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Ultrahigh Speed Endoscopic Optical Coherence Tomography using Micro-motor Imaging Catheter and VCSEL Technology

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Abstract

We developed a micro-motor based miniature catheter with an outer diameter of 3mm for ultrahigh speed endoscopic optical coherence tomography (OCT) using vertical cavity surface-emitting laser (VCSEL) at a 1MHz axial scan rate. The micro-motor can rotate a micro-prism at 1,200-72,000rpm (corresponding to 20-1,200fps) with less than 5V driving voltage to provide fast and stable scanning, which is not sensitive to the bending of the catheter. The side-viewing probe can be pulled back for a long distance to acquire three-dimensional (3D) dataset covering a large area on the specimen. VCSEL provides high a-line rate to support dense sampling under high frame rate operation. With the use of a C++ based high speed data acquisition (DAQ) system, *in vivo* three-dimensional OCT imaging in rabbit GI tract with 1.6mm depth range, 11 μ m axial resolution, 8 μ m lateral resolution, and frame rate of 400fps is demonstrated.

Introduction

Optical coherence tomography (OCT) performs micrometer-scale, cross-sectional imaging by measuring the echo time delay of the backscattered light¹. Fiber-optic based OCT imaging catheters enable the internal body imaging including the human cardiovascular system and gastrointestinal tract². *In vivo* endoscopic OCT imaging is very challenging because fast optical scanning must be implemented inside a small imaging probe. Many scanning mechanisms have been realized in catheter based endoscopic OCT systems, such as proximal rotation of a torque cable actuated fiber micro-prism module^{3,4}, actuating a distal fiber tip by a galvanometric plate⁵, actuating a fiber by piezoelectric cantilever⁶⁻⁸, and scanning the beam using microelectromechanical systems^{9,10}.

Imaging using proximal rotary scanning can cover large area with simple scanner configuration and is used in most of the endoscopic OCT applications, but the scanning is sensitive to the bending of the catheter because the rotation is translated from the proximal motor through a long torque cable. Non-uniform rotation limits the imaging quality even if the optical resolution of the imaging catheter is high. The scanning speed using this method is also limited because the torque cable can generate vibration with small unbalance in the catheter when operated at rotary speed higher than 6,000rpm. Distal scanning methods, on the other hand, can provide micron-level precision scanning because the mechanical motion can be directly controlled, however these methods usually suffer from small scanning coverage because of the size of the scanner is limited by the size of catheter. With advances in micro-motor technology, imaging using distal rotary scanning can be achieved, which can provide large scanning coverage while remaining high speed, uniform rotation without degrading the image quality. Recently, other groups have used micro-motor based OCT catheters to study smoke induced airway injury with imaging frame rates of 20fps¹¹. However, imaging speeds higher than 50

fps have not been demonstrated using this scanning method, due to other hardware limitations such as OCT acquisition speed.

In this study we demonstrate *in vivo* ultrahigh speed endoscopic OCT imaging in the rabbit gastrointestinal (GI) tract using a micro-motor based miniature catheter with an outer diameter of 3mm. The micro-motor has the advantage of high rotary speed with low driving voltage, ease of adjustment of the rotary speed, and small size that can be implemented in a miniaturized imaging catheter. The side-viewing probe can be pulled back over a long distance to acquire three-dimensional (3D) datasets covering a large area on the tissue. A 1MHz axial scan repetition rate from a vertical cavity surface-emitting laser (VCSEL) can support high frame rate while maintaining sufficient lines per frame^{12, 13}. Using a high speed data acquisition (DAQ) system, ultrahigh speed endoscopic OCT imaging can be achieved and large volume datasets can be acquired in seconds.

Methods

Figure 1 shows the schematic diagram of the prototype micro-motor based catheter design. A micro-prism is mounted on a 2mm diameter micro-motor. The OCT beam is delivered by a fiber GRIN lens assembly, reflected by the rotating micro-prism and focused 500 μ m away from the plastic sheath which covers the imaging catheter with a spot size of 8 μ m in air (full width half maximum). By pulling the optical and motor assembly from the proximal end of the torque coil during the rotary image acquisition, a spiral scanning pattern can be performed. The overall diameter of the catheter is \sim 3mm and can pass through an endoscope with a 3.7mm working channel. The micro-motor can be operated with a driving voltage less than 5V at a speed from 1,200rpm to 72,000rpm corresponding to an imaging speed from 20fps to 1,200fps.

Figure 2 (A) shows a schematic of VCSEL based endoscopic OCT system. A VCSEL light source centered at 1,310 nm with 100 nm tuning range (Fig. 2 (B)) and 500 kHz sweep rate, corresponding to a 1MHz bidirectional sweep rate (Fig. 2 (C)) is used as the light source. The axial resolution was 11 μ m in air, corresponding to \sim 8 μ m in tissue. Three-dimensional endoscopic OCT datasets were acquired using custom C++ software. Wavelength-swept signals were acquired using a 12bit, 500MSPS data acquisition card that was triggered using the laser sweep trigger. Wavenumber recalibration was computed in post processing using signal from a dispersion-matched Mach-Zehnder interferometer and volumetric datasets were processed using Matlab.

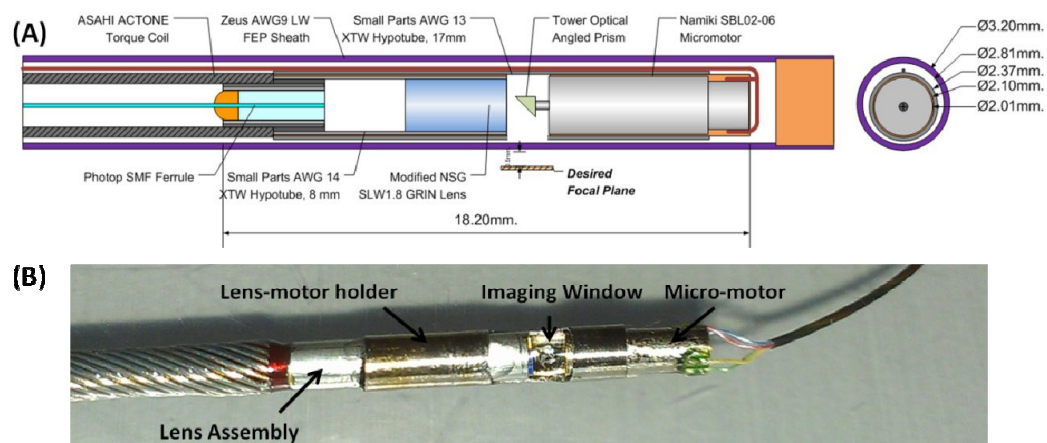


Figure 1. (A) Schematic diagrams of the micro-motor based imaging catheter. (B) Photo of the prototype probe.

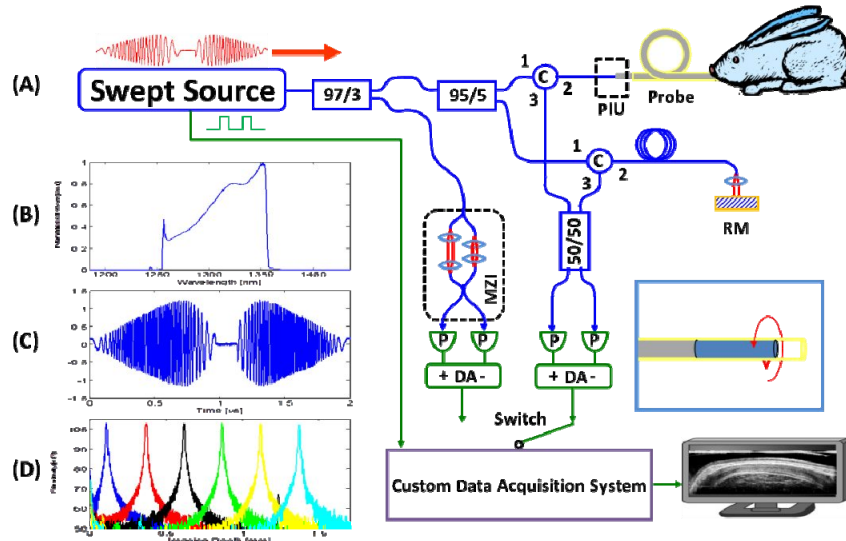


Figure 2. (A) Schematic diagrams of the VCSEL based endoscopic OCT system. (B) Optical spectrum of the laser. (C) Interferometric trace of the laser from the Mach-Zehnder interferometer. (D) Sensitivity roll off of the system over 1.6 mm imaging range.

Results

To demonstrate the ability to image microscopic structures in the gastrointestinal tract, in vivo volumetric 3D-OCT data sets of the rabbit colon and esophagus were acquired. The study was performed under a protocol approved by the Committee on Animal Care (CAC) at MIT. Figure 3 shows example 3D-OCT data sets from the colon and esophagus of a New Zealand White rabbit. The micro-motor was rotated at 24,000rpm, which corresponds to a frame rate of 400fps with 2,500 axial scans per frame. The micro-motor probe was constructed with an optical window that allowed for a circumferential imaging field of ~ 7.5 mm. Each data set was acquired in 7.5seconds and covered a 7.5mm longitudinal pull-back length. The volumetric data sets can be processed and displayed in three dimensions. Fig. 3 (A) and (B) show the *en face* view and cross-sectional image in rotary scan direction in rabbit colon. Both *en face* and cross-sectional images clearly show the crypt structures in the colon. Fig. 3 (C) and (D) show the cross-sectional images in the rotary direction and the pull-back direction respectively. The OCT images allow visualization of the normal esophageal layers including the epithelium (EP), the lamina propria (LP), muscularis mucosa (MM), the submucosa (SM), the circular muscle (Ci), the longitudinal muscle (LM) and the underneath intramuscular connective tissue. Motion artifacts were extremely small throughout the image acquisition period due to the fast and stable scan, so requirements for image post processing, such as frame alignment can be minimized.

Figure 4 shows the three orthogonal views of a volumetric OCT dataset taken from the rabbit gastro-esophageal junction. The high scanning speed of the imaging probe can be used to acquire stable images as well as capturing the dynamics of the tissue movement. From Fig. 4 (A) and (D) the contraction of the stomach can be observed during the acquisition. Figure 5 shows the three orthogonal views of a volumetric OCT dataset taken from the rabbit epiglottis. The large imaging area reveals a variety of the structures in the epiglottis, which is 30x-50x larger than standard pinch biopsy and can reduce sampling error.

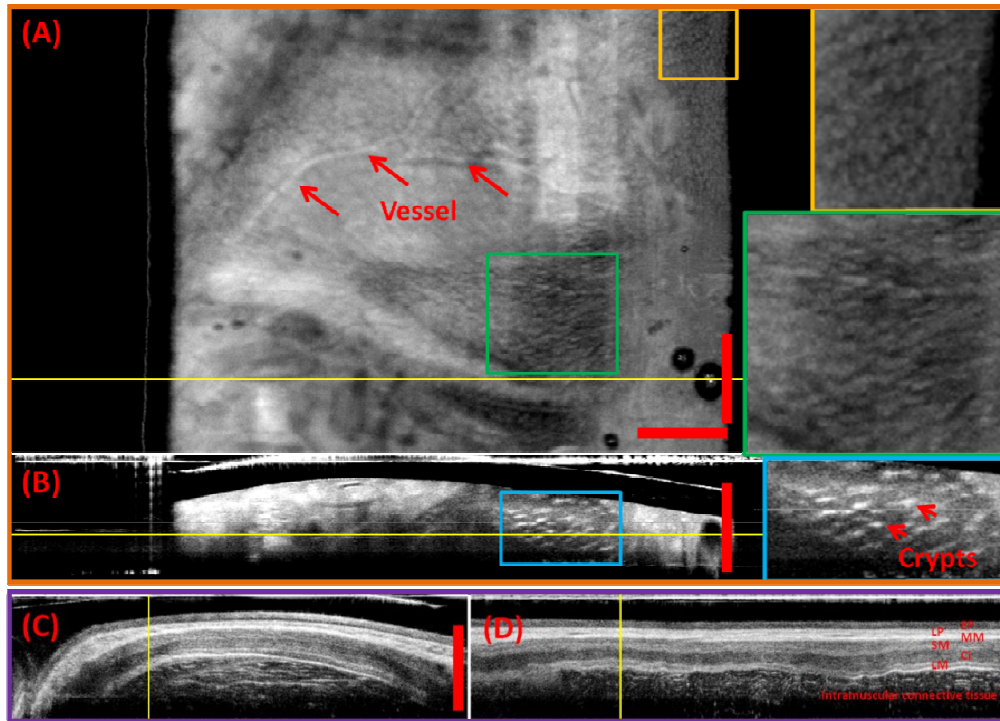


Figure 3. *In vivo* 3D volumetric OCT images from rabbit colon and esophagus. (A) *En face* image reveals the crypt and vessel structures in the colon. (B) Cross-sectional image along the rotary scan direction in the colon. (C) Cross-sectional image along the rotary direction in the esophagus. (D) Cross-sectional images along the pull back direction in the esophagus. Scale bar: 1mm.

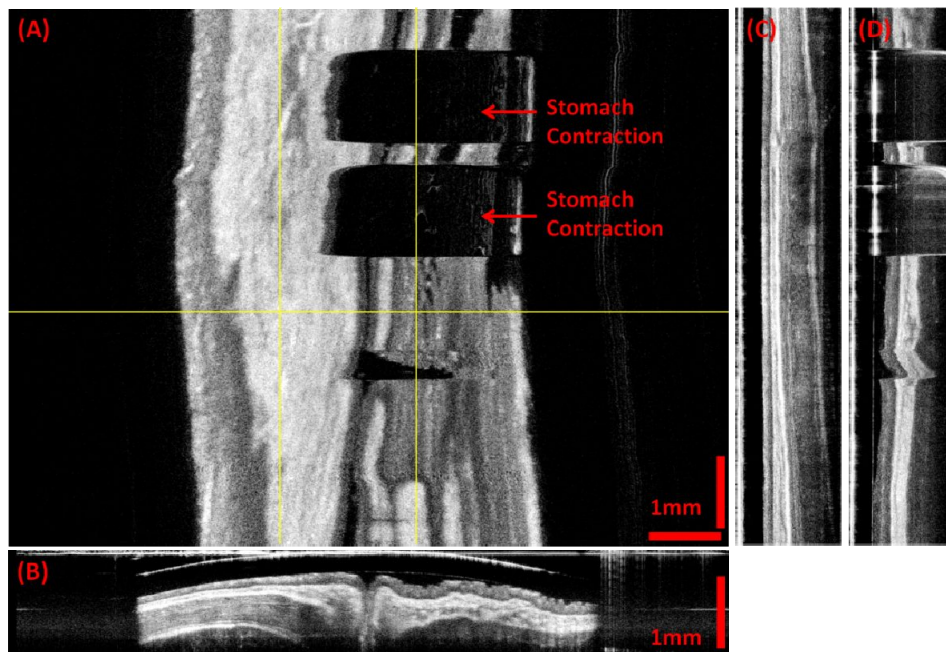


Figure 4. *In vivo* 3D volumetric OCT images from rabbit gastro-esophageal junction. (A) *En face* image. (B) Cross-sectional image along the rotary scan direction. (C) and (D) Cross-sectional images along the pull-back direction.

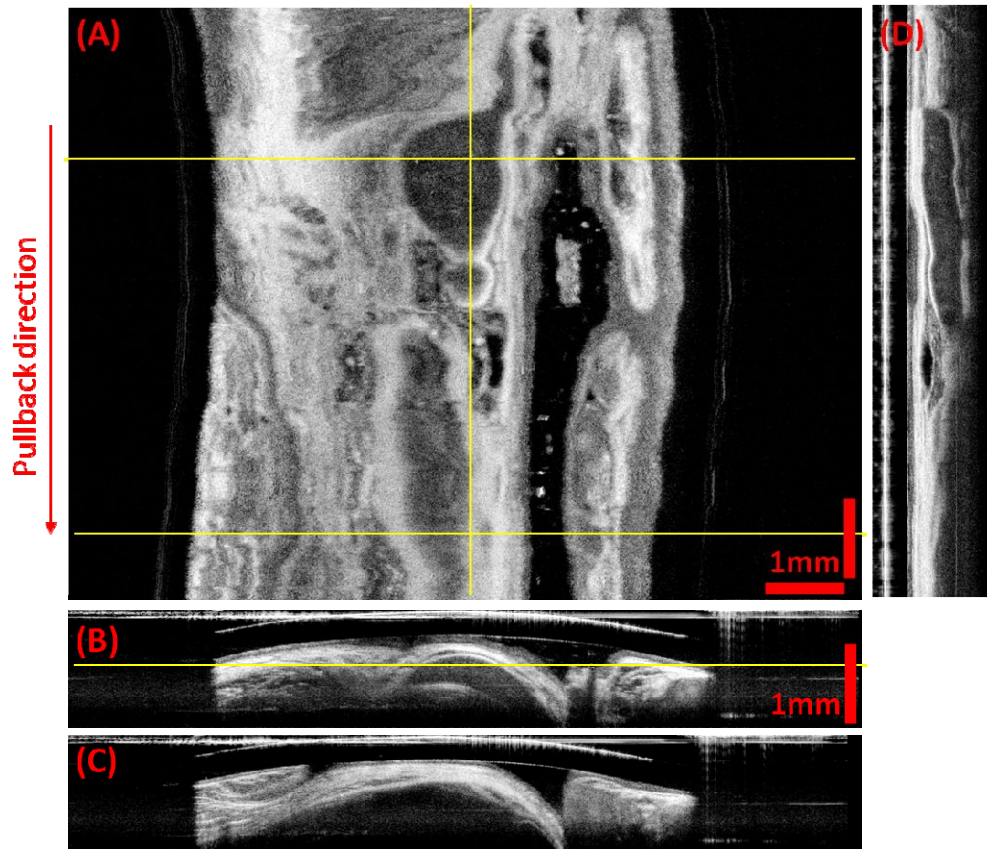


Figure 5. *In vivo* 3D volumetric OCT images from rabbit epiglottis. (A) *En face* image. (B) and (C) Cross-sectional images along the rotary scan direction. (D) Cross-sectional image along the pull-back direction.

In conclusion, we demonstrated *in vivo* imaging in rabbit GI tract with ultrahigh imaging speed using a micro-motor based imaging catheter and a VCSEL at a 1MHz axial scan rate. The system can support 400fps or higher, 11 μ m axial resolution, 8 μ m lateral resolution, and 1.6mm imaging depth range. The micro-motor not only can achieve high scanning speed but provide stable scan. These advantages are important for clinical studies which require distinguishing small features in tissue and averaging multiple images to enhance image quality.

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