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The OCT penlight: In-situ image guidance for microsurgery

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ABSTRACT

We have developed a new image-based guidance system for microsurgery using optical coherence tomography (OCT), which presents a virtual image in its correct location inside the scanned tissue. Applications include surgery of the cornea, skin, and other surfaces below which shallow targets may advantageously be displayed for the naked eye or low-power magnification by a surgical microscope or loupes (magnifying eyewear). OCT provides real-time high-resolution (3 micron) images at video rates within a two or more millimeter axial range in soft tissue, and is therefore suitable for guidance to various shallow targets such as Schlemm's canal in the eye (for treating Glaucoma) or skin tumors. A series of prototypes of the "OCT penlight" have produced virtual images with sufficient resolution and intensity to be useful under magnification, while the geometrical arrangement between the OCT scanner and display optics (including a half-silvered mirror) permits sufficient surgical access. The two prototypes constructed thus far have used, respectively, a miniature organic light emitting diode (OLED) display and a reflective liquid crystal on silicon (LCoS) display. The OLED has the advantage of relative simplicity, satisfactory resolution (15 micron), and color capability, whereas the LCoS can produce an image with much higher intensity and superior resolution (12 micron), although it is monochromatic and more complicated optically. Intensity is a crucial limiting factor, since light flux is greatly diminished with increasing magnification, thus favoring the LCoS as the more practical system.

Keywords: image guided intervention, image guided procedure, optical coherence tomography, OCT, glaucoma, Schlemm's canal, canaloplasty, microsurgery, in-situ, penlight.

1. BACKGROUND AND MOTIVATION

Glaucoma is the second leading cause of irreversible blindness worldwide.[1,2] The single greatest risk factor for the presence and progression of glaucoma is elevated intraocular pressure (IOP).[3-5] The goal of glaucoma therapy and procedures is the reduction of IOP.[3,6] In the human eye, IOP is regulated by a balance between the production and uptake of aqueous humor.[7]

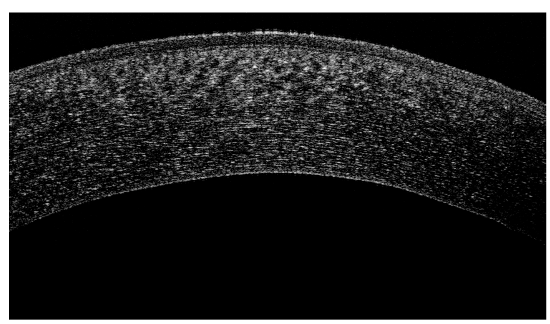

Fig. 1 OCT image of the cornea.

Canaloplasty is a relatively new surgical intervention in glaucoma that can be used when medical therapy has failed.[8] Viscoelastic material is injected into Schlemm's canal and a microcatheter inserted circumferentially to dilate the canal. Schlemm's canal is part of the drainage system of the intraocular fluids and the surgical goal is to restore functional drainage through the canal. During a typical canaloplasty operation, the physician first uses direct visualization and knowledge of anatomy to approximate the location of Schlemm's canal. After two scleral flaps are lifted and Schlemm's canal unroofed, the surgeon identifies the cut ends of Schlemm's canal and inserts a microcatheter to inject the viscoelastic material and re-open channels from the eye to the bloodstream. A suture is threaded through the canal and left to tension the tissue. A stereo surgical microscope is used whose magnification power is adjustable and controlled by the physician, with a typical maximum magnification of 20X. A high frequency ultrasound scanner (40 MHz or higher) may be used to confirm catheter placement.

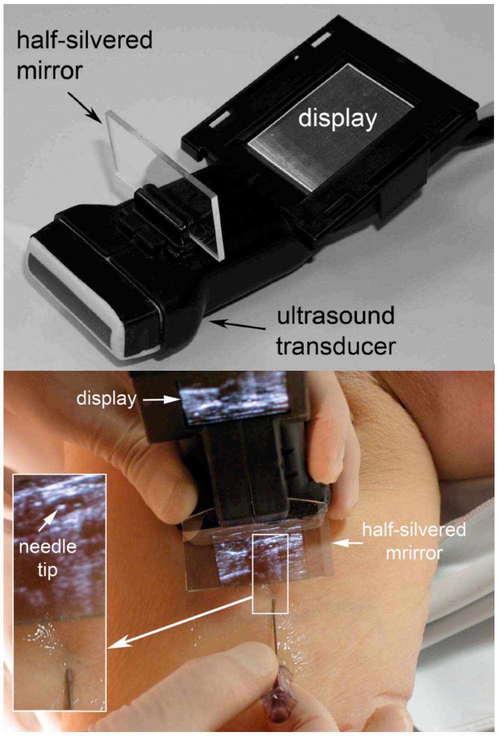

Fig. 2 (top) Sonic Flashlight (SF). **(bottom)** Virtual in-situ image produced by SF in cadaver showing needle placed in deep vein of arm.

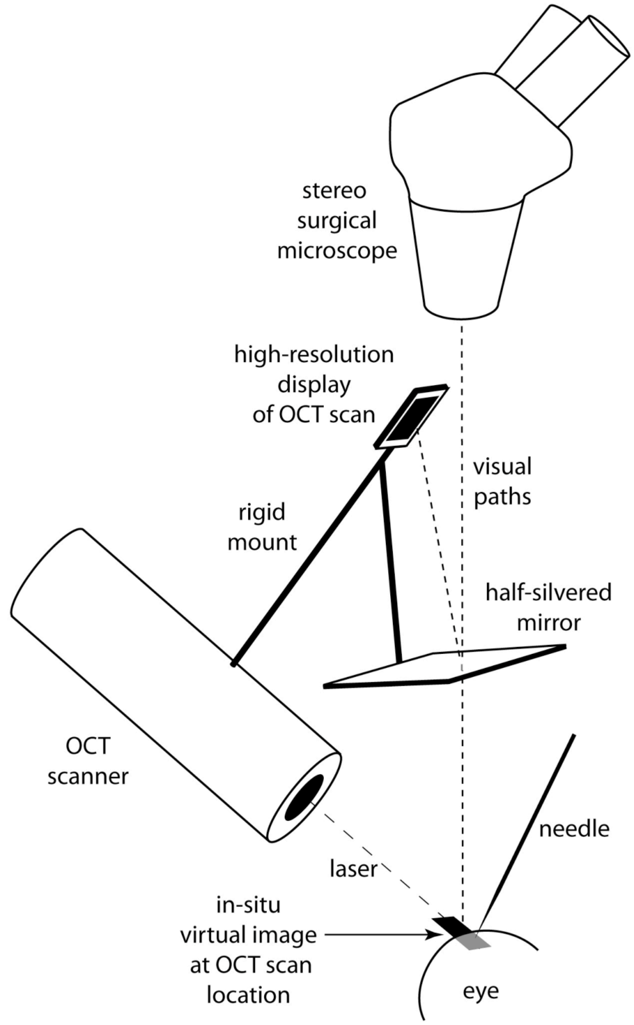

Fig. 3 Basic components of the OCT Penlight, creating an in-situ virtual image of the OCT scan.

A new imaging modality, Optical Coherence Tomography (OCT), has been introduced into clinical medicine, primarily into ophthalmology. OCT employs a beam of low coherence light to sample backscatter from within the first few millimeters of tissue and is capable, with mechanical sweeping of the beam, to compile 2D and even 3D tomographic images at very high resolution (~3 µm). Although the original OCT scanners also used a mechanical system to sample along the range of the beam,[9] the development of Spectral Domain OCT (SD-OCT) has greatly increased the speed of acquisition for 2D and 3D scans by acquiring a complete interrogation along the range dimension at once, deciphering range by means of Fourier analysis.[10]

At present, the predominant clinical applications of OCT are in the retina and cornea, where, in addition to being able to produce extremely high-resolution 3D scans delineating the various layers throughout the entire tissue, OCT can non-invasively image without ever touching the patient, an advantage over high frequency ultrasound. Another clinical application of OCT, evaluating the extent of atherosclerosis in the coronary artery, is also finding acceptance, since OCT's resolution is an order of magnitude better than intravenous ultrasound (IVUS).[11] Experimental applications of OCT are presently under development for cartilage degeneration in arthritis, evaluation of arterial wall motion, breast biopsy guidance, evaluation of surgical tumor resection margins in the operating room, evaluation of the larynx, esophagus, cervix, and skin for potentially malignant lesions, and early detection of dental decay.[12] OCT can produce extremely low-noise and high-resolution images of the cornea (Figure 1). It can be used to clearly visualize structures of the anterior segment including Schlemm's canal,[13] and thus could greatly assist surgeons guiding procedures to Schlemm's canal and monitoring the effects of their surgery on tissues and fluids in real time.

To facilitate such guidance with OCT, we have adapted a technique that we previously developed, which uses a half-silvered mirror to reflect a tomographic image into its actual location. In particular, over the past decade we have developed and tested a device called the *Sonic Flashlight*, which displays in-situ real-time ultrasound images for procedures such as catheter insertion into the deep veins of the arm.[14] The underlying concept of the device is shown in Figure 2. The Sonic Flashlight displays an ultrasound slice in real time by strategically positioning the ultrasound transducer, a half-silvered mirror, and a display such that the virtual image produced by the mirror is registered in space with the ultrasound scan itself. This requires no tracking, either of the observer or the patient. The lack of tracking is possible because of the nature of virtual images. The word, "virtual," is used here in its classical sense: the reflected image is optically indistinguishable from an actual slice suspended at a stable location in space. We have adopted the term *in-situ image guidance*, for the general approach of placing such virtual images within the actual scanned target.

Hofstein originally proposed in-situ visualization in 1980 for interpretation of ultrasound images.[15] Masamune, et al., have demonstrated in-situ images with computed tomography (CT) data,[16] and magnetic resonance imaging (MRI).[17] These applications, as well as other imaging modalities including OCT, were independently described by Stetten.[18]

Adapting in-situ image guidance to OCT-guided microsurgical procedures is the topic of the present paper. In keeping with its derivation from the Sonic Flashlight, we call the new device the *OCT penlight.* The present research extends our in-situ image guidance research into the domain of magnified vision, with the goal of aiding surgeons who use low-powered microscopes or other magnification devices such as those worn as glasses (Loupes). Augmented reality guidance systems have been developed for the magnified domain using head-mounted displays,[19] but we prefer to remain with the relatively simple optical solution of in-situ image guidance. As with the SF, the basic concept is to use a half-silvered mirror to insert an in-situ virtual image of the real-time scan (in this case, OCT) into the line of sight of the clinician performing the invasive procedure. The clinician is now looking through a surgical microscope, but as already noted, with virtual images, light from the display behaves exactly as if it had originated from within the tissue, even when passing through the optics of the surgical microscope. Figure 3 shows the basic components of the OCT penlight, which creates an in-situ virtual image of the scan at its correct location within the target (the patient's eye), to provide guidance for inserting a needle.

2. FIRST PROTOTYPE

We have thus far constructed two prototypes of the OCT penlight. Both employ a commercially available Spectral Domain Optical Coherence Tomography (SDOCT) optics engine (Bioptigen, Research Triangle, North Carolina, USA), which features software based dispersion compensation. This permits the use of a wide-bandwidth super-luminescent

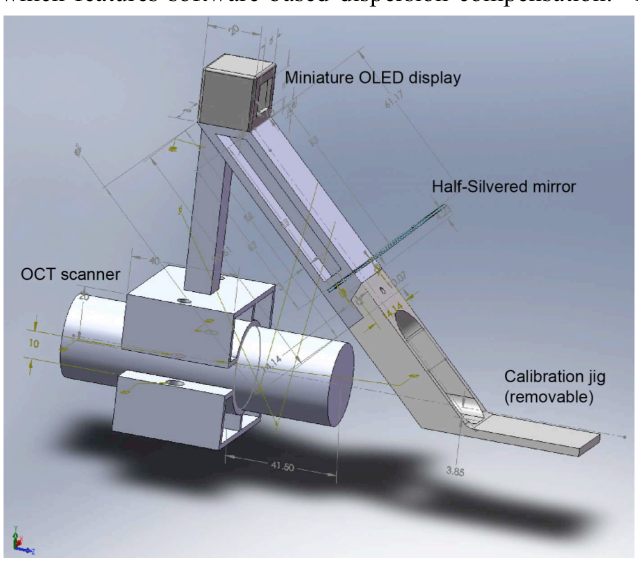

Fig. 4 Drawing of first-generation OCT penlight.

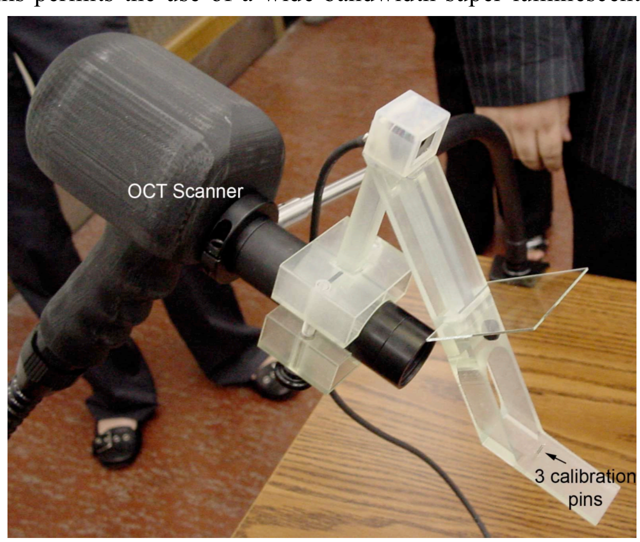

Fig. 5 First generation OCT penlight including OCT scanner and calibration gig with 3 pins.

diode array, a quad diode coupled source with an 870nm center wavelength and a 200nm bandwidth (Q870, Superlum Ltd, Dublin, Ireland). Wider bandwidth translates into shorter coherence length and better axial resolution. This light source has a theoretical axial resolution (coherence length) of 1.3µm in tissue.

The first generation prototype of the OCT penlight is shown in Figures 4 and 5. A miniature organic light emitting diode (OLED) display was used (Microdisplay, eMagin Corp., Hopewell Junction, NY) 12mm by 9mm in size, supporting SVGA+ resolution of 852x600 with 8-micron pixels and 24 bit color. The OLED technology offers a brilliant display in comparison to a liquid crystal display (LCD), and superior off-angle viewing, which is important for our application. The OLED display and a half-silvered mirror are mounted in a rigid geometric relationship to the OCT scanner, so that the virtual image produced by the mirror is guaranteed to occupy the space being imaged by the OCT scanner. The scanner is then adjusted to scan precisely within the plane of the virtual image. Located below the mirror is a removable calibration jig supporting three small (0.5 mm diameter) metal pins. These are used to permit calibration within the image place to properly scale, translate, and rotate the displayed image so as to be fully registered in 3D space with the target. To accomplish these image transforms in real time, we use hardware accelerated 2D texture mapping, now standard in personal computers.

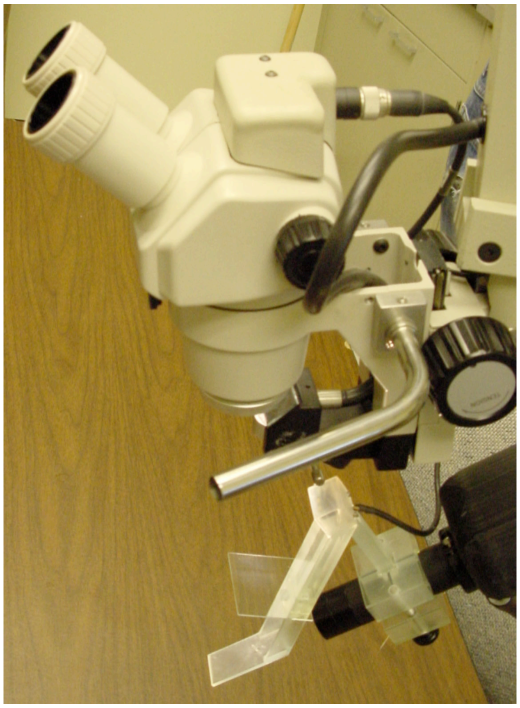

Fig. 6 First-generation OCT penlight positioned under surgical microscope.

Figure 6 shows the positioning of the first-generation OCT penlight with its calibration jig in the operating field of a surgical microscope. Looking into the microscope, the calibration pins are viewed through the half-silvered mirror, which also superimposes the virtual OCT image, permitting the calibration procedure.

Figure 7 shows the miniature OLED screen illuminated with the OCT image of the three calibration pins, and the same image displayed on a large flat panel monitor in the background. Although the OLED is bright relative to conventional back-lit LCD displays, its virtual image proved to be of insufficient brightness to be clearly visible through the microscope. The act of magnification dilutes the flux, the amount of light per unit time per unit cross-sectional area.

3. SECOND PROTOTYPE

Figure 8 shows our second generation OCT penlight. To increase brightness we used a liquid crystal on silicon (LCoS) monochrome reflective display, 15.4 x 8.7 mm in size, supporting a resolution of 1920 x 1080 8-µm pixels and 8 bits of grayscale (model HED-6001, HoloEye). This display works by rotating the polarization of incoming light, and thus it requires two extra polarizing filters for it to operate. As shown in Figure 8, incoming light from an external source hits a diffusion filter and then a first polarizing filter. After being reflected by the LCoS display, the light passes through a second polarizing filter, of higher quality than the first, because now an image must be transmitted. Depending on the extent of rotation of the light at a given pixel on the LCoS display, that light will be attenuated by the second polarizing filter and its brightness thus controlled. Because an external light source is used, the overall brightness of the system is limited only by the heat buildup on the display and within the system of filters, although each filter does decrease the ultimate efficiency of deliverance of the incoming light to the virtual image.

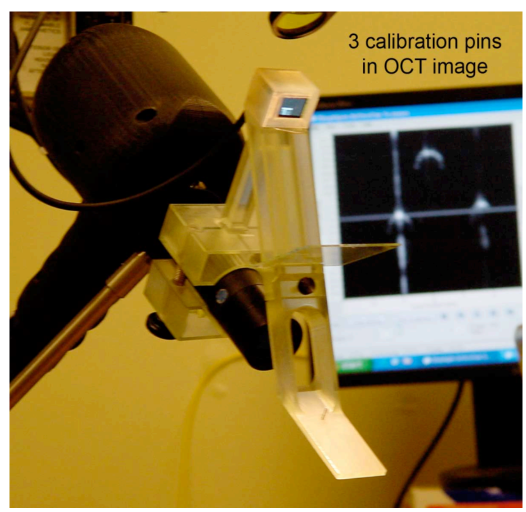

Fig. 7 First-generation OCT penlight with OLED display lit and calibration pins being imaged by OCT scanner.

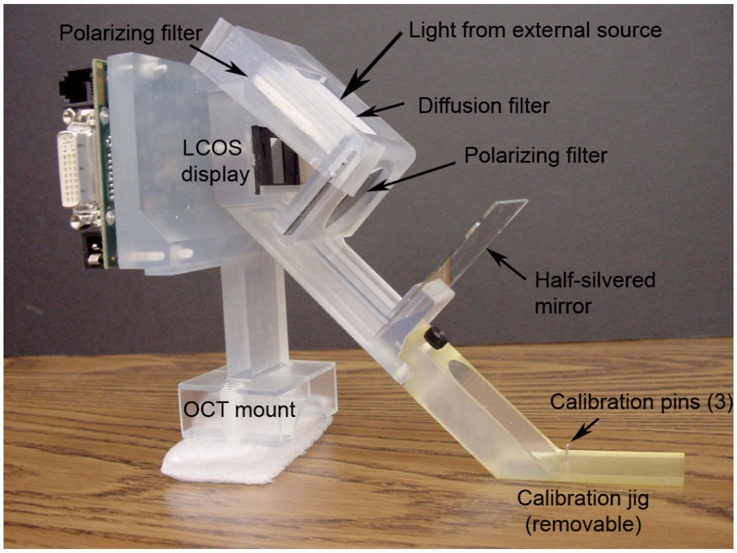

Fig. 8 Second generation OCT penlight.

Figure 9 top shows an OCT image of the 3 calibration pins as seen on the conventional OCT display. The pins are clearly imaged by the OCT in cross-section. As already mentioned, the first prototype did not produce a virtual image bright enough to be useful when viewed through the microscope. The second prototype, however, produced a much brighter image. As seen in Figure 9 bottom, the virtual image is now visible when magnified along with a direct view of the calibration pins. The photograph also demonstrates successful calibration of the OCT penlight.

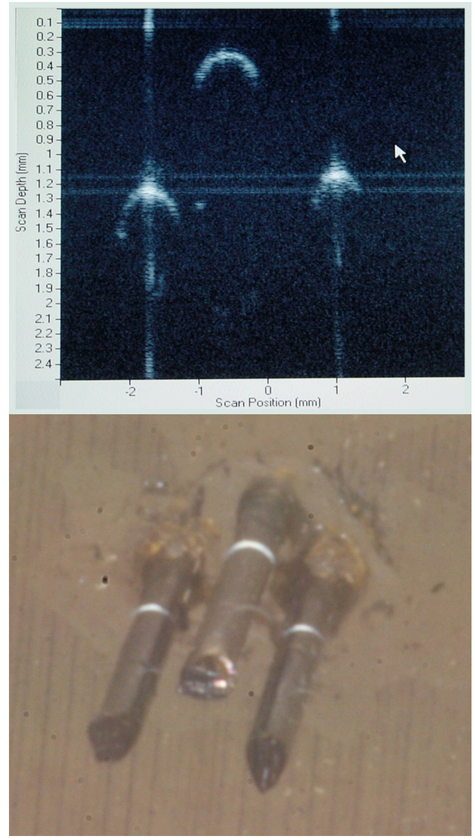

Fig. 9 (top) OCT image of 3 calibration pins displayed on a regular screen. **(bottom)** Direct magnified view of pins with in-situ OCT image in correct alignment.

4. CONCLUSIONS

A prototype OCT in-situ image guidance system was built and successfully demonstrated in our laboratory under conditions similar enough to ophthalmic microsurgery to be nearly ready for experimental use in a clinical setting, e.g., for insertion of a microcatheter into Schlemm's canal for the treatment of glaucoma. Planned future work will address testing this procedure with the prototype instrument on animal eyes, human factors studies for improved understanding of hand-eye coordination under the surgical microscope with and without the in-situ OCT display, and improvement of instrument utility via further development of illumination sources, image displays, and optics leading to brighter and higher resolution virtual images.

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