update/review

Progressive post-LASIK keratectasia

Biomechanical instability or chronic disease process?

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Progressive post-LASIK keratectasia (PPLK) is a progressive deformation of corneal anatomy that occurs rarely but may have severe consequences. Using the scientific literature and new hypotheses, we attempted to determine whether PPLK is a biomechanical result of laser in situ keratomileusis (LASIK), a chronic disease process affecting individuals predisposed to the condition, or a combination of processes. We look at whether the combination of fatigue, specifically a form of dynamic fatigue, and proteolysis provides an environment conducive to the occurrence and progression of PPLK. This review may raise more questions than it answers and in so doing may move us toward a better understanding of this occasionally serious consequence of LASIK.

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Progressive post-LASIK keratectasia (PPLK) is a progressive deformation of the gross corneal anatomy that occurs rarely after laser in situ keratomileusis (LASIK) and results in visual disturbance. This article discusses the biomechanical effects of LASIK and the parallels with an apparently similar condition, keratoconus. We attempt to determine whether PPLK is a biomechanical result of LASIK, in which case weakening of the cornea by LASIK could put anyone at risk if overtreatment occurs, or a chronic disease process affecting only predisposed individuals, in which case patient selection would be paramount. A third possibility is that PPLK is a combination of processes. We also make relevant hypotheses regarding PPLK.

Background

Progressive post-LASIK keratectasia may show itself immediately or many months after LASIK but generally occurs within 2 years.[1,2] It is the delay in some cases that raises the specter of a public health issue for the future. Pallikaris and coauthors[3] recently reported the incidence in a large series to be 0.66% (660 per 100 000) (all eyes had greater than −8 diopters of myopia preoperatively). Whether PPLK occurs after smaller corrections has produced much debate.[4–7] In Pallikaris and coauthors' study, 6 eyes had a residual bed thickness greater than 250 μm, as calculated from intraoperative ultrasonic pachymetry before ablation, although ultrasonic pachymetry would not have revealed the presence of focally thin areas after the flap was made. The regularity of the cut made by the microkeratome (in this case the disposable Flapmaker® [Refractive Technologies]) may be a factor in some cases. The occurrence of PPLK in the apparent presence of posterior corneal thickness greater than 250 μm would cast doubt on the adequacy of the currently accepted practice of leaving at least this amount of posterior lamella untouched on the assumption that PPLK is a purely mechanical process.[2]

Progressive post-LASIK keratectasia presents in 2 ways[8]: a central ectasia with little irregular astigmatism and good corrected acuity and a type resembling keratoconus with paracentral thinning, irregular astigmatism, and poor spectacle-corrected acuity. The latter presentation is of greatest concern.

The following questions about keratectasia have been raised[9]: What causes it? By what mechanism? How do we avoid it? Additional questions include, how common will it become and how is it best managed? Progressive post-LASIK keratectasia appears to be relatively uncommon, and there is a debate about whether LASIK can induce PPLK in truly normal corneas.[3–6,10,11]

Pallikaris and coauthors[3] have called for the organization of a uniform referral system to monitor PPLK. Until this occurs, we can try to answer the questions posed by PPLK. In particular, can we predict the epidemiology or behavior of the disease by our knowledge of corneal biomechanics or through analogy with an apparently similar condition, keratoconus?

Progressive Post-LASIK Keratectasia As a Chronic Disease Process

Keratoconus is a chronically progressive, ectatic corneal dystrophy with occasional acute exacerbations (corneal hydrops). The incidence is reported to be between 4 and 600 per 100 000. Keratoconus requiring keratoplasty makes up a small proportion of cases. The advent of computerized topography, especially slit-scanning topography, has made us aware of large numbers of patients with forme fruste keratoconus who do not have clinical problems. Furthermore, many keratoconus cases do not progress after the patient reaches a certain age. One might be reassured by this, but we need to know how valid it is for patients with PPLK.

The relationship among the various processes involved in keratoconus is not well understood, but the pathophysiology of keratoconus has been studied. Although keratoconus is a noninflammatory disorder clinically, this is not true subclinically.[12–15] Collagenase and gelatinase activity, interleukin-1, and prostaglandin expression are increased, and the disease may represent an imbalance in proteolytic breakdown and repair, which may have a genetic component in some cases.[16] Some authors dispute whether keratoconus is a true ectasia, at least in the early stages of the disease, because the surface area is unaltered.[17] Others have found conservation of mass (more accurately volume), increasing surface area, and alterations in the number and orientation of lamellae.[18–20]

Several mechanisms probably exist in keratoconus, and it is of course possible that the common clinical presentations of keratoconus may be the result of different diseases. The most likely combination of events is a rearrangement of lamellae, possibly due to altered adhesion, associated with increased activity of degradative enzymes affecting lamellae and ground substance. These events may be aggravated by microtrauma. Thus, there are biomechanical and metabolic components. Whether such events occur in PPLK is not clear. However, it is clear that excimer ablation in keratoconus patients tends to accelerate the disease process, and this implies some relationship.[11] Ultrastructural, biochemical, and histological studies as well as topographical work are needed to show how similar or disparate these entities are. In 1 case in which histopathology was available, methyl metalloproteinases 1 and 2 were absent from the corneal wound site in keratectasia.[21]

How could chronic disease processes, which undoubtedly occur in keratoconus, contribute to PPLK? The progressive thinning process in ectasia conceivably begins in the anterior lamella. In confocal microscopic studies,[22] the apparent loss of keratocytes in the anterior flap and interface changes have been reported in association with thin flaps after LASIK. This is similar to working hypotheses for keratoconus that cite keratocyte apoptosis.[23] The anterior lamella is temporarily separated from its nerve supply after keratectomy and may be exposed to metabolic alterations as well as to known changes in the quality of the tear film.[24–26] If the anterior lamella did thin early in PPLK, the importance of this might be uncertain mechanically, but whatever metabolic or biochemical changes occurred would be expected to affect the posterior cornea eventually. Further studies using confocal microscopy, high-resolution ultrasound, or high-resolution optical pachymetry may help determine which part of the cornea is affected first.

Progressive Post-LASIK Keratectasia As a Biomechanical Process

One objection to the idea of PPLK as a result of mechanical instability is that the conditions for such

instability would be present immediately after surgery. A delay in the onset of visual symptoms implies that additional triggers must be involved. Biomechanical information about the cornea has been obtained through extensive laboratory work and clinical studies based on imaging corneal shape changes after surgery.

Early Effects

What are the early biomechanical sequelae of LASIK? Recent work with slit-scanning topography suggests that forward movement of the posterior corneal surface may occur routinely after LASIK, but there is no suggestion that this is progressive.[27–29] Central posterior corneal bulging, if it occurs, would appear to resemble 1 presentation of PPLK. The studies have made significant assumptions, including that the peripheral cornea is unaffected by the procedure, which are disputed.[29]

Intraocular pressure (IOP) has been held responsible for bulging of the posterior lamella after LASIK.[28] Although one might expect that acute bulging would be resisted because of the phenomenon of stress stiffening in biologic tissues and although stress stiffening appears to be important within physiological IOP ranges,[30,31] it may be more important in resisting strain than bending. Although bulging might be expected intraoperatively, when the IOP can be as high as 90 mm Hg, it has been demonstrated that the normal cornea does not change its refractive power with IOP and the refraction does not fluctuate with IOP variations.[30,32,33] Dupps and Roberts [34] fail to show curvature changes due to IOP variations between 15 mm Hg and 50 mm Hg in cadaver eyes with or without central corneal excimer ablations. Hjortdal[30] reports that only keratectomies of 70% depth produce any change in the radius of curvature with IOPs as high as 100 mm Hg. Thus, within physiological ranges, IOP does not seem to lead to corneal stretching or bulging, at least over the short times used in experimental conditions. On the other hand, the cornea is in some respects a viscoelastic material and creep may conceivably occur. Is it possible that PPLK could occur solely as a result of the IOP in an eye with too little mechanical strength to resist it, or could PPLK be due to another form of mechanical instability?

Corneal Strain Redistribution After LASIK

Wang and coauthors[28] suggest that the central anterior corneal concavity resulting from LASIK is less than the ablation delivered. Since the anterior flap appears to form a relatively weak attachment to the posterior lamella after LASIK, it may not contribute as much to the biomechanics of the cornea as a whole as it did before treatment.[1,6,10,11,18] The cornea is known to be under strain under normal physiological conditions.[35] Thus, LASIK might predispose to a gradual creep of tissue, perhaps resulting in ectasia, in a manner similar to that in keratoconus.[14,36] It should be pointed out that the cornea is weakest in bend and shear but strongest in tension,[37] partly due to stress stiffening, which is due to the effect of cross-linking between collagen fibers.[38] However, regional differences in corneal interlamellar cohesive strength exist.[39]

Roberts[40] and others[34,41] suggest that disrupting the anterior lamellae in any refractive procedure allows them to retract peripherally, such that the peripheral cornea steepens and thickens while the central cornea is pulled flatter and might move backward rather than forward. Findings suggestive of peripheral thickening or at least the appearance of a peripheral "knee" have been reported by others.[42] However, Orbscan® findings supporting peripheral corneal thickness changes have not been validated.[29] If Roberts is correct, however, these considerations imply an increased tension in the remaining posterior lamellae after ablation, even without considering the effect of raised IOP. Of course, central flattening may simply reflect a movement to a new steady state, but increased tension implies a state of static fatigue.

Unplanned Corneal Shape Changes After LASIK

If, as Roberts suggests, the peripheral cornea steepens after LASIK, the difference calculations of Wang and coauthors[28] and Baek and coauthors[27] may greatly exaggerate any forward movement. Furthermore, unexpected flattening of the cornea has been reported.[43] In fact, one can show mathematically that if the peripheral cornea moves outward and forward as a result of keratectomy and if one assumes that the limbus does not expand[44] and the surface area of the posterior cornea remains constant, the midpoint of the remaining central cornea would move forward or backward depending on a complex relationship with the anterior chamber angle. This may be relevant to the accuracy of LASIK (Appendix). Since the cornea is stronger in tension than in shear or bend, these seem reasonable assumptions.[37]

In an examination of posterior asphericity and power changes after LASIK, Seitz et al.[45] report small increases in negative power with an increase in oblate asphericity, with more effect when the residual bed is less than 250 μm. Increased negative power could be explained by a small backward movement of the posterior surface, as suggested by Roberts, or an increase in posterior corneal curvature. How could the latter occur if not by central bulging? One might consider transverse contraction of the posterior lamella. One can illustrate this by stretching a large flat elastic band held between finger and thumb in the 2 hands. The middle part of the band will narrow so the 2 edges (representing anterior and posterior surfaces of the posterior stroma, independent of the flap) converge, while the longitudinal center of the band will be encouraged to stay straight, illustrating a flattening effect on the cornea. As discussed by Seiler,[46] the amount of transverse contraction is determined by Poisson's ratio:

$$V = \text{transverse strain/longitudinal strain}$$

In the human cornea, V may be around 0.5[46,47] since its high water content would suggest it is almost incompressible, and thus transverse contraction could contribute a small steepening of both surfaces of the posterior lamella, perhaps a few microns, although it might not be transmitted to the anterior corneal flap. Validated observations of peripheral corneal thickening in combination with increased posterior curvature would support the idea that the posterior lamella is indeed under increased tension, tending to transverse contraction in the short term and possibly creep in the long term. Such considerations imply that only pachymetric measurements of the residual corneal bed will reflect the true corneal thickness after the flap is made in LASIK. Simple subtraction of the proposed flap depth from the preoperative pachymetry does not allow for inaccuracy in cutting or for transverse contraction.

Corneal Resistance to Fatigue

It can be seen that the question of the overall position of the central cornea and its local curvature are separate issues; both may influence the accuracy of LASIK. However, only progressive changes should indicate PPLK. Important to this discussion is whether biomechanical changes resulting from LASIK are likely to increase tension in the posterior lamella. If there is a safe range of residual corneal bed thickness, it has not been determined, although recent clinical practice suggests a corneal bed thickness of 250 μm, 275 μm in extreme myopia, as a reasonable limit to prevent progressive postoperative ectasia.[1,17,48–51] Why should a cornea with less than this amount of tissue automatically progress to ectasia?

A great deal of work has been done to establish constitutive laws for biomechanical modeling of the cornea[52]; for example, through finite element analysis. This method, used in industry to predict the behavior of physical objects over time, is a technique of computer modeling to look at fatigue in mechanical materials. Accurate predictions of time to failure can be made for almost any object, but only when the parameters of the material are fully understood. No successful predictions of the long-term consequences of LASIK have been made using finite element modeling (FEM). However, FEM is a powerful tool and will have an important part to play in this arena.

Although human whole-eye inflation experiments have overcome some of the distortions involved in testing strips of corneal tissue when investigating stress−strain relationships in the cornea, little has been written about the biomechanical effects of external forces on the cornea even though it is known that blinking alters the IOP.[53] The shape and microstructure of the cornea have evolved not only to resist IOP and to focus light but also to resist the deforming forces of the eyelids. In relation to keratoconus, eye rubbing as a result of fatigue or because of inflammation secondary to repeated microtrauma has long been suspected as a causative factor. Much epidemiological evidence supports at least an association.[54–56] Eye rubbing represents a form of dynamic fatigue. Many studies of fatigue effects in soft tissues, including skin, heart valves, intervertebral discs, and even the human crystalline lens, have been published over more than 30 years.[57–60]

Progressive Post-LASIK Keratectasia As a Combined Process: Fatigue and Proteolysis

In relation to fatigue, relevant work has been done on bovine pericardium, which consists of collagen fibers within a ground substance, analogous in some ways to

corneal tissue except for the organization of the fibers. It has been shown that static and dynamic fatigue processes, especially dynamic fatigue, hasten the mechanical failure of such tissue and that enzymatic proteolysis occurs more rapidly in this biomaterial when subjected to fatigue.[61] Inflammatory marker expression, altered proteinase expression, keratocyte apoptosis, adhesion protein changes, and molecular collagen changes are reported to occur in keratoconus.[12–15] It appears plausible that keratoconus may be partly caused by a synergistic effect of abnormal enzymatic degradation and dynamic fatigue.

We hypothesize that mechanisms discussed in relation to fatigue in bovine heart valves and other soft tissues may also predispose to PPLK. Clinically obvious inflammation in the interface is a well-known phenomenon. The corollary is that subclinical interface inflammation must also occur in some cases. We have seen that an increase in static fatigue can routinely occur after LASIK, and this can be exacerbated by dynamic fatigue in eye rubbing. To support this assertion, we have observed a case of unilateral corneal ectasia in 1 eye of a patient treated with bilateral LASIK who had less than 250 μm of posterior lamellae remaining in both eyes. The patient volunteered the information that he was a habitual eye rubber and that the affected eye was the only one he rubbed. We are aware of other cases of PPLK in chronic eye rubbers. Of course, one should note that in many living tissues, the effect of fatigue is to strengthen rather than weaken the tissue.[62] However, corneal repair mechanisms may be different from those in other tissues, whose function depends on form and strength but not transparency. In vitro experiments or computer modeling will have to consider the effects of healing and repair if they are to reflect the situation in vivo.

Conclusion

What can we make of the current level of knowledge about PPLK and keratoconus? We think it is likely that many processes in PPLK will be similar to those in keratoconus. By analogy, we are likely to find that factors predisposing to the one may predispose to the other, and these will include dynamic and static fatigue effects. We believe that PPLK will continue to occur rarely in the absence of a combination of such factors. These consid-

erations may help us avoid unsuitable cases and lower the overall incidence of PPLK by avoiding factors that might stimulate subclinical inflammation. We should be vigilant in preparing the lid and cleaning the flap bed and proactive in the management of dry, irritated eyes after LASIK, and we should continue to monitor residual bed thickness and carefully examine topography to exclude forme fruste keratoconus. Innovative thinkers have proposed ways of managing PPLK with corneal inserts[2] and medical treatments, such as riboflavin or ultraviolet radiation to increase cross-linkages,[63] but prevention will always be better than cure. It is hoped that similar to keratoconus, most PPLK occurrences will remain relatively innocuous.

References

1. Geggel HS, Talley AR. Delayed onset keratectasia following laser in situ keratomileusis. J Cataract Refract Surg 1999; 25:582–586
2. Rao SN, Epstein RJ. Early onset ectasia following laser in situ keratomileusis: case report and literature review. J Refract Surg 2002; 18:177–184
3. Pallikaris IG, Kymionos GD, Astyrakakis NI. Corneal ectasia induced by laser in situ keratomileusis. J Cataract Refract Surg 2001; 27:1796–1802
4. Amoils SP, Deist MB, Gous P, Amoils PM. Iatrogenic keratectasia after laser in situ keratomileusis for less than −4.0 to −7.0 diopters of myopia [letter]. J Cataract Refract Surg 2000; 26:967–977
5. Horn J. Iatrogenic keratectasia [letter[. J Cataract Refract Surg 2001; 27:4
6. Mack RJS. Iatrogenic keratectasia [letter]. J Cataract Refract Surg 2001; 27:5–6
7. Amoils SP, Deist MB, Amoils PM. Iatrogenic keratectasia [reply to letters]. J Cataract Refract Surg 2001; 27:6–7
8. Marinho A, Pinto MC, Vaz F. Corneal ectasia after LASIK— how to manage. Semin Ophthalmol 2000; 15:148–150
9. Koch DD. The riddle of iatrogenic keratectasia [editorial]. J Cataract Refract Surg 1999; 25:453–454
10. Seiler T, Koufala K, Richter G. Iatrogenic keratectasia after laser in situ keratomileusis. J Refract Surg 1998; 14:312–317
11. Seiler T, Quurke AW. Iatrogenic keratectasia after LASIK in a case of forme fruste keratoconus. J Cataract Refract Surg 1998; 24:1007–1009
12. Smith VA, Easty DL. Matrix metalloproteinase 2: involvement in keratoconus. Eur J Ophthalmol 2000; 10:215–226
13. Collier SA, Madigan MC, Penfold PL. Expression of membrane-type 1 matrix metalloproteinase (MT1-

MMP) and MMP-2 in normal and keratoconus corneas. Curr Eye Res. 2000; 21:662–668

14. Takács L, Csutak A, Balázs E, et al. Expression of βig-h3 is lower than normal in keratoconus corneas but increases with scarring. Cornea 1999; 18:599–605

15. Kim W-J, Rabinowitz YS, Meisler DM, Wilson SE. Keratocyte apoptosis associated with keratoconus. Exp Eye Res 1999; 69:475–481

16. Bureau J, Pouliquen Y, Lorans G. Fibrozytenreaktion auf Interleukin-1-Stimulation bei Keratokonus. Klin Monatsbl Augenheilkd 1993; 203:269–274

17. Smolek MK, Klyce SD. Is keratoconus a true ectasia? An evaluation of corneal surface area. Arch Ophthalmol 2000; 118:1179–1186

18. Takahashi A, Nakayasu, K, Okisaka S, Kanai A. [Quantitative analysis of collagen fiber in keratoconus]. [Japanese] Acta Soc Ophthalmol Jpn 1990; 94:1068–1073

19. Daxer A, Fratzl P. Collegen fibril orientation in the human corneal stroma and its implication in keratoconus. Invest Ophthalmol Vis Sci 1997; 38:121–129; errata after table of contents in June issue

20. Edmund C. Corneal topography and elasticity in normal and keratoconic eyes; a methodological study concerning the pathogenesis of keratoconus. Acta Ophthalmol Suppl 1989; 193:1–36

21. Rumelt S, Cohen I, Skandarani P, et al. Ultrastructure of the lamellar corneal wound after laser in situ keratomileusis in human eye. J Cataract Refract Surg 2001; 27:1323–1327

22. Vesaluoma M, Pérez-Santonja J, Petroll WM, et al. Corneal stromal changes induced by myopic LASIK. Invest Ophthalmol Vis Sci 2000; 41:369–376

23. Kenney MC, Brown DJ, Rajeev B. The elusive causes of keratoconus: a working hypothesis. CLAO J 2000; 26:10–13

24. Slowik C, Somodi S, Richter A, Guthoff R. Assessment of corneal alterations following laser in situ keratomileusis by confocal slit scanning microscopy. Ger J Ophthalmol 1997; 5:526–531

25. Latvala T, Barraquer-Coll C, Tervo K, Tervo T. Corneal wound healing and nerve morphology after excimer laser in situ keratomileusis in human eyes. J Refract Surg 1996; 12:677–683

26. Lee JB, Ryu CH, Kim J-H, et al. Comparison of tear secretion and tear film instability after photorefractive keratectomy and laser in situ keratomileusis. J Cataract Refact Surg 2000; 26:1326–1331

27. Baek TM, Lee KH, Kagaya F, et al. Factors affecting the forward shift of posterior corneal surface after laser in situ keratomileusis. Ophthalmology 2001; 108:317–320

28. Wang Z, Chen J, Yang B. Posterior corneal surface topographic changes after laser in situ keratomileusis are related to residual corneal bed thickness. Ophthalmology 1999; 106:406–409; discussion by RK Maloney, 409–410

29. Maloney RK. Discussion of posterior corneal surface topographic changes after laser in situ keratomileusis are related to residual corneal bed thickness. Ophthalmology 1999; 106:409–410

30. Hjortdal JO. Regional elastic performance of the human cornea. J Biomech 1996; 29:931–942

31. Hennighausen H, Feldman ST, Bille JF, McCulloch AD. Anterior-posterior strain variation in normally hydrated and swollen rabbit cornea. Invest Ophthalmol Vis Sci 1998; 39:253–262

32. Hjortdal JØ, Böhm A, Kohlhaas M, et al. Mechanical stability of the cornea after radial keratotomy and photorefractive keratectomy. J Refract Surg 1996; 12:459–466

33. Simon G, Ren Q. Biomechanical behavior of the cornea and its response to radial keratotomy. J Refract Corneal Surg 1994; 10:343–350; comments by RK Maloney, ST Feldman, K Buzard, 351–356

34. Dupps WJ Jr, Roberts C. Effect of acute biomechanical changes on corneal curvature after photokeratectomy. J Refract Surg 2001; 17:658–669

35. Jue B, Maurice D. The mechanical properties of the rabbit and human cornea. J Biomech 1986; 19:847–853

36. Hjortdal JØ, Jensen PK. In vitro measurement of corneal strain, thickness, and curvature using digital image processing. Acta Ophthalmol Scand 1995; 73:5–11

37. Maurice DM. Mechanics of the cornea. In: Cavanagh HD, ed, The Cornea; Transactions of the World Congress on the Cornea III. New York, NY, Raven Press, 1988; 187–193

38. Nash IS, Greene PR, Foster CS. Comparison of mechanical properties of keratoconus and normal corneas. Exp Eye Res 1982; 35:413–424

39. Smolek MK. Interlamellar cohesive strength in the vertical meridian of human eye bank corneas. Invest Ophthalmol Vis Sci 1993; 34:2962–2969

40. Roberts C. The cornea is not a piece of plastic [editorial]. J Refract Surg 2000; 16:407–413

41. Reinstein DZ, Silverman RH, Raevsky T, et al. Arc-scanning very high-frequency digital ultrasound for 3D pachymetric mapping of the corneal epithelium and stroma in laser in situ keratomileusis. J Refract Surg 2000; 16:414–430

42. Fiore T, Carones F, Brancato R. Broad beam vs flying spot excimer laser: refractive and videokeratographic outcomes of two different ablation profiles after photorefractive keratectomy. J Refract Surg 2001; 17:534–541

43. González F, Ortiz D, Saiz JM, et al. Unexpected corneal flattening after laser in situ keratomileusis. J Refract Surg 2001; 17:S180–S186

44. Newton RH, Meek KM. Circumcorneal annulus of collagen fibrils in the human limbus. Invest Ophthalmol Vis Sci 1998; 39:1125–1134

45. Seitz B, Torres F, Langenbucher A, et al. Posterior

corneal curvature changes after myopic laser in situ keratomileusis. Ophthalmology 2001; 108:666–672; discussion by ED Donnenfeld, 673

46. Seiler T. Biomechanical aspects of corneal transverse incisions. In: Cavanagh HD, ed, The Cornea; Transactions of the World Congress on the Cornea III. New York, NY, Raven Press, 1988; 615–618

47. Purslow PP, Karwatowski WSS. Ocular elasticity; is engineering stiffness a more useful characterization parameter than ocular rigidity? Ophthalmology 1996; 103: 1686–1692

48. Joo C-K, Kim T-G. Corneal ectasia detected after laser in situ keratomileusis for correction of less than −12 diopters of myopia. J Cataract Refract Surg 2000; 26:292–295

49. Andreassen TT, Simonsen AH, Oxlund H. Biomechanical properties of keratoconus and normal corneas. Exp Eye Res 1980; 31:435–441

50. Vinciguerra P, Camesasca FI. Prevention of corneal ectasia in laser in situ keratomileusis. J Refract Surg 2001; 17:S187–S189; errata, 293

51. Lyle WA, Jin GJC. Laser in situ keratomileusis with the VISX Star laser for myopia over −10.0 diopters. J Cataract Refract Surg 2001; 27:1812–1822

52. Bryant MR, McDonnell PJ. Constitutive laws for biomechanical modeling of refractive surgery. J Biomech Eng 1996; 118:473–481

53. Percicot CL, Schnell CR, Debon C, Hariton C. Continuous intraocular pressure measurement by telemetry in α-chymotrypsin-induced glaucoma model in the rabbit: effects of timolol, dorzolamide and epinephrine. J Pharmacol Toxicol Meth 1996; 36:223–228

54. Bawazeer AM, Hodge WG, Lorimer B. Atopy and keratoconus: a multivariate analysis. Br J Ophthalmol 2000; 84:834–836

55. Karseras AG, Ruben M. Aetiology of keratoconus. Br J Ophthalmol 1976; 60:522–525

56. Gritz DC, McDonnell PJ. Keratoconus and ocular massage [letter]. Am J Ophthalmol 1988; 106:757–758

57. Comaish JS. Epidermal fatigue as a cause of friction blisters. Lancet 1973; 1:81–83

58. Gloeckner DC, Billiar KL, Sacks MS. Effects of mechanical fatigue on the bending properties of the porcine bioprosthetic heart valve. ASAIO J 1999; 45:59–63

59. Aspden RM, Porter RW. Localized stresses in the intervertebral disc resulting from a loose fragment; a theory for fissure and fragment. Spine 1999; 24:2214–2218

60. Fisher RF. Human lens fibre transparency and mechanical stress. Exp Eye Res 1973; 16:41–49

61. Ellsmere JC, Khanna RA, Lee JM. Mechanical loading of bovine pericardium accelerates enzymatic degradation. Biomaterials 1999; 20:1143–1150

62. Pike AV, Ker RF, Alexander RM. The development of fatigue quality in high- and low-stressed tendons of sheep (Ovis aries). J Exp Biol 2000; 203:2187–2193

63. Spörl E, Schreiber J, Hellmund K, et al. Untersuchungen zur Verfestigung der Hornhaut am Kaninchen. Ophthalmologe 2000; 97:203–206

Appendix

Roberts[1] asserts that due to cross-linking of lamellae, an expansion force pulls on the underlying intact lamellae when the central anterior lamellae of the cornea are cut in refractive procedures. This effect requires that the ends of the lamellae are held tightly by the limbus.[2] An outward force would be generated if this hypothesis is correct, as suggested by Roberts. This would imply that unless such forces are exactly opposed, the posterior surface of the peripheral cornea would move forward; that is, the anterior chamber angle would increase while the central posterior cornea would flatten. The question of where the central point of the posterior cornea would end up is more complex.

The anterior cornea is usually prolate. The posterior surface may be oblate or prolate but is often close to spherical.[3] The most efficient shape to contain volume is a sphere. If the posterior cornea were to become more spherical by these changes, the intraocular pressure (IOP) would favor the change to a spherical posterior corneal shape. If the posterior surface were already oblate, the final shape suggested by Robert's hypothesis might contain less volume and IOP might oppose it. However, the cornea is much stronger in tension than in shear or bend and since Robert's shape changes do not require stretching of the cornea, the IOP may well be overcome by the biomechanical changes.

If the peripheral cornea were to move outward, where would the division between peripheral and central cornea be? It may be impossible to assess without extensive measurements, but it is tempting to assume that there would be a zone of bending beneath the edge of the ablation zone. If one could find the location of the peripheral "knee," one could estimate the posterior central corneal movement as follows.

Let us assume that since the cornea is highly resistant to strain,[4] the central posterior corneal surface area (A) remains constant and the limbus does not change; ie, the white-to-white measurement is constant, δ (Figure 1): R = the radius of curvature of the central posterior corneal surface preoperatively; ϕ = the anterior chamber angle; θ = the semivertical angle subtended by that portion of the cornea inside the knee; l = the surface distance between the knee and limbus; h = the height of the central posterior cornea; ie, the perpendicular distance to a plane described by the limbus. Therefore,

$$A = 2\pi R^2(1 - \cos\theta)$$

which equates to
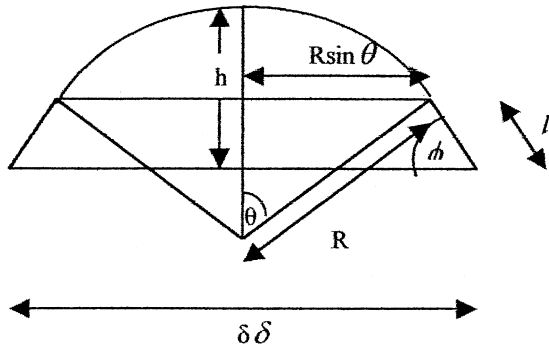
Figure 1. (Comaish) Corneal model: R = radius of curvature of the central posterior corneal surface preoperatively; ϕ = anterior chamber angle; θ = semivertical angle subtended by the portion of the cornea inside the knee; l = surface distance between the knee and the limbus; h = height of the central posterior cornea (ie, perpendicular distance to a plane described by the limbus).

$$A = 4\pi R^2 \sin^2(\theta/2)$$

For convenience, this can be written

$$A = \pi r^2$$

where

$$r = 2R \sin(\theta/2)$$

But from projection perpendicular to the axis of symmetry, we also have

$$\delta/2 = R \sin\theta + l \cos\phi$$

And from the projection parallel to the axis of symmetry, we have

$$h = R - R\cos\theta + l\sin\phi$$

Substituting, we get

$$h = r\sin(\theta/2) + l\sin\phi$$

Expressing in terms of ϕ, we have

$$r\cos(\theta/2) = \delta/2 - l\cos\phi$$

Consequently, the expression for h becomes

$$h = l\sin\phi + \sqrt{r^2 - (\delta/2 - l\cos\phi)^2}$$

From this, it can be seen that the relationship of h to the anterior chamber angle is a complex one. Furthermore, using calculus it can be shown that a critical value for the anterior chamber angle exists such that h can increase or decrease (ie, the posterior cornea moves forward or backward) for increasing values of the anterior chamber angle, depending on whether the original value of the anterior chamber angle is greater or less than the critical angle given by

$$\phi = \cos^{-1}[\delta/2(r + l)]$$

Therefore, some patients may experience anterior movement of the posterior corneal surface associated with any forward movement of the peripheral cornea, whereas other patients may experience posterior movement. To look at it another way, the preoperative anterior chamber angle may have an effect on the postoperative posterior corneal position.

References

1. Roberts C. The cornea is not a piece of plastic [editorial]. J Refract Surg 2000; 16:407–413
2. Maurice DM. Mechanics of the cornea. In: Cavanagh HD, ed, The Cornea; Transactions of the World Congress on the Cornea III. New York, NY, Raven Press, 1988; 187–193
3. McMenamin PG, Steele C, McGhee CNJ. Cornea: anatomy, physiology and healing. In: McGhee CNJ, Taylor HR, Gartry DS, Trokel SL, eds, Excimer Lasers in Ophthalmology; Principles and Practice. London, Dunitz, 1997; 41–63
4. Newton RH, Meek KM. Circumcorneal annulus of collagen fibrils in the human limbus. Invest Ophthalmol Vis Sci 1998; 39:1125–1134