured by a PAR Corneal Topography System. Maximal ablation depth is seen at the center of the profile near the apex. The edges of the ablation zone are seen as knees in the profile at approximately ± 3 mm from the apex at the intersection with the horizontal white line, which depicts a relative zero depth. Outside the ablation zone, the depth profile falls below the relative zero line, indicating a "negative" depth of ablation or increased elevation. Increased elevation of the unablated corneal periphery is consistent with the proposed biomechanical model.



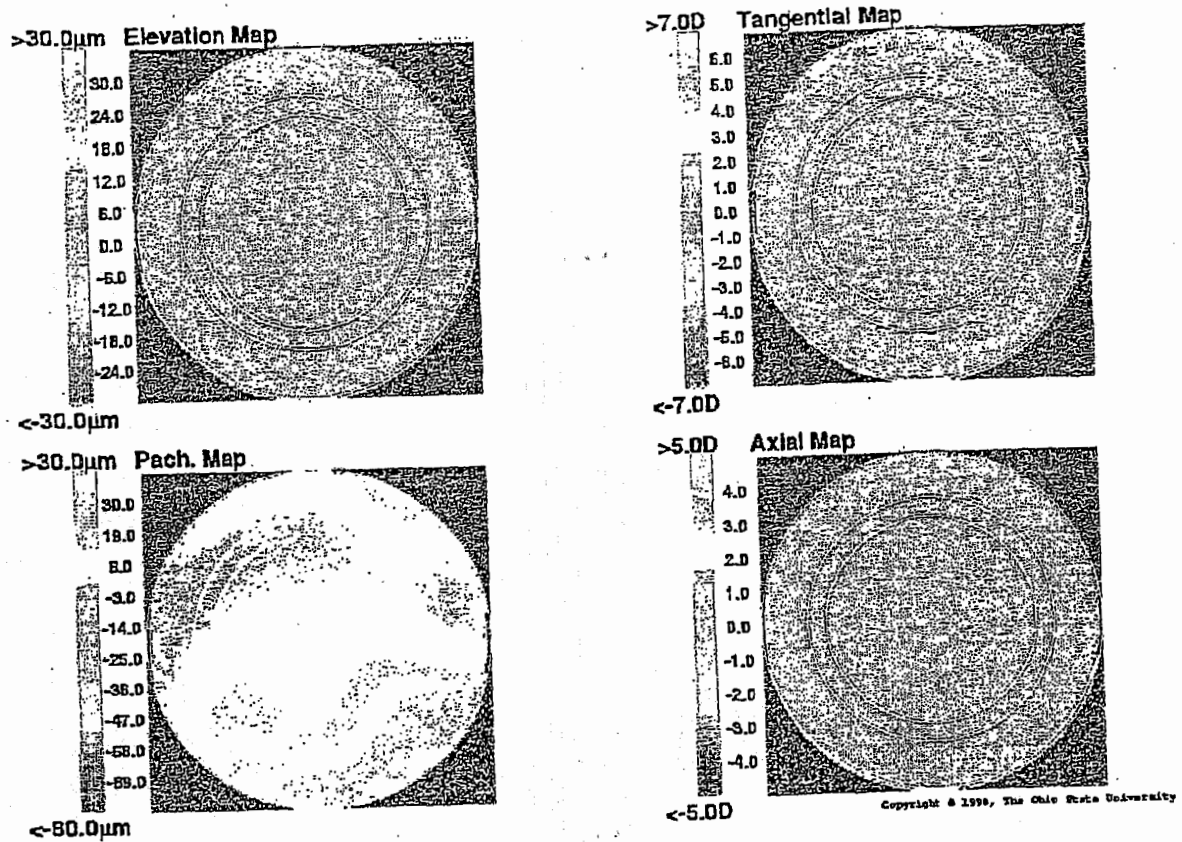


Figure 16: Average Difference Maps between repeated measures of 20 eyes of 10 normal subjects. The white circles define three corneal regions. The central region has radius 2.75mm, the middle region has radius 2.75 to 3.25mm and the outer region has radius 3.25 to 4.5mm. Elevation (upper left) differences were calculated by fitting the two surfaces in the middle region. Average tangential differences (upper right), average pachymetry differences (lower left) and average axial differences (lower right) are also given.

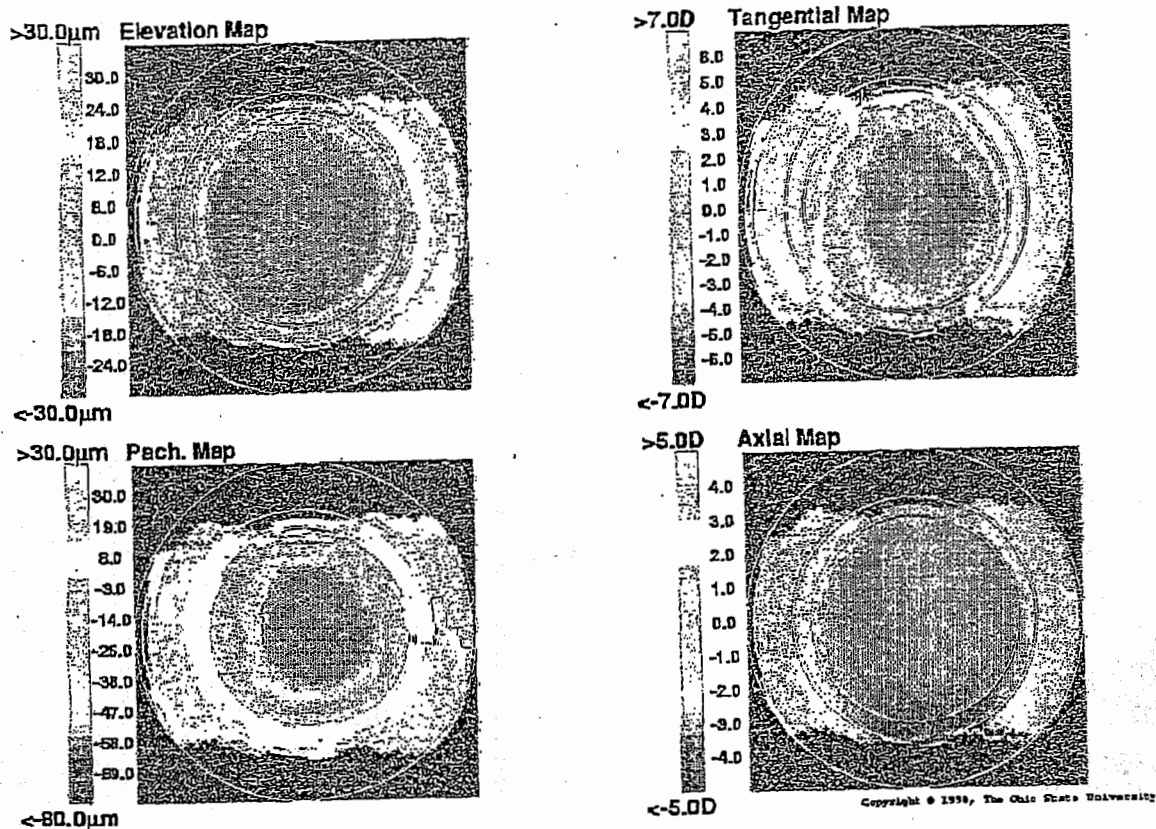


Figure 17: Average difference maps between 1 day post-op LASIK and pre-op state for 8 eyes of 4 patients. The white circles define three corneal regions. The central ablated region has radius 2.75mm, the middle transitional region has radius 2.75 to 3.25mm and the outer non-ablated region has radius 3.25 to 4.5mm. Elevation (upper left) differences were calculated by fitting the two surfaces in the transitional region, and demonstrate increased elevation in the outer zone. Average tangential differences (upper right) show increased curvature in the outer region. Average pachymetry differences (lower left) show increased pachymetry in the outer region after surgery. Average axial differences (lower right) are also given.

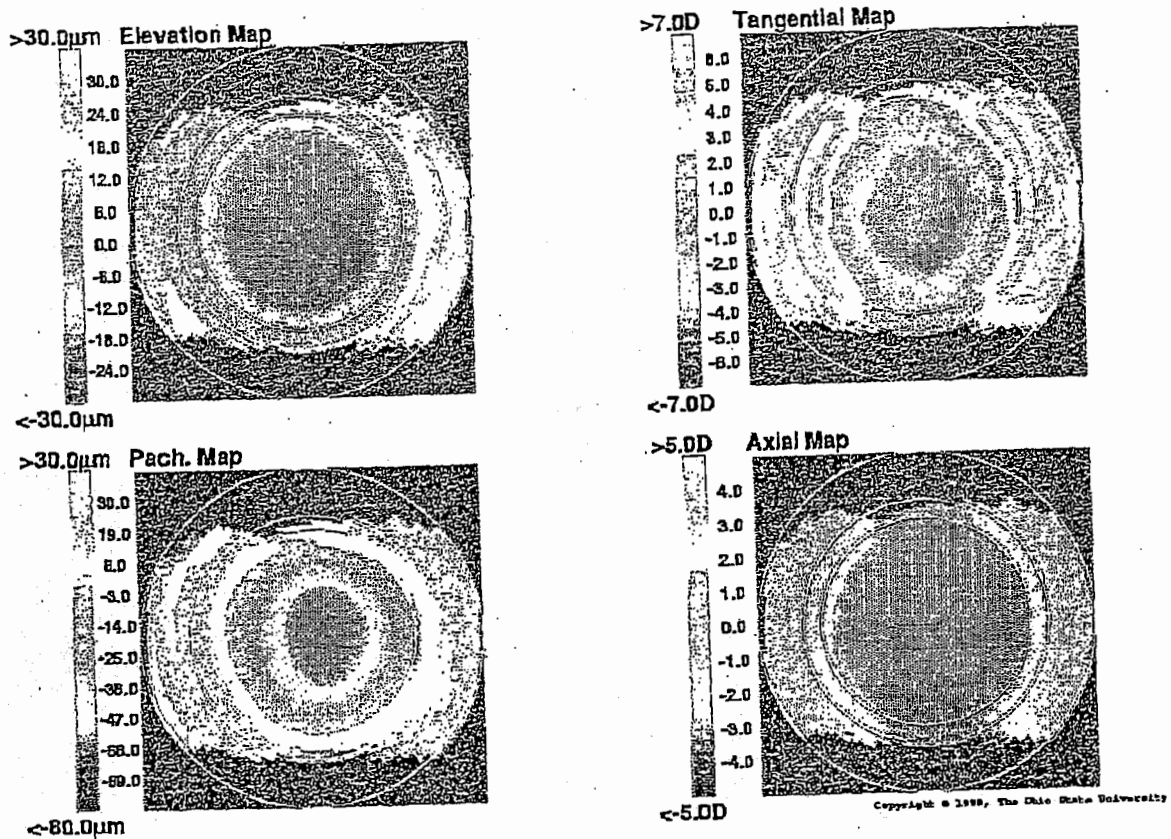
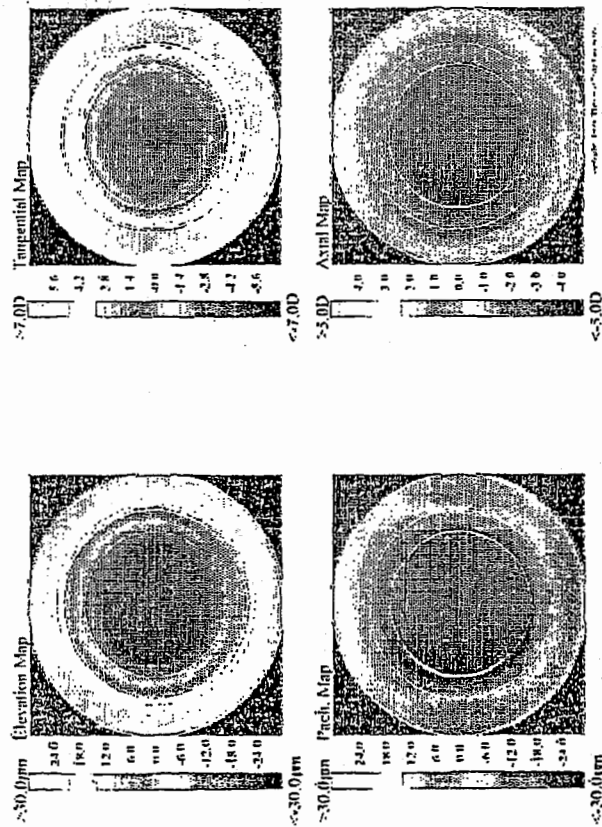


Figure 18: Average difference maps between 1 month post-op LASIK and pre-op state for 8 eyes of 4 patients. The white circles define three corneal regions. The central ablated region has radius 2.75mm, the middle transitional region has radius 2.75 to 3.25mm and the outer non-ablated region has radius 3.25 to 4.5mm. Elevation (upper left) differences were calculated by fitting the two surfaces in the transitional region, and demonstrate persistent increased elevation in the outer zone. Average tangential differences (upper right) show persistent increased curvature in the outer region. Average pachymetry differences (lower left) show persistent increased pachymetry in the outer region. Average axial differences (lower right) are also given.

Composite Anterior Difference Maps

The Ohio State University Corneal Topography Tool
lkcm09lmo00_150-350_2380.ave



■ LASIK with a
Technolas 217
excimer laser

■ Orbscan Topography:
6 month post-op
minus pre-op

■ $N = 2,380$

■ Circles: 2.5, 3.25, 4.5
mm in radius

Figure 19. Pachymetry difference map (left) between pre-op and post-LASIK state, demonstrating central thinning and peripheral thickening, and Meridional Curvature difference map (right) between pre-op and post-LASIK state, showing central flattening and peripheral steepening.

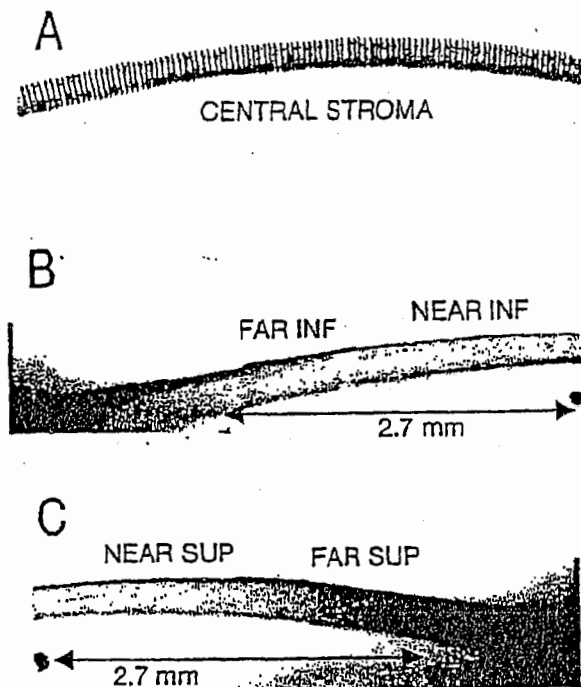


Figure 20. Examples of corneal optical section images. The central region (A) and inferior (B) and superior (C) peripheral regions constitute a section of the vertical meridian in an ablated cornea. Ink dots and corneal landmarks facilitated analysis of corresponding regions in paired controls and replicate images. Digital tracings of the anterior and posterior stromal surfaces (not shown) were used in conjunction with mathematically-derived projections from the posterior corneal surface (shown only in A) to obtain apparent thickness measurements. Corrections for refraction and viewing angle were then applied. Central cornea images (A) were subdivided for analysis of differential thickness losses across the ablation zone.

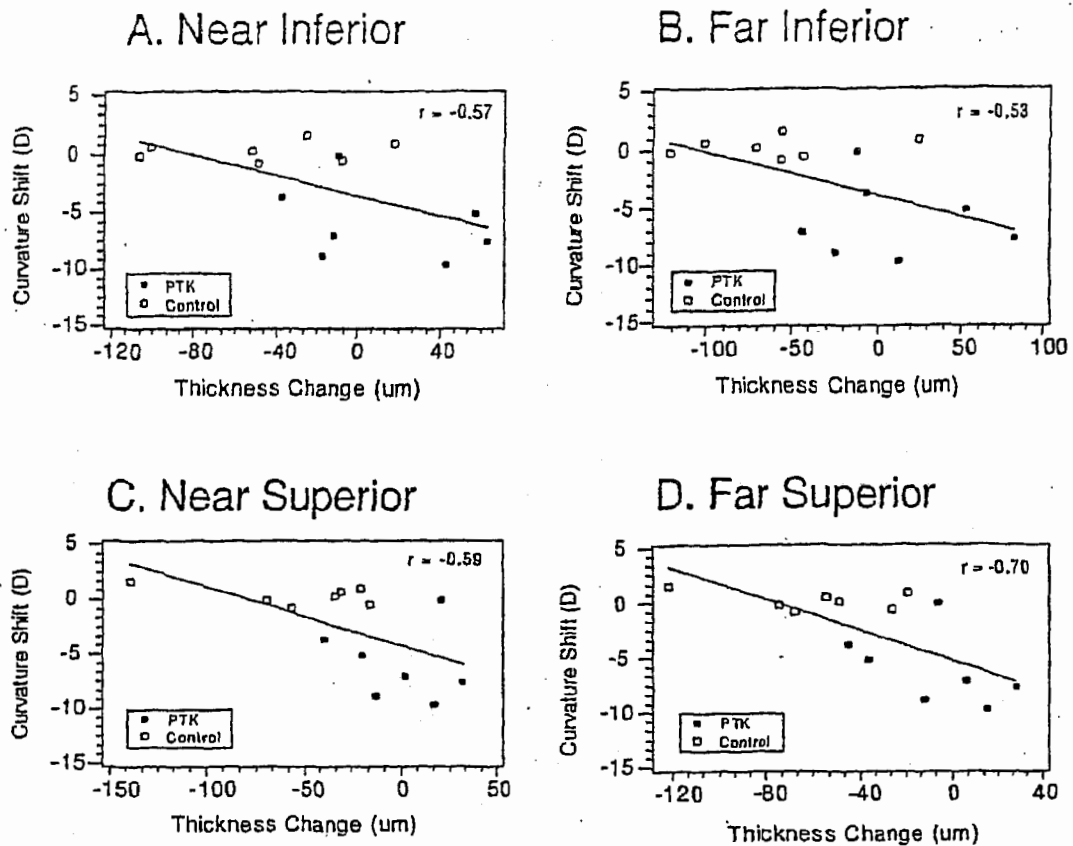


Figure 21. Anterior curvature shifts were correlated to stromal thickness changes in peripheral subregions of the vertical meridian. Negative curvature changes indicate corneal flattening. Correlation coefficients were significant in all but the far inferior periphery (P values = .03, .05, .03 and .01 for A to D, respectively).

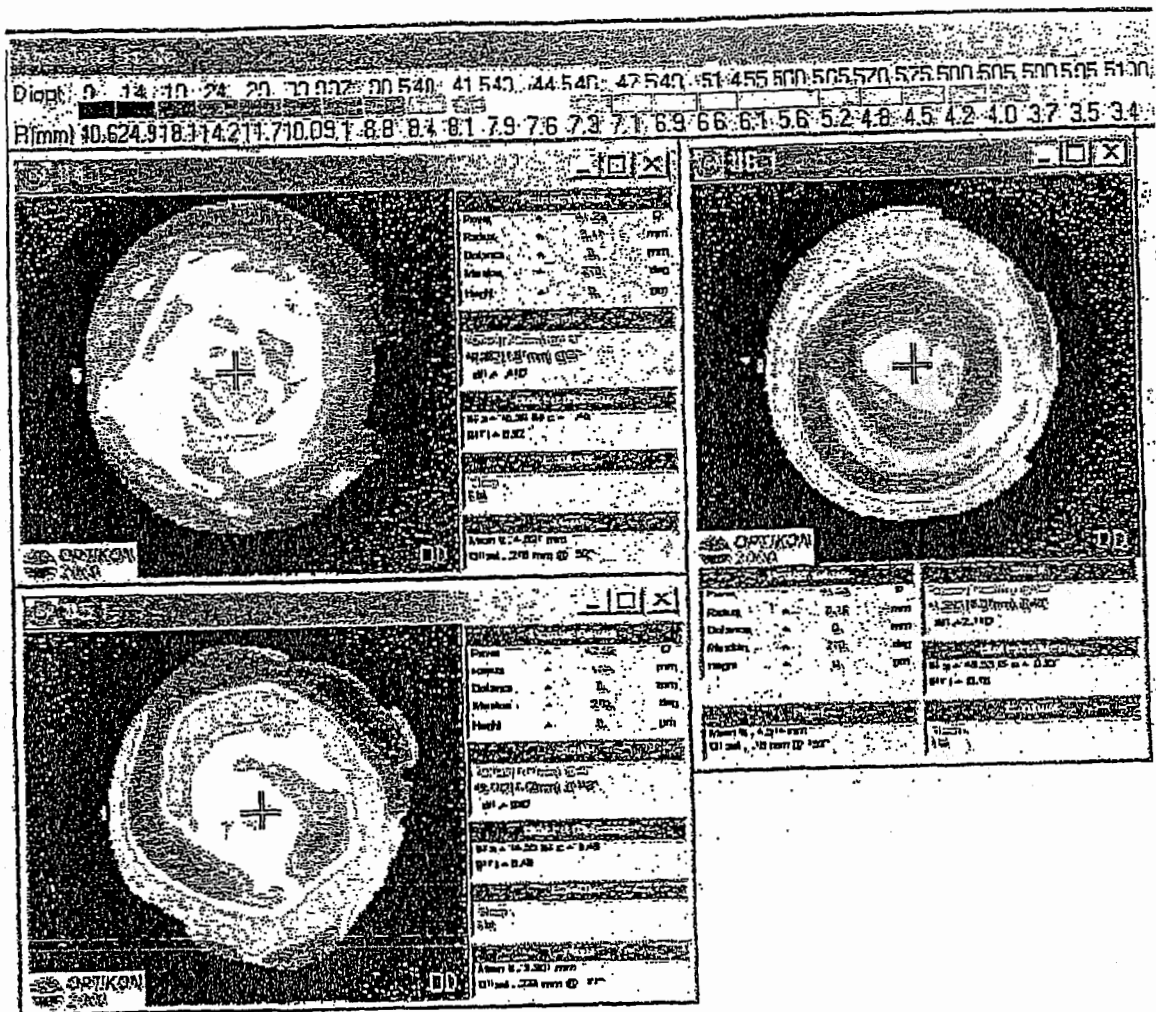


Figure 22: Pre-operative Keratron Scout curvature topography taken while the patient is supine for a LASIK procedure is given on the upper left. The post-flap, pre-ablation topography is given on the lower left. This was acquired immediately after cutting the flap, and before it was reflected. Note that the characteristic post-refractive surgery pattern of central flattening and steep mid-peripheral "red ring" begins to appear after the flap and before the ablation. Finally, the post-ablation topography is given on the upper right, acquired after the flap is replaced, and with the patient supine.

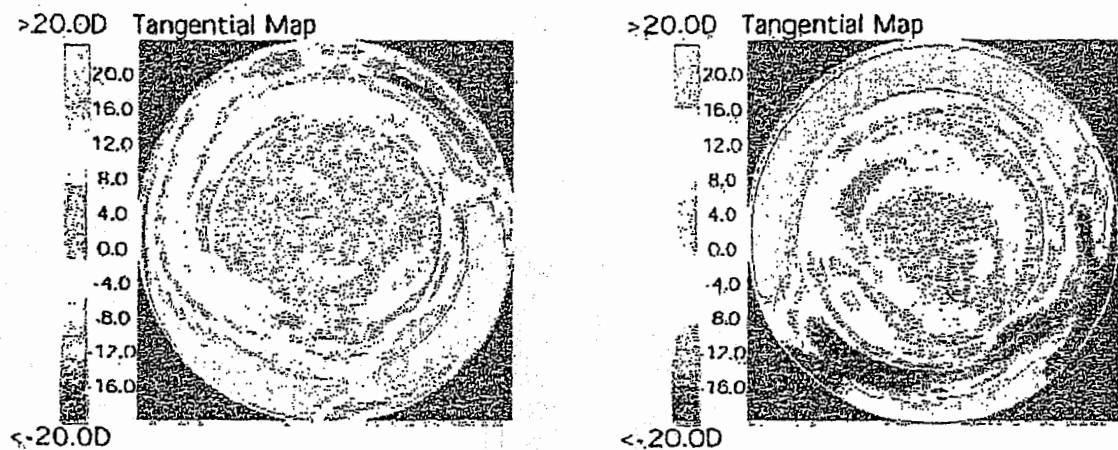
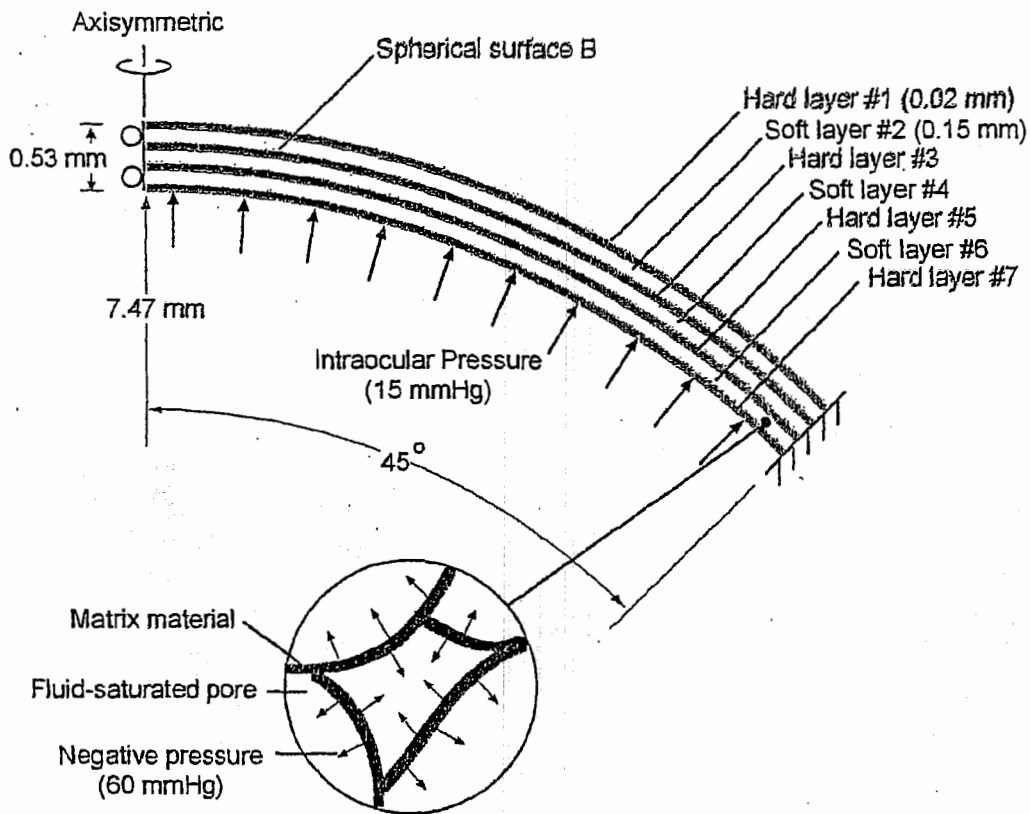


Figure 23: On the left is the curvature difference map between pre-op and post-flap for the patient in Figure 25, calculated and displayed using a customized software. The average dioptric difference in the central region is -1.08 diopters (flattening), and the average dioptric difference in the outer region is $+10.20$ diopters (steepening), all induced just by cutting the flap. On the right is the curvature difference map between post-flap and post-ablation for the patient in Figure 5. The average dioptric difference in the central region is -2.25 diopters (further flattening), and the average dioptric difference in the outer region is $+8.37$ diopters (further steepening).

Figure 24

Intact corneal model subjected to the intraocular pressure (15 mmHg) at the posterior surface and the negative pressure ("Imbibition pressure", 60 mmHg) at the pore boundary of the highly porous soft layers #2, 4 and 6.



A schematic presentation of a highly porous material subjected to the negative pressure ("imbibition pressure", 60 mmHg) applied to the pore boundary

Figure 25

Cut corneal model subjected to the intraocular pressure (15 mmHg) at the posterior surface and the negative pressure ("imbibition pressure", 60 mmHg) at the pore boundary of the highly porous soft layers #4 and 6; zero pore pressure for soft layer #2.

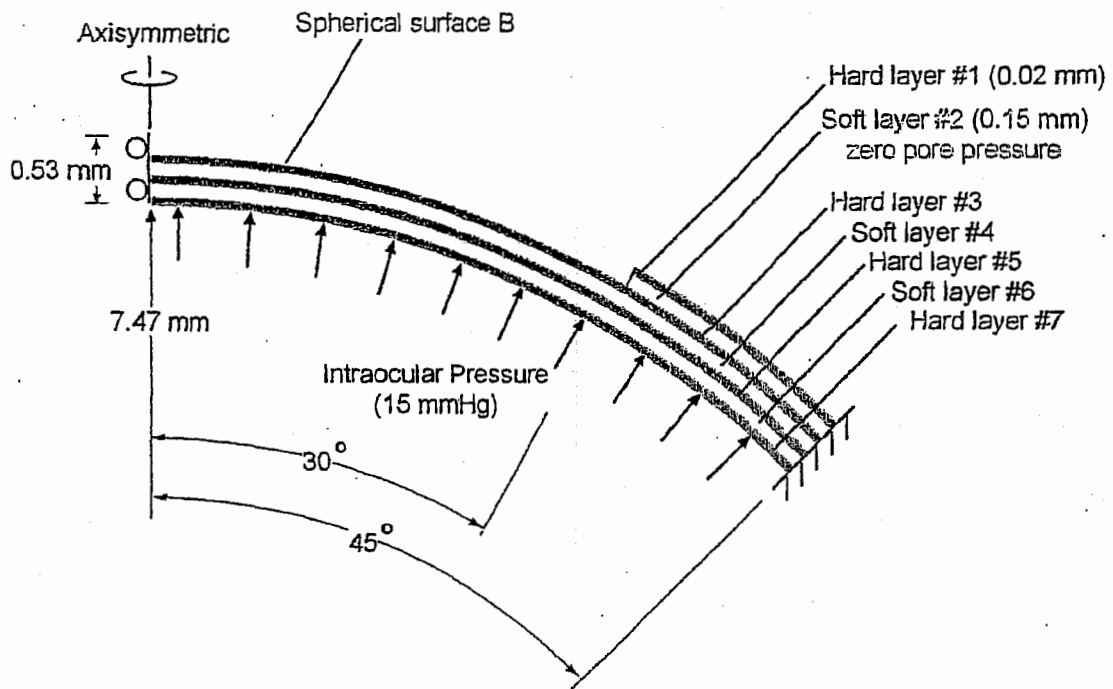


Figure 26
Comparison of corneal deformation (contour of the spherical surface B)
between the intact and cut corneal models
with highly porous material assumption in soft layers #2,4, and 6.
(Displacement scale $\times 10$)

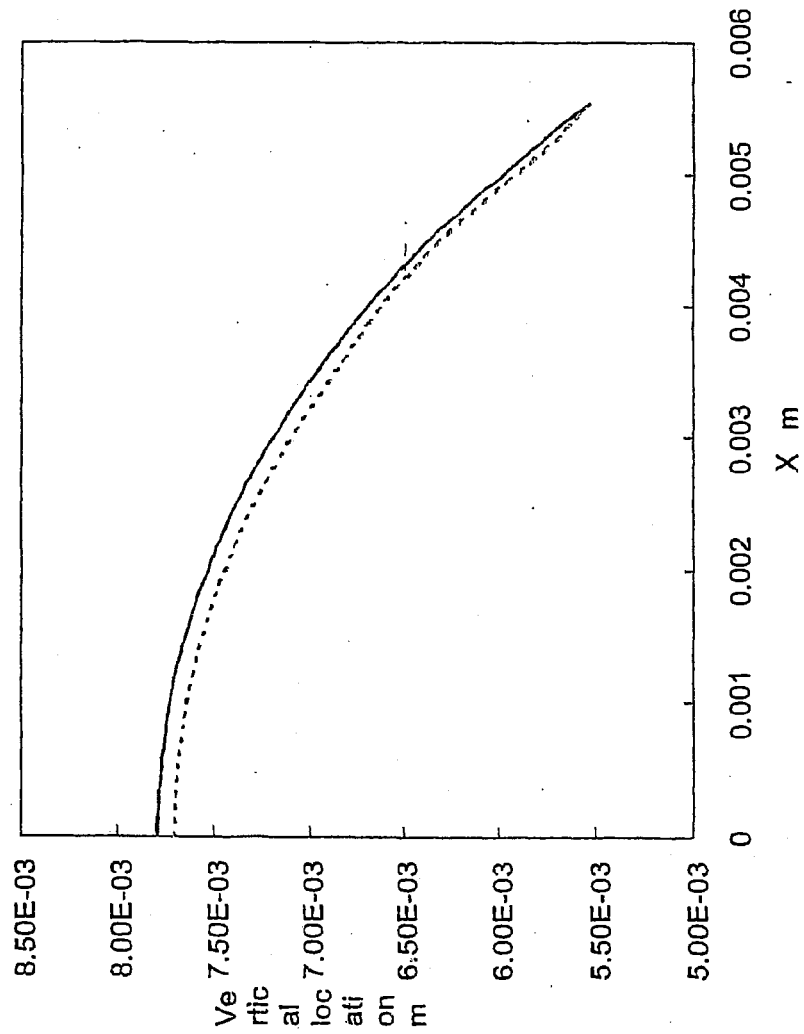


Figure 27
 Comparison of corneal deformation (contour of the spherical surface B)
 between the intact and cut corneal models
 with solid material assumption (without internal pore pressure) in soft layers #2,4, and 6.
 (Displacement scale x200)

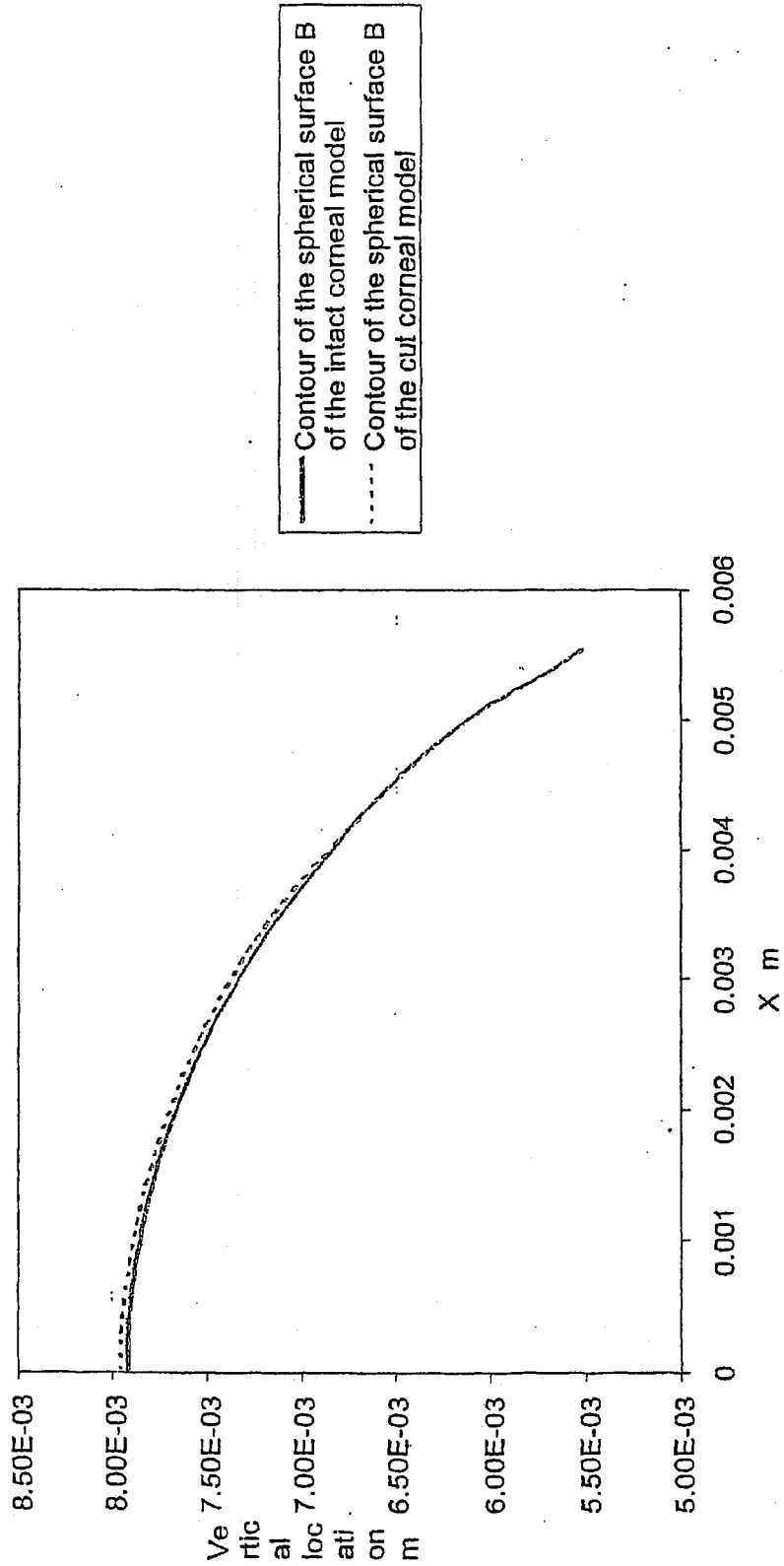


Figure 28

Comparison of the overall corneal deformed shape between the intact and cut corneal models with highly porous material assumption in soft layers #2,4 and 6:

Pink region represents the intact cornea

Blue region represents the cut cornea

(Displacement scale x10)

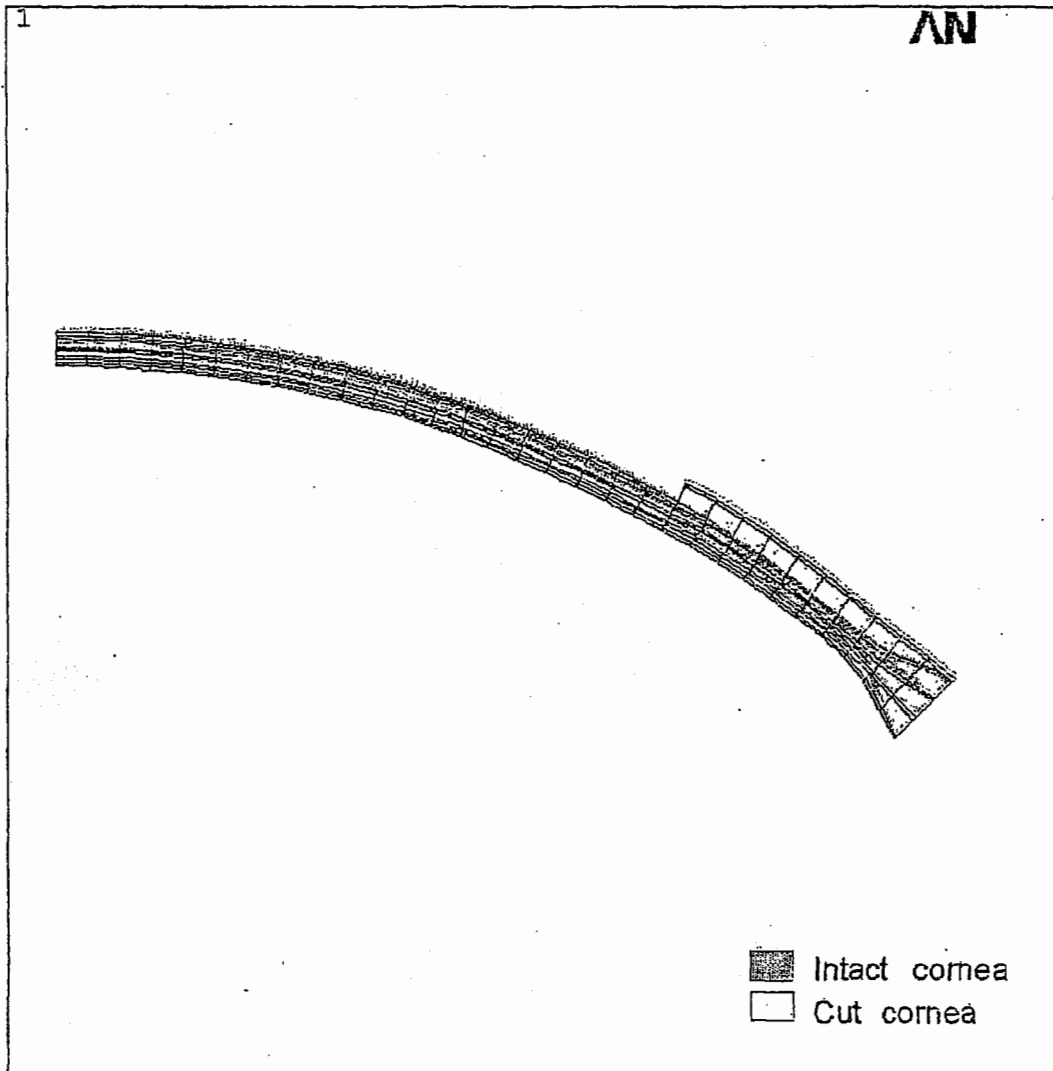


Figure 29

Comparison of the overall corneal deformed shape between the intact and cut corneal models with solid material assumption (without pores) in soft layers #2,4 and 6:

Pink region represents the intact cornea

Blue region represents the cut cornea

(Displacement scale x80)

