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STATE-OF-THE-ART PAPER

Intracoronary Optical Diagnostics

Current Status, Limitations, and Potential

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Optical coherence tomography (OCT), is a novel intravascular imaging modality analogous to intravascular ultrasound but uses light instead of sound. This review details the background, development, and status of current investigation using OCT, and discusses advantages, limitations, and likely future developments. It provides indications for possible future clinical use, and places OCT in the context of current intravascular imaging in what is a rapidly changing field of investigation. (J Am Coll Cardiol Intv 2011;4:1257–70) © 2011 by the American College of Cardiology Foundation

Optical coherence tomography (OCT), like intravascular ultrasound (IVUS) nearly 2 decades ago, is changing the way we see coronary pathophysiology. The detail with which coronary pathophysiology is viewed by this intravascular imaging modality is unprecedented, such that we are only now just beginning to establish how this imaging information might be best used to guide management and influence patient outcomes. This review, therefore, describes the current status of coronary optical diagnosis with OCT, in what is already a rapidly evolving and dynamic field of intracoronary imaging.

OCT Technology

OCT is an imaging technology analogous to IVUS but uses light instead of sound. It was first described by Huang et al. (1) in 1991, with its first application as single-plane cross-sectional imaging of the retina. OCT has since become an established imaging modality in clinical ophthalmology (2), and its biomedical applications have broadened to include gastrointestinal, dermatological, and intravascular imaging (3–5). Intravascular imaging has progressed to the stage where commercially available systems are now approved for use in Europe, Asia, and Australasia, and was recently approved in the United States.

The light source used for OCT imaging is in the near-infrared range, around 1,300-nm wavelength, selected as a compromise to achieve both penetration and delineation of vascular structures. Images are formed by measuring the magnitude and echo time delay of a reflected backscattered light signal in a manner analogous to IVUS. However, since the speed of light (3×10^8 m/s) is several orders of magnitude faster than that of sound (1.5×10^3 m/s), an interferometer is required to record the reflected light echoes (4). The interferometer splits the emitted light source into a reference and sample beam; the reference beam is directed to a reference mirror at known distance, the sample beam is directed to the structures of interest. The sample beam is then reflected back to a detector where it is summed with the reference beam, producing interference (4,6) (Fig. 1A).

Early commercially available versions of the technology used time domain (TD) detection. TD OCT employs a broadband light source with wavelengths centered around 1,300 nm, and a

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reference mirror that is scanned to sequentially measure echoes from different depths (6,7). Currently available systems use a much higher speed method, known as frequency or Fourier domain (FD) detection. FD OCT uses an interferometer with a stationary reference mirror, but the light source frequency or wavelength is rapidly swept in time across 1,250 to 1,350 nm, such that received, reflected signals echo signals from different depths produced by different frequencies from the interferometer. Spatial features are encoded in frequency, in a manner somewhat analogous to magnetic resonance imaging. Axial depth profiles are then reconstructed by Fourier transformation. FD OCT thus essentially measures all echoes of light from different depths simultaneously, rather than sequentially as in TD OCT (Fig. 1B). FD OCT, therefore, achieves a dramatic improvement in sensitivity, enabling imaging speeds that are >10 times faster than TD OCT (6,8). This has been a key advance in clinical applicability, meaning that image acquisition is now possible during a contrast or saline flush lasting 3 to 5 s.

Abbreviations and Acronyms

ACS = acute coronary syndrome(s)
BMS = bare-metal stent(s)
DES = drug-eluting stent(s)
FD = Fourier domain
IVUS = intravascular ultrasound
NI = neointima
NSTEMI = non–ST-segment elevation myocardial infarction
OCT = optical coherence tomography
PCI = percutaneous coronary intervention
SAP = stable angina pectoris
STEMI = ST-segment elevation myocardial infarction
TCFA = thin-cap fibroatheroma
TD = time domain

OCT Image Acquisition

Since blood strongly scatters light, intravascular OCT requires a blood-free field lasting several seconds to allow imaging. In the earlier TD OCT systems, this was achieved either by injecting continuous saline/contrast flushes through the guiding or delivery catheters, or by using a proximal balloon occlusion of the vessel with distal saline/contrast injection. These techniques are safe, including in patients with acute coronary syndromes (ACS), but may be time-consuming, and require a high degree of operator expertise (9,10).

Conversely, FD OCT systems do not require proximal occlusion. The coronary vessel is transiently rendered free of blood by a bolus injection of saline, contrast, or other solution, injected at rates of 2 to 4 ml/s, and an automated 20 mm/s pullback within a monorail rapid exchange catheter allows imaging of a 6-cm-long coronary segment during a 3-s injection (8). The monorail rapid exchange catheter is compatible with 6-F guiding catheters, and can be conveniently incorporated into most interventional procedures. A summary of the characteristics of the FD OCT and TD OCT systems are shown in Table 1 (11). FD systems are being developed by various manufacturers (Lightlab, West-

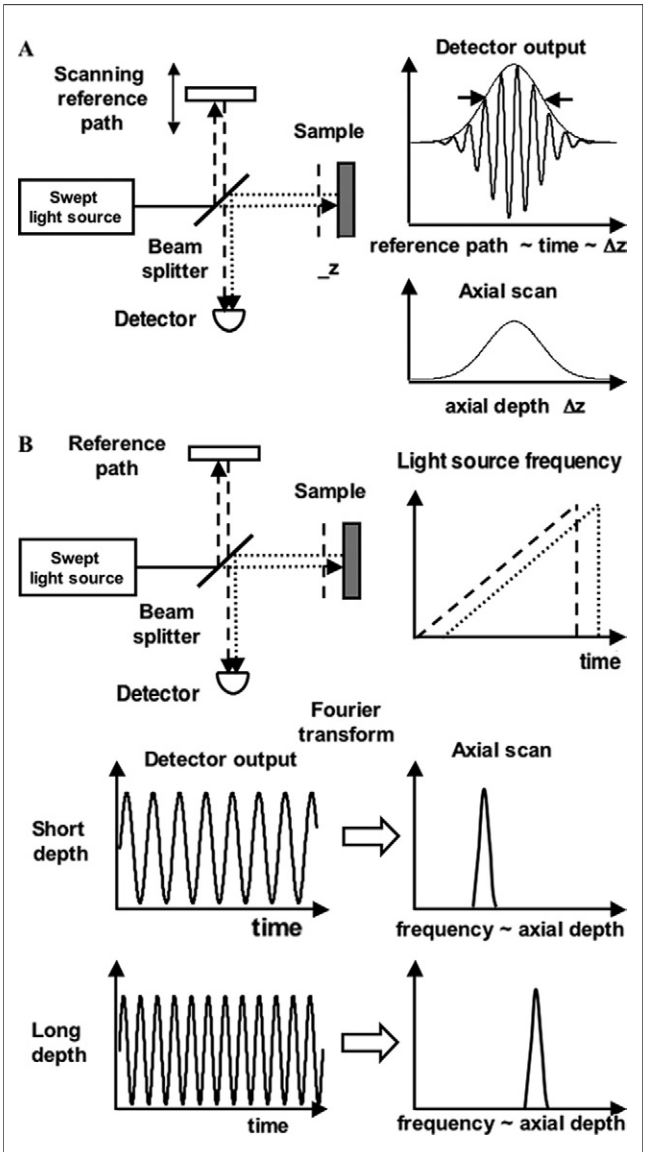

Figure 1. TD OCT and FD OCT: Schematic

(A) Time domain (TD) optical coherence tomography (OCT). Time domain OCT measures light echoes using a scanning interferometer. A low-coherence, broadband light source is split into 2 beams, 1 directed onto the tissue and the other onto a reference mirror. Interference occurs between backscattered light from the tissue and light traveling a known echo time delay from the reference mirror. Interference occurs only when the light from the sample arrives at the same time as light from the reference path. The magnitude and echo time delay of light from the tissue is measured by scanning the reference path, generating an axial scan. In an actual OCT instrument, the interferometer is built using optical fibers, and imaging is performed using an intravascular catheter with a rotating optical fiber and microlens in a transparent sheath. **(B)** Fourier domain (FD) OCT. Frequency or FD detection uses a frequency swept light source. The light is directed onto the tissue and a reference mirror at a fixed delay. Light echoes from different tissue depths return with different delays, resulting in a frequency difference between the signal and reference light. The interference produces a beat frequency (equal to this frequency difference) that depends on the echo delay. The beat frequency is measured by Fourier transforming the signal to recover the echo delay. Each sweep of the laser, therefore, generates an axial scan. Since all echoes are measured simultaneously, the sensitivity is dramatically increased.