

# Optical coherence tomography: A new tool for glaucoma diagnosis

Joel S. Schuman, MD,\* Michael R. Hee, MS,†  
Adarsh V. Arya, MD,\* Tamar Pedut-Kloizman, MD,\*  
Carmen A. Puliafito, MD,\* James G. Fujimoto, PhD,†  
and Eric A. Swanson, PhD‡

\*New England Eye Center, Tufts University School of Medicine, Boston,  
Massachusetts, †Massachusetts Institute of Technology, Cambridge,  
Massachusetts, and ‡MIT-Lincoln Laboratories, Lexington, Massachusetts, USA

Optical coherence tomography (OCT) is a novel technique that allows cross-sectional imaging of the anterior and posterior eye. OCT has a resolution of  $\sim 10 \mu\text{m}$ , with extremely high sensitivity (approximately  $10^{-10}$  of incident light). OCT is analogous to computed tomography, which uses x-rays, magnetic resonance imaging, which uses spin resonance, or B-scan ultrasound, which uses sound waves, but OCT uses only light to derive its image. OCT is a noncontact, noninvasive system by which retinal substructure may be analyzed *in vivo*. OCT is useful in the evaluation of retinal pathologies and glaucoma. In retinal disease, entities such as macular holes, macular edema, central serous chorioretinopathy, retinal vascular occlusion and other factors have been examined. Separation between the posterior vitreous and retina, or lack thereof, are seen and quantitated. In glaucoma, retinal nerve fiber layer (NFL) thickness is measured at standardized locations around the optic nerve head. A circular scan produces a cylindrical cross-section of the retina, from which the NFL can be analyzed. In addition, radial scans through the optic nerve head are used to evaluate cupping and juxtapapillary NFL thickness. OCT, a new imaging technology by which the anterior and posterior segment are seen in cross-section, may permit the early diagnosis of glaucoma, and the early detection of glaucomatous progression.

Current Opinion in Ophthalmology 1995, 6:II:89–95

Optical coherence tomography (OCT) is a new non-invasive technique for high-resolution cross-sectional imaging of tissue. OCT is a means by which tomography of the eye may be accomplished using light. It is analogous to computed tomography, which uses x-rays, and to magnetic resonance imaging, which uses spin resonance, or to an ultrasound B-scan, but OCT utilizes a superluminescent diode as its light source. In OCT, the time-delay of light reflected from various tissue structures is determined using low-coherence interferometry. A light source (the super luminescent diode) is directed simultaneously at a reference arm and at a sample, in this case, the eye. The reference arm moves approximately 3.6 mm at a rate of 40 Hz. The reflections from the reference arm and the sample are then

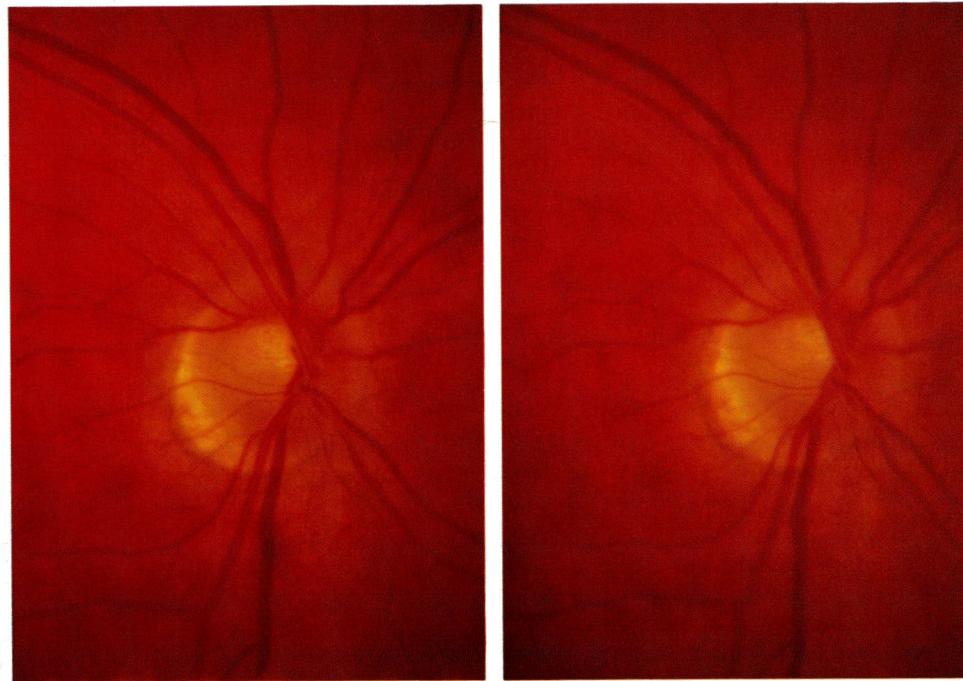
both directed back toward a detector. An interference signal occurs at a detector only when the optical path lengths of the reference and sample match to within the source coherence length. High longitudinal resolution is achieved by utilizing low coherence light, which for OCT is on the order of  $10 \mu\text{m}$ . Optical ranging is based on the principal that the distance traveled by the light is equal to the signal delay times the speed of light.

## Methods

Optical coherence tomography utilizes a super luminescent diode as its light source, coupled to a fiber op-

## Abbreviations

NFL—nerve-fiber layer; OCT—optical coherence tomography.



**Fig. 1.** Stereo optic nerve head of a normal individual.

tic delivery system. The same fiber optic delivering the beam to the sample arm is used to return the signal to the detector, from which it proceeds to a demodulator, then to an analogue to digital board, and then to a computer. OCT has a spatial resolution on the order of  $10\text{ }\mu\text{m}$ , with an extremely high detection sensitivity, of  $10^{-10}$  of the incident power. The power is within the American National Standards Institute requirements, at 200 mW continuous wave at 830 nm. The system is completely noninvasive, utilizing noncontact measurement, and is compatible with existing instrumentation, such as the slit lamp.

A plot of reflectivity versus distance is achieved by translating the reference arm and measuring the interference signal, allowing the size and position in space of the sample to be measured. OCT is accomplished by combining several of the longitudinal scans, scanning transversely, and interpolating between scans. In OCT a single axial scan is analogous to an ultrasound A-scan, and the transverse series of scans forming a cross-sectional image is analogous to an ultrasound B-scan, but with much higher resolution.

Retinal examination by OCT is similar to indirect slit-lamp biomicroscopy, with a 78-D Volk lens mounted to a slit lamp delivery system. The OCT beam is directed into the eye, via a fiber optic sampling arm, using two galvanometer-driven mirrors, which allows scanning of the probe beam across the retina. This system allows direct visualization of the fundus while the OCT is being performed, via visible light or using infrared videoscopy. The image acquisition time is 2.5 seconds with continuous live display update. Our initial studies concentrated on OCT in postmortem eyes, in which we found good correlation between OCT and histology [1]. In vivo analysis introduced the problem of

subject movement, and a computer image-processing algorithm was developed to smooth images acquired *in vivo* [2,3]. *In vivo* scanning of the human retina demonstrated the ability of OCT to reveal the substructure of the retina. OCT of the macula showed the foveal pit, with an absence of all retinal layers with the exception of the photoreceptor layer [4<sup>•</sup>,5<sup>•</sup>]. The retinal nerve fiber layer, the inner plexiform layer, the outer plexiform layer, the photoreceptor layer, the choroid and sclera were also distinguished. A scan from the fovea to the optic nerve head showed the foveal pit, and the thickening of the nerve fiber layer as it approached the optic disc from the fovea. Scans of the optic nerve head showed not only the very thick nerve fiber layer adjacent to the optic disc, but the end of the choroid at the margin of the optic nerve head [4<sup>•</sup>,5<sup>•</sup>].

Scans can be translated in any direction desired. Radial scans can proceed along any vector, and circular scans may be performed as well. Circular scans are especially useful in the evaluation of nerve fiber layer thickness in the region of the optic nerve head.

Reproducibility studies demonstrated a very low standard deviation for measurements, on the order of 10 to  $15\text{ }\mu\text{m}$ . This was true whether a repeated series of scans was done at a single point or if the subject was repositioned for each set of scans [4<sup>•</sup>].

## Results

Optical coherence tomography has multiple applications in both the anterior and posterior segment of the eye. In the anterior segment, it can be used to measure corneal thickness and surface profile, anterior chamber

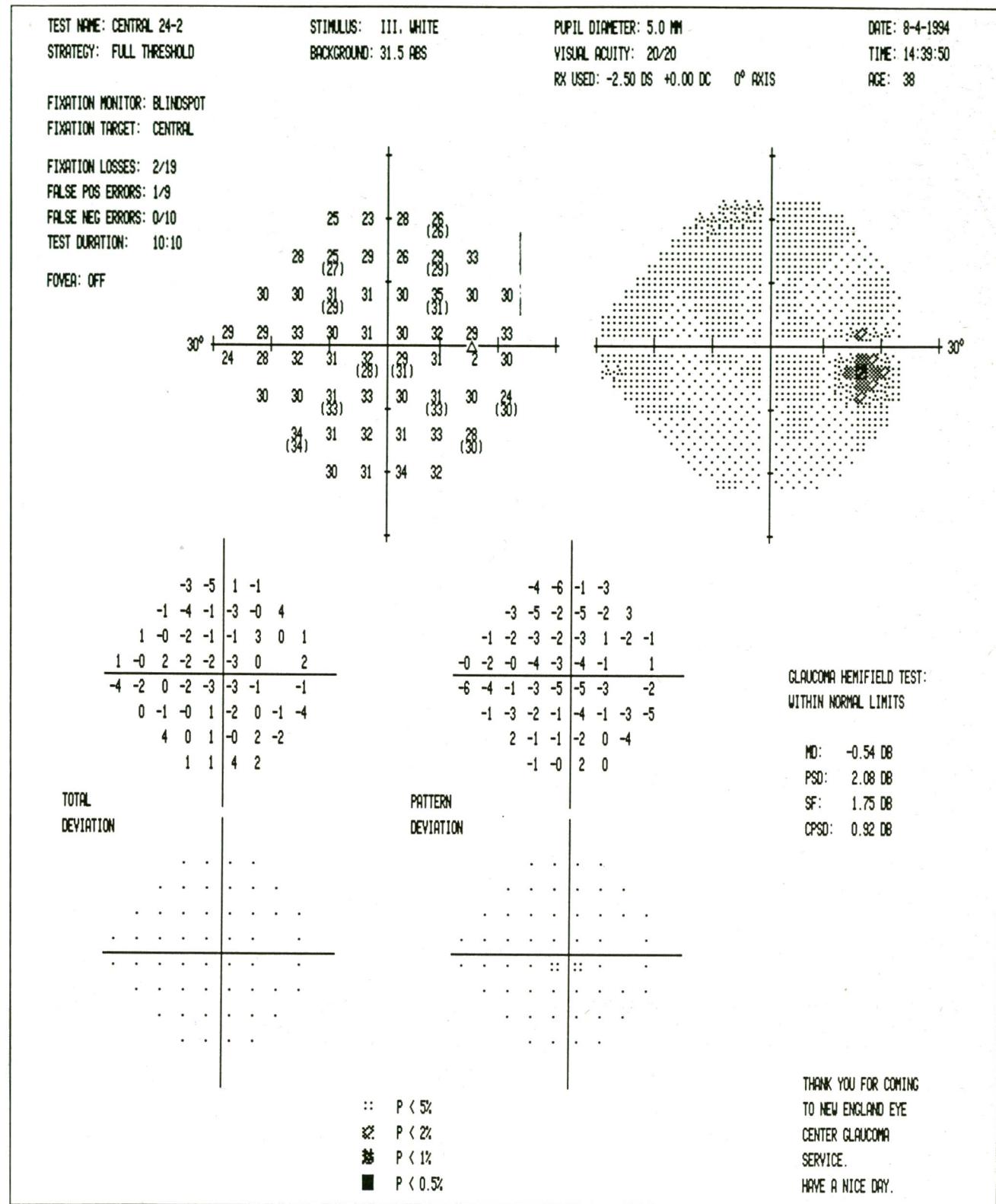
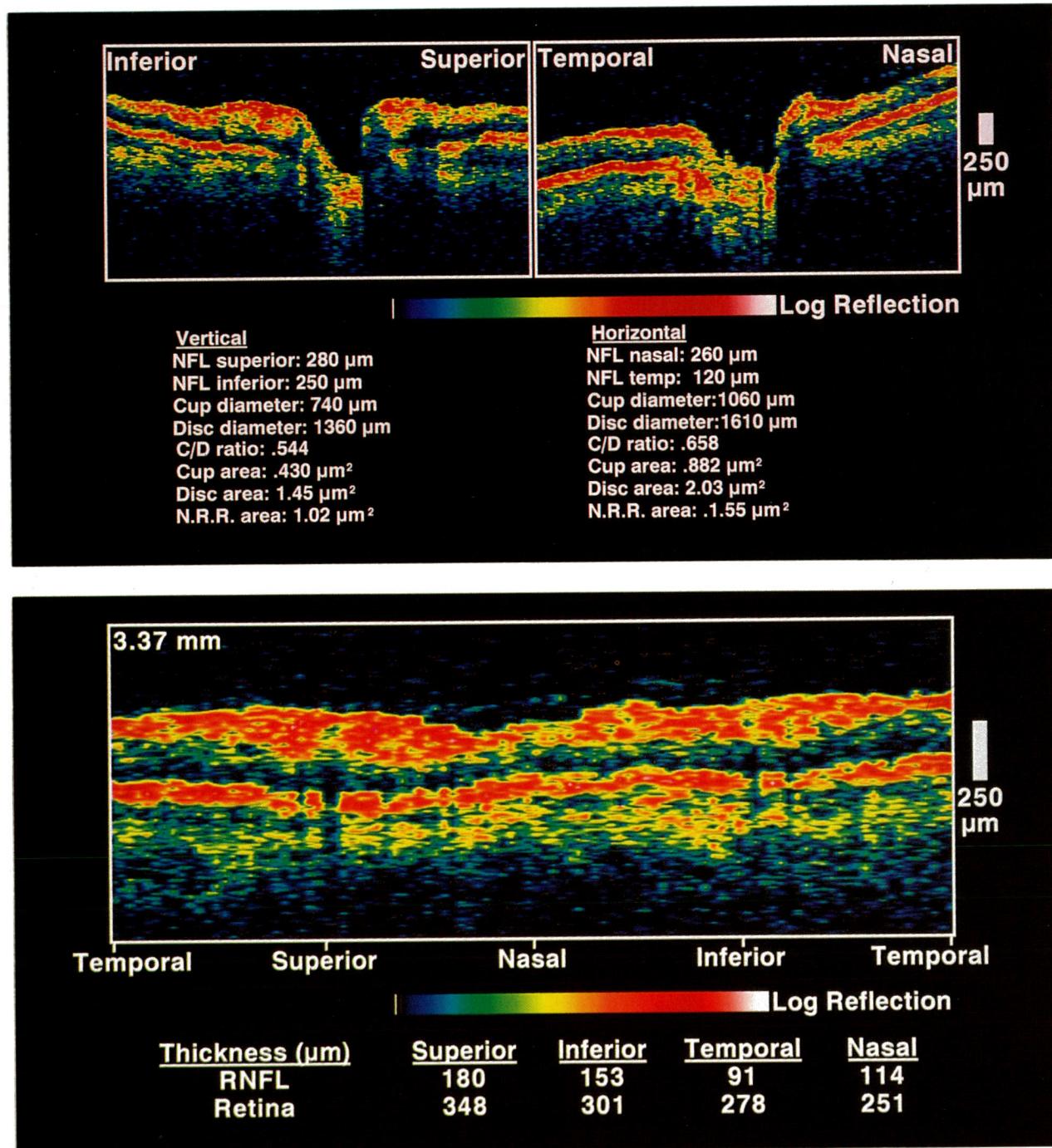


Fig. 2. Full Humphrey 24-2 (Humphrey Instruments, San Leandro, CA) visual field in a normal eye.

depth and characteristics of the anterior chamber angle, and iris thickness and surface profile. It is also useful for noncontact biometry, identification of intraocular masses and tumors, and for analyzing pathologies

of the cornea, iris, and crystalline lens. Cataract grading, which is currently subjective, may be amenable to quantitative measurement by OCT, by analyzing the magnitude and distribution of scattered and reflected

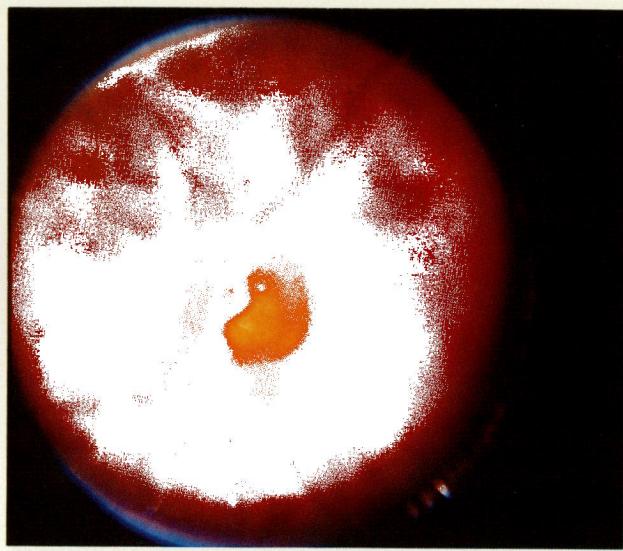


**Fig. 3.** **Top**, Radial optical coherence tomographs (OCTs) in normal eye taken from the 12:00 to 6:00 position and the 9:00 to 3:00 position through the optic nerve head (ONH). There is absence of signal at the end of the choriocapillaris, with thick nerve fiber layer (NFL) immediately adjacent to the optic nerve. Note the larger cup in the vertical scan compared with the horizontal scan. The photoreceptor layer is optically quiet. **Bottom**, Circular OCT in normal eye taken in cylindrical section of tissue surrounding the ONH, with scan at 3.37-mm diameter, centered on the ONH. The vertical scale has been expanded by a factor of three to accentuate axial depth information. Note thicker NFL, the anteriomost red reflection in the false color image, superiorly and inferiorly. A number of layers may be distinguished in the OCT, including the NFL, the inner and outer plexiform layers (yellow), the photoreceptor layer (dark on OCT), and a red reflection of the retinal pigment epithelium, choroid, and sclera.

light. In studies which we performed utilizing the cold cataract model in calf eyes, we found that OCT could reproducibly assess the character and density of cold-induced cataracts [6\*].

#### Retinal imaging

Optical coherence tomography has proven to be extremely valuable in the diagnosis and assessment of macular disease. Macular holes lend themselves to this



**Fig. 4.** Stereo optic disc of subject with glaucoma. Moderate to marked cupping of the optic nerve head is seen, particularly inferiorly.

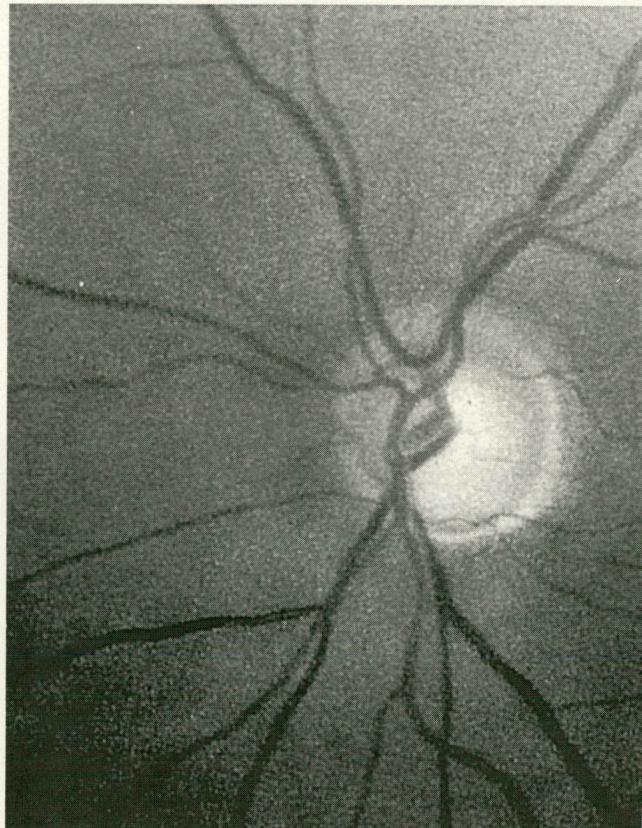
type of analysis extremely well. It is possible to determine whether the macular hole is full or partial thickness, whether it is operculated, the thickness of the retina in the region adjacent to the hole, and whether the posterior vitreous face is attached or detached [5••]. This type of imaging has proven invaluable clin-

ically, permitting the retinal surgeon to decide whether surgery is indicated in a given case.

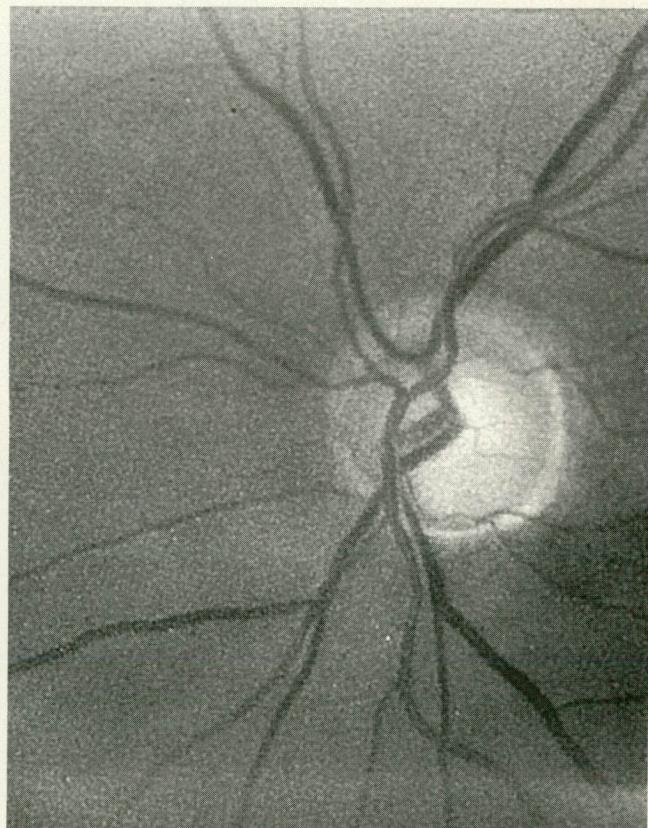
Central serous chorioretinopathy can be analyzed using OCT, with the area of the neurosensory retinal detachment defined by this technology, and the disease can be followed over time using OCT. Age-related macular degeneration can be assessed, as well as retinal vascular occlusion and macular edema. OCT images of cystoid macular edema show the cystic spaces in the inner and outer retina, and imaging of diabetic macular edema reveals the characteristic thickening of the macula with cystic spaces intraretinally. Lipid exudates in diabetic retinal disease may be seen as well, in the inner and outer plexiform layers. Epiretinal membranes can be seen using OCT, and traction on the macula can be assessed [5••]. Again, this may be useful clinically in decision making regarding surgical intervention.

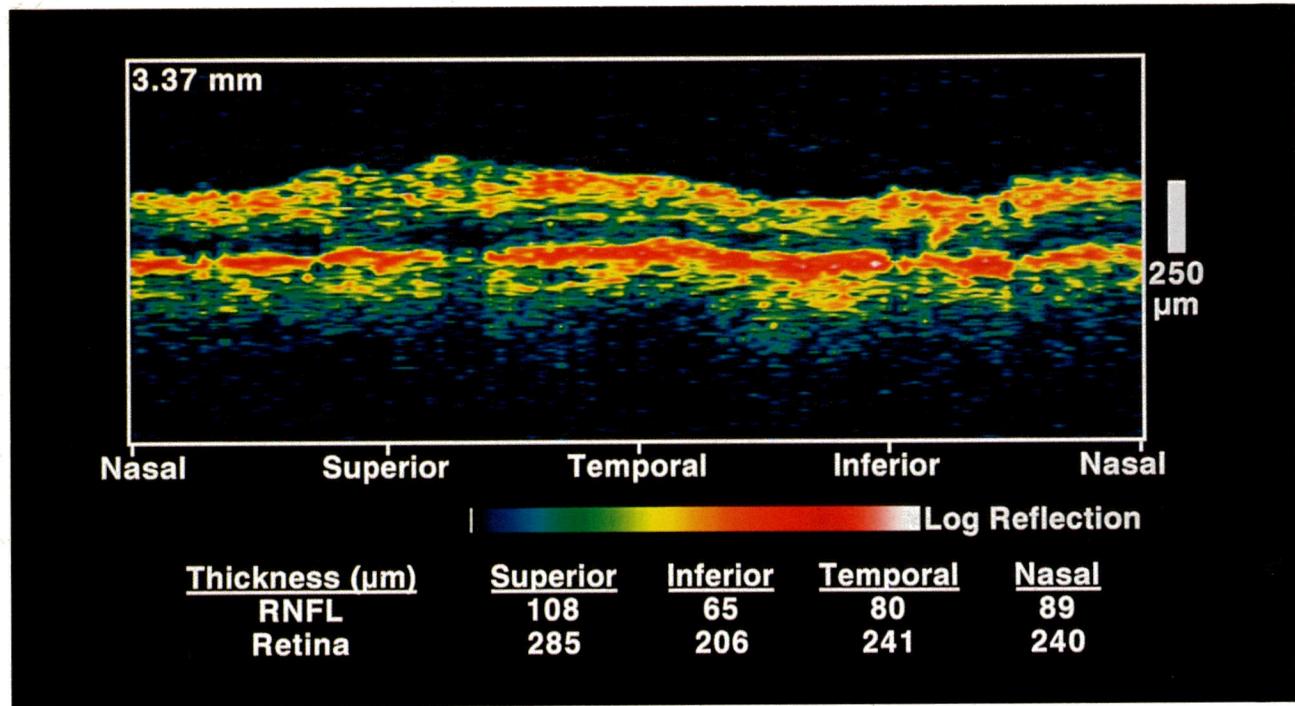
### Glaucoma

The optic nerve head and nerve fiber layer can be evaluated using either circular scans around the optic nerve head or radial scans through the optic nerve head. We have found the circular scans to be most useful. These scans produce a cylinder of information, by creating a cross-sectional circle around the optic nerve head. This cylinder is the unfolded, and looked at in cross-section. We have analyzed several circle diameters, and found a circle diameter of 3.37 mm to be optimal [7••].



**Fig. 5.** Nerve fiber layer (NFL) of eye. Note thinning of NFL inferiorly.





**Fig. 6.** Optical coherence tomograph of eye. Note thinning of NFL inferiorly, corresponding to superior visual field loss.

This differs from other technologies, such as the confocal laser scanning ophthalmoscopes, and the Nerve Fiber Analyzer (Laser Diagnostic Technologies, San Diego, CA). The confocal laser scanning ophthalmoscopes take coronal sections through the optic nerve head. A series of 32 sections are created in the Z axis, with equal distance between each sample plane. The device then analyzes several criteria concerning the optic nerve head. The total retinal thickness can be estimated using this technique, but it is impossible to measure the nerve fiber layer thickness with this device [8]. The Nerve Fiber Analyzer utilizes the principal of birefringence to measure nerve fiber layer thickness. This indirect technique of nerve fiber layer thickness assessment assumes that the nerve fiber layer is the only birefringent structure in the eye [9].

Figure 1 (*top left*) shows a normal stereo optic nerve head. Figure 1 (*top right*) illustrates the visual field in the same eye, which is full. Figure 1 (*bottom left*) illustrates radial scans through the optic nerve head in this eye, one from the 6:00 to 12:00 position, and the other from the 3:00 to 9:00 position. Figure 1 (*bottom right*) shows the cylindrical OCT sections in this eye. At a circle diameter of 3.37 mm, the nerve fiber layer thickness in the superior quadrant is 180 μm, 153 μm in the inferior quadrant, 91 μm in the temporal quadrant, and 114 μm in the nasal quadrant. The circular OCT is created from a series of 100 axial scans, and each quadrant consists of 25 such scans. The quadrants are defined as follows: the superior quadrant is from the 10:30 to 1:30 position, the inferior quadrant from the 4:30 to 7:30 position, and the temporal and nasal quadrants represent the remainder of the circle. The scan may also be ana-

lyzed point by point, at each of the 100 points, or summarized by clock hour, or by the overall mean.

The total retinal thickness in this particular eye at a circle diameter of 3.37 mm centered on the optic nerve head is 348 μm superiorly, 301 inferiorly, 278 μm temporally, and 251 μm nasally.

Figure 2 (*top left*) is a stereo optic nerve head photograph demonstrating cupping inferotemporally, with thinning of the neuroretinal rim in that area. The corresponding visual field, shown in Figure 2 (*top right*), illustrates a superior arcuate scotoma, corresponding to the area of cupping. Figure 2 (*bottom left*) is the nerve fiber layer from this individual, showing attenuation of the nerve fiber layer in the area of notching. Finally, Figure 2 (*bottom right*) is the OCT image from this eye. Note the slight attenuation of the superior nerve fiber layer thickness at 108 μm, but the severe attenuation of the inferior nerve fiber layer thickness, corresponding to the visual field defect, with thinning of the inferior nerve fiber to 65 μm.

## Conclusions

Optical coherence tomography represents a new technology, the first means by which to directly evaluate the nerve fiber layer cross-sectionally, and to quantitate nerve layer thickness. It represents a significant advance both for the assessment of ocular disease in general, whether anterior segment or retinal, but especially for glaucoma. It is possible that through OCT we may be able to diagnose glaucoma early on, prior to evidence

of optic nerve head or visual field damage, and that we may be able to detect changes in glaucoma earlier than we are able to now. Further studies are required, with regard to cross-sectional assessment of the population, development of a normative database, longitudinal studies on a set of individuals, as well as animal studies in a glaucoma model, to further assess and increase the utility of OCT.

## References and recommended reading

Papers of particular interest, published within the annual period of review, have been highlighted as:

- Of special interest
  - Of outstanding interest
1. Huang D, Swanson EA, Lin CP, Schuman JS, Stinson WG, Chang W, Hee MR, Flotte T, Gregory K, Puliafito CA, Fujimoto JG: Optical coherence tomography. *Science* 1991, 254:1178.
  2. Izatt JA, Hee MR, Huang D, Fujimoto JG, Swanson EA, Lin CP, Schuman JS, Puliafito CA: Ophthalmic diagnostics using optical coherence tomography. In *Ophthalmic Technologies III*. Edited by Ren Q, Pavel JM. Proc SPIE, 1993:1877.
  3. Swanson EA, Izatt JA, Hee MR, et al.: In vivo retinal imaging using optical coherence tomography. *Opt Lett* 1993, 18:1864. The first in vivo measurements of human retinal structure using OCT are presented. The tomographic system, image-processing techniques, and examples of high-resolution tomography and their clinical relevance are discussed.
  4. Hee MR, Izatt JA, Swanson EA, et al.: Optical coherence tomography of the human retina. *Arch Ophthalmol* 1995, 113:in press.
- Optical coherence tomography of the human retina in vivo discriminate the cross-sectional morphology of the fovea and optic disc, the layered structure of the retina, and normal anatomic variations in retinal and retinal NFL thickness with 10-μm resolution.
5. Puliafito CA, Hee MR, Lin CP, et al.: Imaging of macular diseases with optical coherence tomography (OCT). *Ophthalmol* 1995, in press.
  6. Izatt JA, Hee MR, Swanson EA, et al.: Micron-resolution imaging of the anterior eye with optical coherence tomography. *Arch Ophthalmol* 1994, 112:1584-1589.
  7. Schuman JS, Hee MR, Puliafito CA, Wong C, Pedut-Kloizman T, Lin CP, Hertzmark E, Izatt JA, Swanson EA, Fujimoto JG: Quantification of nerve fiber layer thickness in normal and glaucomatous eyes using optical coherence tomography: A pilot study. *Arch Ophthalmol* 1995, 113:in press.
  8. Webb RH, Hughes GW, Delori FC: Confocal scanning laser ophthalmoscope. *Appl Opt* 1987, 26:1492.
  9. Weinreb RN, Dreher AW, Coleman A, Quigley HA, Shaw B, Reiter K: Histopathologic validation of Fourier-ellipsometry measurements of retinal nerve fiber layer thickness. *Arch Ophthalmol* 1990, 108:557.

---

Joel S. Schuman, MD, New England Eye Center, Tufts University School of Medicine, 750 Washington Street, Box 450, Boston, MA 02111, USA.