A Micromotor Catheter for Intravascular Optical Coherence Tomography

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ABSTRACT We have developed a new form of intravascular optical coherence tomography (IV-OCT) that allows the extremely fast acquisition of high-resolution images of the coronary arteries. This process leads to much better image quality by eliminating cardiac motion artefacts and undersampling. It relies on a catheter that incorporates a synchronous micromotor with a diameter of 1.0 mm and a rotational speed of up to 5600 revolutions per second, enabling an IV-OCT frame rate of 5.6 kHz. This speed is matched by a wavelength-swept laser that generates up to 2.8 million image lines per second. With this setup, our team achieved IV-OCT imaging of up to 5600 frames per second (fps) *in vitro* and 4000 fps *in vivo*, deployed at a 100 mm·s^{-1} pullback velocity. The imaging session is triggered by the electrocardiogram of the subject, and can scan a coronary artery in the phase of the heartbeat where the heart is at rest, providing a name for this new technology: the "Heartbeat OCT."

Optical coherence tomography (OCT) is an optical imaging technique that provides depth-resolved imaging of biological tissue with high resolution. Generally, an imaging beam scans across the tissue surface to acquire a two- or three-dimensional image. This technique is commonly used in ophthalmology and in cardiology. For cardiovascular applications, the OCT light beam is transmitted through a catheter that is advanced into the coronary arteries of a patient being treated for coronary artery disease. The imaging beam emitted from the catheter is swept along the vessel wall in a rotary fashion, while the catheter is pulled back inside the artery to investigate the vessel over a length of 5–10 cm. The resulting data set shows coronary interventions and vessel-wall pathologies such as atherosclerosis, with a resolution of approximately 10 μm.

Percutaneous coronary revascularization (PCR) procedures, the catheter-based opening of closed coronary arteries, are routinely performed under X-ray angiography guidance, which provides a two-dimensional visualization of the coronary-artery lumina. Several limitations of angiography—lack of three-dimensional information, lack of information on vessel wall anatomy, limited spatial resolution, poor sensitivity for mural thrombus, and inability to visualize radiolucent devices, to name a few—suggest a prominent role for intravascular imaging in PCR guidance. Recent studies have started to explore the clinical benefit of various catheter-based imaging technologies for procedure outcomes. PCR has become the standard therapeutic intervention for patients with acute heart attack, or acute coronary syndrome (ACS). The recent shift in the catheterization laboratory population from one with stable angina to one dominated by ACS patients means that thrombectomy, stent, and balloon interventions are performed in more complex vascular territory, characterized by heterogeneous tissue composition and thrombus. Adequate visualization of the local tissue structure and composition becomes all the more critical in this environment. Intravascular optical coherence tomography (IV-OCT) is a catheter-based imaging technique that provides comprehensive volumetric microscopy of the artery, with a resolution on the order of 10 μm.

IV-OCT has been available for clinical use for about a decade, and has generated a wealth of data that has deepened our understanding of coronary artery disease and catheter-based interventions thereupon. A number of issues, however—chiefly undersampling, cardiac motion artefacts, and non-uniform rotational distortion (NURD)—affect the quality and interpretability of IV-OCT images, particularly in volumetric data sets. The OCT data-acquisition rate is limited by the scanning speed of the catheter and the speed of the OCT engine. The imaged artery needs to be flushed with a transparent media to create a blood-free field of view, allowing only a few seconds for a scan. Commercial systems implement a scan sequence in which the artery is imaged in 3–5 s, with a pullback speed of 20–40 mm·s^{-1} and a frame rate of 100–180 frames per second (fps). The resulting data set thus covers several cardiac cycles, which leads to image artefacts as a result of catheter motion during pullback. Longitudinal displacement of the vessel relative to the catheter causes inaccuracy in frame spacing, and possibly frame order, affecting length measurements and the fidelity of the longitudinal rendering and three-dimensional reconstruction of the data [1, 2]. The frame pitch in conventional pullbacks is typically 200 μm, which, combined with a beam width of around 30 μm, means that the rendered volume is undersampled by a factor of 7 in the longitudinal direction. Consequently, there is a distinct difference in the image quality of the longitudinal rendering compared to that of the cross-sectional images. NURD is a result of rotational friction of the hollow drive-shaft in the catheter, leading to variable torque transfer from the proximal motor to the imaging tip. It appears as a distortion in a single frame, or as wobbling of frames relative to each other.

The motion and sampling limitations of IV-OCT can be overcome by adopting a scanning protocol that acquires data in between two subsequent left-ventricle contractions, thus

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avoiding excessive motion. Data is obtained by a catheter that scans quickly enough to enable a frame pitch smaller than the width of the imaging beam. Fast scanning can be achieved with a distal actuator, which should also eliminate NURD resulting from variable frictional loading of the rotation mechanism. An additional benefit of short imaging time is a reduction of the necessary flush volume. In this report, we describe an intravascular imaging system, called the "Heartbeat OCT" [3], that is based upon this principle, relying on a high-speed OCT engine and a 1 mm diameter micromotor. We conducted *in vitro* and *in vivo* imaging experiments to evaluate the functionality of the system.

Figure 1 shows a photograph of the catheter we built. Within an outer diameter of 1.1 mm, the device contains a synchronous micromotor, supplied with a driving current through four copper leads. The micromotor was developed in our group [4] and is manufactured by Kinetron BV (Tilburg, the Netherlands). A lens-tipped fiber probe creates an imaging beam with a focus located 1 mm outside the catheter. A mirror is mounted on the rotating shaft of the motor, which sweeps the beam along the vessel wall to sample the tissue. As the micromotor is a synchronous motor, its rotational speed is determined by the frequency of the driving current. At a current of 0.7 A, the temperature increase due to resistive heating in the catheter is limited to < 1 K, making it suitable for *in vivo* intravascular imaging. This current allowed a speed of 4000 revolutions per second (rev·s^{-1}).
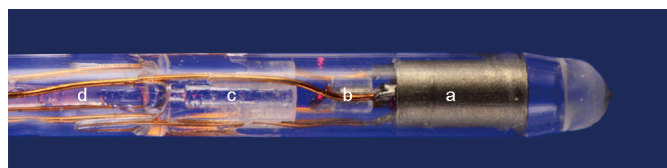

Figure 1. Microphotograph of the catheter with an outer diameter of 1.1 mm. (a) Micromotor; (b) mirror on holder, mounted on motor shaft; (c) GRIN lens on fiber; (d) current wires.

We performed *in vitro* imaging experiments using the catheter and a Fourier domain mode locking laser system operated at a 2.8 MHz sweep rate. This laser system was developed by a German research team headed by Professor Robert Huber [5]. Figure 2 shows a cross-sectional image of a human coronary artery *ex vivo* with an implanted bioresorbable vascular scaffold (BVS), a stent that will dissolve within a time frame of roughly two years. Four shadows can be seen in this figure, which are cast by the copper wires. Figure 2 parts (a) and (c) compare longitudinal sections through pullback data sets acquired at a 100 mm·s^{-1} pullback speed. In Figure 2(b), the motor was driven at 400 rev·s^{-1}, giving rise to a longitudinal frame pitch of 250 μm, which is comparable to that delivered by commercial systems. The image is poorly sampled, although the line density in the cross-sectional image is very large. In Figure 2(c), the motor speed was 3200 rev·s^{-1}, and the frame pitch is 31 μm. This number is approximately equal to the beam width in the focus. As a result, the longitudinal image is now properly sampled and shows the same amount of detail as the cross section. The smooth appearance of the data in all directions renders it highly suitable for three-dimen-

sional (3D) representation. Figure 3 shows a 3D rendering of another vessel *ex vivo*, with a calcified plaque.
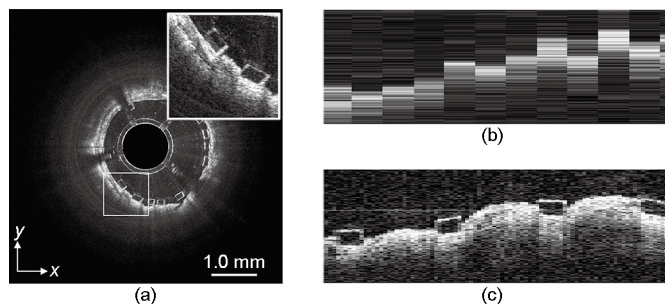
Figure 2. (a) Cross-sectional image of a human coronary artery *ex vivo* with an implanted bioresorbable vascular scaffold, a stent that will dissolve within two years. The vessel wall architecture and the scaffold are faithfully rendered; (b) Longitudinal section through the artery, with a frame pitch of 250 μm, leading to undersampling; (c) Longitudinal section through the artery, with a frame pitch of 31 μm.
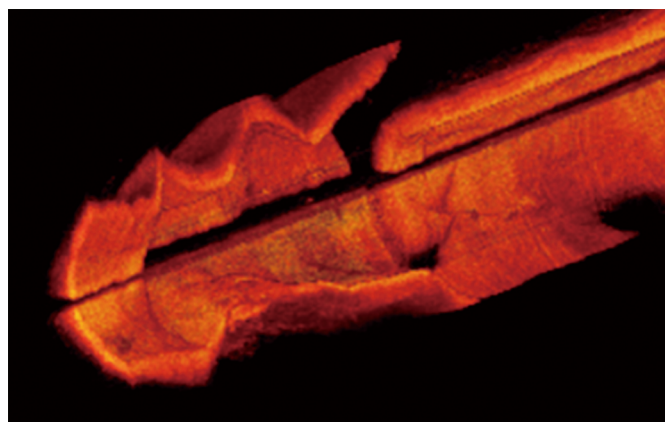
Figure 3. 3D rendering of an *ex vivo* calcified plaque in a human coronary artery. Imaged by Heartbeat OCT (line rate 1.6 MHz, motor speed 3200 rev·s^{-1}) [6].

The pullback speed of the catheter when deployed *in vivo* is at least 100 mm·s^{-1}. As a result, 6–7 cm of coronary artery can be imaged with isotropic sampling and without cardiac motion artifacts in the time span between two ventricular contractions. To achieve this, the pullback and data acquisition are triggered from the electrocardiogram (ECG) of the subject. Cardiac motion in the left ventricle is the strongest source of artifacts, and is associated with the T-wave of the ECG. Applying an appropriate, and possibly patient-specific, delay to the synchronization of the measurement will allow us to avoid cardiac motion effects in the data. The resulting pullback data sets are smooth and isotropically sampled. Such data will allow more reliable length measurements in OCT, and enable patient-specific vascular biomechanics computations. These developments will give the Heartbeat OCT a key role in the guidance of coronary interventions and the personalized prognostic-imaging of coronary atherosclerosis.

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