

Two-Year Preclinical Testing of Perfluoropolyether Polymer as a Corneal Inlay

Ruo Zhong Xie,¹ Margaret D. M. Evans,^{1,2} Barbara Bojarski,¹ Timothy C. Hughes,^{1,3} Grace Y. Chan,^{1,3} Xuan Nguyen,^{1,3} John S. Wilkie,^{1,3} Keith M. McLean,^{1,3} Antti Vannas,^{1,4} and Deborah F. Sweeney¹

PURPOSE. To assess the long-term biocompatibility and optical clarity of a perfluoropolyether (PFPE) polymer as a corneal inlay.

METHODS. A 4-mm-diameter PFPE inlay was implanted under a microkeratome flap in the corneas of rabbits ($n = 16$) and maintained for predetermined time points of 6, 12, or 24 months. These were compared with normal ($n = 3$) and time-matched sham-wounded rabbit corneas ($n = 8$). All corneas were monitored clinically with a slit lamp. Histology was performed on all eyes on termination to assess the tissue response.

RESULTS. Some sham and implanted animals were discontinued from study 1 to 2 days after surgery because of flap dislodgement. Ten animals with PFPE inlays remained in the study, and 7 of these were maintained to their predetermined time point for up to 2 years (3 were discontinued because of peripheral corneal defects). The corneas of these 7 animals remained clear and healthy, tear film remained normal, and there were no signs of inflammation, neovascularization, or increased conjunctival redness. All inlays remained centered and optically clear (clarity 85% or greater). Histology showed PFPE was biostable. The epithelia of operated corneas were stratified but slightly thinned compared with those of normal corneas. Stromal tissue anterior and posterior to each inlay appeared normal. Keratocytes in the vicinity of the inlay were normal in distribution but showed increased vacuolation, indicating tissue repair after the surgery.

CONCLUSIONS. The PFPE polymer maintained a high level of optical clarity and showed long-term biocompatibility for up to 2 years when implanted as an inlay in the rabbit cornea. (*Invest Ophthalmol Vis Sci.* 2006;47:574–581) DOI:10.1167/iovs.05-0872

There is a growing market for new technologies to correct refractive errors which is stimulated by patient demand for safety, convenience, and cosmesis. Laser-based procedures

such as photorefractive keratectomy (PRK), laser in situ keratomileusis (LASIK), and laser-assisted subepithelial keratomileusis (LASEK) have been meeting much of this demand.¹ However, each of these techniques is associated with a range of postoperative complications that include epithelial abnormalities, corneal haze, diffuse lamellar keratitis, flap problems, epithelial ingrowth, corneal ectasia, changes to ocular surface hemostasis, and reduced corneal sensation caused by the damage to corneal nerves (Waring GO, et al. *IOVS* 1999;40:ARVO Abstract 3088; Restivo L, et al. *IOVS* 1999;40:ARVO Abstract 4730; Srivannaboon S, et al. *IOVS* 1999;40:ARVO Abstract 4723).^{2–13} One newer technique—EpiLASIK, in which an epithelial sheet is separated mechanically from Bowman's layer before laser ablation and replaced afterward—offers the advantages of the LASIK and LASEK techniques and may address some of the problems arising from either of the original techniques in the treatment of low myopia.¹⁴

Another approach is additive refractive keratoplasty. This involves the insertion of a synthetic or biologic material into the cornea to change the refractive power of the eye by altering the curvature of the cornea or by the refractive index of the material itself.^{15–23} The implanted material may be placed within the stromal tissue or immediately beneath the epithelium. Additive technologies offer several advantages over currently used refractive surgical techniques, paramount of which is that the implant may be removed, giving the procedure the potential to be adjustable and reversible.

Previous efforts at correcting refractive error by implanting materials of biologic origin into the cornea have failed because of remodeling of the implant and difficulty in maintaining a functional epithelium over the implanted material (McCarey BE, et al. *IOVS* 1997;4:ARVO Abstract 2362).^{24–30} The use of synthetic materials for corneal augmentation has provided an alternative solution. Early attempts at implanting synthetic polymers into the cornea demonstrated the absolute requirement for permeability in the implanted material, the significance of implant thickness and diameter, and the depth at which the implant was placed in the cornea.^{16,21,22,31,32} Non-permeable polymers have also been tested as annular ring segments implanted in the peripheral cornea to expand and flatten the corneal surface (Burriss TE, et al. *IOVS* 2000;41:ARVO Abstract 4876).^{33–36} The long-term success of these implants overall has been thwarted by problems such as dehydration, crystal formation, lipid deposits, opacities, and difficulties with implant edges that have caused thinning, fibrosis, ulceration of the stroma, keratitis, and corneal vascularization.^{34–42} In recent years, synthetic materials with a high water content and high permeability to nutrient flow have been developed for corneal implantation. One hydrogel material has been tested as an inlay using a microkeratome flap (PermaVision; Anamed Inc., Lake Forest, CA) with encouraging early data, though complications including haze, inlay encapsulation, epithelial opacification, and inlay decentration have since been reported.^{43–47} Another hydrogel material has been implanted under a corneal flap made in rabbits using the technique of

From the ¹Vision Cooperative Research Centre, University of NSW, Sydney, Australia; ²CSIRO Molecular and Health Technologies, Sydney, Australia; ³CSIRO Molecular and Health Technologies, Clayton, Australia; and ⁴Central Military Hospital, Helsinki, Finland.

Supported by the Commonwealth of Australia through the Cooperative Research Centre scheme.

Submitted for publication July 7, 2005; revised September 1, 2005; accepted December 5, 2005.

Disclosure: **R.Z. Xie**, None; **M.D.M. Evans**, None; **B. Bojarski**, None; **T.C. Hughes**, None; **G.Y. Chan**, None; **X. Nguyen**, None; **J.S. Wilkie**, None; **K.M. McLean**, None; **A. Vannas**, None; **D.F. Sweeney**, None

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be marked "advertisement" in accordance with 18 U.S.C. §1734 solely to indicate this fact.

Corresponding author: Margaret D. M. Evans, CSIRO Molecular and Health Technologies, PO Box 184, North Ryde, Sydney NSW 1670, Australia; meg.evans@csiro.au.

photoablative inlay laser in situ keratomileusis (PAI-LASIK) with stable outcomes out to 16 months.⁴⁸

We have developed a different type of material specifically for use as a corneal implant to correct refractive error by altering corneal curvature (additive refractive keratoplasty). The perfluoropolyether (PFPE) material offers many advantages for corneal augmentation in that it is isorefractive, inert, transparent, and chemically and thermally stable. When implanted in the feline cornea during short-term onlay studies, a porous version of PFPE was shown to have sufficient permeability to maintain corneal health.^{49,50} The present study was designed to test the long-term biocompatibility and optical clarity of the PFPE polymer when implanted as an inlay in the rabbit cornea.

MATERIALS AND METHODS

Inlay Material

PFPE used in this experimental series was formulated for an inlay application and was a high zwitterion-concentration variant of that tested previously for corneal onlay application.^{49,50} Briefly, a porous PFPE-zwitterion copolymer was made by the UV copolymerization of the PFPE-dimethacrylate and (2-(methacryloyloxy)ethyl) dimethyl (3-sulfopropyl) ammonium hydroxide inner salt.⁵¹ The porous PFPE-zwitterion copolymer was cast in the laboratory into inlays using polypropylene molds that measured 4 mm in diameter and were approximately 85 μm thick at the center, with tapering edges. The equilibrium water content of the PFPE inlays was 51%. The PFPE formulation used for the inlays had a permeability of $1634 \pm 262 \mu\text{g/hr per cm}^2$ to water and $905 \pm 46 \mu\text{g/hr per cm}^2$ to tryptophane (used as a model for glucose). Permeability measurements were made using 100- μm -thick PFPE membranes in stirred diffusion chambers with 0.05% solute in PBS at 15 mm Hg pressure applied to the solute chamber.

Surgery

The animal research in this study was approved by the Animal Care and Ethics Committee of the University of New South Wales. All procedures were performed in compliance with the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research. Twenty-seven New Zealand White rabbits, aged 1 to 2 years and weighing 2.5 to 3.5 kg each, were used in this study. Nictitating membranes in all rabbits were removed from both eyes at least 2 weeks before surgery, as previously described.⁵² Animals were anesthetized using an intramuscular injection of ketamine 35 mg/kg and xylazine 5 mg/kg to a depth of stage 3, plane 2. One eye of each animal was chosen at random for surgery; 2 drops of 0.4% oxybuprocaine hydrochloride (Bausch & Lomb, Rochester, NY) and 2 drops of 0.3% tobramycin (Alcon, Ft. Worth, TX) were placed in the selected eye. Animals were randomly assigned to 3 groups: implanted ($n = 16$), sham-wounded ($n = 8$), and normal rabbits that had not undergone any surgical procedures at any time ($n = 3$). In implanted animals, a conventional corneal flap was created by a microkeratome (Krumeich-Barraquer; Summit Technology) with the setting of flap diameter, thickness, and hinge, respectively, as 8 to 8.5 mm, 160 μm , and 5 to 7 mm. The corneal flap was rolled over to the nasal portion of the cornea, a PFPE inlay was placed onto the center of the stromal bed, and the flap was rolled back to cover the inlay. A soft contact lens (PureVision, Balafilcon A; Bausch & Lomb) was placed over the corneal flap for 1 to 3 days after surgery and was removed on day 3 if it had not spontaneously dislodged. In sham-wounded animals, identical procedures were followed, but no inlay was implanted (hereafter referred to as sham). Eye ointment (10 mg/g chloramphenicol and 5 mg/g hydrocortisone acetate) was administered to all operated eyes twice daily for the first week, daily for a month, and then at least monthly until termination.

Clinical Evaluation

Clinical evaluation was performed on each animal at least twice during the first week after surgery, then weekly for the first month, and then

every 2 to 3 weeks using a slit lamp biomicroscope until termination. This evaluation included integrity of the corneal flap, assessment of conjunctival redness, appearance of the cornea anterior and posterior to the inlay, position of inlay, and optical clarity and integrity of the inlay. The tear film of the rabbits in our study was assessed with a tearscope, as described elsewhere.⁵³ The uniformity of the lipid layer on the tear film surface was assessed by observing the lipid pattern during the natural opening of the eye. Greater homogeneity of the lipid layer indicated greater uniformity of the tear-film surface. Stability of the tear film was assessed by observing changes in the lipid pattern 10 to 12 seconds after artificial blinking that was necessary because rabbits do not blink as often as humans. Less change in the lipid pattern indicated more stable tear film during the observation period. Oxygen uptake was measured in the implanted and the contralateral eyes in 4 animals 18 months after surgery using a pH/blood gas monitor (PHM73, Radiometer; Copenhagen, Denmark) controlled by customized computer software. Oxygen was supplied to a silicon membrane reservoir within a probe that consisted of a platinum-reducing electrode and a silver reference electrode bathed in a sterile water bath at 37°C. Oxygen tension in the reservoir was set at 155 mm Hg. The probe was touched onto the cornea, central and peripheral to the inlay, respectively. Oxygen tension within the probe slowly dropped as oxygen was consumed by the cornea under the probe when an airtight seal had formed between the tip of the probe and the cornea. This decline in partial oxygen pressure over time (mm Hg per second) was recorded as a measure of the flow rate of oxygen through the cornea. Five readings for each measurement were collected to provide a mean result. The difference in the flow rate of oxygen for the same site of measurements between the operated and control eyes was analyzed (paired *t* test). Optical clarity of the inlays was assessed using biomicroscopy 30 minutes after the application of a single drop of a topical mydriatic (0.5% wt/vol tropicamide BP), and backscattered light was graded according to the scale shown in Figure 1. Animals were maintained for predetermined times of 6, 12, and 24 months after surgery, at which point they were humanely killed and their eyes dedicated to histology (light microscopy [LM] and electron microscopy [EM]) or immunohistochemistry examination. Eyes of the healthy group were used as controls to match the histology of the operated eyes at the three time points.

Histology (Light and Electron Microscopy)

The eyes from all animals except those of animal 2, dedicated to immunochemistry (see below), were fixed for LM and EM immediately after euthanasia. Eyes were fixed in 4% paraformaldehyde solution for a minimum of 24 hours, and then corneas were excised and placed in fresh 4% paraformaldehyde solution for another 24 hours. Corneas were bisected in the nasotemporal plane, with half dedicated to paraffin histology (LM), and a 3-mm strip cut limbus to limbus from the other half was dedicated to resin histology (transmission electron microscopy [TEM]). Tissue for LM was processed, and 5- μm sections were cut onto gel-coated slides that were routinely stained with hematoxylin and eosin. These were examined using a microscope (DMLB; Leica, Wetzlar, Germany) fitted with a digital camera. Ultrathin transverse sections 100 nm thick were cut from resin-embedded tissue, stained en grid with uranyl acetate and Reynold's lead citrate, and viewed using a transmission electron microscope (CM-100; Philips, Eindhoven, The Netherlands) fitted with a digital camera (Gatan, Pleasanton, CA). LM sections were assessed for the position and integrity of the inlay, the structure and thickness of the epithelium, stroma, and keratocytes in the vicinity of the inlay, and the thickness and position of the corneal flap. TEM sections were used to check the stromal-inlay interface for signs of keratocyte activity and the presence of inflammatory cells. TEM was also used to monitor the central epithelium in implanted, sham, and normal corneas with microvilli, desmosomes, hemidesmosomes, and basement membrane used as markers for epithelial integrity and function. Rough counts of microvilli, desmosomes, and hemidesmosomes were made in representative sections selected from each of the three groups (sham, implanted, and normal).

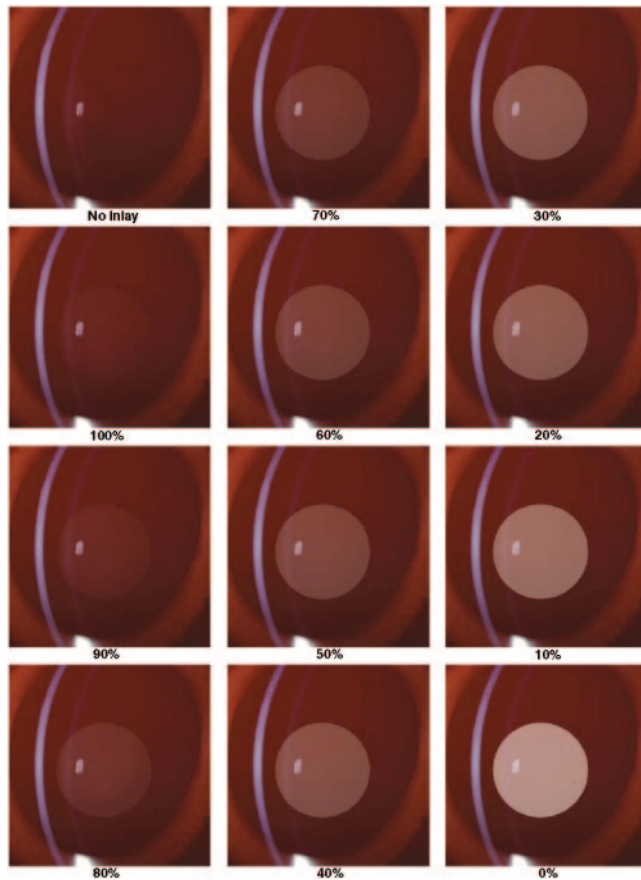


FIGURE 1. Grading scale developed to evaluate the optical clarity of the PFPE inlay, assessed with back-scattering through the inlay under retroillumination of the fundus. A higher percentage of back-scattering denoted greater optical clarity of the inlay.

Immunohistochemistry

Corneas from 2 animals (1 sham, 1 implant) at the 24-month time point were dedicated to immunohistochemistry to assess the wound healing status of the corneas. These corneas were placed into cold PBS immediately after termination and snap-frozen in optimal cutting temperature (OCT) compound. Sections 7 to 8 μm thick were cut onto gel-coated slides using a cryostat. Sections were blocked in 3% BSA/PBS for 60 minutes at room temperature. Sections were incubated in either a monoclonal antibody against fibronectin (A35; CSIRO Molecular and Health Technologies, Sydney, Australia) or a monoclonal antibody against α -smooth muscle actin (α -sma; Sigma, St. Louis, MO) overnight at 4°C. Fibronectin was used as a representative marker of extracellular matrix proteins present during wound healing; α -sma is a marker of a contractile keratocyte phenotype known to be associated with the formation of haze and corneal scarring.⁵⁴ Sections were washed 3 times in PBS and incubated in FITC-conjugated rabbit anti-mouse secondary antibody (DAKO, Glostrup, Denmark) for 60 minutes at room temperature in the dark. Sections were washed 3 times in PBS, mounted, and viewed using a laser confocal microscope.

RESULTS

Clinical Outcomes

At the time of surgery, a PFPE inlay was placed under the corneal flap in the implanted group ($n = 16$). For the sham group ($n = 8$), the flap was lifted and replaced with no inlay implanted. During the first 1 to 2 days after surgery, 6 of the animals in the implanted group and 3 in the sham group were

excluded from the trial because the corneal flap was irregularly thick, dislodged, or too thin. We noted that the rate of flap dislodgement was the same for the sham (3 of 8 eyes) and implanted (6 of 16 eyes) groups, indicating that the presence of an implanted inlay under the flap was unlikely to be a significant contributing issue to this problem. Most likely, the cause of these surgical failures in the sham and implanted groups was the use of a microkeratome and a suction ring designed for the size and curvature of the human eye, which made it difficult to guarantee a corneal flap of even thickness in the rabbit, especially if the eye was slightly small. The corneal flap in the animals remaining in the trial (10 implanted, 5 sham) remained in place and was observed to be approximately 90 to 120 μm thick. One animal from the sham group died on day 182 of causes unrelated to the ophthalmic surgery. Three animals from the implanted group were terminated earlier than planned because peripheral focal corneal defects developed on days 195, 251, and 553. The remaining 11 animals (7 implanted, 4 sham) were maintained to the original predetermined time points without any problems.

Clinically, the PFPE inlays were well tolerated by the corneal tissue over the 2-year period of the study (Fig. 2). In an early tissue reaction to surgery, some edema was observed at the flap-stromal interface (sham corneas) and the flap-inlay interface (implanted corneas) of operated corneas immediately after surgery that largely subsided within 3 to 7 days. Apart from interfacial debris, all operated corneas remained clear anterior and posterior to the corneal incision; the epithelium remained intact, and there was no evidence of stromal thinning. No infiltration, neovascularization, or increased conjunctival redness was observed in any of the operated corneas for the period of the study. A normal tear film over the cornea in implanted and sham eyes was maintained for the entire duration of the study, as demonstrated by a highly homogeneous lipid pattern in implanted and contralateral (unoperated) eyes. The pattern color of the tear film in both eyes of each rabbit varied slightly from yellow to light brown in different animals, indicating that the rabbits had a thick, even tear film. In addition, little or no change occurred in the lipid pattern in implanted or contralateral eyes after artificial blinking, indicating that the tear film was stable. In the implanted corneas, polymer transparency was maintained between 85% and 95% at the 24-month time point of the study (Fig. 3). During implantation, some inlays were noted to be not completely homogeneous in their transparency, though this did not occur in all cases. Oxygen uptake data at the 18-month time point showed no significant difference between the implanted and the contralateral eyes in either the central or the peripheral cornea (Table 1), though the implanted eye had 12% slower oxygen uptake in the central cornea and 6.4% faster oxygen uptake in the peripheral cornea than the contralateral eye.

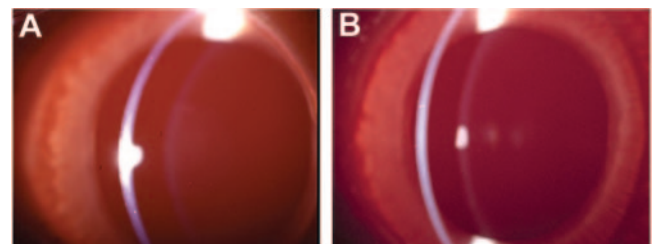


FIGURE 2. Slit lamp biomicrographs. (A) Implanted cornea 742 days after surgery indicating the high level of tolerance of the inlay by the host cornea and the high level of clarity of the inlay (100% in back-scattering). (B) Sham-wounded cornea 727 days after surgery in which the flap edge is not visible and the cornea is clear with no haze, deposits, or other adverse responses.

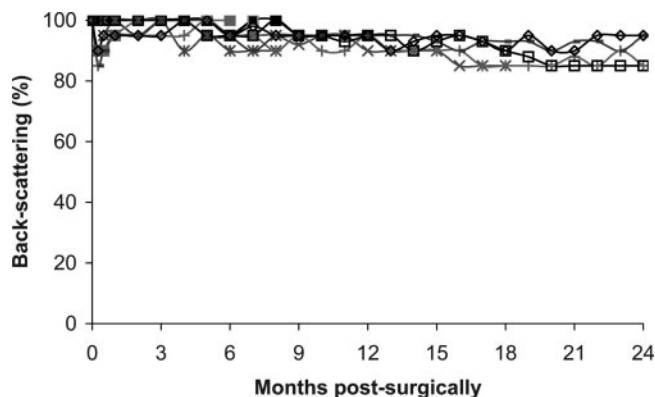


FIGURE 3. Optical clarity of inlays in the implanted group was evaluated individually with back-scattering under slit lamp microscopy. Inlays maintained optical clarity between 85% and 95% throughout the observation period.

Histology

In implanted corneas at each time point, an intact polymer inlay with tapered edges was present beneath the corneal flap. In each case, the inlay was intact and undamaged, demonstrating biostability in the corneal environment. In all operated corneas (sham and implanted groups), the original microkeratome incision across the cornea was marked by a fine line of fibrosis, which, in TEM, showed some irregularity of stromal collagens along the original incision line. The epithelium anterior to the microkeratome incision (sham) and polymer inlay (implanted) was stratified but thinned slightly in both groups compared with the central corneal epithelium of normal rabbit (Fig. 4). This was the case at each time point to 24 months. Changed basal cell morphology (cuboidal rather than columnar) and reduced numbers of cell layers (five rather than six) accounted for the epithelial thinning. Local epithelial hyperplasia marked the distal flap edge of sham and implanted corneas at each time point.

Ultrastructural examination (by TEM) of the central portion of each cornea in the study showed that the morphology and distribution of many of the features monitored in the operated groups (implanted and sham) were similar to those of normal rabbit cornea. This was the case for microvilli/microplicae on the anterior ocular surface, which were similar to normal in morphology, distribution, and density (Figs. 5A-C). Desmosomes, the cell-cell junctions responsible for the adhesion between adjacent epithelial cells, were similar in morphology and distribution to those of normal rabbit cornea but fewer in number (Figs. 5D-F). Hemidesmosomes, the cell-matrix junctions responsible for the anchorage of the epithelium to its underlying stroma, were present along the basement membrane with similar morphology and distribution to normal

rabbit cornea but fewer in number (Figs. 5G-I). Apart from the fibrosis associated with the microkeratome incision, stromal tissue and keratocyte distribution and density anterior and posterior to the implanted inlay appeared normal at each time point. TEM showed that keratocytes in the region of the original incision line in the sham and implanted corneas were more vacuolated than those in normal cornea, suggesting an increased level of activity (Figs. 5K-L). In implanted corneas, keratocytes were located in places in direct contact with the inlay on anterior and posterior surfaces. Sometimes these were associated with fine cellular processes that had penetrated the surface of the inlay. Extracellular matrix and cell debris that resulted from the degeneration of keratocytes was also evident around the inlay. No inflammatory cells or neovascularization were observed in the vicinity of the microkeratome incision in sham or implanted corneas at any of the time points studied.

Immunohistochemistry

Immunohistochemistry results from the 24-month corneas showed that fibronectin was present in the extracellular matrix along the original incision line in both the sham and the implanted cornea (Fig. 6). No α -sma was detected in the stromal keratocytes or fibroblasts of either sham or implanted rabbit cornea at this time.

DISCUSSION

PFPE inlays were well tolerated by most (7 of 10) rabbit corneas over the 24 months of this trial, demonstrating that it is possible to successfully maintain an inlay under a corneal flap for up to 2 years. In these animals, the inlays were centered under the corneal flap, and the corneas remained clear apart from low levels of interfacial debris with no signs of infiltration or neovascularization in the implanted corneas for the duration of the test period. In each case, the tear film was normal, the epithelium was intact and healthy, and there was no stromal thinning. Problems apparently related to casting imperfections in the inlays and/or to difficulties with consistency of the surgical procedure developed in three animals in the implanted group that then had to be removed from the trial earlier than planned (on days 195, 251, and 553). One animal was discontinued on day 195 because of a small focal defect in the peripheral area of the inlay in the temporosuperior region. Histologic examination of this implanted cornea showed a small, very focal patch of stromal erosion and epithelial thinning anterior to the inlay. This defect was confined, and no other obvious abnormality was observed in the inlay or tissue of this cornea. A second animal was discontinued from the trial on day 251 because of a focal epithelial defect directly above a single split in the inlay. The split was first noted on day 207 and might have resulted from uneven mechanical pressure on the inlay during the period of implantation. A third animal was

TABLE 1. Oxygen Uptake in the Corneas of Implanted and Contralateral Eyes 18 Months after Surgery

	Central to Inlay/*Central Cornea		Superior to Inlay/*2 mm from Superior Limbus	
	Implanted Eye	Contralateral Eye	Implanted Eye	Contralateral Eye
Mean (SD)	2.805 (1.22)	3.25 (0.61)	3.32 (0.39)	3.12 (0.32)
Number of eyes	4	4	4	4
<i>P</i> (paired <i>t</i> test)	0.58		0.06	

Oxygen uptake is measured in mm Hg per second.

* Sites of measurement for the contralateral eyes.

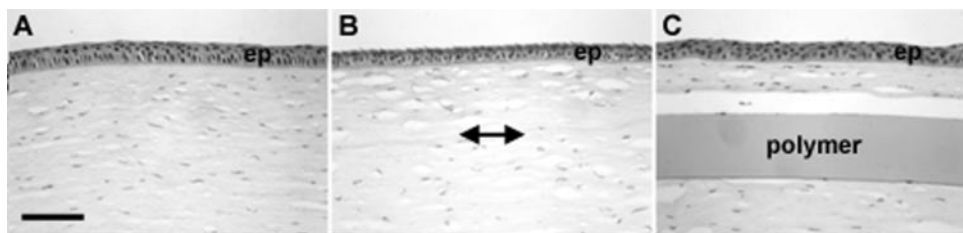


FIGURE 4. Light micrographs of central cornea in (A) normal rabbit, (B) sham-wounded cornea on day 730, and (C) implanted cornea on day 742 (ep indicates corneal epithelium; arrow shows line of original microkeratome cut in sham; polymer is the polymer inlay). Bar, 80 μ m; all images are shown at the same magnification.

removed from the study on day 553 because of a small peripheral focal defect in the nasoinferior region. Histologic examination of this cornea showed focal stromal thinning and erosion anterior to the inlay in that area, and a small foreign body (perhaps a free piece of inlay polymer) was noted on the anterior surface of the inlay in this region. As noted, the use of a microkeratome designed for human eyes in the cutting of a corneal flap in rabbit eyes made it difficult to achieve a flap of consistent depth and thickness on every occasion given the

variability in the size and shape of the rabbit eyes and made it difficult to achieve and maintain the desired suction pressure during the cutting of the flap. In addition, casting and molding of the inlays was recognized as significant for achieving a good long-term outcome. All inlays used in this study were prepared under laboratory conditions, and it is likely that some slight irregularities in formulating and casting would be eliminated if these procedures were to be conducted outside a research environment.

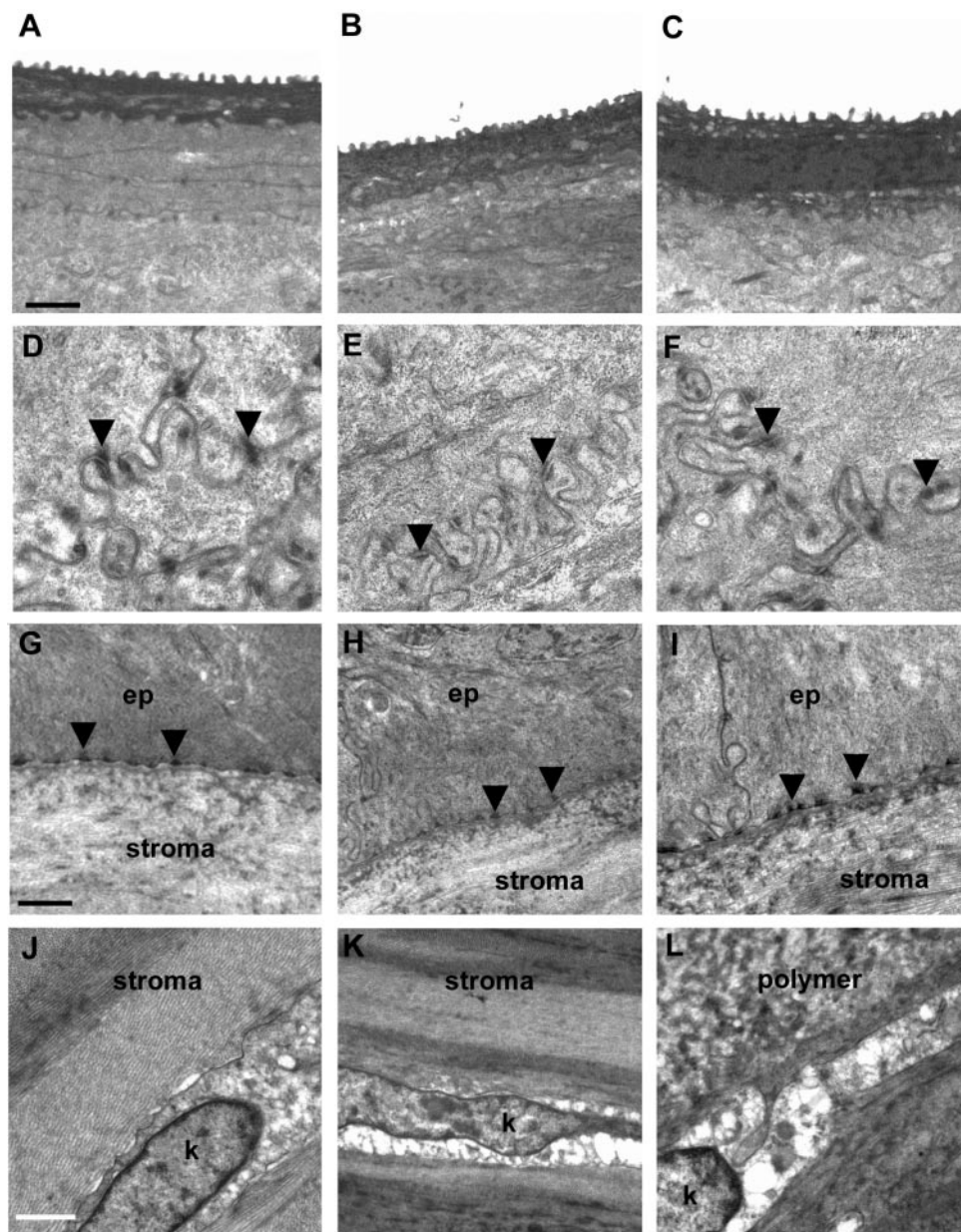


FIGURE 5. Transmission electron micrographs of the central cornea in normal rabbit cornea (A, D, G, J), sham-wounded rabbit cornea on day 730 (B, E, H, K), and implanted rabbit cornea on day 742 (C, F, I, L). Microvilli are seen on the anterior ocular surface (A-C). Desmosomes (arrowheads) are seen between adjoining epithelial cells (D-F). Hemidesmosomes (arrowheads) are seen at the basal aspect of epithelial cells (ep) along the basement membrane (G-I). Keratocytes (k) with vacuolated cytoplasm are seen in the stromal tissue (J-L). Bar, 1 μ m; all images are shown at the same magnification.

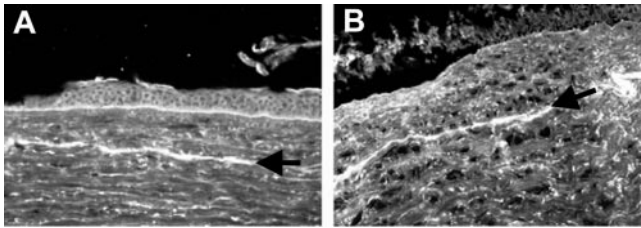


FIGURE 6. Laser confocal images of fibronectin-stained (A) sham-wounded cornea on day 730. (B) Implanted cornea on day 742. Arrows indicate the line of fibronectin deposition along the original microkeratome incision). Images are shown at the same magnification.

Comparative clinical and histologic data from normal, sham, and implanted rabbit corneas maintained to their predetermined time points of 6, 12, and 24 months showed subtle responses to the presence of an implanted PFPE inlay. Operated corneas (sham and implanted groups) healed, and the presence of the PFPE inlay was well tolerated in 7 of 10 implanted corneas. The epithelia over the flaps in the sham and implanted groups were similar histologically and differed from that of normal rabbit corneal epithelium only in slightly decreased overall thickness because of a change in the basal cell morphology. Specific epithelial markers (microvilli, desmosomes, hemidesmosomes) monitored during the study were similar in morphology and distribution in sham and implanted groups, but the numbers of desmosomes and hemidesmosomes were slightly lower than those seen in normal rabbit cornea. Despite this slight decrease, the epithelium over the flap in the operated eyes was stratified and maintained a high level of integrity throughout the duration of the study.

The reasons for the epithelial thinning are unclear and may involve several factors, one of which appears to have been species. Other groups have reported long-term epithelial thinning after LASIK procedures in rabbit corneas that were also evaluated by histology after 6 months⁵⁵ and 9 months.⁵⁶ This differs from reports in human corneas after LASIK surgery, with no change in flap epithelium up to 4 months after surgery as noted by histologic examination⁵⁷ or a thickened epithelium for 1 to 12 months after surgery as measured by *in vivo* confocal microscopy.^{58,59} It is possible that there were differences between histologic and laser confocal data, and we are cautious of direct comparisons with these studies because our study used a microkeratome incision but did not involve the laser ablation used in conventional LASIK procedures. Cutting of the corneal nerves during the microkeratome incision might also have contributed to the epithelial thinning.⁶⁰ Postoperative nerve damage and loss of corneal sensation have been reported after various refractive procedures involving the human cornea, including LASIK,^{57,59,61–63} LASEK,⁶⁴ epikeratophakia,^{59,65} and long-term corneal graft surgery.⁶⁶ Concurrent thinning of the central epithelium has been noted in the two latter procedures. Yet another factor involved in the epithelial thinning noted in our study may be the effects of any contour feedback mechanism operant in the corneas; though this phenomenon is not well understood, there has been some suggestion of the eyelid acting as a template for corneal curvature.⁶⁷

Ultrastructural examination of the stroma along the microkeratome incision (sham corneas) and along the incision line and in the vicinity of the inlay (in implanted corneas) revealed keratocytes swollen with vacuoles that were greater in number and size than those of normal rabbit cornea. Confocal microscopy of human corneas has shown a decreased keratocyte density in the stromal flap and anterior retroablation area for up to 3 years after LASIK procedures.^{68,69} This suggests that the increased keratocyte numbers observed in sham and implanted corneas in our study may be related to species and/or

to the microkeratome incision without the accompanying laser ablation used in refractive LASIK procedures. The persistent keratocyte activity observed in our study is not an unexpected outcome after wounding of the cornea; rather, such activation is part of the stromal wound healing process in which keratocytes synthesize extracellular matrix to repair damaged tissue.^{70,71} Activated keratocytes have been reported in the vicinity of microkeratome incisions and ablation areas for some months in human^{57,59,61} and rabbit corneas^{55,72} after LASIK surgery. In our study, a microtome incision was made, but no tissue ablation was performed as would have occurred in a LASIK procedure. Nevertheless, activated keratocytes were present in the vicinity of the wounded tissue at each time point, but this activity did not increase with time during the 24-month period. Keratocytes around the implanted inlays were typically swollen with vacuoles, and there was evidence of cellular degeneration in places. Fine cell processes had penetrated the polymer surface in places around the inlay, as noted at the 12- and 24-month time points. Fibronectin immunodata from our study confirmed that extracellular matrix (ECM) was still being produced in the vicinity of the original corneal incision 24 months after surgery. Interestingly, our concurrent α -sma immunodata showed that the stromal wound healing process did not involve the transformation of keratocytes involved in the wound healing process into a contractile keratocyte phenotype. This indicated that any scar formation was likely to be the result of disorganization in the stromal collagens and proteoglycans,⁷³ which was consistent with data from our ultrastructural examination along the region of the original microkeratome incision using electron microscopy.

The corneas of rabbits implanted with PFPE inlays maintained transparency for the entire period of the study, whereas the clarity of inlays decreased slightly with time (5% to 15% loss over the 24-month period). We do not fully understand the reasons for this. Oxygen uptake on implanted eyes 18 months after surgery was compared with that of their contralateral eyes, and data showed no significant change in the oxygen flow rate. This demonstrated the long-term permeability of the PFPE inlays during the period of implantation. The healthy condition of the stroma and epithelium anterior to the implanted inlays during the 24-month test period was further testament to this. We noted no accumulation of deposits and opacification at the edge or on the surface of the inlays, as reported in hydrogel corneal inlays implanted in human trials.⁴⁶ The biologic response in our study was characterized by a low level of keratocyte activity that was localized to the immediate vicinity of the original line of corneal incision and inlay, which might have been the cause of the interfacial debris noted clinically in the sham and the implanted groups. It is possible that the penetration of fine cell processes and ECM material into the polymer surfaces might have been responsible for the slight loss in optical clarity and the occasional inhomogeneity of the inlays.

In conclusion, refractive surgical procedures initiate a corneal repair process. The challenge is to minimize the wound healing response and to maximize the refractive outcome for the patient. In this study, PFPE inlays were implanted in rabbit corneas to evaluate the clarity of the polymer and the long-term biologic response. Data demonstrated that the polymer was biostable in the corneal environment over 24 months, with only a slight reduction in optical clarity of the inlays during that time. During the period of implantation, the implanted corneas remained clear, with no infiltration, neovascularization, or increase in conjunctival redness. The polymer elicited only a low-level wound healing response that was confined to the stromal tissue in the immediate vicinity of the inlay and that did not involve inflammatory cells. Keratocyte activity was the key feature of this low-level response and was characterized by

repair/degeneration and was accompanied by ECM/cellular debris production. Together this constituted an inert foreign body response to the PFPE inlay that was prolonged but benign. Products of this biologic response might, at least partially, have accounted for the slight loss of clarity in the polymer over the 24-month period of this study.

Acknowledgments

The authors would like to thank Denise and Robyn Lawler for their expert care of the animals involved in this study and Ajay Kumar for the monitoring of operated corneas.

References

- Sandoval HP, Fernández de Castro LE, Vroman DT, Solomon KD. Refractive surgery survey 2004. *J Cataract Refract Surg.* 2005;31:221-233.
- Gipson IK, Spurr-Michaud S, Tisdale A, Keough M. Reassembly of the anchoring structures of the corneal epithelium during wound repair in the rabbit. *Invest Ophthalmol Vis Sci.* 1989;30:425-434.
- Gipson IK. Corneal epithelium and stromal reactions to excimer laser photorefractive keratectomy: concerns regarding the response of the corneal epithelium to excimer laser ablation. *Arch Ophthalmol.* 1990;108:1539-1540.
- Seiler T, Holschbach A, Derse M, Jean B, Genth U. Complications of myopic photorefractive keratectomy with the excimer laser. *Ophthalmology.* 1994;101:153-160.
- Anderson JA, Binder PS, Rock ME, Vrabcic MP. Human laser excimer keratectomy—immunohistochemical analysis of healing. *Arch Ophthalmol.* 1996;114:54-60.
- Wilson SE. Molecular cell biology for the refractive corneal surgeon: programmed cell death and wound healing. *J Refract Surg.* 1997;13:171-175.
- Geggel HS, Talley AR. Delayed onset keratectasia following laser in situ keratomileusis. *J Cataract Refract Surg.* 1999;25:582-586.
- Iskander NG, Peters NT, Penno EA, Gimbel HV. Postoperative complications in laser in situ keratomileusis. *Curr Opin Ophthalmol.* 2000;11:273-279.
- Davis EA, Hardten DR, Lindstrom RL. LASIK complications. *Int Ophthalmol Clin Refract Surg.* 2000;40:67-76.
- Pallikaris IG, Kymionis GD, Astyrakakis NI. Corneal ectasia induced by laser in situ keratomileusis. *J Cataract Refract Surg.* 2001;27:1803-1811.
- Carlson AN. LEO clinical topic update: refractive surgery. *Am Acad Ophthalmol.* 2001;9-15.
- Duffey RJ, Leaming D. US trends in refractive surgery: 2001 International Society of Refractive Surgery Survey. *J Refract Surg.* 2002;18:185-188.
- Jacobs JM, Taravella MJ. Incidence of intraoperative flap complications in laser in situ keratomileusis. *J Cataract Refract Surg.* 2002;28:23-28.
- Pallikaris IG, Kalyvianaki MI, Katsanevaki VJ, Ginis HS. Epi-LASIK: preliminary clinical results of an alternative surface ablation procedure. *J Cataract Refract Surg.* 2005;31:879-885.
- Belau PG, Dyer JA, Ogle KN, Henderson JW. Correction of ametropia with intracorneal lenses: an experimental study. *Arch Ophthalmol.* 1964;72:541-547.
- Barraquer JI. Modification of refraction by means of intracorneal inclusions. *Int Ophthalmol Clin.* 1966;6:53-79.
- McCarey BE, Andrews DM. Refractive keratoplasty with intrastromal hydrogel lenticular implants. *Invest Ophthalmol Vis Sci.* 1981;21:107-115.
- Lane SL, Lindstrom RL, Cameron JD, et al. Polysulfone corneal lenses. *J Cataract Refract Surg.* 1986;12:50-60.
- Barrett G, Moore MB. A new method of lathing corneal lenses for keratorefractive procedures. *J Refract Surg.* 1988;4:142-147.
- Dupont D, Gravagna P, Albinet P, et al. Biocompatibility of human type IV intracorneal implants. *Cornea.* 1989;8:251-258.
- McCarey BE. Current status of refractive surgery with synthetic intracorneal lenses: Barraquer Lecture. *Refract Corn Surg.* 1990;6:40-46.
- McCarey BE, Storie BR, Van Rij G, Knight PM. Refractive predictability of myopic hydrogel intracorneal lenses in nonhuman primate eyes. *Arch Ophthalmol.* 1990;108:1310-1315.
- McCarey BE. Refractive keratoplasty with synthetic lens implants. *Refract Surg.* 1991;31:87-99.
- Yamaguchi T, Koenig SB, Kimura T, Werblin TP, McDonald MB, Kaufman HE. Histological study of epikeratophakia in primates. *Ophthalmic Surg.* 1984;15:230-235.
- Rao GN, Ganti S, Aquavella JV. Specular microscopy of corneal epithelium after epikeratophakia. *Am J Ophthalmol.* 1987;103:392-396.
- Lass JH, Stocker EG, Fritz ME, Collie DM. Epikeratoplasty: the surgical correction of aphakia, myopia and keratoconus. *Ophthalmology.* 1987;94:912-925.
- McDonald MB. The future direction of refractive surgery. *J Refract Surg.* 1988;4:158-168.
- Rodrigues M, Nirankari V, Rajagopalan S, Jones K, Funderburgh J. Clinical and histopathologic changes in the host cornea after epikeratophakia for keratoconus. *Am J Ophthalmol.* 1992;114:161-170.
- Thompson KP, Hanna KD, Gipson IK, Gravagna P, Waring GO, Johnson-Wint B. Synthetic epikeratoplasty in rhesus monkeys with human type IV collagen. *Cornea.* 1993;12:35-45.
- Kornmehl EW, Bredvik BK, Kelman CD, Raizman MB, DeVore DP. In vivo evaluation of collagen corneal allograft derived from rabbit dermis. *J Refract Surg.* 1995;11:502-506.
- Climenhaga H, Macdonald JM, McCarey BE, Waring GO. Effect of diameter and depth on the response to solid polysulfone intracorneal lenses in cats. *Arch Ophthalmol.* 1988;106:818-824.
- McCarey BE, Schmidt FH. Modeling glucose distribution in the cornea. *Curr Eye Res.* 1990;9:1025-1039.
- Holmes-Higgin DK, Burris TE. Corneal surface topography and associated visual performance with INTACS for myopia: phase III clinical trial results. The INTACS Study Group. *Ophthalmology.* 2000;107:2061-2071.
- Linebarger EJ, Song D, Ruckhofer J. Intacs: the intrastromal corneal ring. *Int Ophthalmol Clin Refract Surg.* 2000;40:199-208.
- Ruckhofer J, Bohnke M, Alzner E, Grabner G. Confocal microscopy after implantation of intrastromal corneal ring segments. *Ophthalmology.* 2000;107:2144-2151.
- Ruckhofer J, Stoiber J, Alzner E, Grabner G. One year results of European multicenter study of intrastromal corneal ring segments. *J Cataract Refract Surg.* 2001;27:287-296.
- Choyce DP. Semi-rigid corneal inlays in the management of albinism, aniridia and ametropia. In: Henkind P, ed. *Proceedings of the 24th International Congress of Ophthalmology.* Philadelphia: JB Lippincott; 1982:1230.
- Beekhuis WH, McCarey BE, Waring GO, Van Rij G. Hydrogel keratophakia: a microkeratome dissection in the monkey model. *Br J Ophthalmol.* 1986;70:192-198.
- Beekhuis WH, McCarey BE, Van Rij G, Waring GO. Complications of hydrogel intracorneal lens in monkeys. *Arch Ophthalmol.* 1987;105:116-122.
- McCarey BE, Lane SS, Lindstrom RL. Alloplastic corneal lenses. *Int Ophthalmol Clin.* 1988;28:155-163.
- Werblin TP, Patel AS, Barraquer JI. Initial human experience with Permalens myopic hydrogel intracorneal lens implants. *Refract Corn Surg.* 1992;8:23-32.
- McDonald MB, McCarey BE, Storie B, et al. Assessment of the long-term corneal response to hydrogel intrastromal lenses implanted in monkey eyes for up to five years. *J Cataract Refract Surg.* 1993;19:213-222.
- Ismail MM. Correction of hyperopia with intracorneal implants. *J Cataract Refract Surg.* 2002;28:527-530.
- Kaufman HE. An intracorneal lens for hyperopia and presbyopia. Presented in part at the annual meeting of the American Academy of Ophthalmology, New Orleans, LA, October 2004.
- Knorz MC. Corneal stromal implants. Presented in part at the annual meeting of the American Academy of Ophthalmology, New Orleans, LA, October 2004.

46. Alio JL, Mulet EM, Zapata LF, Vidal MT, De Rojas V, Javaloy J. Intracorneal inlay complicated by intrastromal epithelial opacification. *Arch Ophthalmol*. 2004;122:1441-1446.
47. Michieletto P, Ligabue E, Balestrazzi A, Balestrazzi A, Giglio S. PermaVision intracorneal lens for the correction of hyperopia. *J Cataract Refract Surg*. 2004;30:2152-2157.
48. Peyman GA, Beyer CF, Bezerra Y, et al. Photoablative inlay in situ keratomileusis (PAI-LASIK) in the rabbit model. *J Cataract Refract Surg*. 2005;31:389-397.
49. Evans MDM, Xie RZ, Fabbri M, et al. Epithelialization of a synthetic polymer in the feline cornea—a preliminary study. *Invest Ophthalmol Vis Sci*. 2000;41:1674-1680.
50. Evans MDM, Xie RZ, Fabbri M, et al. Progress in the development of a synthetic corneal onlay. *Invest Ophthalmol Vis Sci*. 2002;43:3196-3201.
51. Hughes TC, Chan GY, inventors. Biomedical device WO 03/097711, Publication date: 27 November, 2003.
52. Xie RZ, Sweeney DF, Griesser HJ, Tout SD, Cheng HY, Steele JG. A thin glycoprotein coating of a synthetic lenticule does not cause nutritional deficiency of the anterior cornea. *Curr Eye Res*. 1999;18:335-341.
53. Guillon J-P, Guillon M. Tear film examination of the contact lens patient. *Contax*. 1988;May:14-18.
54. Jester JV, Petroll WM, Barry PA, Cavanagh HD. Expression of a-smooth muscle (a-SM) actin during corneal stromal wound healing. *Invest Ophthalmol Vis Sci*. 1995;36:809-819.
55. Amm M, Wetzel W, Winter M, Uthoff D, Duncker GIW. Histopathological comparison of photorefractive keratectomy and laser in situ keratomileusis in rabbits. *J Refract Surg*. 1996;12:758-766.
56. Kato T, Nakayasu K, Hosoda Y, Watanabe Y, Kanai A. Corneal wound healing following laser in situ keratomileusis (LASIK): a histopathological study in rabbits. *Br J Ophthalmol*. 1999;83:1302-1305.
57. 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.
58. Erie JC, Patel SV, McLaren JW, et al. Effect of myopic laser in situ keratomileusis on epithelial and stromal thickness: a confocal microscopy study. *Ophthalmology*. 2002;109:1447-1452.
59. Tervo T, Moilanen J. In vivo confocal microscopy for evaluation of wound healing following corneal refractive surgery. *Prog Ret Eye Res*. 2003;22:339-358.
60. Muller LJ, Marfurt CF, Kruse F, Tervo TMT. Corneal nerves: structure, contents and function. *Exp Eye Res*. 2003;76:521-542.
61. Anderson NJ, Edelhauser HF, Sharara N, et al. Histologic and ultrastructural findings in human corneas after successful laser in situ keratomileusis. *Arch Ophthalmol*. 2002;120:288-293.
62. Lee BH, McLaren JW, Erie JC, Hodge DO, Bourne WM. Reinnervation in the cornea after LASIK. *Invest Ophthalmol Vis Sci*. 2002;43:3660-3664.
63. Calvillo MP, McLaren JW, Hodge DO, Bourne WM. Corneal reinnervation after LASIK: prospective 3-year longitudinal study. *Invest Ophthalmol Vis Sci*. 2004;45:3991-3996.
64. Herrmann WA, Shah CP, von Mohrenfels CW, Gabler B, Hufendiek K, Lohmann CR. Tear film function and corneal sensation in the early postoperative period after LASEK for the correction of myopia. *Graefes Arch Clin Exp Ophthalmol*. 2005;243:383-385.
65. Cahill M, Condon P, O'Keefe M. Long-term outcome of epikeratophakia. *J Cataract Refract Surg*. 1999;25:500-507.
66. Tervo T, Vannas A, Tervo K, Holden BA. Histochemical evidence of limited reinnervation of human corneal grafts. *Acta Ophthalmol*. 1985;63:207-214.
67. Spadea L, Fasciani R, Necozone S, Balestrazzi E. Role of the corneal epithelium in refractive changes following laser in situ keratomileusis for high myopia. *J Refract Surg*. 1999;16:133-139.
68. Mitooka K, Ramirez M, Maguire LJ, et al. Keratocyte density of central human cornea after laser in situ keratomileusis. *Am J Ophthalmol*. 2002;133:307-314.
69. Erie JC, Nau CB, McLaren JW, Hodge DO, Bourne WM. Long-term keratocyte deficits in the corneal stroma after LASIK. *Ophthalmology*. 2004;111:1356-1361.
70. Wilson SE, Kim W-J. Keratocyte apoptosis: implications on corneal wound healing, tissue organization and disease. *Invest Ophthalmol Vis Sci*. 1998;39:220-226.
71. Fini ME. Keratocyte and fibroblast phenotypes in the repairing cornea. *Prog Ret Eye Res*. 1999;18:529-551.
72. Mohan RR, Hutcheson AEK, Choi R, et al. Apoptosis, necrosis, proliferation and myofibroblast generation in the stroma following LASIK and PRK. *Exp Eye Res*. 2003;76:71-87.
73. Dawson DG, Edelhauser HF, Grossniklaus HE. Long-term histopathologic findings in human corneal wounds after refractive surgical procedures. *Am J Ophthalmol*. 2005;139:168-178.