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Optical Coherence Tomography Accurately Measures Corneal Power Change from Laser Refractive Surgery

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Purpose: To determine the ability of motion-corrected optical coherence tomography (OCT) to measure the corneal refractive power change due to LASIK.

Design: Evaluation of a diagnostic test or technology in a cohort.

Subjects: A total of 70 eyes from 37 subjects undergoing LASIK were measured preoperatively. A total of 39 eyes from 22 subjects were measured postoperatively and completed the study.

Methods: Consecutive patients undergoing LASIK at the Duke Eye Center who consented to participate were imaged with Placido-ring topography, Scheimpflug photography, and OCT on the day of their surgery. Patients were then reimaged with the same imaging systems at the postoperative month 3 visit. Change in preoperative to postoperative corneal refractive power as measured by each of the imaging modalities was compared with the preoperative to postoperative change in manifest refraction (MRx) using the *t* test with generalized estimating equations.

Main Outcome Measures: Corneal refractive power change due to LASIK as measured by Placido-ring topography, Scheimpflug photography, and OCT compared with the MRx change vertexed to the corneal plane. The change in MRx should correspond to the change in the corneal refractive power from LASIK and was considered the reference measurement.

Results: In 22 individuals (39 eyes) returning after LASIK, we found no significant difference between the clinically measured pre- to post-LASIK change in MRx and both Scheimpflug photography ($P = 0.714$) and OCT ($P = 0.216$). In contrast, keratometry values from Placido-ring topography were found to be significantly different from the measured refractive change ($P < 0.001$). In addition, of the 3 imaging modalities, OCT recorded the smallest mean absolute difference from the reference measurement with the least amount of variability.

Conclusions: Motion-corrected OCT more accurately measures the change in corneal refractive power due to laser refractive surgery than other currently available clinical devices. By offering accurate corneal refractive power measurements in normal and surgically modified subjects, OCT offers a compelling alternative to current clinical devices for determining corneal refractive power. *Ophthalmology 2015;122:677-686* © *2015 by the American Academy of Ophthalmology.*

The ability to accurately measure corneal optical power after LASIK and other popular laser refractive surgeries is an important diagnostic challenge.[1] More than 12 million individuals—and counting—have already undergone laser refractive surgery. As these individuals age, they will naturally develop visually significant cataracts, an ailment that will affect 1 of every 2 individuals by age 80 years in the United States.[2] Although cataract surgery is one of the most commonly performed and most successful surgical procedures in modern medicine, an important requisite is the ability to accurately measure the optical properties of the eye before surgery. Current clinical instruments have difficulty measuring corneal refractive power in individuals who have undergone laser refractive surgery, which has resulted in ambiguities in surgical planning and unpredictable, undesired refractive cataract outcomes for these patients.[3]

Current clinical instruments to measure corneal power—keratometers and Placido-ring topographers—measure the shape of the front surface of the cornea. From only this front surface measurement, assumptions are used to determine the optical power of the whole cornea.[4,5] Laser refractive surgery is effective because it alters the front surface curvature of the cornea, thereby changing its optical power. Unfortunately, this undermines the very assumptions used by keratometers to determine corneal power. This has resulted in inaccurate corneal power measurements with undesired visual outcomes after cataract surgery,[3] and for these individuals, additional surgery with the attendant risks of reoperation may be required to achieve the intended result. This diagnostic dilemma has led to the creation of multiple disparate methods to compensate for the shortfalls of current diagnostic instruments.[6–14] There currently remains no established single method to clinically determine the power of the cornea after laser refractive surgery.

In contrast to keratometry and topography, tomographic imaging techniques such as optical coherence tomography

Published by Elsevier Inc.
http://dx.doi.org/10.1016/j.ophtha.2014.10.003
ISSN 0161-6420/14

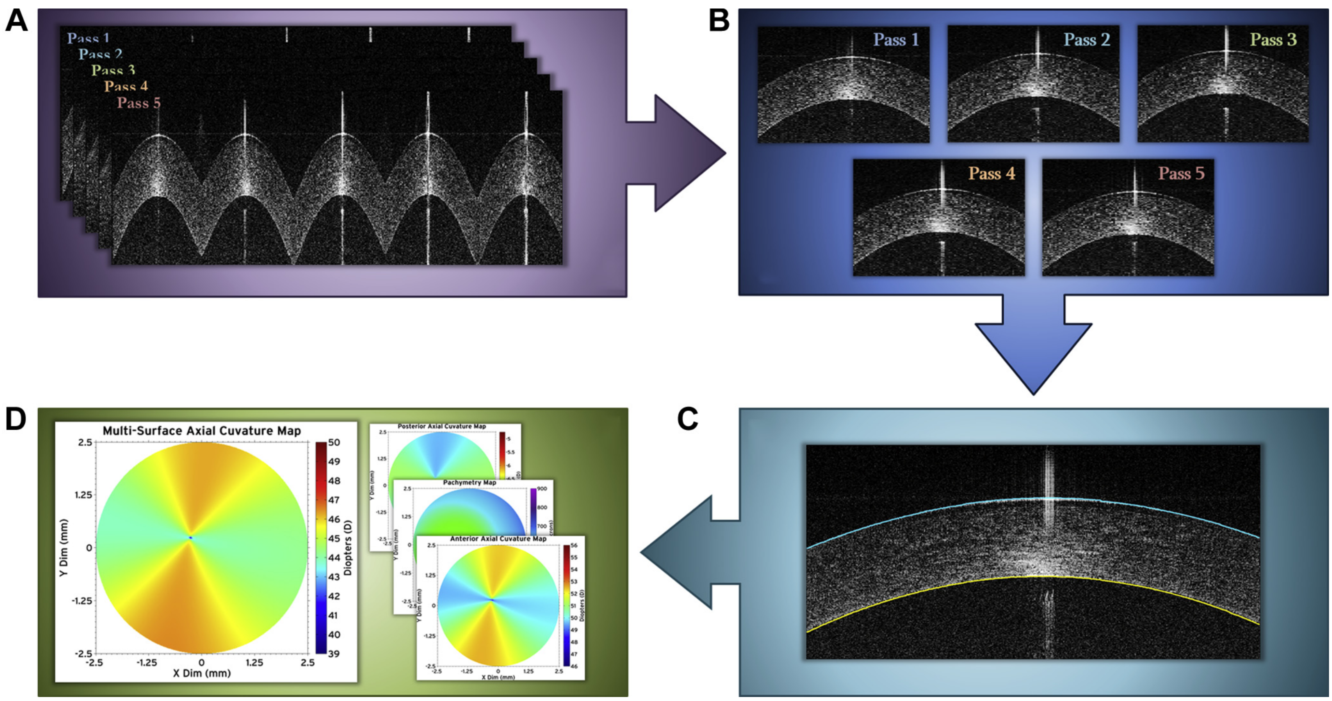

Figure 1. Process to extract clinically relevant measures from corneal optical coherence tomography (OCT). **A,** Distributed scan OCT volume of a cornea is acquired with a clinical OCT system. **B,** Each distributed scanning OCT (DSOCT) B-scan meridian is reconstructed from multiple subsampled B-scans along a given meridian to mitigate patient motion.[23] **C,** Each reconstructed meridian is automatically segmented. The anterior corneal surface segmentation is depicted in *cyan*, and the posterior surface segmentation is depicted in *yellow*. **D,** The surface segmentations are corrected for distortions in the scanning optics and refraction within the cornea. The corrected segmentations are then used to generate corneal topographic maps for the anterior and posterior surfaces of the cornea and to calculate local corneal thicknesses. These maps are then used to calculate overall corneal spherical and astigmatic refractive power.[27]

(OCT) are able to volumetrically image the cornea. Optical coherence tomography is based on low-coherence optical interferometry and is capable of clinical micrometer-scale imaging.[15–21] Volumetric images of the cornea contain both front and back corneal surfaces and its thickness—the elements needed to determine corneal power; thus, OCT offers the promise of improved measurement of corneal power, even in corneas altered by laser refractive surgery.[22]

Although prior efforts have examined only the post-LASIK corneal power measurement with OCT and shown that isolated measurement is different from standard diagnostics,[22] we show in this work that OCT accurately and quantitatively measures the actual change in corneal power before and after LASIK. Further, we provide the first demonstration of the additional ability to measure astigmatic change. Together, these findings have important implications for the looming cataract surgery outcomes of the large number of individuals who have undergone or will undergo laser refractive surgery.

Methods

Optical Coherence Tomography System Design for Corneal Biometry

Optical coherence tomography uses a flying spot scanning technique to acquire a volume, where each spot corresponds to a single depth profile, or A-scan. The volume is then built from sequentially acquired A-scans. Because each point within a given volume is acquired at a separate, distinct point in time, patient motion during volume acquisition is encoded within the images of the volume. To reduce the effects of patient motion during acquisition, we used a technique we previously developed termed "distributed scanning OCT" (DSOCT).[23] This technique uses a custom scanning protocol applied on a commercial spectral domain OCT (SD-OCT) instrument that reduces the temporal correlation between adjacent A-scans and allows for motion estimation and removal of patient bulk motion that occurs during volume acquisition. With the use of DSOCT, we previously found that differences in corneal power measurements between OCT and standard keratometric techniques were reduced over no motion correction in normal eyes.[23,24] Figure 1 illustrates the DSOCT technique. Figure 1A shows multiple corneal profiles from several meridians in a DSOCT volume. Figure 1B shows the multiple corneal profiles collected along a single meridian. The multiple passes within the meridian are motion compensated and interlaced to generate a critically sampled B-scan, as illustrated in Figure 1C. After recovering the surface profiles using fully automated segmentation and correcting for optical artifacts,[24–26] spherical and astigmatic refractive power and corneal topographic maps can be measured (Fig 1D).[23,27]

In this study, the DSOCT software was implemented on a commercially available SD-OCT system (λ=840 nm, $\Delta\lambda$=49 nm; Bioptigen, Inc., Durham, NC). The OCT system acquisition rate was 10 000 A-scans per second. We used a temporally distributed rosette scan pattern that resulted in a volume that was equivalent to a conventional radial scan pattern consisting of 20 meridians and 500 A-scans per meridian. The reconstruction algorithm was updated from McNabb et al[23] to de-noise and directly register the subsampled meridians to improve the speed and accuracy of the reconstruction algorithm. Biometric values were then determined as described in the previous paragraph.