Intraoperative Use of Three-Dimensional Spectral-Domain Optical Coherence Tomography

Takeshi Ide, MD, PhD; Jianhua Wang, MD, PhD; Aizhu Tao, MD; Theodore Leng, MD; George D. Kymionis, MD, PhD; Terrence P. O’Brien, MD; Sonia H. Yoo, MD

BACKGROUND AND OBJECTIVE: To develop a prototype three-dimensional anterior segment spectral-domain optical coherence tomography (SD-OCT) device and demonstrate the feasibility of its use in the operating room.

PATIENTS AND METHODS: Single-institution interventional case series including six consecutive patients undergoing Descemet’s stripping automated endothelial keratoplasty (DSAEK). The prototype anterior segment SD-OCT was used intraoperatively to search for the presence of interface fluid between the host cornea and the DSAEK graft.

RESULTS: Anterior segment SD-OCT was successfully used intraoperatively during DSAEK. After the initial placement of the graft, no fluid was clinically apparent; however, interface fluid was identified by anterior segment SD-OCT in two of the six cases. After additional aspiration, all patients were fluid-free on follow-up anterior segment SD-OCT scanning.

CONCLUSION: Intraoperative anterior segment SD-OCT was used successfully to find interface fluid that was clinically undetectable under the microscope. As such, all patients were able to leave the operating room with a fully attached graft.

quality for detailed cross-sectional analysis. Additionally, some instruments require long operational times and others require ocular surface contact, making their use in the immediate postoperative period untenable.\textsuperscript{1,2} In the operating room, the anterior segment is routinely observed with diffuse lighting without a slit lamp installed on the surgical microscope. Given this limitation, it is difficult to recognize the minute anatomical structures of the anterior segment, especially when the cornea has an opacity or is edematous.

Optical coherence tomography (OCT) is a non-invasive and non-contact technique that provides high-resolution cross-sectional images of the eye. Although time-domain OCT is currently the most widely adopted form of OCT in clinical use, the anterior segment spectral-domain OCT (SD-OCT) is an emerging OCT technology in which the moving mirror in the time-domain OCT is replaced with a spectrometer. The reduced acquisition time results in images with a higher resolution.\textsuperscript{3}

In this study, a prototype three-dimensional anterior segment SD-OCT instrument was developed that was able to provide an in vivo, in situ, non-contact, and cross-sectional optical biopsy of the cornea during operative procedures on patients in the supine position. This novel feature was specifically used during Descemet’s stripping automated endothelial keratoplasty (DSAEK) procedures because it allowed the surgeon to image the potential space that exists between the host and donor corneal tissues, especially when the host cornea was opacified. If fluid was observed with anterior segment SD-OCT during DSAEK, it could be aspirated before the patient left the operating room, potentially affecting the surgical success of the procedure.

\textbf{PATIENTS AND METHODS}

\textbf{Patients}

Six eyes of six patients undergoing DSAEK and intraoperative anterior segment SD-OCT at a single institution were included in this study. Preoperatively, three patients had a diagnosis of Fuchs’ endothelial dystrophy and three patients had a diagnosis of pseudophakic bullous keratopathy. All surgeries were performed by the same surgeon (SHY).

\textbf{Anterior Segment SD-OCT Instrument}

A prototype anterior segment SD-OCT device using a superluminescent diode laser with a 75-nm bandwidth centered at 1,310 nm was constructed as previously described.\textsuperscript{4} The spectrometer was custom developed by Bioptigen (Durham, NC). The anterior segment SD-OCT system used a telecentric scan system with parallel scanning beams. The instrument was connected to a telecentric light delivery probe and mounted on a stabilization arm (Fig. 1). The device had an axial resolution of 8 µm in the cornea and had an acquisition speed of approximately 7,000 A-scans/second. It was able to acquire real-time two-dimensional B-scans, each consisting of 512 A-scans, at 14 frames/second and full three-dimensional datasets in approximately 7 seconds. Images were acquired using 12 × 12 × 3 mm rectangular and radial scan patterns through the cornea, centered on the corneal apex. Three-dimensional anterior segment SD-OCT datasets of 100 B-scans, each consisting of 512 A-scans, were acquired of the host–graft junction during DSAEK procedures.

\textbf{Surgical Procedure}

Four of the six patients had DSAEK alone and two of the six patients underwent a triple procedure (phacoemulsification and posterior chamber intraocular lens implantation followed by DSAEK). These procedures were performed as previously described.\textsuperscript{5}

During the procedure, a diamond slit blade was used to make four equally spaced midperipheral corneal vent incisions. A 27-gauge cannula was used to fill the anterior chamber with balanced salt solution and unfold the donor corneal lenticule. After the graft was centered in the anterior chamber, filtered air was injected to tamponade it into position. The cornea was gently massaged to remove all wrinkles from the do-
nor lenticule and the interface fluid was aspirated until there was no interface fluid under the surgical microscope.

After allowing the graft to adhere for 10 minutes, the anterior segment SD-OCT instrument was centered on the corneal apex using a real-time video monitor and the stabilization arm was locked in place. The video image was used to guide the scan position and locate the pupil center for three-dimensional scanning. When an eye was in primary gaze position, the specular reflex was detected in the center of the cornea. However, if a patient was not fixing on any target, three-dimensional scanning was performed with the eye manually centered and aligned with the instrument by the surgeon.

A radial scan pattern was first used to view the entire host–graft interface, after which a square scan pattern was used to acquire three-dimensional datasets and construct an en face image of the entire cornea. A cube was generated with the 3DView software (RMR Systems, East Anglia, UK) to analyze the host–graft interface and search for interface fluid. This dataset was rotated in three-dimensional space and individual B-scans were viewed in all three axes to analyze the anatomy of the host–graft junction. If interface fluid appeared on the three-dimensional anterior segment SD-OCT scans, a combination of corneal massage with fluid aspiration from the four vents was performed with a 27-gauge cannula. After these maneuvers, the anterior segment SD-OCT scans were repeated to confirm the absence of fluid.

RESULTS

To scan an eye during surgery, the instrument was moved next to the surgical bed. This was facilitated by having the instrument on a cart with locking wheels. After the device was adjacent to the patient, the sensor was positioned over the operative eye with a movable arm. The use of an arm also prevented any inadvertent contamination of the sterile operative field. Proper alignment of the device over the patient was easily accomplished through a real-time en face reconstruction of the cornea, so the surgeon was able to precisely line up the sensor with the patient.

Image acquisition took approximately 7 seconds and the entire process of moving the device into place, aligning the sensor with the patient’s eye, and capturing the scans added approximately 2 minutes to the total operative time. Furthermore, even with a 7-second acquisition time for a three-dimensional scan, there was essentially no motion artifact because the device cart had locking wheels, the movable arm was stabilized, and the patient’s eye was anesthetically blocked and akinetic with an eyelid speculum in place.

Anterior segment SD-OCT scans produced a series of B-scans that could be reconstructed to form three-dimensional images and en face images of the entire cornea (Fig. 2). In a well-centered cross-sectional scan, the corneal apex was identified from a reflection that saturated the imaging system and produced a vertical flare.

After initial placement of the graft with smoothing or fluid aspiration in all six cases, no fluid was clinically apparent when the eyes were viewed through the surgical microscope (a slit lamp was not used to search...
for interface fluid); however, interface fluid was identified by anterior segment SD-OCT in two of the six cases (Table). After repeat aspiration and mechanical smoothing was performed, all eyes were fluid free on repeat anterior segment SD-OCT scans. The use of intraoperative anterior segment SD-OCT in DSAEK in a representative case is described as follows.

Patient 1 was an 85-year-old woman with pseudophakic bullous keratopathy who underwent DSAEK in her left eye. Ten minutes after graft placement and air injection, the presence of interface fluid and partial lenticular detachment from the host were apparent on anterior segment SD-OCT scanning even though the interface could not be visualized through the surgical microscope because of host corneal edema (Fig. 3). Fluid was aspirated with a 27-gauge cannula and the corneal surface was mechanically smoothed. Repeat anterior segment SD-OCT scanning confirmed that the fluid was removed in all areas of the host–graft interface.

**DISCUSSION**

Current ophthalmic practice uses slit-lamp biomicroscopy as the primary means of evaluating the anterior segment. To improve clinical evaluation, several innovative instruments have been introduced. These devices include topography, A- and B-scanning ultrasound, slit-scanning technology (eg, Orbscan; Bausch and Lomb, Rochester, NY), confocal microscopy (eg, Confoscan, Nidek, Tokyo, Japan; and HRT, Rostock Cornea Module, Heidelberg Engineering, Heidelberg, Germany), ultrasound biomicroscopy, wavefront sensors, Scheimpflug camera systems (Pentacam, Oculus-Optikgeräte GmbH, Wetzlar, Germany; and Galilei, Ziemer, Port, Switzerland), and the ocular response analyzer (ORA; Reichert, Buffalo, NY). However, due to the inherent properties of each system, image quality is often insufficient for a detailed cross-sectional analysis. Additionally, some of these devices have an extended acquisition time, whereas others require ocular surface contact, making their use in the immediate postoperative period undesirable.1,2

In the operating room, anterior segment examination is usually performed through a surgical microscope with diffuse lighting. A slit lamp is rarely installed to a surgical microscope. With a surgical microscope and diffuse lighting, subtle anatomic details of the anterior segment are difficult to visualize, especially when the cornea has opacifications or is edematous. In this report, DSAEK was employed as a model for future applications of a novel intraoperative anterior segment SD-OCT instrument.

Time domain OCT and SD-OCT are widely used to acquire cross-sectional and three-dimensional datasets of pathologic findings from the anterior and posterior segments in the clinic with patients in the sitting position. By using a modified anterior segment SD-OCT device, this non-contact, non-invasive technology may help surgeons determine the real-time status of the procedure intraoperatively without having to bring a patient into the upright position or to the clinic later.

---

**TABLE**

Summary of Descemet’s Stripping Automated Endothelial Keratoplasty (DSAEK) Cases

<table>
<thead>
<tr>
<th>Age (Y)</th>
<th>Sex</th>
<th>Eye</th>
<th>Reason for DSAEK</th>
<th>Intraoperative OCT</th>
<th>Postoperative OCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>F</td>
<td>Left</td>
<td>Pseudophakic bullous keratopathy</td>
<td>Interface fluid</td>
<td>No interface fluid</td>
</tr>
<tr>
<td>45</td>
<td>M</td>
<td>Left</td>
<td>Fuchs’ endothelial dystrophy</td>
<td>No interface fluid</td>
<td>No interface fluid</td>
</tr>
<tr>
<td>55</td>
<td>M</td>
<td>Left</td>
<td>Pseudophakic bullous keratopathy</td>
<td>No interface fluid</td>
<td>No interface fluid</td>
</tr>
<tr>
<td>88</td>
<td>M</td>
<td>Left</td>
<td>Pseudophakic bullous keratopathy</td>
<td>No interface fluid</td>
<td>No interface fluid</td>
</tr>
<tr>
<td>80</td>
<td>F</td>
<td>Left</td>
<td>Fuchs’ endothelial dystrophy</td>
<td>Interface fluid</td>
<td>No interface fluid</td>
</tr>
<tr>
<td>90</td>
<td>F</td>
<td>Left</td>
<td>Fuchs’ endothelial dystrophy</td>
<td>No interface fluid</td>
<td>No interface fluid</td>
</tr>
</tbody>
</table>

OCT = optical coherence tomography.
Furthermore, anterior segment SD-OCT is able to acquire volumetric data that can be rendered and manipulated in three dimensions. It provides for increased utility when compared to the cross-sectional data gathered from commercially available anterior segment time-domain OCT instruments. Volumetric data has the distinct advantage over a single time-domain B-scan because the full three-dimensional architecture of the cornea can be rendered. Although two-dimensional time-domain OCT has shown utility in measuring corneal pachymetry maps, total corneal power, corneal light backscatter, and anterior chamber depth, a three-dimensional anterior segment SD-OCT instrument mounted on a stabilization arm is also able to measure these parameters intraoperatively while the patient is in a supine position.

Anterior segment SD-OCT of the cornea has been described previously with both an 830-nm and a 1,310-nm device. The longer wavelength of the 1,310-nm anterior segment SD-OCT has a theoretical advantage because it is associated with reduced backscatter in hazy media and allows for deeper tissue penetration and enhanced resolution of deeper structures. Thus, the full-thickness cornea, sclera, and iris can be imaged, allowing for a full assessment of anterior segment anatomy.

Although intraoperative anatomic success does not always ensure clinical success, the possibility of using intraoperative anterior segment SD-OCT technology may aid surgeons in achieving an anatomically desired result before leaving the operating room.

Because the anterior segment SD-OCT device used in this study was a prototype, image quality has not yet been optimized. In the future, image quality will be improved through averaging techniques. Scan speeds will increase and motion artifacts will be reduced. Additionally, the function to register the separate scans will be incorporated into future iterations of the device.

This pilot study, which employed DSAEK as a surgical model, described a small number of cases demonstrating the feasibility of intraoperative three-dimensional anterior segment SD-OCT scanning with a patient in the supine position. A study with a larger sample size and an enhanced OCT instrument with improved image quality and greater speed will be required before conclusions regarding the efficacy of this technology can be made.

REFERENCES