Micromotor endoscope catheter for in vivo, ultrahigh-resolution optical coherence tomography

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Received April 19, 2004

A distally actuated, rotational-scanning micromotor endoscope catheter probe is demonstrated for ultrahigh-resolution in vivo endoscopic optical coherence tomography (OCT) imaging. The probe permits focus adjustment for visualization of tissue morphology at varying depths with improved transverse resolution compared with standard OCT imaging probes. The distal actuation avoids nonuniform scanning motion artifacts that are present with other probe designs and can permit a wider range of imaging speeds. Ultrahigh-resolution endoscopic imaging is demonstrated in a rabbit with <4-μm axial resolution by use of a femtosecond Cr:forsterite laser light source. The micromotor endoscope catheter probe promises to improve OCT imaging performance in future endoscopic imaging applications. © 2004 Optical Society of America

Optical coherence tomography (OCT) is an emerging medical imaging technology that permits high-resolution, cross-sectional imaging of tissue pathology in situ and in real time. The development of scanning, fiber-optic endoscope catheters was an important advance that made possible in vivo OCT imaging applications in different organ systems. The first imaging studies in human subjects were performed using a novel, magnetically actuated, forward-imaging fiber scanning probe. Linear as well as rotary scanning fiber-optic endoscope catheters have been demonstrated for imaging the gastrointestinal tract in human subjects. Clinical endoscopic OCT imaging studies have been performed by several groups, and the results demonstrate the ability of OCT imaging to visualize pathologies of the upper and lower gastrointestinal tracts.

Minimally invasive endoscope catheter imaging probes that can focus and scan a beam inside the body have been a key technology for making possible endoscopic OCT imaging studies. The most common probe design to date uses a mechanical cable, an optical fiber, and a lens assembly housed in a transparent plastic sheath. The cable within the sheath is either rotated or translated in a push–pull motion to produce a rotary or linear scanning motion of the optics and generate a transverse or longitudinal OCT image. Imaging speeds and duty cycles are limited. In addition, for rotary scan designs, a proximally located optical coupling is required. Forward-imaging designs avoid these problems, but scan ranges can be limited. Recent developments in novel microelectromechanical systems scanning technologies promise to facilitate distal beam scanning, which would improve the speed and reduce image distortion in endoscopic imaging. In spite of these advances, previous endoscope catheter probe designs could not provide focus adjustment during OCT imaging. For this reason relatively large spot sizes were necessary to preserve a sufficient depth of field to permit OCT imaging in intraluminal structures. This limits the transverse image resolution.

In this letter we present a new high-resolution micromotor endoscope catheter with adjustable focus capability. The mechanical scanning and micro-optic components are located at the distal end of the probe, eliminating the need for proximally actuated rotating or translating elements. Distal actuation provides better uniformity of beam scanning with reduced image distortion artifacts and an improved range of image speeds. Standard OCT imaging probes usually require a long depth of field, and therefore the minimum transverse focused beam sizes are limited. With the ability to independently adjust the optical beam focal position and use optics with a higher numerical aperture, transverse image resolution can be improved. In addition, an adjustable focus device can make possible C-mode OCT imaging (acquiring images with several focal planes and fusing them together) to overcome depth-of-field limitations. The micromotor imaging probe also has a larger field of view than conventional OCT endoscope catheter devices, allowing larger diameter lumens to be more readily visualized.

Figure 1 shows a schematic and a photograph of the micromotor endoscope catheter probe assembly. The probe consists of a distally actuated micromotor and an optical assembly for the beam focusing. The micromotor is a commercially available subsystem (manufactured by Micro Precision Systems AG) that consists of a three-phase brushless dc motor. It has a planetary gearhead design and is configured with a 125:1 gear reduction ratio. A vertical Hall sensor built into the motor is used to accurately control and stabilize the rotation speed with a 5-V operating voltage. The optical assembly consists of a gradient-index lens collimator and an achromatic focusing lens that move
independently of the probe sheath (in a longitudinal direction) to adjust the focus position within the tissue. The transverse resolution of the focused optical beam was measured to be \( \sim 8 \mu m \) \((2\omega_0 \text{ spot diameter})\) by use of a knife-edge beam profile technique. The corresponding depth of field or confocal parameter is \( \sim 80 \mu m \) at a 1250-nm center wavelength. An aluminum-coated rod mirror is mounted onto the motor shaft to direct the focused light onto the tissue and make a rotational OCT scan possible. The motor speed could be adjusted, permitting rotation speeds from 1 to 100 Hz. The motor and distal optics fit within a 4.8-mm outer diameter stainless-steel housing that is enclosed within a 5-mm outer diameter transparent plastic sheath. Control wires to actuate the motor are fed through the tubing to the proximal end of the probe. The fiber collimator and the focusing lens are attached to a mechanical speedometer cable that enables the distal focus to be adjusted by translation of the fiber and lens assembly with respect to the fixed scanning motor at the distal end.

The OCT interferometer consists of a broadband optical circulator and 90/10 fiber-optic beam splitter to transmit 90\% of the light into the sample arm and 10\% into the reference arm. Dual-channel detection using polarization diversity is used before digital signal demodulation. A rapid scanning delay line is used in the system reference arm with 2000 axial scans per second. This corresponds to 1000 axial scans per OCT image at a 2-Hz image frame rate. For a probe diameter of 5 mm, this gives a transverse pixel spacing of 15 \( \mu m \)/pixel along the probe circumference. A broadband femtosecond Cr:forsterite laser and a nonlinear optical fiber are used as the light source. The measured axial image resolution in air is 5 \( \mu m \) and corresponds to a resolution of \( \sim 3.7 \mu m \) in tissue. The imaging scan depth is 4 mm, and the axial pixel spacing is 2 \( \mu m \)/pixel. The sensitivity is measured to be 92 dB at an incident power of 12 mW.

To demonstrate the micromotor endoscope catheter probe we performed \textit{in vivo} OCT imaging on an anesthetized New Zealand white rabbit. Animal handling was performed in accordance with protocols approved by the Massachusetts Institute of Technology Committee on Animal Care. Imaging was performed on the colon because the columnar epithelial structure of colonic mucosa provided well-defined tissue morphology for validation of the adjustable focus probe operation. To minimize animal discomfort and to reduce the risk of damaging the colonic mucosa we used a sterile bacteriostatic lubricant during catheter insertion. Multiple locations within the colon were imaged, and at each imaging position OCT scans were taken at several focus depths to demonstrate the adjustable focusing capability of the probe. The beam focal depth was changed by translation of the collimator and the focusing lens assembly with respect to the fixed motor assembly.

Figure 2 shows an OCT image obtained with the micromotor probe inserted 3 cm inside the colon. The raw image information was converted to polar coordinate display form. Since the axial scans are radially oriented, a bilinear interpolation was performed at larger radii to account for the wider separation of the axial scans. The probe sheath radius is 2.5 mm, while the OCT scan depth extends an additional 2 mm beyond the sheath. The OCT image was able to clearly delineate the upper mucosa, muscularis mucosae, and submucosa regions within the colon. Adjustment of the optical beam focus in real time was also demonstrated. Figure 3 shows enlarged OCT images of a region in the colon with two different beam focus positions. When the focus was set shallower, closer to the

![Fig. 2. OCT image of rabbit colon \textit{in vivo}. Imaging was performed with <4-\mu m axial resolution. Visualization of the colonic upper mucosa (um), muscularis mucosae (mm), and submucosa (sm) layers is clear within the colon with over 1-mm image penetration. The shadow regions at 11, 4, and 7 o’clock positions indicate areas of housing support struts that occlude approximately 20\% of the scan field.](image-url)
enhancement at different depths inside the tissue. The two focus depth settings (a and b) illustrate the signal (mg). (c) Plots of axial scans along the dashed lines for of deeper mucosal layers (ml) and glandular structure (mg). (c) Plots of axial scans along the dashed lines for the two focus depth settings (a and b) illustrate the signal enhancement at different depths inside the tissue.

In conclusion, a new micromotor endoscope catheter imaging probe for OCT has been developed. This design promises to improve imaging performance in future endoscopic OCT imaging studies.

We thank Stephane Bourquin, Hiroshi Ishikawa, and Vikas Sharma for their technical assistance and helpful discussions. This research was sponsored in part by National Institutes of Health R01-CA75289-06 and R01-EY11289-18, by National Science Foundation ECS-01-19452 and BES-0119494, by the Air Force Office of Scientific Research Medical Free Electron Laser Program F49620-01-1-0186 and F49620-01-01-0084, by the Poduska Family Foundation Fund for Innovative Research in Cancer, and through the philanthropy of Gerhard Andlinger.

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