EXCIMER LASER PHOTOTHERAPEUTIC KERATECTOMY IN EYES WITH ANTERIOR CORNEAL DYSTROPHIES: PREOPERATIVE AND POSTOPERATIVE ULTRASOUND BIOMICROSCOPIC EXAMINATION AND SHORT-TERM CLINICAL OUTCOMES WITH AND WITHOUT AN ANTIHYPEROPIA TREATMENT

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ABSTRACT

Purpose: To evaluate the use of high-frequency ultrasound biomicroscopy (UBM) in determining the depth of corneal pathology in eyes undergoing excimer laser phototherapeutic keratectomy (PTK) for primary or recurrent anterior stromal corneal dystrophies. Corneal clarity, visual acuity and refractive changes in eyes with and without an antihyperopia treatment were also analyzed.

Methods: Twenty eyes of 14 patients with anterior stromal corneal dystrophies were treated with PTK. Eyes were evaluated preoperatively and 6 to 8 weeks postoperatively with slit-lamp biomicroscopy, manifest refraction, keratometry, computerized corneal topography, ultrasound pachymetry, and UBM.

Results: Nineteen of 20 corneas (95%) had greatly improved corneal clarity after PTK. Mean uncorrected Snellen vision improved from 20/102 to 20/69 and best corrected vision improved from 20/62 to 20/38. Nine eyes (45%) improved 2 or more lines of uncorrected vision, and 13 eyes (65%) improved 2 or more lines of best corrected vision. Mean change in spherical equivalent was just –0.92 diopters (D); however, the range was large (–13 to +3.88 D). UBM measurement of central corneal pathology did not correlate with the actual PTK ablation depth ($P = .07$). The amount of antihyperopia treatment did not correlate with changes in manifest refraction spherical equivalent, keratometry, or computerized corneal topography readings, but did correlate with length of time until corneal reepithelialization after PTK ($P = .003$).

Conclusions: PTK resulted in improvements in corneal clarity and visual acuity in most patients with superficial corneal stromal dystrophies. UBM was not an effective tool to accurately measure the depth of corneal pathology preoperatively. The combined approach of minimizing ablation depth and selective use of an antihyperopia treatment resulted in minimal mean change in spherical equivalent; however, the range was large. PTK is a very good minimally invasive technique to improve vision in eyes with anterior stromal corneal dystrophies.


INTRODUCTION

The excimer laser has been used since the late 1980s to reshape the anterior corneal curvature in a procedure known as photorefractive keratectomy (PRK), initially for myopia and later for astigmatism and hyperopia. In this surgery, the epithelium is removed and the laser is applied to ablate a specific amount of Bowman’s membrane and stroma. The excimer laser can also be used to remove superficial corneal pathology in a procedure termed phototherapeutic keratectomy (PTK). Unlike PRK and PTK, laser-assisted in-situ keratomileusis (LASIK) is a procedure where a thin flap of corneal tissue, including epithelium, Bowman’s membrane, and stroma, is fashioned, and the excimer laser is used to reshape the stroma under the hinged flap. Afterward the flap is repositioned on the corneal surface without sutures. The excimer laser clinically used in ophthalmology utilizes 193-nm wavelength ultraviolet light to break molecular bonds in the cornea to remove tiny amounts of tissue. One pulse of excimer laser light removes approximately 0.25 µm of tissue, depending on the specific laser system. Excimer laser PRK and LASIK are approved by the US Food and Drug Administration (FDA) to treat mild to high degrees of myopia and mild to moderate degrees of hyperopia and astigmatism.

When excimer laser PTK was approved by the FDA in 1995 for clinical use in eyes with corneal pathology, many ophthalmologists thought that this procedure would eliminate the need for a significant number of corneal transplants in the United States. While excimer laser PTK is excellent for certain types of corneal pathology, it is not...
Including symptoms of pain and/or decreased vision. It is treat anterior corneal pathology affecting visual function, when it is not.

Over the past 7 years, we have learned a number of patients, including those with anterior corneal dystrophies, anterior corneal scars, and superficial corneal irregularities. After PTK, and induced refractive error, most typically hyperopia, but also myopia and astigmatism, is common.

While one of the goals of the procedure is to decrease corneal irregularity, it is not unusual for PTK to cause worsened irregular astigmatism. Patients should understand that PTK is often being performed in lieu of a more invasive procedure such as lamellar or penetrating keratectomy. Occasionally, PTK is unsuccessful and corneal grafting is required to improve vision.

PTK PROCEDURE
The exact procedure used to perform PTK depends

Rapuano

The exact procedure used to perform PTK depends greatly on the specific corneal pathology being treated. There are three general techniques employed to treat most corneas. The three approaches are used to treat (1) relatively smooth central anterior stromal opacities (eg, Reis-Bücklers' or granular dystrophies), (2) elevated corneal lesions (eg, Salzmann's nodular degeneration), and (3) recurrent erosions, most commonly associated with anterior basement membrane dystrophy. Often, more than one of these techniques is used in an eye.

PTK for Stromal Opacities
Eyes with anterior stromal opacities, such as corneal dystrophies of Bowman's membrane (eg, Reis-Bücklers' dystrophy) and anterior stromal dystrophies (eg, lattice and granular dystrophies, recurrent dystrophies in a graft), generally respond well to PTK. In most of these cases, the epithelial layer is relatively smooth. Often the superficial stromal opacities extend anteriorly into the posterior aspect of the epithelium. In these cases, the epithelium acts as a smoothing or masking agent. Here, removing the epithelium manually actually creates a more irregular surface in many eyes. Therefore, the epithelium is preferably removed with the excimer laser. Laser epithelial removal potentially creates a smooth surface in the stroma as existed in the epithelium. A large-diameter ablation zone (eg, 6 to 7 mm) is centered over the entrance pupil, and the ablation is performed through the epithelium and Bowman's membrane and into the stroma. Preoperatively, an estimate of the depth of the pathology needs to be determined, typically using a combination of slit-lamp biomicroscopy and ultrasound pachymetry. Only a percentage of this depth (eg, 50% to 75%) should be programmed into the laser system computer for initial delivery. When this amount of ablation has been performed, the patient is brought to a slit lamp and examined. Generally, more ablation is then required to remove the majority of the corneal pathology to improve the patient's symptoms. Not all of the opacity needs to be removed to significantly improve vision. This "ablate and check" technique is essential to remove only the amount of opacity necessary to improve symptoms, but not any additional tissue, which would increase the risks of significant refractive change and corneal haze or scar.

PTK for Elevated Lesions
Elevated opacities, most commonly Salzmann's nodular degeneration lesions and keratoconus nodules, are often treatable with mechanical superficial keratectomy using a blade. Those lesions not amenable to removal with a blade, generally because of some stromal involvement, can be treated with PTK. In these eyes, the epithelium is removed manually only from the elevated portion of the lesion and left in place adjacent to the lesion. A small-

Caution should be taken in patients with potential healing abnormalities such as patients with keratitis sicca, neurotrophic corneas (eg, after herpes simplex or herpes zoster keratitis), exposure keratopathy, collagen vascular disorders (eg, rheumatoid arthritis), and diabetes mellitus.

Eyes with a history of herpes simplex keratitis are at risk for recurrence of herpes after PTK.

Generally, the best candidates for excimer laser PTK are patients with corneal opacities in the anterior 10% to 20% of the cornea without significant irregularity or thinning. Eyes with localized elevated lesions are also good candidates for this procedure. Complications of PTK include infectious keratitis, corneal haze, and corneal scarring. In addition, opacities and dystrophies can recur after PTK, and induced refractive error, most typically hyperopia, but also myopia and astigmatism, is common.
diameter ablation zone (eg, 1 to 2 mm) is used to “shave” down the lesion. Ideally, the lesion is ablated to the level of the surrounding stroma, resulting in a smooth cornea. When there are areas of cornea that do not require ablation in close proximity to more elevated areas, the areas not requiring ablation can be coated with a masking agent to protect them. Different viscosities of masking agents can be employed for different lesions. Most surgeons use a variety of thinner viscosity and thicker viscosity preservative-free tears as masking agents. Once the elevated area is relatively smooth, a larger-diameter ablation zone (eg, 4 to 6 mm) can be used to smooth the entire area. In the future, BioMask (Maverick Technologies, Inc, Clearwater, Fla), a material derived from porcine type I collagen, has the potential to be an effective masking agent to aid in the treatment of corneal irregularities with PTK.15,14

PTK in Thin Corneas
When corneal opacities associated with corneal thinning (eg, corneal ulcer scars) are being treated, it is difficult to create a smooth corneal surface without causing a large area of significant corneal thinning. Masking agents are often necessary to produce even a somewhat smooth surface. When required, such lesions can be treated, but the resulting corneal flattening, which can be dramatic, must then be managed, often with a rigid gas permeable contact lens.

PTK for Recurrent Erosions
The third technique is used to treat recurrent erosions, most commonly associated with anterior basement membrane dystrophy. Most eyes with recurrent erosions can be managed with medical therapy such as lubrication, hypertonic agents, and bandage soft contact lenses. With failure of medical management, surgical options are available, including anterior stromal puncture, diamond burr polishing of Bowman’s membrane, and excimer laser PTK. When PTK is used, the entire area of loose epithelium is removed, and the cornea is treated to ablate 5 to 6 µm of Bowman’s membrane. Care should be taken to remove all areas of loose epithelium and then to treat all of the exposed Bowman’s membrane to prevent recurrences outside the treated area.

PTK-Induced Refractive Error
One of the most frustrating aspects of PTK surgery is induced refractive error. Most of the time ablations are performed centrally, causing central corneal thinning and flattening, resulting in induced hyperopia. When peripheral ablations are performed, induced myopia may occur. Induced astigmatism is not uncommon, because corneal opacities are often not uniform and are difficult to completely smooth out with current techniques, even with the use of masking agents. During the early PTK experience, hyperopic shifts of 5 to 15 D were routinely induced. As more procedures were performed and patients were followed for longer periods of time, surgeons realized that deep ablations were responsible for this hyperopic shift. Techniques were developed, including the “ablate and check” procedure discussed earlier, to combat this adverse effect. Additionally, an antihyperopia ablation was proposed to decrease corneal flattening and induced hyperopia. The effectiveness of these modalities is uncertain. One problem is that precisely how much tissue needs to be removed in any given patient is not known preoperatively. Also, exactly how much hyperopia is induced per amount of tissue removed during PTK is unknown, as is the best method to counteract induced hyperopia.

STUDY GOALS
This study evaluated methods to objectively measure depth of pathology preoperatively and prevent significant hyperopic shift in eyes with relatively superficial corneal stromal dystrophies undergoing excimer laser PTK. Specifically, ultrasound biomicroscopic analysis of the cornea was performed preoperatively to determine whether it was an effective technique to predict the exact depth of excimer laser PTK ablation required to remove the majority of the corneal opacity. Additionally, varying degrees of antihyperopia treatment were applied to different corneas after PTK, and the refractive effects were studied. The first hypothesis is that ultrasound biomicroscopy is an effective tool to determine depth of corneal pathology. The second hypothesis is that greater degrees of antihyperopia treatment would cause less hyperopic shift.

PTK PUBLISHED RESULTS
PTK Case Reports
One of the first reports of the clinical use of PTK was a case of successful removal of a corneal nodule in a patient with keratoconus, which allowed the patient to resume comfortable contact lens wear. Since that time, PTK has been used to treat many different corneal conditions. Others have also used PTK to successfully remove keratoconus nodules in contact lens–intolerant patients. PTK has been used to remove primary amyloidosis from the cornea, band keratopathy, corneal scarring from trachoma, shield ulcers and plaques in vernal keratoconjunctivitis, subepithelial cryoglobulin deposits, corneal scarring during recurrent pterygium surgery, corneal fibrosis after radial keratotomy, corneal scarring after presumed infection after PRK, corneal scarring in an epikeratophakia lenticule, and subepithelial scarring in a child with Rothmund-Thomson syndrome. It has also been used to treat painful bullous keratopathy (Table I).
A multitude of series of PTK results have been published over the past decade (Table I). The first large series reported on 33 eyes of 33 patients with a wide variety of corneal diseases, including corneal scarring from trauma, infection, herpes simplex virus, Salzmann’s nodular degeneration, band keratopathy, granular dystrophy, and pterygium scars.15 Best corrected vision improved in approximately half of the eyes, but vision worsened in 15%. A significant hyperopic shift was noted in 50% of eyes, especially at the beginning of the study, before the investigators combined their central treatment with a peripheral antihyperopia treatment.

A second large series was published the following year. Stark and associates16 reported on 27 eyes after PTK done for a variety of corneal conditions, including primary and recurrent lattice dystrophy, primary and recurrent granular dystrophy, and corneal scarring. They found that 78% had a functional improvement in vision. However, there was a large amount of induced hyperopia in many eyes. Using their initial standard ablation, they found 5.7 D of induced hyperopia at 3 months and 5.9 D of induced hyperopia at 24 months. Because of this large amount of hyperopic shift seen in their early patients, they modified the laser ablation in later eyes and noted 7.1 D of induced hyperopia at 3 months, but it had declined to 2.7 D at 6 months. At 3 months postoperatively there was an association between depth of ablation and degree of induced hyperopia. No eye treated with 85 µm of stromal ablation had 9 D or more of induced hyperopia. The investigators concluded that “the central flattening of the cornea appears to be the principal undesirable effect of phototherapeutic keratectomy.”

The largest early study was by Fagerholm and coworkers,18 who reported on 166 eyes treated for anterior corneal abnormalities, including recurrent erosions, postinfectious keratitis scarring, corneal dystrophies, and herpes simplex keratitis scars. Because of the diversity of corneal pathology in their study, they set individual goals of treatment for each patient; they reportedly achieved their goal in 84% of eyes. They, too, found that the major complication was induced hyperopia. Regression analysis revealed that the number of pulses (ie, depth of ablation) was correlated with degree of hyperopic shift.

Another study of PTK for a variety of corneal conditions found success in 14 of 18 eyes (78%).17 Mean manifest spherical refraction became more hyperopic by approximately 7 D at 1 month and 6.5 D at 3 months postoperatively. Hersh and colleagues performed PTK on 12 eyes of 11 patients with various corneal diseases. They noted symptomatic improvement in 11 of 12 eyes; however, a hyperopic shift was found in 8 of 12 eyes.

### Table 1: References for Case Reports and Series of PTK for Corneal Pathology

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<thead>
<tr>
<th>Corneal Pathology</th>
<th>1-4 Cases</th>
<th>5-10 Cases</th>
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<tr>
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<td>Band keratopathy</td>
<td>7, 9, 15, 17</td>
<td>18, 34</td>
<td>11, 23, 36, 44</td>
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<td>Climatic droplet keratopathy</td>
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<td>45</td>
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<td>Corneal scar after bacterial/unspecified infection</td>
<td>29, 35, 41</td>
<td>15, 17, 34</td>
<td>18, 43</td>
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<td>Corneal scar after radial keratotomy</td>
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<td>Corneal scar after trauma</td>
<td>17, 34, 35</td>
<td>15, 18, 41, 43</td>
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<td>Corneal scar after viral infection</td>
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<td>Corneal scar in Rothmund-Thomson syndrome</td>
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<td></td>
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<tr>
<td>Corneal scar related to pterygium surgery</td>
<td>7, 15, 35, 38, 39, 40</td>
<td>18, 43</td>
<td>34, 44, 27</td>
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<td>9, 16, 36</td>
<td>11, 42, 44</td>
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<td>Keratoconus nodule</td>
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<td>18, 21, 44</td>
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<td>Painful bullous keratopathy</td>
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<td>32, 33</td>
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<td>44</td>
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<td>Stevens Johnson syndrome</td>
<td>18</td>
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<td>Subepithelial cryoglobulin deposits</td>
<td>26</td>
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<td>Subepithelial infiltrates after viral keratoconjunctivitis</td>
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<td>Thygeson’s superficial punctate keratopathy</td>
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<td></td>
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<td>Trachoma scar</td>
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<td>Vernal/atopic keratoconjunctivitis scar</td>
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Excimer Laser Phototherapeutic Keratectomy In Eyes With Anterior Corneal Dystrophies

(mean, +5.4 D in these 8 eyes at 1 to 4 months). Hersh and colleagues later reported PTK results for 28 eyes of 26 patients with diverse corneal pathology. Mean hyperopic shift was +1.4 D, but was greater for deeper ablations. The investigators described different ablation strategies to most effectively treat different pathologies while minimizing untoward side effects, especially hyperopic shift. They concluded that blending the peripheral treatment and minimizing total ablation depth are important to not excessively flatten the cornea.

Trumennan and Tervo achieved a 50% success rate in treating 39 eyes of 38 patients with a variety of corneal pathology. Eyes with corneal dystrophies and band keratopathy had better success rates than eyes with corneal scars. Mean hyperopic shift was 1.79 D at 6 months. Rao and coworkers reported PTK results for 11 eyes of 10 patients, primarily for scars and Salzmann’s nodular degeneration. Best corrected vision improved 2 or more lines in 6 of the 10 eyes treated to improve vision. A hyperopic shift was seen in 5 eyes (mean, +3.25 D) and a myopic shift was seen in 2 eyes (-2.25 D, -5.0 D). Hyperopic shifts were seen primarily in those eyes treated with deeper central ablations, while myopic shifts were seen in the two eyes with pterygium scars that received peripheral ablations.

Amano and associates reported results of PTK for 31 eyes of 26 patients, most with band keratopathy, granular dystrophy, and scars. Eyes with granular dystrophy showed much greater improvement in best corrected vision than eyes with band keratopathy. About half of the eyes had a hyperopic shift greater than +1.0 D at 1 and 2 years. Kasettsaman and coworkers performed PTK on 17 eyes of 10 patients, almost all of which had lattice or Reis-Bücklers’ dystrophy. All but two eyes underwent stromal ablations of greater than or equal to 80 µm. Even though they performed midperipheral antihyperopia ablations, all eyes with both preoperative and postoperative refractions available for analysis had hyperopic shifts. The investigators concluded that the severe degree of pathology, at least partly due to lack of corneal donors for corneal transplantation, required deeper than average ablations, causing greater corneal flattening. Interestingly, they believe PTK to be an excellent alternative for some patients awaiting corneal transplantation (which is typically 4 to 6 years in Thailand).

Rapuano and colleagues reported several studies evaluating results of PTK in the treatment of anterior corneal pathology. In the largest study, there were 28 eyes of 24 patients, primarily with granular dystrophy, dystrophies of Bowman’s membrane, Salzmann’s nodular degeneration, recurrent erosions, and keratoconus nodules. With a mean follow-up time of 22 months, the preoperative goal was achieved in 22 eyes (78.5%) and one eye (3.5%) was worse. Mean hyperopic shift was 2.13 D (range, 7.75 D flatter to 6.5 D steeper). Five eyes (18%) developed recurrences of their pathology during the follow-up period.

Migden and associates reported their results of PTK in 22 eyes of 21 patients with corneal scars. Vision improved in 50% and 39% of eyes at 1 month and 3 months, respectively. The results were better in traumatic scars than in postinfectious scars. At 3 months, 44% had a hyperopic shift greater than 2 D. Another report of PTK on 48 eyes of 45 patients for a variety of corneal conditions noted a success rate of approximately 70% to 75%. The investigators found a hyperopic shift of 3.1 D at 3 months. Starr and colleagues found good clinical results of PTK in 45 eyes of 45 patients with a diverse group of corneal pathology, with approximately 50% enjoying improved vision. With an average depth of stromal treatment of 132 µm, they found a mean hyperopic shift of 2.81 D at last follow-up. However, for eyes treated with greater than 180 µm of stromal ablation, the hyperopic shift was 5.39 D. There was a nonstatistically significant trend toward ablation depth being correlated with degree of hyperopic shift. They noted much more hyperopic shift with stromal ablations greater than 100 µm than with stromal ablations less than 100 µm.

The Summit Technology (Waltham, Mass) multicenter study reviewed the results of PTK in 232 eyes of 211 patients. The investigators reported improved vision in 45% at 1 year. Depending on follow-up time, they found a hyperopic shift in 40% to 50% of eyes. This shift was seen in all types of pathology treated except anterior basement membrane dystrophy, where minimal tissue was removed. Foster and associates reported PTK in 252 eyes of 216 patients. Most eyes had recurrent erosions (41%), corneal scars after pterygium surgery (34%), and band keratopathy (12%). Ninety-one percent of eyes with recurrent erosions were symptom-free at a minimum of 12 months follow-up, and all eyes with band keratopathy were pain-free. PTK corneal smoothing after pterygium surgery did not appear to greatly improve clinical results. The investigators concluded that hyperopic shift and induction of severe irregular astigmatism can be avoided by using a large ablation zone (eg, 8-mm diameter) and minimizing the depth of ablation.

A large study evaluated the success in the smooth and irregular varieties of climatic droplet keratopathy. The investigators found better corneal clarity and improved visual acuity results in the smooth climatic keratopathy eyes than the irregular climatic keratopathy eyes. They also found higher rates of delayed reepithelialization (>14 days) and bacterial keratitis in the irregular climatic keratopathy eyes compared with the smooth variety. They noted a statistically significant hyperopic shift at 3 months, which was stable at 6 and 12 months.
PTK for Anterior Basement Membrane Dystrophy and Recurrent Erosion Syndrome

There are many effective medical and surgical treatments for anterior basement membrane dystrophy and recurrent erosion syndrome, but they do not work well in all situations. Excimer laser PTK can also be quite successful. Sridhar and colleagues\textsuperscript{46} retrospectively compared the results of PTK and diamond burr polishing of Bowman’s membrane in patients with recurrent erosions and anterior basement membrane dystrophy. Fifteen eyes underwent PTK and were followed for a mean of 17.6 months. Twenty-seven eyes underwent diamond burr polishing of Bowman’s membrane and were followed for a mean of 6.7 months. The success rates were 73% in the PTK group and 89% in the diamond burr group. The investigators found no statistically significant difference in haze, recurrences, or change in vision between the two treatment groups and concluded that diamond burr treatment was as effective as PTK and generally less costly and more convenient for the patient and the surgeon.

Dausch and colleagues\textsuperscript{47} reported on PTK for traumatic recurrent erosions not responding to conventional treatment in 74 eyes of 73 patients. They ablated epithelium with the laser in some cases and removed it manually in others. Their goal was to ablate just into Bowman’s membrane. With a minimal follow-up of 6 months and a mean follow-up of 21.1 months, they found that 74% of eyes remained symptom-free at last follow-up. Recurrences occurred from 1 to 22 months (mean, 8.4 months) after PTK. Their impression was that their treatment did not induce a notable hyperopic shift. In a series of three eyes with recalcitrant recurrent erosions, John and coworkers\textsuperscript{48} debrided the loose epithelium and ablated Bowman’s membrane. They did not find any recurrent painful episodes for the 18 months duration of their study. Lohmann and associates\textsuperscript{49} also debrided loose epithelium before PTK ablation in 31 eyes of 24 patients with traumatic and anterior basement membrane dystrophy–related recurrent erosions. With a follow-up of 3 to 12 months, they found no recurrent erosions in 30 eyes (97%). Additionally, no corneal haze and no significant change in refraction were found. Bernauer and colleagues\textsuperscript{50} and Orndahl and Fagerholm\textsuperscript{51} also noted good success in treating 15 eyes and 17 eyes, respectively.

In another study, PTK in 23 eyes of 23 patients with recalcitrant recurrent erosions was successful in 83% with 12 to 60 months of follow-up (mean, 38 months).\textsuperscript{52} There was no significant change in refraction. Ho and associates\textsuperscript{53} performed PTK on 35 eyes of 32 patients with recurrent corneal erosions not responding to conventional therapy. Approximately half had an anterior corneal dystrophy and half had previous corneal trauma. With a mean follow-up of 12 months (range, 0-56 months), 74% were pain-free after PTK. The results were slightly better in eyes with post-traumatic erosions compared with dystrophy-related erosions. No refraction changed by greater than 1 D. Minimal haze was noted in three eyes. Cavanaugh and coworkers\textsuperscript{54} reported on 48 eyes of 43 consecutive patients with anterior basement membrane dystrophy and recalcitrant recurrent erosions who underwent PTK treatment. Of the 36 eyes with 12 months of follow-up, 5 (14%) required an additional PTK treatment for recurrence or erosions. One eye required a third treatment. All recurrences occurred within 6 months of the PTK. There was a statistically significant correlation between number of laser pulses applied and induced hyperopic shift.

Jain and Austin\textsuperscript{55} reported PTK results for 77 eyes of 68 patients with recurrent erosions refractory to other forms of treatment. Fifty-two percent were related to trauma, 31% were related to anterior basement membrane dystrophy, and 17% were idiopathic. In the trauma group, 67.5% were pain-free, while 10% required a second PTK. In the corneal dystrophy cases, only 1 eye (4%) required a second treatment. In the idiopathic cases, 1 eye (8%) required a retreatment. Interestingly, the investigators combined PTK for recurrent erosions with PK for refractive error in 6 patients. In this small group, they found no recurrences of erosions and a satisfactory refractive outcome, such that no patient required additional surgery. Kremer and Blumenthal\textsuperscript{56} also performed combined PK and PTK in 16 eyes of 16 patients with myopia and recurrent erosions. At 26 to 42 months, no patient had had an episode of recurrent painful symptoms, and uncorrected vision was better than or equal to 20/40 in all eyes. Overall, PTK is a very successful treatment for recalcitrant recurrent erosions with minimal side effects.

PTK for Other Anterior Corneal Dystrophies

There have been several reports of excimer laser PTK to treat stromal dystrophies where the bulk of the pathology lies in the anterior cornea (Table II). Small case series described successful treatment of Reis-Bücklers’ dystrophy,\textsuperscript{57} Avellino dystrophy,\textsuperscript{58} macular dystrophy,\textsuperscript{59,60} Schnyder’s crystalline dystrophy,\textsuperscript{61} granular and lattice dystrophies,\textsuperscript{62} and recurrent granular dystrophy after corneal transplantation.\textsuperscript{63} Two somewhat larger series describing good results in Reis-Bücklers’ dystrophy, one with 9 eyes of 7 patients\textsuperscript{64} and the other with 11 eyes of 8 patients,\textsuperscript{65} were reported by the same authors. Best corrected vision improved at least 2 lines in all eyes, with all patients reaching 20/40 or better. A hyperopic shift was seen in all eyes, ranging from minimal to +8.0 D at 1 month and +7.0 D at 6 months. One of the largest series of PTK for patients with corneal dystrophies included 33...
eyes, 11 with lattice dystrophy, 8 with anterior basement membrane dystrophy, 5 with Schnyder’s crystalline dystrophy, and 4 with granular dystrophy. With a mean follow-up time of 9 months, they found vision improved 2 or more lines in 23 of 27 eyes (85%) treated for decreased vision, and no eye developed worse vision. A consistent finding in most of these reports was hyperopic shift, the degree of which appeared to be associated with depth of ablation.

**Corneal Surface Changes After PTK**

A study evaluated ocular surface changes before and 3 months after PTK in 45 eyes of 33 patients and compared them to controls (40 eyes of 20 patients). Thirty-three percent of eyes had Avellino dystrophy, 31% had granular dystrophy, 18% had band keratopathy, and 13% had corneal scars. The investigators found significant improvements in corneal sensitivity, tear film break-up time, lipid layer interference results, and conjunctival squamous metaplasia grades. Schirmer test and goblet cell density did not show significant changes after PTK. The investigators concluded that improved corneal regularity led to a healthier, more stable tear film and healthier epithelium. Many of the same investigators also reported ocular surface changes in 5 eyes of 5 patients with recurrent granular/Avellino dystrophy after PTK. They found improvements in the health of the ocular surface, as measured by corneal sensitivity, tear film break-up time, lipid layer interference, and conjunctival squamous metaplasia grades, in all eyes after PTK. They also noted that these improvements deteriorated with recurrence of the disease process. The recurrences occurred between 7 and 15 months after PTK.

**PTK Complications and Side Effects**

As with any corneal surgery, PTK has complications and side effects. Since an epithelial defect is created, there tends to be a significant amount of discomfort or pain after surgery. These symptoms can be managed by pressure patching, frequent application of ointment, a bandage soft contact lens, and topical nonsteroidal anti-inflammatory medications. Great care needs to be taken to promote reepithelialization. Prolonged epithelial defects are not uncommon after PTK, as PTK is often performed in eyes predisposed to healing difficulties, such as eyes with corneal grafts or previous herpetic keratitis. Chronic epithelial defects can cause corneal scarring. Additionally, there is always a chance of infection. Bacterial keratitis has been reported after PTK. Reactivation of latent herpes simplex virus by the excimer laser has been demonstrated in mice. Three cases of recurrent herpetic simplex keratitis after PTK were reported. A Wessely-type immune ring has also been reported after PTK. Severe scarring developed in an eye with Fuchs’ dystrophy treated with PTK, requiring a corneal transplant to improve vision. Many eyes develop an anterior stromal reticular haze similar to what is seen after PRK. In some eyes it can be substantial and may reduce vision. Severe haze, while rare, has been treated with topical mitomycin C with good results. Fortunately, the corneal endothelial cells do not seem to be adversely affected by PTK. The exact amount of hyperopia that is induced during a PTK procedure varies greatly with the specific corneal pathology, PTK technique, use of masking agents, and especially ablation diameter and ablation depth. The Munnerlyn formula was developed for myopic excimer laser treatments. It relates the diopters of flat-
Diopter effect = 3(ablation depth in microns) / (ablation zone diameter in mm)^2

Some surgeons have used this formula as an approximation for the hyperopic shift after PTK; however, the correlation is much weaker than for PRK. With typical stromal ablations in the 25- to 100-µm range, several dioptries of hyperopic shift can be expected after PTK, which is not commonly a desirable change.

There are several techniques used to avoid significant corneal flattening and induced hyperopia. In general, a large ablation zone, such as 6-mm diameter, is used. As per the Munkerlyn formula, the larger the ablation zone diameter, the smaller the degree of induced hyperopia for the same ablation depth. An extremely important parameter is to minimize the depth of ablation. A critical point in the successful performance of PTK is to realize that the cornea does not need to be crystal-clear to function well. A patient with a corneal opacity with 20/200 vision may improve to 20/30 vision with a 75-µm total ablation that removes 90% of the opacity and does not induce significant hyperopia. To clear the last 10% of the opacity and potentially improve the vision to 20/20 might require another 75 µm of ablation. However, that extra 75 µm of ablation may induce an added 3 to 6 D of hyperopia, and possibly increase the risk of post-PTK haze.

Additional techniques to reduce induced hyperopia include blending the edges of the ablation by gently rocking the head during stromal ablation. Another option is to perform an ablation at the edge of the central stromal ablation. This peripheral ablation is similar to the treatments for hyperopia, which just treat the paracentral cornea to steepen the central cornea. The best antihyperopia ablation size and exact amount of peripheral ablation to neutralize the central flattening are unknown.

Two studies specifically evaluated refractive changes after PTK. In 45 patients primarily with recurrent corneal erosions, central corneal scars, and corneal dystrophies, Amm and Duncker found a hyperopic shift in 41% of eyes treated with a stromal ablation (mean, +1.7 D; range, 0.5-4.0 D). Twenty-two percent developed an increase in regular astigmatism (maximum increase, 2.75 D). Nine percent developed a myopic shift (maximum, −1.5 D). Not unexpectedly, the investigators found no refractive change in the patients with recurrent erosion who were treated with minimal-depth ablations. They noted a correlation between depth of ablation and hyperopic shift and concluded that stromal ablations of 100 µm or less were desirable to achieve the best clinical results.

Dogru and coworkers evaluated 112 eyes of 80 patients with a variety of corneal disorders, including stromal dystrophies, band keratopathy, and corneal scars. They found a +4.25 D shift at 1 month, which declined to +3.42 D at 1 year, at which point it was stable. As expected, eyes with greater than 100 µm stromal ablation had a statistically significantly greater degree of induced hyperopia (+4.42 D) than eyes treated with less than 100 µm stromal ablation (+2.85 D). Additionally, eyes treated with a 1.0-mm transition zone beyond the ablation also had less hyperopic shift than those treated without the transition zone. Interestingly, the investigators did not find a difference in induced hyperopia between 5.0- and 6.0-mm ablation zone diameters, although the number of eyes was small and the treatment depths were less than 100 µm in the 5.0-mm ablation zone group. They concluded that limiting the depth of corneal stromal ablation, when possible, was important to avoid a significant hyperopic shift.

RECURRENT OF DISEASE AFTER PTK

Unfortunately, PTK is not a “cure” for corneal dystrophies. Just as corneal dystrophies can recur after corneal transplantation, they can recur after PTK. Dinh and colleagues reviewed 50 PTK procedures in 43 eyes of 33 patients with corneal dystrophies before and after corneal transplantation, evaluating them for recurrence of the dystrophy. These included 13 eyes with Reis-Bücklers’ dystrophy, 13 eyes with granular dystrophy, 11 eyes with anterior basement membrane dystrophy, 7 eyes with lattice dystrophy, and 1 eye with Schnyder’s crystalline dystrophy. Recurrence occurred in 47% of the Reis-Bücklers’ dystrophy eyes a mean of 22 months after PTK, in 23% of the granular dystrophy eyes a mean of 40 months after PTK, and in 14% (1 eye) of lattice dystrophy eyes 6 months after PTK. Dystrophies recurred at similar rates in eyes with and without previous corneal transplantation. As mentioned earlier, recurrence of granular/Avellino dystrophy was noted in 1 eye of 5 patients between 7 and 15 months after PTK. Postviral subepithelial infiltrate scars removed with PTK were reported to recur in one case 4 months after surgery.

ULTRASOUND BIOMICROSCOPY OF THE CORNEA AND ANTERIOR SEGMENT

Accurate preoperative determination of the depth of corneal pathology would be extremely beneficial in selecting the best candidates for PTK by avoiding patients with deep central pathology. Additionally, it would guide the surgeon in determining the exact depth of PTK treatment in each patient. Ultrasound biomicroscopy (UBM) is a relatively new method for obtaining high-resolution images of the cornea and anterior portion of the globe. This technique involves using high-frequency ultrasound...
(50 MHz) to produce cross-sectional views of the anterior segment to a depth of approximately 5 mm. UBM has been used to evaluate numerous conditions in the front portion of the eye, including anterior segment masses,\textsuperscript{82} cystinosis,\textsuperscript{82} intracorneal epithelial cyst,\textsuperscript{84} and Maroteaux-Lamy syndrome.\textsuperscript{85} It is also extremely useful in the detection and localization of both known and occult anterior segment foreign bodies.\textsuperscript{86,87} UBM has been helpful in determining the status of intraocular structures in eyes with corneal opacities undergoing corneal transplantation.\textsuperscript{92} This information can guide the surgeon in both surgical planning and predicting the success of the surgery. UBM has also been shown to be useful in the surgical planning of limbal dermoid removal.\textsuperscript{93} In this condition, the exact depth of the limbal dermoid often cannot be determined by slit-lamp evaluation because of the density of the lesion. UBM evaluation could differentiate the dermoid tissue from the normal surrounding and underlying tissue.

One of the difficulties of excimer laser PTK is predicting the depth of pathology preoperatively to help determine whether the patient is a good candidate for this procedure. Additionally, the depth of pathology predicted preoperatively aids the surgeon in determining how much tissue to remove during the actual PTK procedure. Slit-lamp examination combined with ultrasound corneal pachymetry measurement is useful, but often not conclusive. The ultrasound pachymeter measures the full thickness of the cornea, while the slit-lamp evaluation gives an estimate of the percentage of corneal involvement, eg, 20% involvement in a 500-µm cornea gives a value of 100 µm of pathology. If the involvement was really only 15%, then the pathology would be only 75 µm. If 100 µm of tissue were removed based on preoperative slit-lamp estimation, then an extra 25 µm of tissue would have been removed.

A key goal in PTK surgery is to remove as little tissue as necessary in order to reduce the chances of significant refractive shift, especially induced hyperopia. If UBM could accurately predict the depth of corneal pathology before PTK, candidates could be screened better and the likelihood of excess tissue removal could be reduced. A major goal of this study was to evaluate the efficacy of UBM in predicting the depth of pathology that was removed during PTK.

**MATERIALS AND METHODS**

**PATIENT POPULATION**

This prospective study included 20 consecutive eyes (12 left, 8 right) of 14 patients (5 women, 9 men) with corneal stromal dystrophies who underwent excimer laser PTK at our institution. Patients’ ages ranged from 22 to 81 years (mean, 51 ± 16 years) (Table III). All patients older than 21 years with a stromal corneal dystrophy and anterior corneal pathology that affected visual function were eligible for inclusion. Eyes with significant corneal thinning (<400 µm centrally), deep corneal pathology, or corneal edema were excluded. Eyes with uncontrolled uveitis, uncontrolled glaucoma, or significant ocular surface disease were also not eligible.

Nine eyes of 6 patients had granular dystrophy. Both eyes of one patient with granular dystrophy had undergone excimer laser PK 6 to 7 years previously. One eye had lattice dystrophy, and 4 eyes of 3 patients had recurrent lattice dystrophy in grafts performed 7 to 25 years previously. Six eyes of 4 patients had recurrent Reis-Bücklers’ dystrophy. Four of the 6 Reis-Bücklers’ eyes had undergone corneal transplantation 6 to 25 years previously. Two of these eyes had also undergone previous PTK, and one eye had undergone lamellar keratectomy in the most recent corneal graft. Two eyes of one patient with Reis-Bücklers’ dystrophy had had prior lamellar keratectomy and later PTK prior to entrance into this study. The study was approved by the institutional review board of Wills Eye Hospital, and all patients gave informed consent.

**EXAMINATIONS**

All patients underwent routine ophthalmic examinations, including uncorrected Snellen visual acuity, best manifest spectacle-corrected Snellen visual acuity, slit-lamp biomicroscopy, keratometry readings (Haag-Streit Co, Bern, Switzerland), computerized corneal topography (EyeSys/Premier, Irvine, CA), central ultrasound pachymetry (Accutome Inc, Malvern, PA), anterior segment photography, and ultrasound biomicroscopy (Humphrey Instruments Inc, San Leandro, CA, upgraded by Paradigm Inc, Salt Lake City, UT). The corneal topography analysis determines a simulated keratometry reading and a central corneal power determination. All measurements were repeated approximately 6 to 8 weeks postoperatively. In certain eyes, it was impossible to obtain keratometry readings and/or computerized corneal topography readings because of corneal irregularity. In other eyes, the corneal topography analysis revealed a central power reading but no simulated keratometry reading.

**ULTRASOUND MICROSCOPY**

UBM was performed by a highly experienced technician using a 50-MHz transducer. Examinations were performed using an eyecup and carboxymethylcellulose 1% (Celluvisc, Allergan Inc, Irvine, CA) as the coupling agent. Scans were performed with the settings of 60- to 72-dB/mm gain, 5-dB/mm time-gain compensation, and a 2.24-mm delay. An attempt was made to keep the corneal image at the focal point of the ultrasound probe for best resolution. The cornea was imaged horizontally and verti-
cally. Images were obtained centrally and then 1, 2, and 3 mm off center nasally, temporally, superiorly, and inferiorly. The images were stored on the hard drive of the system for subsequent interpretation. The surgeon did not see the UBM images prior to the PTK procedure.

At a later date, the technician retrieved the UBM images and, using the cursor on the screen, measured the total corneal thickness and determined the depth of pathology for each image. Often the depth of pathology varied throughout the image. In these cases, the middle of the pathology was measured in the center of the image.

THE PTK PROCEDURE
Phototherapeutic keratectomy was performed with the VISX S2 excimer laser (VISX Inc, Santa Clara, CA). The laser operates at a radiant exposure of 160 mJ/cm². Eyes were treated preoperatively with topical ofloxacin (Allergan) and proparacaine 0.5%. A lid speculum was applied to the operative eye, and the fellow eye was covered. A transepithelial approach utilizing a 6.0-mm ablation zone with no transition zone was used for all eyes. The ablation was centered on the entrance pupil. A pulse rate of 6 Hz was used. An initial 60- to 75-µm treatment was applied based on the clinical appearance of the depth of pathology from the preoperative slit-lamp evaluation. The patient was then examined at the slit lamp, and additional treatment was applied as needed. Occasionally, a small amount of balanced salt solution was then applied as a masking agent to smooth out the ablation. The treatment goal was a smoother, clearer central cornea.

Typically, the central cornea was not crystal-clear at the end of the PTK treatment. The amount of laser treatment was recorded. For purposes of calculation of ablation depth when a masking agent was used, the surgeon estimated how much laser treatment was masked and subtracted that amount from the depth delivered according to the laser system computer. To prevent bias in amount of ablation performed, the surgeon had not seen the UBM images prior to PTK treatment.

In certain eyes, especially those with deep ablations

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LK, lamellar keratectomy; PK, penetrating keratoplasty; PRK, photorefractive keratectomy; PTK, phototherapeutic keratectomy.

<p>| Table III: Patient Demographic Information |
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LK, lamellar keratectomy; PK, penetrating keratoplasty; PRK, photorefractive keratectomy; PTK, phototherapeutic keratectomy.
and preoperative hyperopia, the surgeon performed an antihyperopia ablation. In these cases, the joystick of the laser was used to apply a 2-mm-diameter circular ablation to the periphery of the 6-mm central ablation, straddling the initial ablation. The total depth of antihyperopia treatment varied between 80 and 200 µm, depending on the degree of expected corneal flattening. Using the joystick, the 2-mm ablation was slowly moved around the periphery of the central ablation for two full circles, ablating 50% of the total depth with each circle.

Postoperatively, patients were treated with 1 drop of ofloxacin, scopolamine 0.25%, ketorolac (Acular, Allergan) and 0.5% ophthalmic ointment and a pressure patch. Patients were prescribed acetaminophen with codeine as needed. The pressure patch was removed on postoperative day 1 and healing was evaluated. Eyes were treated with erythromycin ophthalmic ointment every 2 hours while patients were awake and when they returned 2 days later. Patients were examined every few days until the epithelial defect had completely healed. Topical corticosteroids (ie, fluorometholone, loteprednol, or prednisolone acetate) were used in some patients once the epithelial defect had resolved if corneal haze or graft inflammation was noted.

STATISTICAL ANALYSIS

Visual acuity results were converted to decimal numbers for analysis and then reconverted to Snellen acuity. Mean ± standard deviation is reported. Spearman correlations and least squares regression were used to determine the association between the different variables. The power of this study could detect a correlation of 0.6 given the number of eyes evaluated. A P value of <.05 was considered significant.

RESULTS

All 20 procedures were performed by the author between February 1999 and April 2001. Follow-up examinations were performed in all patients at a mean of 7.1 weeks (range, 6-14 weeks) postoperatively.

TREATMENT

In all patients, the ablation proceeded through the entire thickness of the epithelium, through Bowman's membrane and into the stroma. Patients were then examined at a slit lamp and had additional ablation performed as determined by the surgeon to substantially clear the central cornea. Total excimer laser ablation depths, including epithelium and stroma, ranged from 85 to 130 µm (mean, 103.5 ± 14.2 µm) (Table IV). A small amount of balanced salt solution masking agent was used in 7 of 20 eyes (35%). It was not used during the initial transepithelial/stromal ablation, but only when smoothing was required after the first deep ablation and the cornea had been evaluated at the slit lamp. One patient (9L) had a thin corneal membrane removed mechanically when a distinct edge was noted after the initial ablation. It was estimated to be 10 µm in thickness, which was added to the laser ablation of 75 µm, for a total treatment of 85 µm.

CLINICAL FEATURES

Superficial corneal opacities were successfully removed in all but one eye (patient 14). This patient had moderately deep corneal amyloid deposits of lattice dystrophy, which were not sufficiently removed even with the deepest PTK treatment in this study (130 µm) (Figure 1). In all the other eyes, the central cornea was much clearer (Figures 2 through 4). In several eyes, especially those with granular dystrophy, many deep, scattered opacities remained after PTK treatment (Figure 5).

VISUAL ACUITY OUTCOME

Visual acuity results are summarized in Table V. Uncorrected visual acuity ranged from 20/40 to 20/400 preoperatively and from 20/30 to 20/400 postoperatively. There was a mean improvement of 1.25 ± 3.27 Snellen lines (range, 7 lines better to 4 lines worse). Mean uncorrected Snellen acuity improved from 20/102 to 20/69. Six eyes were essentially unchanged (±1 line), four eyes gained 2 or 3 lines, two eyes gained 4 or 5 lines, and three eyes gained 6 or 7 lines. Four eyes lost 2 or 3 lines, and one eye lost 4 lines (Figure 6).

Preoperative best spectacle-corrected visual acuity ranged from 20/30 to 20/200 and postoperatively from 20/25 to 20/200. There was a mean improvement of 2.35 ± 2.48 Snellen lines (range, 7 lines better to 4 lines worse). Mean best spectacle-corrected Snellen visual acuity improved from 20/62 to 20/38. Six eyes were essentially unchanged (±1 line), 10 eyes gained 2 or 3 lines, none gained 4 or 5 lines, and three eyes gained 6 or 7 lines. No eyes lost 2 or 3 lines, and one eye lost 4 lines (Figure 7).

Preoperative uncorrected vision correlated with preoperative best corrected vision (Spearman correlation 0.56, P = .01), and postoperative uncorrected vision correlated with postoperative best corrected vision (Spearman correlation 0.59, P = .007). Preoperative and postoperative uncorrected vision were not correlated (Spearman correlation 0.15, P = .54) nor were preoperative and postoperative best corrected vision (Spearman correlation 0.17, P = .47).

REFRACTIVE CHANGES

Manifest Refraction Spherical Equivalent

Refractive results are summarized in Table VI.
Preoperatively, the mean spherical equivalent was \(-0.17 \pm 2.84\) D. Postoperatively, the mean spherical equivalent was \(-1.09 \pm 4.17\) D. Comparing preoperative and postoperative refractions for individual patients, there was a mean change in refraction of \(-0.92 \pm 4.32\) D (range, \(-13\) to +3.88 D). There was no statistically significant correlation between the change in manifest refraction spherical equivalent and the actual PTK laser ablation depth (Spearman correlation \(-0.01, P = .96\)) (Figure 8).

Haag-Streit Keratometry Readings
Mean preoperative Haag-Streit keratometry reading in the 17 eyes where readings were obtainable was 43.45 ± 2.17 D. Mean postoperative keratometry reading in the 19 eyes in which it was obtainable measured 43.81 ± 3.27 D. In the 16 eyes with both preoperative and postoperative keratometry readings, the mean change was \(-0.25 \pm 2.54\) D (range, 5.24 D steeper to 2.75 D flatter). There was no statistically significant correlation between change in keratometry reading and the laser ablation depth (Spearman correlation \(-0.22, P = .40\)). There was also no statistically significant correlation between change in keratometry reading and change in manifest refraction spherical equivalent (Spearman correlation \(-0.47, P = .0651\)).

Corneal Topography Simulated Keratometry Readings
Preoperative EyeSys corneal topography analysis generated simulated keratometry measurements in 17 eyes. Mean simulated keratometry reading was 44.23 ± 2.2 D. Postoperative measurements were obtainable in 19 eyes. Mean postoperative measurement was 43.24 ± 3.37 D. In the 16 eyes with both preoperative and postoperative measurements, the mean change in simulated keratometry readings was \(-1.57 \pm 2.34\) D (range, 3.39 D steeper to
Excimer Laser Phototherapeutic Keratectomy In Eyes With Anterior Corneal Dystrophies

**FIGURE 1A**
Preoperative lattice dystrophy with moderately deep lattice lines in patient 14.

**FIGURE 1B**
Six weeks postoperatively, lattice lines in patient 14 were essentially unchanged. Mild anterior stromal reticular haze at the edge of the ablation can be seen.

**FIGURE 2A**
Preoperatively, patient 7L had severe central corneal opacities secondary to granular dystrophy. Most of the opacities were relatively superficial.

**FIGURE 2B**
Six weeks after PTK, superficial central opacities in patient 7L were eliminated. A deep stellate granule was still present centrally; however, the patient reported much improved quality of vision.

**FIGURE 3A**
Preoperatively, patient 11 had recurrent Reis-Bücklers’ dystrophy 6 years after a corneal transplant and 3 years after PTK.

**FIGURE 3B**
Ten weeks postoperatively, there was considerable clearing of the central opacity in patient 11, although some haziness persisted.
Preoperatively, patient 10R had recurrent Reis-Bücklers’ dystrophy 13 years after a 9-mm-diameter superficial keratectomy and 8 and 3 years after two previous 6-mm-diameter PTKs.

Eight weeks postoperatively, the central cornea in patient 10R is considerably clearer.

Preoperatively, patient 5R had almost confluent central corneal opacities from granular dystrophy and complained of poor vision.

Postoperatively, there are notably more clear zones between the deeper residual granular deposits in patient 5R. Patient noted much improved quality of vision even though significant deposits persisted.

Change in lines of uncorrected Snellen visual acuity after excimer laser PTK.

Change in lines of best spectacle corrected Snellen visual acuity after excimer laser PTK.
6.24 D flatter). There was no statistically significant correlation between change in corneal topography simulated keratometry reading and the laser ablation depth (Spearman correlation −0.48, \( P = .0616 \)). There was no statistically significant correlation between the change in Haag-Streit keratometry and the change in corneal topography simulated keratometry readings (Spearman correlation 0.47, \( P = .0906 \)) or change in manifest refraction spherical equivalent and change in corneal topography simulated keratometry readings (Spearman correlation −0.42, \( P = .0979 \)) (Figures 9 through 14).

**Corneal Topography Central Corneal Power Measurements**

Central corneal power measurements from the EyeSys corneal topographic analyses were generated in 19 eyes preoperatively and all 20 eyes postoperatively. Mean central power was 44.71 ± 2.23 D preoperatively and

### Table V: Visual Acuity Results

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Mean: 7.1 20/102 20/69 1.25 20/62 20/38 2.35

Postop, Postoperative; Preop, preoperative; Vacc, best spectacle-corrected visual acuity; Vasc, uncorrected visual acuity.
Preoperative computerized corneal topography for patient 2. The simulated keratometry readings are found in the lower left cornea of the color map located on the left. The central corneal power measurement is found in the lower right cornea of the same color map.

Postoperative computerized corneal topography for patient 2. Patient underwent 100-µm PTK ablation without use of masking agent and with no antihyperopia treatment. While there appears to be significant central steepening compared to preoperative corneal topography in Figure 9A, color scales found on left are different.

Preoperative (upper left), postoperative (lower left), and difference (right) computerized corneal topography maps for patient 2. Note the central area of the difference map demonstrates only a mild steepening from preoperatively to 6 weeks postoperatively.

Preoperative (upper left), postoperative (lower left), and difference (right) computerized corneal topography maps for patient 2. After 90-µm PTK ablation and no antihyperopia treatment, there was approximately 3.5 D of central corneal flattening. There was corresponding 1.5-D hyperopic shift in manifest refraction.

Preoperative (upper left), postoperative (lower left), and difference (right) computerized corneal topography maps for patient 7R. The difference map revealed essentially no change in central corneal curvature after a 100-µm PTK ablation and 200-µm total antihyperopia treatment. There was a 2.5-D myopic shift in manifest refraction.

Preoperative (upper left), postoperative (lower left), and difference (right) computerized corneal topography maps for patient 7R. After a 123-µm PTK treatment and 120-µm total antihyperopia treatment. While the difference map demonstrates almost no change in central corneal curvature, there was a 3.5-D myopic shift in manifest refraction.
44.33 ± 3.73 postoperatively. There was a mean change of
–0.44 ± 4.12 D (range, 7.91 D steeper to 9.06 D flatter) in
the 19 eyes with both preoperative and postoperative data.
There was no statistically significant correlation between
the change in corneal topography central power measure-
ments and change in manifest refraction spherical equiva-
lent (Spearman correlation –0.42, P = .0760) or change in
Haag-Streit keratometry readings (Spearman correlation
0.19, P = .4914). There was a statistically significant corre-
lation between the change in corneal topography central
power measurements and the change in corneal topogra-
phy simulated keratometry readings (Spearman correla-
tion 0.72, P = .0017) (Figures 9 through 14).

Astigmatism
Since a primary goal of PTK is creating a more regular
cornea, the absolute amount of astigmatism, regardless of
axis, was evaluated. There was minimal change in mani-
fest refraction cylinder (±1 D) in 14 eyes (70%) and an
increase of >1 to 2 D in two eyes (10%). There was a
decrease in manifest refraction cylinder of 2 to 3 D in one
eye (5%) and 4 to 6 D in three eyes (15%).

Haag-Streit keratometry readings were available
preoperatively and postoperatively in 16 eyes. The kerato-
metric cylinder was essentially unchanged (±1 D) in 8 eyes
(50%). There was an increase in keratometric cylinder of
>1 to 2 D in one eye (6%), >2 to 3 diopters in two eyes
(13%), and 4 to 5 diopters in one eye (6%). There was a
decrease of >1 to 2 diopters of keratometric cylinder in
three eyes (19%) and 2.5 diopters in one eye (6%).

Simulated keratometry readings from the EyeSys
corneal topography machine were available preopera-
tively and postoperatively for 16 eyes. In six eyes (38%)
there was minimal change in cylinder (±1 diopter). In six
eyes (38%) there was an increase of >1 to 2 D, in one eye
(6%) an increase of 2.5 D, and in one eye (6%) an increase
of 3.5 D. There was a decrease of >1 to 2 diopters of
topographic simulated keratometric cylinder in two eyes
(13%). There were no statistically significant correlations
between the three measurements of astigmatism.

Effect of Anti-hyperopia Treatment
Anti-hyperopia treatments were performed on 16 of the 20
eyes. Depth of ablation for the entire anti-hyperopia treat-
ment ranged from 80 to 200 µm (mean, 125 ± 29 µm).
There was no statistically significant correlation between
amount of central ablation and amount of anti-hyperopia
treatment (Spearman correlation 0.13, P = .57). There was
no statistically significant correlation between the amount
of anti-hyperopia treatment and change in manifest refrac-
tion spherical equivalent (Spearman correlation –0.30,
P = .20) (Figure 15), change in Haag-Streit keratometry
(Spearman correlation 0.34, P = .20), change in EyeSys
topographic simulated keratometry (Spearman correlation
0.17, P = .52) or change in EyeSys topographic central
power (Spearman correlation -0.02, P = .93). There was a
statistically significant correlation between the amount
of anti-hyperopia treatment and number of days required
for reepithelialization (Spearman correlation 0.64, P = .0026).

ULTRASOUND MEASUREMENTS
Ultrasound Pachymetry
Preoperatively, central ultrasound pachymetry ranged
from 400 to 780 µm (mean, 650 ± 87 µm). Postopera-
tively, central ultrasound pachymetry ranged from 380 to 645 µm (mean, 479 ± 58 µm). Taking each
eye individually, there was a mean decrease in central
pachymetry of 82 ± 57 µm (range, increase of 40 µm to a
decrease of 265 µm) (Table VII). There was no statisti-
cally significant correlation between difference in ultra-
sound pachymetry from preoperatively to postoperatively
and the PTK ablation depth calculated at the time of
surgery (Spearman correlation 0.02, \( P = .93 \)) (Figure 16).

**UBM Analysis**

Because of a hard-drive malfunction, UBM data was available for 35 of the 39 examinations performed. One patient declined to undergo the postoperative UBM examination because of discomfort during the preoperative examination. The central vertical and horizontal images were used to evaluate total corneal thickness and depth of pathology. The average of the vertical and horizontal measurements was used for statistical analysis (Figures 17 through 19). The 1-, 2-, and 3-mm off-center UBM images were not used for analysis in this study.

**Central Corneal Thickness.** Preoperative UBM central corneal thickness measurements ranged from 510 to 730 µm (mean, 616 ± 58 µm). Postoperatively, UBM central corneal thickness measurements ranged from 430 to 701 µm (mean, 547 ± 64 µm). There was a highly statistically significant correlation between preoperative ultrasound pachymetry and preoperative UBM pachymetry (Spearman correlation 0.82, \( P < .001 \)) (Figure 20) and postoperative ultrasound pachymetry and postoperative UBM pachymetry (Spearman correlation 0.92, \( P < .001 \)) (Figure 21). For the 16 eyes with both preoperative and postoperative data, UBM central pachymetry decreased 29 to 113 µm (mean, 70 ± 26 µm) (Table VII). There was no statistically significant correlation between the difference in UBM corneal thickness measurements from preoperatively to postoperatively and the PTK ablation depth calculated at the time of surgery (Spearman correlation –0.20, \( P = .47 \)) (Figure 22). There was also no statistically significant correlation between difference in ultrasound pachymetry measurements and difference in UBM corneal thickness measurements from preoperatively to postoperatively (Spearman correlation 0.04, \( P = .89 \)).

**Corneal Pathology Thickness.** UBM estimates of
corneal pathology preoperatively ranged from 105 to 191 µm (mean, 147 ± 23 µm) (Table VII). When this measurement was compared with the actual PTK treatment depth for each patient, there was no statistically significant correlation (Spearman correlation –0.45, \( P = .07 \)) (Figure 23). There was actually a trend toward the UBM measurement of corneal pathology being inversely correlated with the amount of treatment necessary to clear the majority of the corneal opacity. That is, the deeper the UBM measurement of pathology, the less PTK treatment tended to be required. UBM measurement of corneal pathology also generally overestimated the depth of treatment.

### DAYS TO REEPITHELIALIZATION AND COMPLICATIONS
Thirteen eyes (65%) were totally reepithelialized by postoperative day 3 (Figure 24). Three additional eyes reepithelialized by postoperative day 4 or 5. Three eyes required 8 to 10 days and one eye required 41 days to reepithelialize (Table IV). The eye that required 41 days to reepithelialize had undergone a penetrating keratoplasty 10 years prior to PTK for lattice dystrophy. This delay in reepithelialization resulted in a small paracentral corneal scar (Figure 25). The fellow eye underwent PTK in this study for recurrent lattice dystrophy in a penetrating graft performed 7 years earlier and required 9 days to reepithelialize. There was a statistically significant correlation between the amount of antihyperopia treatment and number of days for the surface to reepithelialize (Spearman correlation 0.64, \( P = .0026 \)). There was no correlation between actual PTK treatment depth and days to reepithelialize (Spearman correlation –0.11, \( P = .6341 \)).

### TABLE VII: A-SCAN AND UBM PACHYMETRY RESULTS

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All values in microns.
N/A, not available; Postop, postoperative; Preop, preoperative; UBM, ultrasound biomicroscopy.
Trace to mild reticular haze was seen at the periphery of the ablations in most eyes. In none of the eyes was this reticular haze considered significant. Eleven eyes (55%) developed mild central haze and were treated with a topical corticosteroid drop (fluorometholone 0.1% in 7 eyes, loteprednol 0.5% in 3 eyes, and prednisolone acetate 1% in 2 eyes; one received both fluorometholone and loteprednol). It was generally used four times a day for the first month and then tapered over 2 to 4 months. No eye developed significant central haze. There was no difference found in corneal clarity, visual acuity, or refractive or reepithelialization results between the 11 eyes that were treated and the nine eyes that were not treated with topical corticosteroids postoperatively.

There were no corneal infections or graft rejections. Two patients (11 and 14) underwent subsequent penetrating keratoplasty, 12 and 3 months, respectively, after the PTK because of poor vision after PTK (Figure 26). These procedures were not any different than in eyes that had not previously undergone PTK.

RESULTS AFTER PREVIOUS CORNEAL SURGERY
There was no difference found in corneal clarity, visual acuity, refractive, or reepithelialization results between the 12 eyes with and the 8 eyes without previous corneal surgery.

Selected statistical correlations are found in the Appendix.

HISTOPATHOLOGY
Histopathologic analysis was performed on the two corneas that underwent penetrating keratoplasty. Patient 11 had undergone previous corneal transplantation and PTK for Reis-Bücklers’ dystrophy. Centrally in the area of photoablation, Bowman’s layer and the anterior part of the stroma were absent and the epithelium was irregular in caliber with a saw-toothed configuration. A thin layer of intensely eosinophilic finely crystallloid material consistent with the subepithelial deposits of Reis-Bücklers’ dystrophy was present beneath the epithelium. The periphery of the specimen contained larger deposits of the eosinophilic material.

Patient 14 had undergone PTK for lattice corneal dystrophy type I. The corneal button showed marked variation in the caliber of the corneal epithelium (Figure 27A). Peripherally, the epithelium was normal in thickness. Centrally, where PTK had photoablated Bowman’s layer and nearly half of the stroma, the epithelium had undergone massive compensatory hyperplasia. Here, a large placoid facet of epithelium approximately 100 µm in thickness filled the defect in the anterior stroma and served to maintain a smoothly curved anterior corneal surface. The underlying stroma was approximately 300 µm in thickness. The Congo red stain and polarization microscopy disclosed ovoid deposits of amyloid material consistent with lattice corneal dystrophy deep to the area of ablation and throughout the thickness of the corneal stroma (Figure 27B).

DISCUSSION
Twenty eyes of 14 patients were prospectively enrolled in this study to evaluate the use of UBM analysis of anterior corneal pathology as a predictor of depth for excimer laser PTK treatment. The visual and refractive results were also analyzed, especially in relation to an antihyperopia peripheral ablation. A relatively uniform patient population with superficial stromal corneal dystrophies was studied to obtain the most consistent results. It has been shown that visual recovery after PTK for corneal dystrophies occurs relatively quickly, usually in the first several months. The postoperative follow-up period of 6 to 8 weeks was selected for this study to maximize visual recovery while minimizing corneal remodeling and long-term recurrence of dystrophies to obtain the best analysis of the actual effects of the laser ablation on corneal pathology and curvature. By 6 to 8 weeks, epithelialization has generally been completed for several weeks and the corneal surface is typically quite smooth. However, there has not been enough time for significant epithelial or stromal remodeling or recurrence of the dystrophy to occur, minimizing the effect of these potential confounding variables. It is possible that UBM measurements would have different correlations with the amount of PTK required to treat pathology with longer follow-up periods.

VISUAL ACUITY
Uncorrected visual acuity improved 2 to 7 Snellen lines in 9 eyes (45%) and decreased 2 to 4 lines in 5 eyes (25%). Best corrected visual acuity improved 2 to 7 lines in 13 eyes (65%) and decreased 4 lines in one eye (5%). This improvement in visual acuity is consistent with previously published reports. Preoperative and postoperative uncorrected vision were not correlated ($P = .54$) nor were preoperative and postoperative best corrected vision ($P = .47$), as many eyes with poor preoperative vision improved greatly and those with better preoperative vision could not improve as much. Consequently, preoperative vision was not found to be a determinant of postoperative vision.

UBM MEASUREMENT OF DEPTH OF CORNEAL PATHOLOGY
One of the most important factors determining the success of excimer laser PTK is the depth of the pathology. The depth of pathology determines the extent of treatment required to remove the majority of the opacity. Deep abla-
Excimer Laser Phototherapeutic Keratectomy In Eyes With Anterior Corneal Dystrophies

**FIGURE 17A** Preoperatively, a UBM image was obtained to measure the corneal thickness and thickness of pathology in patient 7 with granular dystrophy. Cursor is placed at the most anterior and posterior extent of the central cornea at a 90° angle, and length is measured at the bottom of the screen (0.602 mm).

**FIGURE 17B** The same image as in Figure 17A was used to measure the thickness of the corneal opacity in an identical manner. It measured 0.162 mm.

**FIGURE 17C** Six weeks postoperatively, the UBM image is used to remeasure the corneal thickness (0.567 mm) in patient 7.

**FIGURE 18A** Preoperatively in patient 9R with recurrent Reis-Bücklers’ dystrophy in a graft, the central corneal thickness measured 0.671 mm.

**FIGURE 18B** Preoperatively, the pathology in patient 9R measured 0.162 mm.

**FIGURE 18C** Postoperatively in patient 9R, the corneal thickness measured 0.625 mm.
Rapuano

FIGURE 19A
UBM image of central cornea of patient 14 with lattice dystrophy before PTK. Note deep hyperreflective area on right of the image, which corresponded to deep amyloid deposits. Central corneal thickness measured 0.613 mm.

FIGURE 19B
Same image as in Figure 19A is used to measure central anterior corneal pathology (0.104 mm).

FIGURE 19C
Six weeks postoperatively, the UBM measured the central corneal thickness in patient 14 to be 0.521 mm.

FIGURE 20
Comparison preoperative ultrasound pachymetry measurement of corneal thickness to UBM measurement of corneal thickness. Measurements were highly correlated ($P < .001$).

FIGURE 21
Comparison postoperative ultrasound pachymetry measurement of corneal thickness to UBM measurement of corneal thickness. Measurements were highly correlated ($P < .001$).

FIGURE 22
Change in UBM pachymetry compared to actual PTK treatment depth. There was no statistically significant correlation.

FIGURE 23
Comparison of UBM measurement of corneal pathology and actual PTK treatment depth. There was no statistically significant correlation. There was a trend ($P = .07$) of an inverse correlation between UBM measurement of corneal pathology and actual PTK treatment depth.
Excimer Laser Phototherapeutic Keratectomy In Eyes With Anterior Corneal Dystrophies

FIGURE 24
Three days after PTK in patient 7L, surface has reepithelialized. Corneal thinning in the central 6-mm area of PTK treatment is apparent and there is fluorescein pooling at edge of the ablation zone.

FIGURE 25A
Preoperatively, patient 3R had significant recurrent lattice dystrophy 10 years after penetrating keratoplasty.

FIGURE 25B
This eye (3R) required 41 days to completely reepithelialize. The chronic paracentral epithelial defect left a corneal scar when it finally resolved. Seven weeks after PTK, the scar is visible at the inferonasal pupillary margin. The surrounding central cornea is much clearer than preoperatively and both uncorrected and best corrected visual acuity improved 3 Snellen lines.

FIGURE 26
Patient 14 underwent a penetrating keratoplasty 4 months after PTK on account of worsened vision. One year after transplant, corneal graft is clear and the vision without correction is 20/50.

FIGURE 27A
Penetrating keratoplasty specimen for patient 14. A large placoid facet of epithelium that has undergone compensatory hyperplasia fills the defect in anterior part of central cornea caused by photobleaching. Approximately 100 µm in thickness, the thickened epithelium maintains the smooth contour of anterior corneal surface (hematoxylin-eosin, original magnification ×50).

FIGURE 27B
Polarization microscopy discloses birefringent apple-green deposits of amyloid consistent with lattice corneal dystrophy throughout the corneal stroma. A large deposit is seen deep to the hyperplastic epithelium in the area of photobleaching. (Congo red stain with crossed polarizers, original magnification ×60).
tions have been associated with significant corneal flattening and hyperopic shift. A goal of this study was to determine whether UBM was effective in predicting the depth of treatment required to clear the bulk of corneal pathology prior to PTK treatment. The results of this research demonstrated that preoperative estimation of depth of pathology using UBM was not correlated with actual treatment depth required during the procedure (Spearman correlation -0.45, P = .07). There was actually a trend toward an inverse correlation between UBM measurement of corneal pathology and PTK treatment. That is, the greater the UBM pathology measurement, the less PTK treatment tended to be necessary. In addition, UBM measurement of corneal pathology tended to overestimate the amount of PTK treatment required to remove the majority of the pathology. If the UBM measurement of corneal pathology were used to screen candidates for PTK, many acceptable candidates might be turned away, as the depth of their pathology tended to be overestimated. Additionally, if the UBM measurement were used to treat a patient, more tissue than necessary would tend to be removed. While the number of eyes in this study was relatively small, given the results, it is doubtful that a larger number of eyes would have shown UBM to accurately predict PTK treatment depth.

The reason that UBM could not predict actual treatment depth is most likely multifactorial. One of the most important issues is that, while UBM resolution is relatively good, it is certainly not capable of the submicron accuracy of the excimer laser. Attempting to measure the extent of the pathology on the UBM computer screen, even by a very experienced technician, was quite difficult in many eyes. Explanations for this difficulty include suboptimal resolution and the fact that the pathology was not uniform throughout the UBM sections. This nonuniformity is quite evident clinically at the slit lamp in certain eyes. A patient with granular dystrophy may have localized areas of deep, relatively confluent granules and other areas of relatively clear cornea. In addition, the cursor on the UBM computer screen has a minimal change of 6 µm horizontally and 12 µm vertically, preventing higher degrees of precision. Another reason is that the depths of pathology and the depths of treatment of eyes in this study did not vary greatly, since all procedures were performed in eyes that were thought to be good candidates for PTK based on slit-lamp evaluation. That is, all patients had enough pathology to cause visual symptoms, but the opacities were not extremely deep. This relative uniformity in extent of pathology and treatment depth makes small differences difficult to confirm statistically.

CHANGES IN CORNEAL CURVATURE
Multiple measurements of corneal curvature were evaluated in this study, because manifest refractions are not always accurate in eyes with poor vision. Keratometry and corneal topography measurements are more objective, but are not always obtainable, or very precise, in corneas with irregular surfaces. Haag-Streit keratometry readings, EyeSys simulated keratometry readings, and EyeSys corneal power measurements all correlated with each other both preoperatively and postoperatively, demonstrating consistency in corneal curvature measurements. The refractive effects of PTK, measured by changes in manifest refraction spherical equivalent, Haag-Streit keratometry readings, EyeSys corneal topography simulated keratometry readings, and central corneal power measurement, could not be correlated to depth of ablation or antihyperopia treatment, most likely because the depth of ablation and antihyperopia treatment tended to cancel each other out.

While depth of ablation has been shown to correlate with corneal flattening and induced hyperopia, most of these studies used a wide variety of ablation depths, including many eyes with very deep ablations (>100 µm stromal ablation). Additionally, previous studies generally did not use antihyperopia treatments in attempts to reduce corneal flattening and hyperopic shift. In this study, deep ablations were avoided. Furthermore, all ablation depths were in a relatively narrow band, between 75 and 130 µm, which included epithelium (typically 40 to 50 µm thick) and stroma. On account of the relatively small number of patients who did not receive an antihyperopia treatment, it was not possible to separately evaluate the refractive effects of depth of ablation and the antihyperopia treatment. The results of this study found an approximately 1 D mean myopic shift 6 to 8 weeks after PTK; however, the range of change in spherical equivalent refraction was large, –13 to +3.88 D. The unpredictability was much more of an issue than a hyperopic shift in this study. The unpredictability is at least partly due to the difficulty in obtaining accurate refractions in patients with poor vision and precise measurements of corneal curvature in eyes with irregular surfaces. There was no statistically significant correlation between central PTK treatment depth and change in spherical equivalent, change in Haag-Streit keratometry readings, change in EyeSys simulated keratometry readings, or change in EyeSys corneal power measurements. This lack of correlation between central PTK treatment depth and measures of corneal curvature is most likely related to several factors, especially relatively shallow treatment depths and the antihyperopia treatments.

GOALS OF PTK
The ultimate goal of PTK treatment is good clinical results and patient satisfaction. This objective makes isolating one variable, such as treatment depth, difficult to achieve. Without the antihyperopia treatment, many of the abla-
Excimer Laser Phototherapeutic Keratectomy In Eyes With Anterior Corneal Dystrophies

Contrary to previously published research, the entire PTK process used in this study did not result in a consistent and predictable refractive shift. This “process” includes numerous steps, each of which is important to avoid poor corneal clarity and refractive results. The process begins with patient selection based on refraction and slit-lamp examination. Eyes with deep pathology, that is, greater than 20% to 25% corneal thickness on slit-lamp evaluation, are deemed not to be good candidates for PTK. Determining depth of pathology at the slit lamp can be difficult as anterior pathology blocks the view of more posterior pathology.

Based on results of this study, UBM evaluation does not appear to be helpful, since preoperative UBM measurement of corneal pathology was not correlated with actual PTK ablation depth. The surgical procedures were quite similar for all patients. A transepithelial approach was used with minimal to no masking agent to obtain the smoothest surface possible. The “ablate and check” method was used in each patient to remove the least amount of corneal tissue while eliminating the bulk of the opacity. Depending on depth of ablation, preoperative refraction, and refraction of the fellow eye, the surgeon elected to perform an antihyperopia treatment in selected eyes. The total depth of antihyperopia treatment, ranging from 80 to 200 µm, was also determined by similar factors. The amount of antihyperopia treatment could not be correlated with changes in manifest refraction, keratometry readings or corneal topographic analyses; therefore, the best amount of antihyperopia treatment for a given ablation depth is still unknown. A statistically significant correlation was found between amount of antihyperopia treatment and

<table>
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<th>VARIABLE 1</th>
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<td>Preop best-corrected vision</td>
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<td>Mean postop EyeSys central corneal power</td>
<td>Mean EyeSys central corneal power</td>
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<td>Days to reepithelialization</td>
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<td>0.003</td>
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<td>0.634</td>
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<td>0.071</td>
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</table>
Another limitation of this study is the relatively short follow-up of 6 to 8 weeks. This time period was selected to maximize visual recovery while minimizing corneal remodeling and recurrence of the dystrophy in order to obtain the best analysis of the effect of the PTK treatment on corneal pathology and curvature. It is likely that visual acuity and refractive and corneal clarity results would be different with longer follow-up. It is possible that the UBM measurements of depth of pathology would have different correlations with the amount of treatment required to remove the bulk of the pathology at longer follow-up intervals. However, longer follow-up times would increase the variables potentially confounding the results.

CONCLUSION

The PTK procedure results in improved vision, both uncorrected and best corrected for many or most patients. Epithelial healing is typically rapid; however, certain eyes may have delayed reepithelialization, especially those undergoing more extensive antihyperopia treatments. Close follow-up is required for all eyes until reepithelialization has occurred. If PTK does not result in significantly improved vision, a corneal transplant can be performed without additional risk from the PTK procedure. Using ablations just deep enough to remove the majority of the pathology and antihyperopia treatments in selected eyes, no predictable refractive error was induced while best-corrected vision was improved in most patients. Change in refraction was variable and occasionally quite large, potentially requiring a contact lens for binocular vision. PTK is a very good option for a relatively small number of patients with visual symptoms due to anterior corneal pathology. UBM did not accurately predict the depth of PTK treatment due to limitations of this technology. Further study with better imaging techniques than UBM, perhaps using more refined optical coherence tomography, may help identify which patients respond best to this procedure. In the meantime, careful evaluation at the slit lamp and a judicious surgical technique typically lead to very good clinical results and gratified patients.

ACKNOWLEDGMENT

The author would like to thank Elizabeth L. Affel, MS, for help with the ultrasound biomicroscopic evaluation and interpretation, Marcia Polansky, ScD, for biostatistical support, and Ralph C. Eagle, Jr, MD, for assistance in histopathological analysis.

REFERENCES

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