Published in final edited form as:

J Cataract Refract Surg. 2017 April ; 43(4): 525–536. doi:10.1016/j.jcrs.2017.03.004.

Guiding flying-spot laser transepithelial phototherapeutic keratectomy with optical coherence tomography

Yan Li, PhD, Hideaki Yokogawa, MD, PhD, Maolong Tang, PhD, Winston Chamberlain, MD, PhD, Xinbo Zhang, PhD, and David Huang, MD, PhD

Center for Ophthalmic Optics and Lasers (Li, Yokogawa, Tang, Chamberlain, Zhang, Huang), Casey Eye Institute and Department of Ophthalmology, Oregon Health and Science University, Portland, Oregon, USA; and the Department of Ophthalmology (Yokogawa), Kanazawa University Graduate School of Medical Science, Kanazawa, Japan

Abstract

PURPOSE—To analyze transepithelial phototherapeutic keratectomy (PTK) results using optical coherence tomography (OCT) and develop a model to guide the laser dioptric and depth settings.

SETTING—Casey Eye Institute, Portland, Oregon, USA.

DESIGN—Prospective nonrandomized case series.

METHODS—Patients with superficial corneal opacities and irregularities had transepithelial PTK with a flying-spot excimer laser by combining wide-zone myopic and hyperopic astigmatic ablations. Optical coherence tomography was used to calculate corneal epithelial lenticular masking effects, guide refractive laser settings, and measure opacity removal. The laser ablation efficiency and the refractive outcome were investigated using multivariate linear regression models.

RESULTS—Twenty-six eyes of 20 patients received PTK to remove opacities and irregular astigmatism due to scar, dystrophy, radial keratotomy, or previous corneal surgeries. The uncorrected distance visual acuity (UDVA) and corrected distance visual acuity (CDVA) were significantly improved ($P < .01$) by 3.7 Snellen lines and 2.0 Snellen lines, respectively, to a mean of 20/41.2 and 20/22.0, respectively. Achieved laser ablation depths were 31.3% (myopic ablation) and 63.0% (hyperopic ablation) deeper than the manufacturer's nomogram. The spherical equivalent of the corneal epithelial lenticular masking effect was 0.73 diopter $\pm$ 0.61 (SD). The

Corresponding author: David Huang, MD, PhD, 3375 Southwest Terwilliger Boulevard, Portland, Oregon 97239-4197, USA. davidhuang@alum.mit.edu.

Yan Li, PhD, and Hideaki Yokogawa MD, PhD, contributed equally to this work.

Disclosures: Oregon Health and Science University (OHSU). Drs. Huang, Tang, and Li have significant financial interests in Optovue, Inc., a company that may have a commercial interest in the results of this research and technology. Drs. Huang, Li, and Tang receive patent royalty and research grant support from Optovue, Inc. through OHSU. Dr. Huang owns stock in Optovue, Inc. This potential individual conflict of interest has been reviewed and managed by OHSU. Dr. Yokogawa receives financial support provided by the Alcon Novartis Hida Memorial Award 2014 funded by Alcon Japan Ltd. None of the other authors has a financial or proprietary interest in any material or method mentioned.

Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

refractive outcome highly correlated to the laser settings and epithelial lenticular masking effect (Pearson $R = 0.96$, $P < .01$). The ablation rate of granular dystrophy opacities appeared to be slower. Smoothing ablation under masking fluid was needed to prevent focal steep islands in these cases.

CONCLUSIONS—The OCT-measured ablation depth efficiency could guide opacity removal. The corneal epithelial lenticular masking effect could refine the spherical refractive nomogram to achieve a better refractive outcome after transepithelial ablation.

Excimer laser ablation in human corneas is performed as phototherapeutic keratectomy (PTK) to treat corneal pathologies and as photorefractive keratectomy (PRK) to correct refractive errors. Phototherapeutic keratectomy has been used to treat various anterior corneal pathologies, including superficial stromal scars, corneal dystrophies, irregularity, and recurrent epithelial erosion.^{1–6} Transepithelial PTK uses an excimer laser to ablate the corneal epithelium and has several advantages over traditional PTK accomplished by manual removal of the epithelial layer, including less postoperative haze and faster healing time.⁷ More importantly, transepithelial PTK uses the corneal epithelium as a natural masking agent, which facilitates smoothing anterior stromal irregularities.^{8–10}

Previously, we reported a series of 9 cases of optical coherence tomography (OCT)–guided transepithelial PTK using a broad-beam excimer laser (Visx S4, Abbott Medical Optics, Inc.).⁸ The results showed that OCT simulation was useful for ablation planning and that epithelial thickness measurement can be used to predict post-transepithelial PTK refraction. However, the corneal ablation rates measured in that study could not be applied to excimer laser systems that had different laser beam deliveries.

In the current study, we performed transepithelial PTK using a flying-spot excimer laser (Wavelight Allegretto, Alcon Surgical, Inc.). Unlike the broad-beam excimer laser, the flying-spot excimer laser does not leave steep central islands after treatment. Because the Allegretto PTK mode (piston-shaped ablation profile) has not been approved by the U.S. Food and Drug Administration (FDA), in this study we performed transepithelial PTK by combining myopic and hyperopic astigmatism ablations. We investigated the usefulness of OCT corneal mapping to guide flying-spot laser PTK and developed a model to predict the refractive outcomes after transepithelial PTK using epithelial lenticular masking effects and excimer laser settings.

PATIENTS AND METHODS

Patients

Patients whose vision was primarily limited by superficial opacities in the corneal stroma and irregularities suitable for transepithelial PTK treatment were recruited at the Casey Eye Institute of Oregon Health and Science University (OHSU). The study followed the tenets of the Declaration of Helsinki and was in accord with the Health Insurance Portability and Accountability Act of 1996. The study protocol was approved by the OHSU institutional review board and registered as a clinical trial at clinicaltrials.gov.^A Written informed consent was obtained from all participants. Eyes with active corneal inflammation were excluded from the study. Other exclusion criteria were eyes in which adequate removal of corneal

opacity would have left less than 250 μm of residual stroma or eyes with opacities superficial to the Bowman layer.

Preoperative and Postoperative Examinations

Detailed ophthalmic history and demographic information were obtained from medical records of the study participants. Patients had a preoperative ophthalmic examination and postoperative examinations at 1, 3, 6, and up to 12 months after surgery. Slitlamp biomicroscopy, uncorrected and corrected distance visual acuity (UDVA) and uncorrected distance visual acuity (CDVA), manifest refraction, Fourier-domain OCT (RTVue-XR with a corneal adaptor module, Optvue, Inc.), and Placido disk anterior corneal topography (Orbscan II, Bausch & Lomb, Inc.) were performed.

Optical Coherence Tomography

A 70 KHz Fourier-domain OCT system was used to obtain high-resolution OCT images. The system had an axial (depth) resolution of 5 μm in tissue and a transverse resolution of approximately 20 μm . The pachymetry scan pattern (6.0 mm scan diameter, 8 radials, 1024 axial radial scans, repeated 5 times) was used to image the eye. Cross-line scans (8.0 mm long horizontal and vertical line scans) were also acquired. The OCT scans were centered on the pupil.

Preoperative and postoperative corneal, epithelial, and stromal thickness maps of all study eyes were calculated from OCT pachymetry scans using custom computer software algorithms. After dewarping was done to correct distortion due to refraction at corneal interfaces, all thickness measurements were made along the optical axis (parallel to the corneal vertex flare and the optical axis of the OCT system) on OCT images. Thickness was measured parallel to the optical axis so ablation depth could be measured parallel to the excimer beam incidence. The central epithelial thickness was averaged over the central 2.0 mm diameter zone of the epithelial thickness map. The peripheral epithelial thickness was averaged over an annular zone (diameter from 4.8 to 5.2 mm). Similarly, the central and peripheral corneal and stromal thicknesses were calculated from the pachymetry and stromal thickness maps. Preoperatively, a computer caliper tool was used to measure stromal opacity depth at its deepest point in the central 6.0 mm optical zone for the purpose of planning laser ablation depth.

Topography

A combined Placido disk–slit-scanning topographer was used to acquire the anterior corneal topography. Placido-disk topography-based simulated keratometry (K) and 3.0 mm irregularity index were recorded after it was verified that the anterior axial power map had valid measurements inside the central 4.0 mm diameter area.

^AOther Cited Material

U.S. National Institutes of Health Clinical Trials. Optical Coherence Tomography Guided Transepithelial Phototherapeutic Keratectomy. NCT01243931. Available at: <https://clinicaltrials.gov/ct2/show/NCT01243931>. Accessed March 2, 2017

In Vitro Phototherapeutic Keratectomy Laser Ablation Profile

As the Allegretto PTK mode was not available in the U.S., myopic and hyperopic ablations were combined to provide PTK treatment. In vitro experiments were performed to verify that the combined myopic and hyperopic correction could provide piston-shaped ablation profiles. Dioptrically balanced myopic and hyperopic laser ablations were delivered to a flat plastic plate. The Wavelight wavefront-optimized ablation pattern compensates the incidence angle effect of both myopic and hyperopic ablations using the surgeon-entered simulated K values. Simulated K settings of 44.0 diopters (D) were used in the in vitro experiment. The profile of the ablation achieved on the plastic plate was measured using a 3-dimensional profiling system (MTS Systems Corp.) and compared with the theoretical ablation profile.

Transepithelial Phototherapeutic Keratectomy

Transepithelial PTK was performed in all patients by 1 of 2 surgeons (D.H., W.C.) using a flying-spot excimer laser (Wavelight Eye-Q 400 Hz). After the application of topical anesthetic eyedrops (proparacaine hydrochloride 0.5%), sterile preparation and draping were performed, a lid speculum was inserted, and the eye was centered under the excimer laser. The corneal surface was moistened with a balanced salt solution. The patient was instructed to fixate on the fixation light. The cornea was centered, and tracking was locked on the pupil. The preprogrammed laser ablations were delivered.

To plan for the laser ablations, myopic ablation to remove most of the stromal opacity within the optical zone was combined with hyperopic astigmatic ablation to achieve the intended refractive correction. The astigmatism treatment was programmed as part of the hyperopic astigmatism ablation according to the preoperative refraction. The epithelium was not scraped before transepithelial myopic ablation (8.0 mm diameter optical zone) was performed, followed by hyperopic astigmatism ablation (6.5 mm diameter optical zone). If additional smoothing was required, a third smoothing ablation pass was performed using the myopic ablation program. During the smoothing ablation, a smoothing agent (carboxymethylcellulose 0.5%) was applied with a polyvinyl alcohol sponge (Merocel) every 2 seconds during the -0.5 D to -2.5 D myopic ablation (8.0 mm diameter optical zone). Preoperative calculations ensured that the residual stromal thickness would be more than $250\text{ }\mu\text{m}$, considering that actual ablation depth was deeper than the nominal depth given by the manufacturer's ablation table as measured in our previous PTK study.⁸

After the laser ablation, a 7.0 mm polyvinyl alcohol cellulose sponge soaked in mitomycin-C 0.02% (0.2 mg/mL) was placed on the corneal surface, covering the ablation zone, for 2 minutes.¹¹ The surface was then irrigated with a balanced salt solution for 2 minutes and a bandage soft contact lens was applied. Topical bromfenac 0.07% (Prolensa) and moxifloxacin 0.5% (Vigamox) eyedrops were instilled, and the speculum and draping were removed.

In the first week after PTK, ofloxacin 0.3% (Ocuflox) and prednisolone acetate 1.0% eyedrops were used 4 times daily. Prednisolone drops were tapered over the following month. Following protocol, the bandage soft contact lens was removed 1 week after PTK unless epithelial healing was delayed, which did not occur in this study.

Statistical Analysis

Visual acuity was converted from Snellen notation to logMAR for statistical analysis.¹² Paired *t* tests were used to compare preoperative and postoperative measurements. The generalized estimating equations approach was used to account for the intereye correlation.¹³ Patient visual acuity changes over time were plotted in box-and-whisker plots. A *P* value less than 0.05 was considered statistically significant. Statistical analysis were performed using Excel software (2010, Microsoft Corp.) and SAS (9.4, SAS Institute Inc.).

Measurement of Laser Ablation Efficiency

A custom algorithm developed with Matlab R2010a software (The Mathworks, Inc.) was used to calculate the ablation map, ablation efficiency, and epithelial lenticular masking effect. The nominal laser ablation map of each eye being treated was calculated using parabolic profiles. Each map included myopic and hyperopic corrections. The nominal central setting of the myopic correction and the maximum setting of the hyperopic correction matched those provided by the Allegretto laser reports. The target central (average over the central diameter 2.0 mm zone) and the target peripheral (average over an annular zone diameter from 4.8 to 5.2 mm) ablation settings of the myopic and hyperopic corrections were calculated accordingly. It was difficult to estimate the amount of tissue ablation precisely in the presence of the masking agent. Therefore, a case would be excluded from the analysis to estimate the ablation efficiency and model the transepithelial PTK refractive outcome if a smoothing pass was involved. The actual ablation depth was calculated as the difference between preoperative corneal thickness and postoperative 1-month stromal thickness measured by OCT. The mean nominal and actual ablation depths were reported in mean $\mu\text{m} \pm$ standard deviation (range minimum to maximum) format.

Ablation efficiency was estimated by multivariate linear regression between the nominal ablation setting and the actual ablation depth measured by OCT. Ablation efficiency was evaluated for myopic and hyperopic corrections. Myopic ablation efficiency was estimated by multivariate linear regression between the nominal central ablation setting and the actual central ablation depth. In the center, the hyperopic ablation removed only a small amount of tissue; therefore, the ablation efficiency of the central hyperopic ablation was set to 1. Hyperopic ablation efficiency was estimated by multivariate linear regression between the nominal peripheral ablation settings and the actual peripheral ablation depth. The peripheral ablation depth of the myopic ablation was accounted for by assuming the peripheral myopic ablation had the same efficiency as the myopic ablation efficiency measured centrally. The intercept of the linear regressions was set to zero.

Measurement of Epithelial Lenticular Masking Effect

Because transepithelial PTK is programmed to ablate through the entire corneal epithelium within the optical zone, the uneven thickness of the corneal epithelial layer can introduce refractive change to the transepithelial PTK treatment. For example, if the central epithelium is thicker than the peripheral epithelium (Figure 1, A), the central stroma would be shielded more than the peripheral stroma from the transepithelial ablation, resulting in a deeper ablation in the periphery, similar to a hyperopic ablation.

The lenticular refractive power of the corneal epithelium masking effect was estimated using Zernike polynomial decomposition of the OCT epithelial thickness map^{14,15} as follows:

$$SEQ_e = (n-1) \frac{4\sqrt{3}}{R^2} h_{2,0} \quad (1)$$

where SEQ_e was the spherical equivalent of the epithelial lenticular power, R was the radius of the circular analytic zone with a value of 3.0 mm, n was the corneal refractive index with a value of 1.376, and $h_{2,0}$ was the Zernike coefficient for the Zernike defocus term $Z(2,0)$ in micrometers.

The mean epithelial lenticular masking effect was reported in mean $\pm$ standard deviation (range minimum to maximum) format (diopter units).

A formula to model the transepithelial PTK refractive correction with the SEQ_e and excimer laser settings was developed using multivariate linear regression. The PTK-induced refractive correction was calculated as the preoperative manifest refraction spherical equivalent (MRSE) minus the postoperative MRSE.

RESULTS

In Vitro Phototherapeutic Keratectomy Laser Ablation Profile

Dioptrically balanced myopic and hyperopic laser ablations (-6.0 D sphere with 8.0 mm optical zone and 0.5 mm transition zone followed by $+6.0$ D sphere with 6.0 mm optical zone and 1.5 mm transition zone) were delivered to a flat plastic plate. The measured central ablation profile (Figure 2, *A*) showed a small approximately plano central zone (3.0 mm diameter) surrounded by an elevated annular region. This contrasts with the theoretical profile (Figure 2, *B*) in which the hyperopic and myopic ablations formed a plano piston-shaped profile within the 6.0 mm optical zone.

Using simulated K settings of 44.0 D ($R = 7.67$ mm), it was estimated that 6% to 9% additional pulses were needed for ablation zones of 5.0 to 6.0 mm diameter to compensate for the incidence angle effect. The measured ablation profile (Figure 2, *A*) showed that more than 50% more pulses were delivered at the periphery (5.0 to 6.0 mm diameter) than in the center. These results show that the laser was programmed to ablate deeper for each diopter of hyperopic correction than for the comparable myopic correction.

Transepithelial Phototherapeutic Keratectomy Clinical Study

Between August 2011 and May 2015, transepithelial PTK was performed in 26 eyes of 20 patients (mean age 55.7 years $\pm$ 11.7 (SD) (range 29 to 80 years) with anterior corneal pathologies. The pathologies included post-refractive surgery complications (post-radial keratotomy [RK], 10 eyes in 6 patients; post-laser in situ keratomileusis [LASIK], 2 eyes in 2 patients), post-microbial keratitis scar (1 eye), other types of scars (6 eyes in 6 patients), post-penetrating keratoplasty (3 eyes in 2 patients), granular corneal dystrophy (3 eyes in 2 patients), and irregular astigmatism post-cataract surgery (1 eye).

Visual Outcomes—The visual acuity significantly improved after the transepithelial PTK treatment (Table 1). The UDVA improved by 3.7 Snellen lines from a mean of 20/95.1 to 20/41.2 ($P = .0014$), and the CDVA improved by 2.0 lines from a mean of 20/34.4 to 20/22.0 ($P < .0001$). Postoperatively, 23 eyes (88.5%) had CDVAs equal to or better than 20/25. No eye lost Snellen lines of CDVA (Figure 3). The CDVA continued to improve for at least 6 months after surgery (group mean differences using generalized estimating equations approaches between logMAR CDVA 1 versus 3 months postoperatively and 3 versus 6 months postoperatively were significant; $P = .02$ and $P = .01$, respectively) (Figure 4). The astigmatism magnitude decreased significantly after PTK by a mean of 1.28 D ($P < .0001$).

Six months after the transepithelial PTK, slitlamp microscopy showed corneal haze in 3 eyes. Among the eyes with corneal haze, trace haze was seen in 2 eyes and 2+ ring haze in 1 eye that had severe post-PRK haze before the PTK treatment.

Case Reports

Case 1: Granular Dystrophy with No Smoothing Ablation: A 57-year-old woman presented with a history of granular dystrophy (Figure 5), PTK, and cataract surgery. Preoperatively, the UDVA was 20/80, the CDVA was 20/60, the manifest refraction was $-1.75 +0.50 \times 40$, and the simulated K was 38.7 D (flat) and 39.9 D (steep) at 128 degrees. The epithelial lenticular masking effect was 0.45 D. The transepithelial laser ablation included myopic ablation (-3.25 D, optical zone 8.0 mm, nominal central ablation depth 74.3 μm) followed by hyperopic astigmatism ablation ($+3.75 +0.50 @ 40$, optical zone 6.5 mm, nominal maximum ablation depth 70.5 μm).

This was the first granular dystrophy case in the case series. The first transepithelial PTK treatment in the study was conducted without additional smoothing ablation. A paracentral granular deposit was observed by the surgeon under the operating microscope after the PTK. The granule was associated with a focal steep island on postoperative topography maps and was visible on OCT cross-sectional images (Figure 5). Postoperatively, the patient experienced starbursts and glare at night, possibly caused by the focal elevated granular opacities. The visual symptoms gradually improved but did not completely resolve. At 12 months, the UDVA improved to 20/40 and the CDVA improved to 20/25 with a refraction of -0.75 D sphere. A second transepithelial PTK treatment was performed to remove residual and recurrent opacities. The retreatment included a myopic ablation (-1.5 D, optical zone 8.0 mm, nominal central ablation depth 35.1 μm) and a hyperopic astigmatism ablation ($+3.25 +1.75 @ 3$, optical zone 6.5 mm, nominal maximum ablation depth 83.6 μm) followed by a smoothing ablation (-2.5 D, optical zone 8.0 mm) under masking fluid to remove focal elevated granular opacities. Because the patient lived out of state, further follow-up information was not available.

The laser ablation efficiency was hypothesized to be lower at the granule than in the surrounding corneal tissue. Therefore, in later cases of granular dystrophy, central islands, and thick corneal scars, a final smoothing ablation in the presence of masking fluid was added to improve the final smoothness of the stromal surface. Improved results were obtained, as shown in Case 2.

Case 2: Granular Dystrophy with Smoothing Ablation: A 67-year-old man presented with granular dystrophy in both eyes. Preoperatively, the UDVA in the left eye was 20/50, the CDVA was 20/40 with manifest refraction $-2.50 +2.25 \times 118$, and the simulated K was 41.2 D (flat) and 44.4 D (steep) at 99 degrees. The epithelial lenticular masking effect was 0.22 D. Simulated ablation based on preoperative OCT imaging showed that an ablation depth of 108.0 μm would remove the superficial layer of the central corneal opacity (Figure 6). The transepithelial PTK included myopic ablation (-4.0 D, optical zone 8.0 mm, nominal central ablation depth 98.7 μm) and hyperopic astigmatism ablation ($+1.50 +1.75 @ 116$, optical zone 6.5 mm, nominal maximum ablation depth 53.1 μm) followed by smoothing ablation (-1.25 D, optical zone 8.0 mm) under the smoothing agent. The stromal opacities and surface irregularities were removed by the ablation (Figure 6). Six months postoperatively, the UDVA improved to 20/25 and the CDVA improved to 20/20 with refraction $-0.25 +0.75 \times 0$.

Case 3: Post-Microbial Keratitis Scar: A 70-year-old woman presented with traumatic corneal opacity after a bacterial ulcer in the right eye (Figure 7). Preoperatively, the UDVA was 20/100, the CDVA was 20/80 with a manifest refraction of $-0.25 +0.75 \times 45$, and the simulated K was 42.4 D (flat) and 44.6 D (steep) at 88 degrees. The deepest scar was 192 μm in the central cornea. The epithelial lenticular masking effect was 0.39 D. The transepithelial laser ablation included myopic ablation (-5.75 D, optical zone 8.0 mm, nominal central ablation depth 127.7 μm) followed by hyperopic astigmatism ablation ($+5.00 +0.50 @ 64$, optical zone 6.5 mm, nominal maximum ablation depth 92.8 μm). A smoothing ablation (-1.50 D, optical zone 8.0 mm) was performed with a smoothing agent. The stromal opacities and surface irregularities were removed by the ablation. Six months postoperatively, the UDVA improved to 20/70 and the CDVA improved to 20/25 with refraction $+2.00 +2.75 \times 110$. The OCT cross-sectional images showed that most of the corneal opacities were removed.

Case 4: Post-Radial Keratotomy: A 49-year-old man presented with corneal scarring and irregular astigmatism; radial keratotomy (RK) and astigmatic keratotomy (AK) had been performed 20 years earlier (Figure 8). Before PTK, the UDVA was 20/150, the CDVA was 20/50 with a manifest refraction of $-4.25 +2.00 \times 76$, and the preoperative simulated K was 37.1 D (flat) and 38.8 D (steep) at 82 degrees. The epithelial lenticular masking effect was 1.84 D. The transepithelial laser ablation included myopic ablation (-6.00 D, optical zone 8.0 mm, nominal central ablation depth 132.9 μm) followed by hyperopic astigmatism ablation ($+0.25 +1.25 @ 79$, optical zone 6.5 mm, nominal maximum ablation depth 24.0 μm). Six months after PTK, the UDVA improved to 20/50 (4.8-line gain) and the CDVA improved to 20/20 (4-line gain) with refraction $-1.00 +1.75 \times 39$. The focal flattening inside the pupil margin where the temporal AK incision intersected the RK cut decreased after PTK.

Laser Ablation Efficiency—Four eyes (3 granular dystrophy and 1 post-microbial keratitis scar cases) that had laser smoothing ablation with a masking agent were excluded from the laser ablation efficiency estimation. The target central (2.0 mm diameter area) ablation setting was averaged to $93.6 \pm 39.5 \mu\text{m}$ (range 39.5 to 165.5 μm) for the myopic

correction and $1.7 \pm 1.0 \mu\text{m}$ (range 0.4 to 4.2 μm) for the hyperopic correction. The OCT-measured central ablation depth was $125.8 \pm 50.2 \mu\text{m}$ (range 56.1 to 215.9 μm). The target peripheral (4.8 to 5.2 mm annular zone) ablation setting was $55.2 \pm 20.3 \mu\text{m}$ (range 24.8 to 84.4 μm) for the myopic correction and $21.0 \pm 11.9 \mu\text{m}$ (range 4.7 to 52.6 μm) for the hyperopic correction. The OCT-measured peripheral ablation depth was $110.7 \pm 36.4 \mu\text{m}$ (range 59.7 to 191.1 μm), and the OCT-measured minimum residual stromal thickness was $401.3 \pm 65.1 \mu\text{m}$ (range 291.7 to 519.3 μm). The laser ablation efficiency determined by linear regression analysis was 131.3% ($R = 0.996$) for the myopic correction and 163.0% ($R = 0.971$) for the hyperopic correction (Figure 9).

Epithelial Lenticular Masking Effect—The preoperative epithelium lenticular masking effect measured by OCT was $0.73 \pm 0.61 \text{ D}$ (range -0.31 to 2.21 D) in the study eyes.

Achieved Versus Calculated Refractive Outcomes—Multivariate linear regression was performed to model the transepithelial PTK refractive outcome using the OCT epithelial lenticular masking effect, excimer laser settings, and RK history. The intercept of the regression line was set to zero. Eight eyes involving smoothing ablations with masking agent or with CDVA worse than 20/40 (manifest refraction may not be accurate) were excluded from the refractive outcome regression analysis. Postoperative refractive outcome was assessed at 6 months, except in 2 eyes that were not available at that time. In those eyes, it was assessed at 12 months. The following regression formula was used:

$$\text{Refractive Correction} = 1.29 \times SEQ_m + 1.59 \times SEQ_h + 1.28 \times SEQ_e \quad (2)$$

where *refractive correction* was the surgically induced correction, SEQ_m and SEQ_h were the SEs of the myopic and hyperopic laser correction settings, SEQ_e was the epithelium lenticular masking effect measured by OCT. All were measured in diopteric units.

The formula was highly predictive of refractive outcomes in this dataset ($R = 0.962$), and the coefficient of each variable was significant: SEQ_m and SEQ_h (both $P < .0001$) and SEQ_e ($P = .010$). The relationship between the actual refractive correction and the calculated refractive correction was linear (Figure 10). The difference between the actual and calculated refraction corrections ($0.07 \pm 0.69 \text{ D}$, range -0.95 to 1.43 D; $P = .66$) was significantly smaller than the difference between the actual refractive corrections and the nominal laser settings ($1.10 \pm 1.23 \text{ D}$, range -0.50 to 4.06 D; $P = .001$).

DISCUSSION

In this study, we used a flying-spot excimer laser to perform transepithelial PTK in eyes with irregular astigmatism and superficial corneal stromal opacities. We developed a method to estimate the corneal epithelium lenticular masking effect and used that information to model the transepithelial PTK refractive outcome. We also evaluated flying-spot excimer laser ablation efficiency in corneas with opacities.

The flying-spot excimer laser has a smaller incidence of steep central island formation and is therefore more desirable than the broad-beam excimer laser used in transepithelial

PTK.^{8,16–18} No flying-spot excimer laser has an FDA-approved PTK mode (piston-shaped ablation profile). To circumvent this restriction, surgeons in the U.S. use a combination of myopic and hyperopic ablations to perform PTK. It is considered an off-label use of this technology in the U.S. Rush et al.^{19,20} used the Allegretto instrument in 64 eyes to conduct transepithelial PTK studies with large-zone (7.0 to 8.0 mm optical zone) spherical myopic ablation to completely remove the anterior corneal scar and then spherical hyperopic ablation to achieve the intended refractive correction. They reported that the epithelial thickness uniformity was restored with decreased anterior surface irregularity. The mean CDVA improved by 4.4 Snellen lines from 20/117.8 (preoperatively) to 20/43.8 (postoperatively). The postoperative SE was more hyperopic ($+0.91 \pm 0.71$ D) than the target refractive outcome.

We combined myopic and hyperopic ablations to deliver transepithelial PTK treatment. Unlike Rush et al.,^{19,20} we programmed in astigmatic correction, which was incorporated into the hyperopic ablation. Patient vision was significantly improved after the treatment, reflecting an approximately 4 Snellen line gain in UDVA and a 2-line gain in CDVA. The number of line improvements on CDVA was less in our study than in Rush et al.'s study, probably because our patients started with better preoperative CDVA. The patients in our study achieved better postoperative CDVA.

Reinstein and Archer²¹ and Reinstein et al.²² first described the phenomenon that the epithelial masking effect could shift the refractive outcome of the transepithelial PTK procedure. In a 2012 case report,²² they predicted that the transepithelial ablation in an eye with superior and inferior epithelial thinning would effectively result in a hyperopic astigmatic ablation of 3.5 D. In our 2014 study,⁸ we modeled the epithelial refractive masking effect using the difference between the central and peripheral epithelial thicknesses. In the current study, instead of using only point measurements at the center and periphery, we incorporated information from the entire epithelial thickness map using Zernike decomposition after Gram-Schmidt orthogonalization.^{14,15} This provided a dioptric value for the epithelial lenticular masking effect. Our multivariate regression model (equation 2) was highly predictive ($R = 0.962$) using the epithelial lenticular masking effect and the laser setting to model the refractive outcome of the transepithelial PTK procedures. Using our formula, the difference between the predicted and achieved refractive outcomes was less than 1.0 D in 89% of eyes; ie, the CDVA was equal to or better than 20/40 in 16 of 18 eyes. The formula enables prediction of the refractive effect of epithelial masking in transepithelial PTK and could be used in preoperative planning to improve the refractive outcome. It may also be used in planning transepithelial PRK.

In this study, the Allegretto excimer laser ablation efficiency was 131.3% for myopic ablation and 163.0% for hyperopic ablation, relative to the manufacturer's nominal settings. The result of our in vitro PTK laser ablation experiment confirmed that the laser was programmed to ablate deeper for each diopter of hyperopic correction than for the comparable myopic correction. This knowledge can prevent unnecessarily deep ablations, which could lead to less predictable refractive outcomes and possible ectasia due to a thin residual corneal stroma. The pattern and depth of ablation need to be empirically calibrated for each laser platform and control software. Previously, we reported that Visx S4 laser

ablation efficiency was 120% in the center and 127% at the periphery using the piston-shaped PTK ablation program for transepithelial PTK.⁸ The Wavelight Eye-Q 400 platform was likely to be different because its wavefront-optimized ablation pattern was designed to compensate for expected surgically induced spherical aberration. We know that postoperative epithelial thickening in the peripheral trough of hyperopic ablation induces prolate spherical aberration, and central epithelial thickening induces oblate spherical aberration.^{14,23} Therefore, it makes sense for the wavefront-optimized ablation pattern to compensate for that by performing additional ablation. The additional ablation required to compensate for epithelial thickness modulation is greater for hyperopic ablation than for myopic ablation.

Contrary to our findings, Kanellopoulos et al.²⁴ reported a lower central ablation efficiency of 97.2% with a similar laser (Wavelight EX500) in myopic LASIK. The difference may be explained by the following: First, Kanellopoulos et al. measured the difference between the preoperative and postoperative stromal thicknesses. The flap thickness can increase after LASIK because of the release of tension (biomechanical effect).²⁵ The flap thickness was included in the postoperative stromal thickness measurement. This could artifactually decrease the measured ablation depth in the study.²⁴ Second, the ablation efficiency tends to be higher for a deeper ablation (nonlinear effect) due to stromal dehydration. The tissue ablation depth used in our study was deeper than the LASIK stromal ablation depth in the study by Kanellopoulos et al. In addition, there was a time interval between the myopic ablation and hyperopic ablation (approximately 50 seconds) in our study. That interval could cause additional stromal dehydration and increase the efficiency of the hyperopic ablation. Furthermore, the ablation rate could be higher in the epithelium relative to the stroma, leading to relatively higher efficiency for transepithelial ablation than for LASIK.^{26,27} In turn, the laser ablation efficiency was higher in our transepithelial PTK study.

Focal islands were present in a granular dystrophy case after PTK without smoothing ablation. We hypothesized that it may have occurred because of lower ablation efficiency in granular deposits. Both type 1 and type 2 granular dystrophy deposits contain hyaline. The excimer laser may ablate the granules slower than the surrounding corneal tissue, resulting in a steep topographic island. The differential ablation speed may also exist in other types of opacities. Smoothing the ablation with a masking fluid is important to prevent focal islands at the location of granule or other thick opacities.²⁸

Our regression model showed that transepithelial PTK myopic ablation had refractive effects higher than the nominal setting (coefficient of 1.29 for myopic correction in equation 2). This is possibly explained by the lack of a myopic ablation epithelial remodeling effect (epithelial thickening) because myopic ablation is balanced by hyperopic ablation in transepithelial PTK procedures. The lack of an epithelial remodeling effect could also be due to the larger myopic ablation zone used in this study. Moreover, there was a higher refractive effect of hyperopic ablation (coefficient of 1.59) relative to myopic ablation (coefficient of 1.29 in equation 2). This could be explained by 2 factors. First, deeper hyperopic ablation was programmed per diopteric correction as seen on the plastic plate. Second, the hyperopic ablation was performed after the myopic ablation; therefore, the corneal dehydration may have had a larger effect on hyperopic ablation. If the nominal laser setting had been used to

plan the ablation, there would likely have been a large number of hyperopic outcomes up to +4.0 D in our study. The knowledge gained in this study regarding the higher refractive correction efficiency and the epithelial lenticular masking effect is important for proper laser programming and avoidance of large refractive errors after PTK.

The limitations of this study include the relatively small number of study participants, as well as that the ablation programs were limited to myopic and hyperopic astigmatism. Topography-guided ablation was not available to correct higher-order aberrations associated with the corneal irregularities. Furthermore, the lack of an integrated PTK treatment program on the Wavelight laser necessitated laser recalibration between the myopic and hyperopic ablations, which could cause stromal dehydration and make the refractive outcome less predictable. The use of masking fluid in a third ablation pass for smoothing could also introduce some unpredictability to the ablation depth and refractive outcome. Finally, the achieved CDVA might have been better if we had used masking fluid in the cases of granular dystrophy early in the series.

In conclusion, a flying-spot excimer laser can perform PTK by combining myopic ablation and hyperopic astigmatism ablation in the absence of a dedicated PTK mode. The spherical refractive outcome of the transepithelial PTK treatment could be modeled by the epithelial lenticular masking effect and the laser settings. Knowledge of refractive correction larger than the nominal settings can prevent undesired large hyperopic outcomes. Optical coherence tomography corneal maps can guide refractive laser settings and opacity removal. Ablation efficiency is higher than the manufacturer's nominal setting in transepithelial PTK treatment. This knowledge can prevent corneal ectasia due to the presence of a thin residual stroma. Smoothing ablation is necessary to prevent focal islands at the location of thick opacities and can be achieved by using a large-zone myopic ablation pattern with masking fluid.

Acknowledgments

Supported by grants R01 EY018184 and P30 EY010572 from the National Institutes of Health, Bethesda, Maryland, and unrestricted departmental funding from Research to Prevent Blindness, New York, New York, and material support from Optovue Inc., Fremont, California, USA.

References

1. Dedes W, Faes L, Schipper I, Bachmann LM, Thiel MA. Phototherapeutic keratectomy (PTK) for treatment of recurrent corneal erosion: correlation between etiology and prognosis – prospective longitudinal study. *Graefes Arch Clin Exp Ophthalmol*. 2015; 253:1745–1749. [PubMed: 25900814]
2. Ghanem RC, Ghanem VC, Ghanem EA, Kara-José N. Corneal wavefront-guided photorefractive keratectomy with mitomycin-C for hyperopia after radial keratotomy: two-year follow-up. *J Cataract Refract Surg*. 2012; 38:595–606. [PubMed: 22440434]
3. Hersh PS, Burnstein Y, Carr J, Etwaru G, Mayers M. Excimer laser phototherapeutic keratectomy; surgical strategies and clinical outcomes. *Ophthalmology*. 1996; 103:1210–1222. [Accessed March 2, 2017] Available at: http://www.vision-institute.com/new-jersey/pdfs/excimer_laser_ptk.pdf. [PubMed: 8764789]
4. Hieda O, Kawasaki S, Wakimasu K, Yamasaki K, Inatomi T, Kinoshita S. Clinical outcomes of phototherapeutic keratectomy in eyes with Thiel-Behnke corneal dystrophy. *Am J Ophthalmol*. 2013; 155:66–72. [PubMed: 22967865]

5. Mori H, Miura M, Iwasaki T, Goto H, Sakurai Y, Watanabe Y, Yasuno Y. Three-dimensional optical coherence tomography-guided phototherapeutic keratectomy for granular corneal dystrophy. *Cornea*. 2009; 28:944–947. [PubMed: 19654514]
6. Rapuano CJ. Excimer laser phototherapeutic keratectomy: long-term results and practical considerations. *Cornea*. 1997; 16:151–157. [PubMed: 9071527]
7. Fadlallah A, Fahed D, Khalil K, Dunia I, Menassa J, El Rami H, Chlela E, Fahed S. Transepithelial photorefractive keratectomy: clinical results. *J Cataract Refract Surg*. 2011; 37:1852–1857. [PubMed: 21840678]
8. Cleary C, Li Y, Tang M, Samy El Gendy NM, Huang D. Predicting transepithelial phototherapeutic keratectomy outcomes using Fourier domain optical coherence tomography. *Cornea*. 2014; 33:280–287. [Accessed March 2, 2017] Available at: <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3946298/pdf/nihms544613.pdf>. [PubMed: 24452208]
9. Muller LT, Candal EM, Epstein RJ, Dennis RF, Majmudar PA. Transepithelial phototherapeutic keratectomy/photorefractive keratectomy with adjunctive mitomycin-C for complicated LASIK flaps. *J Cataract Refract Surg*. 2005; 31:291–296. [PubMed: 15767148]
10. Steinert RF, Ashrafzadeh A, Hersch PS. Results of phototherapeutic keratectomy in the management of flap striae after LASIK. *Ophthalmology*. 2004; 111:740–746. [Accessed March 2, 2017] Available at: <http://www.vision-institute.com/UserFiles/File/Results%20of%20Phototherapeutic%20Keratectomy%20in%20the%20%20Management%20of%20Flap%20Striae%20after%20LASIK.pdf>. [PubMed: 15051207]
11. Majmudar PA, Schallhorn SC, Cason JB, Donaldson KE, Kymionis GD, Shtein RM, Verity SM, Farjo AA. Mitomycin-C in corneal surface excimer laser ablation techniques; a report by the American Academy of Ophthalmology (Ophthalmic Technology Assessment). *Ophthalmology*. 2015; 122:1085–1095. [Accessed March 2, 2017] Available at: [http://www.aaojournal.org/article/S0161-6420\(15\)00089-5/pdf](http://www.aaojournal.org/article/S0161-6420(15)00089-5/pdf). [PubMed: 25795477]
12. Holladay JT, Prager TC. Mean visual acuity [letter]. *Am J Ophthalmol*. 1991; 111:372–374. [PubMed: 2000910]
13. Liang K-Y, Zeger SL. Longitudinal data analysis using generalized linear models. *Biometrika*. 1986; 73:13–22. [Accessed March 2, 2017] Available at: <http://www.biostat.jhsph.edu/~fdominic/teaching/bio655/references/extra/liang.bka.1986.pdf>.
14. Huang D, Tang M, Shekhar R. Mathematical model of corneal surface smoothing after laser refractive surgery. *Am J Ophthalmol*. 2003; 135:267–278. [PubMed: 12614741]
15. Tang M, Shekhar R, Huang D. Mean curvature mapping for detection of corneal shape abnormality. *IEEE Trans Med Imaging*. 2005; 24:424–428. [PubMed: 15754992]
16. Fiore T, Carones F, Brancato R. Broad beam vs. flying spot excimer laser: refractive and videokeratographic outcomes of two different ablation profiles after photorefractive keratectomy. *J Refract Surg*. 2001; 17:534–541. [PubMed: 11583223]
17. Hashimoto A, Kamiya K, Shimizu K, Igarashi A, Kobashi H. Central islands: rate and effect on visual recovery after phototherapeutic keratectomy. *Jpn J Ophthalmol*. 2015; 59:409–414. [PubMed: 26289725]
18. Müller B, Boeck T, Hartmann C. Effect of excimer laser beam delivery and beam shaping on corneal sphericity in photorefractive keratectomy. *J Cataract Refract Surg*. 2004; 30:464–470. [PubMed: 15030843]
19. Rush SW, Han DY, Rush RB. Optical coherence tomography-guided transepithelial phototherapeutic keratectomy for the treatment of anterior corneal scarring. *Am J Ophthalmol*. 2013; 156:1088–1094. [PubMed: 24075433]
20. Rush SW, Matulich J, Rush RB. Long-term outcomes of optical coherence tomography-guided transepithelial phototherapeutic keratectomy for the treatment of anterior corneal scarring. *Br J Ophthalmol*. 2014; 98:1702–1706. [PubMed: 24990872]
21. Reinsteint DZ, Archer T. Combined Artemis very high-frequency digital ultrasound-assisted transepithelial phototherapeutic keratectomy and wavefront-guided treatment following multiple corneal refractive procedures. *J Cataract Refract Surg*. 2006; 32:1870–1876. [PubMed: 17081871]

22. Reinstein DZ, Archer TJ, Gobbe M. Refractive and topographic errors in topography-guided ablation produced by epithelial compensation predicted by 3D Artemis VHF digital ultrasound stromal and epithelial thickness mapping. *J Refract Surg.* 2012; 28:657–663. [PubMed: 22947295]
23. Oshika T, Klyce SD, Applegate RA, Howland HC, El Danasoury MA. Comparison of corneal wavefront aberrations after photorefractive keratectomy and laser in situ keratomileusis. *Am J Ophthalmol.* 1999; 127:1–7. [PubMed: 9932992]
24. Kanellopoulos AJ, Georgiadou S, Asimellis G. Objective evaluation of planned versus achieved stromal thickness reduction in myopic femtosecond laser-assisted LASIK. *J Refract Surg.* 2015; 31:628–632. [PubMed: 26352569]
25. Dupps WJ Jr, Wilson SE. Biomechanics and wound healing in the cornea. *Exp Eye Res.* 2006; 83:709–720. [PubMed: 16720023]
26. Luger MHA, Ewering T, Arba-Mosquera S. Consecutive myopia correction with transepithelial versus alcohol-assisted photorefractive keratectomy in contralateral eyes: one-year results. *J Cataract Refract Surg.* 2012; 38:1414–1423. [PubMed: 22814048]
27. Seiler T, Kriegerowski M, Schnoy N, Bende T. Ablation rate of human corneal epithelium and Bowman's layer with the excimer laser (193 nm). *Refract Corneal Surg.* 1990; 6:99–102. [PubMed: 2248922]
28. Kornmehl EW, Steinert RF, Puliafito CA. A comparative study of masking fluids for excimer laser phototherapeutic keratectomy. *Arch Ophthalmol.* 1991; 109:860–863. [PubMed: 2043076]

WHAT WAS KNOWN

- Combination of myopic and hyperopic ablations can be used to perform transepithelial PTK in the absence of a dedicated PTK mode.
- Optical coherence tomography can measure corneal opacity depth.

WHAT THIS PAPER ADDS

- The corneal epithelial lenticular masking effect measured by OCT can improve the selection of laser dioptric settings in transepithelial PTK.
- The OCT-measured laser ablation depth efficiency was significantly higher than the manufacturer's nominal settings of a flying-spot excimer laser using wavefront-optimized ablation patterns.

Synopsis

Ablation efficiency and epithelial lenticular masking effects measured by OCT were used to develop a model to guide laser dioptric and depth settings in transepithelial PTK.

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Figure 1.

Representative preoperative epithelial thickness maps. *A*: In this case, the central epithelium was thicker than the peripheral epithelium and gave an epithelial lenticular masking effect of 1.84 D. Transepithelial ablation would produce a hyperopic correction in this example. *B*: In this case, the central epithelium was thinner than the peripheral epithelium and gave an epithelial lenticular masking effect of -0.3 D. Transepithelial ablation would produce a myopic correction in this example.

Figure 2.

Actual and simulated PTK ablation profiles composed of dioptrically balanced myopic (-6.0 D sphere with 8.0 mm optical zone and 0.5 mm transition zone) and hyperopic ($+6.0$ D sphere with 6.0 mm optical zone and 1.5 mm transition zone) ablations. *A*: Profile of actual excimer laser ablation performed on a plastic plate and then measured by a 3-dimensional profilometer. The hyperopic ablation exceeded the myopic ablation outside of the central plano zone. *B*: The simulated profile using a parabolic profile and nominal ablation depth given by the laser system printout showed that myopic and hyperopic ablation should cancel and produce a plano profile within the 6.0 mm diameter optical zone.

Figure 3.
Bar graph showing preoperative to postoperative changes in Snellen lines of CDVA.

Figure 4.

Box-and-whisker plots of UDVA and CDVA in the form of logMAR. The vision was recorded before PTK and 1, 3, and 6 months after PTK. The boxes are delimited by the first and third quartiles and the horizontal lines within indicate the median. The whiskers indicate the maximum and minimum values and the squares indicate the average values.

Figure 5.

Case 1. Granular dystrophy with no smoothing ablation. *A* to *C*: Imaging characteristics prior to PTK. *E* to *G*: Imaging characteristics 1 month after PTK. *D* and *H*: Magnified images of the red rectangles marked in OCT images (*C* and *G*), respectively. Comparison of preoperative and postoperative slitlamp photographs (*A* and *E*) and OCT images (*C* and *G*) showed that corneal granular deposits were greatly reduced after PTK. However, a focal island at the location of a thick granular opacity (*H*, *white chevron*) was observed after the laser ablation. The focal island showed as focal steepening at the center of the post-PTK axial power map (*F*).

Figure 6.

Case 2. Granular dystrophy that had transepithelial PTK with smoothing ablation. *A to C:* Imaging characteristics prior to PTK. *D to F:* Imaging characteristics 6 months after PTK. Before PTK, corneal granular deposits were visible on the slitlamp photograph (*A*) and shown as superficial corneal opacities in the cross-sectional OCT images (*C*, *white arrows*). The granular deposits were greatly reduced after PTK (*D* and *F*). The topographic axial power map had an asymmetric bowtie pattern with skewed axis before the surgery (*B*). After PTK, the central steepening was reduced and the skewness on the axial power map was removed (*E*).

Figure 7.

Case 3. Corneal post-microbial keratitis scarring. *A to C*: Imaging characteristics prior to PTK. *D to E*: Imaging characteristics 6 months after PTK. Pre-PTK slitlamp photograph (*A*) and OCT images (*C*) showed anterior corneal opacity (*white arrows*). Pre-PTK axial power map (*B*) was highly irregular, showing focal flattening in the center and focal steepening at the periphery. Six months after PTK, the slitlamp photograph (*D*) and OCT images (*F*) showed that the central corneal opacity was greatly reduced. The axial power map at that time showed a normal symmetric bowtie pattern (*E*).

Figure 8.

Case 4. Transepithelial PTK in an eye with a history of RK and AK. *A to C*: Imaging characteristics prior to PTK. *D to E*: Imaging characteristics 6 months after PTK. Pre-PTK slitlamp photograph (*A*) showed 4 AK incisions (*white arrows*) intersecting the RK cuts on the cornea. Pre-PTK topographic axial power map (*B*) showed focal flattening (quatrefoil pattern) at the locations where AK incisions intersected RK cuts. The quatrefoil pattern was smoothed out after PTK (*D*); the temporal lobe located inside the pupillary margin was significantly reduced. Cross-sectional OCT images (*C* and *D*) showed corneal scarring due to RK cuts and AK incisions (*white arrowhead*) before PTK. The AK scarring (*hollow white arrows*) decreased significantly after PTK.

Figure 9.

Linear regression evaluation of excimer laser ablation efficiency in the center (A) and at the periphery (B) (triangles = post-RK cases; diamonds = non-RK cases).

Figure 10.

Achieved versus predicted SE correction after transepithelial PTK. The predictions were based on the laser setting and epithelial lenticular masking effect calculated from OCT (equation 2) (triangles = post-RK cases; diamonds = non-RK cases).

Table 1

Outcome of phototherapeutic keratectomy.

Parameter	Preoperative (Range)	Postoperative (Range)	Post-Pre Change (Range)
UDVA (20/X)	95.1 (20~400)	41.2 (15~125)	—
LogMAR UDVA	0.68 ± 0.41 (0.0~1.30)	0.31 ± 0.24 (−0.12~0.80)	−0.37* ± 0.42 (−1.43~0.48)
CDVA (20/X)	34.4 (15~80)	22.0 (15~50)	—
LogMAR CDVA	0.24 ± 0.19 (−0.12~0.60)	0.04 ± 0.13 (−0.12~0.40)	−0.20* ± 0.18 (−0.51~0.0)
SEQ (D)	−1.69 ± 3.33 (−10.0~2.75)	−0.53 ± 1.24 (−2.38~3.38)	1.16* ± 3.2 (−4.13~8.25)
Astigmatism magnitude (D)	2.41 ± 2.43 (0.0~8.0)	1.13 ± 0.86 (0.0~3.0)	−1.28* ± 2.22 (−6.0~2.75)
Topography irregularity 3.0 mm (D)	3.14 ± 1.58 (0.7~6.4)	3.17 ± 1.70 (1.3~7.7)	0.03 ± 1.43 (−1.7~4.7)
Epithelial lenticular masking effect SEQ (D)	0.73 ± 0.61 (−0.31~2.21)	—	—

LogMAR = logarithm of the minimum angle of resolution; UDVA = uncorrected distance visual acuity; CDVA = corrected distance visual acuity; SEQ = spherical equivalent; D = diopters

* $P < .05$