

REVIEW ARTICLE—CARDIOVASCULAR IMAGING FOR NUCLEAR CARDIOLOGISTS

Current Clinical Applications of Intravascular Optical Coherence Tomography in Coronary Artery Disease

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Abstract

Optical coherence tomography (OCT) has emerged as a high-resolution (10–20 μm), light-based, intravascular imaging technique capable of investigating detailed coronary plaque morphology. OCT is highly sensitive and specific for characterizing fibrous, fibrocalcific, and lipid-rich plaque. OCT is capable of discriminating 3 types of unstable plaque morphologies underlying coronary thrombosis such as plaque rupture, erosion, and calcified nodules. The high resolution of OCT has a potential to identify important features of vulnerable plaques such as thin-cap (<65 μm thick) fibroatheroma, macrophages, vasa vasorum, cholesterol crystals, and microcalcifications. As compared with conventional intravascular ultrasound, OCT provides more accurate measurements of coronary lumen diameter and lesion length, which is useful in determining stent size. OCT is much more sensitive in detecting inadequate stent findings such as intrastent tissue protrusion, incomplete stent apposition, stent edge dissection, and intrastent thrombus, which is helpful in optimizing stent implantation. Recently developed new stent optimization software such as OCT/angiography co-registration and 3-dimensional view enhances ease of use, simplifies interpretation and allows us to literally visualize a better outcome of percutaneous coronary intervention (PCI). In conclusion, OCT is a promising technology to assess coronary atherosclerosis and to guide PCI.

Keywords: Atherosclerosis, Coronary artery disease, Optical coherence tomography, Percutaneous coronary intervention

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Catheter-based intravascular imaging techniques offer a valuable opportunity to evaluate atherosclerosis in coronary arteries. Intravascular ultrasound (IVUS) allows tomographic assessment of lumen area, plaque size, distribution, composition, and vascular remodeling. Coronary angioscopy permits direct visualization of thrombus, plaque rupture, and variations in color of the coronary arterial wall. Recently, optical coherence tomography (OCT) has emerged as a high-resolution (10–20 μm) imaging technique capable of investigating detailed coronary plaque morphology. This review focuses on the ability of OCT to visualize coronary

atherosclerotic plaque and guide percutaneous coronary intervention (PCI).

OCT technology

OCT uses near infrared light, at a wavelength of 1,250–1,350 nm, to create images. The resolution of OCT is 10–20 μm , which is approximately 10 times higher than that of IVUS. The imaging depth of OCT is 1.0–2.0 mm (depending on tissue type), which is approximately one-tenth of that of IVUS. The scan diameter of OCT is up to 10 mm. Imaging catheter of OCT has 2.5–2.8 Fr crossing profile. The imaging catheter is

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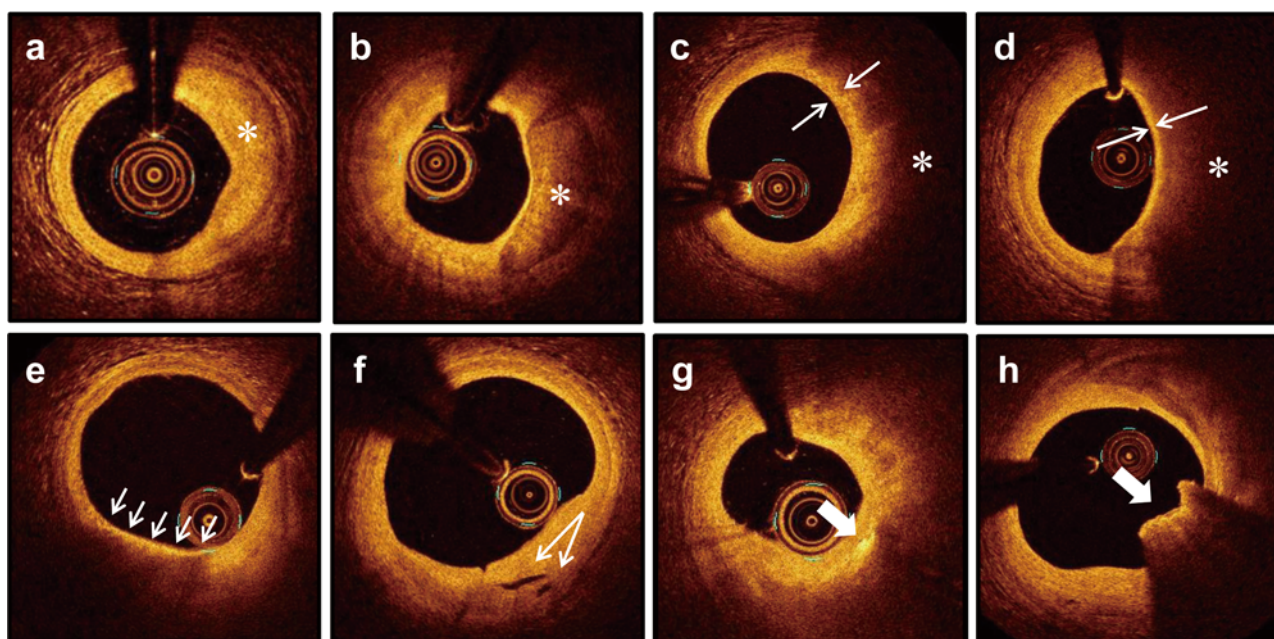


Fig. 1 Representative OCT images of coronary atherosclerosis.

Images were obtained by using ILUMIEN™ OPTIS™ OCT System (Abbot Vascular Inc., St. Paul, Minnesota, USA). [a] Fibrous plaque (asterisk). [b] Fibrocalcific plaque (asterisk: calcium). [c] Lipid-rich plaque (thick-cap fibroatheroma: arrows: fibrous cap of >65 μm thick, asterisk: lipid-rich necrotic core). [d] Lipid-rich plaque (thin-cap fibroatheroma: arrows: fibrous cap of <65 μm thick, asterisk: lipid-rich necrotic core). [e] Macrophages accumulations (arrows). [f] Vasa vasorum (arrows). [g] Cholesterol crystal (arrow). [h] Thrombus (arrow). OCT: optical coherence tomography.

delivered over a 0.014-inch guidewire through a 6 Fr or larger guiding catheter. As near-infrared light penetrates only a short distance through blood, temporary blood clearance is required for the OCT imaging. The images of OCT is obtained during contrast injection (3.0-3.5 ml/sec during 3-4 sec) from a guiding catheter. The high frame rate (180 frame/sec) and fast pullback speed (40 mm/sec) of OCT allows to image long coronary segments (150 mm). Currently, 2 types of OCT systems (ILUMIEN™ OPTIS™, Frequency-domain OCT, Abbot Vascular Inc., St. Paul, Minnesota, USA; and LUNAWAVE™, Optical frequency domain imaging, Terumo Corporation, Tokyo, Japan) are commercially available.

Plaque characterization

OCT is highly sensitive (71-96%) and specific (90-98%) for characterizing 3 types of atherosclerotic plaques such as fibrous, fibrocalcific, and lipid-rich plaque (Fig. 1) (1). A fibrous plaque has high backscattering and a relatively homogeneous OCT signal. A fibrocalcific plaque contains OCT evidence of fibrous tissue, along with calcium that appears as a signal-poor or heterogeneous region with a sharply delineated border. A lipid-rich necrotic core is a signal-poor region within an atherosclerotic plaque, with poorly delineated borders, a fast OCT signal drop-off, and little or no OCT signal backscattering, within a lesion that is covered by a fibrous cap (characterized by a signal-rich layer

overlying a signal-poor region).

Unstable plaques

OCT is feasible and safe for assessing coronary lesions with thrombosis in acute coronary syndrome (ACS). Thrombus by OCT appears as a mass attached to luminal surface or floating within the lumen. A red (red blood cell-rich) thrombus is highly backscattering and has a high attenuation (resembles blood), and a white (platelet-rich) thrombus is less backscattering, is homogeneous, and has low attenuation (2).

OCT is capable of discriminating three types of unstable plaque morphologies underlying coronary thrombosis such as plaque rupture, erosion, and calcified nodules (3-5). Plaque rupture is identified by the presence of fibrous cap discontinuity with a clear cavity formed inside the plaque. Plaque erosion is defined and categorized according to the absence of fibrous cap disruption and the presence of thrombus. Definite OCT-erosion is defined by the presence of attached thrombus overlying an intact and visualized plaque. Probable OCT-erosion is defined by luminal surface irregularity at the culprit lesion in the absence of thrombus; or attenuation of underlying plaque by thrombus without superficial lipid or calcification immediately proximal or distal to the site of thrombus. Calcified nodule is identified when fibrous cap disruption is detected over a calcified plaque characterized by protruding calcification, superficial calcium,

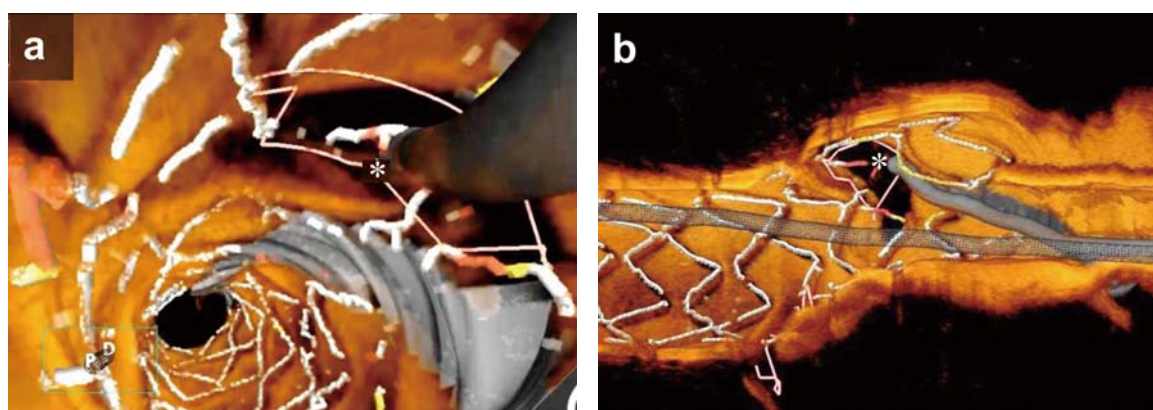


Fig. 2 Coronary stent 3D navigation.

Images were obtained by using OPTIS™ Metallic Stent Optimization Software (Abbot Vascular Inc., St. Paul, Minnesota, USA). The 3D navigation menu supports functions to move throughout the 3D rendering and object segmentation to turn on and off the displayed 3D objects including tissue, lumen, stent, wires, and side branches. [a] The 3D flythrough displays a view from the main vessel into a side branch. [b] The 3D bifurcation mode highlights a view of detected side branch ostium of a vessel. Asterisks: guide wire in the side branch, D: distal, P: proximal, Pink dots: side branch ostium, and 3D: three-dimensional.

and the presence of substantive calcium proximal and/or distal to the lesion. An OCT study reported that the frequency of plaque rupture, erosion, and calcified nodules in ACS was 44%, 31%, and 8%, respectively.

Vulnerable plaques

Thin-cap fibroatheroma (TCFA: defined by thin fibrous cap of $<65\mu\text{m}$ thick and large lipid-rich necrotic core) is considered to be a precursor of plaque rupture. The high resolution of OCT has a potential to identify the thin fibrous cap of $<65\mu\text{m}$ thick as well as the large lipid-rich necrotic core (1). In addition, OCT is capable of discriminating important features of vulnerable plaques such as macrophages, vasa vasorum, cholesterol crystals, and micro-calcifications (1). Macrophages accumulations are seen as signal-rich, distinct, or confluent punctate regions that exceed the intensity of background speckle noise. Vasa vasorum, which are microvessels within the intima/plaque, are seen as signal-poor voids that are sharply delineated and can usually be followed in multiple contiguous frames. Cholesterol crystals are seen as thin, linear regions of high intensity, usually associated with a fibrous cap or necrotic core. Micro-calcifications, so-called spotty calcifications, are seen as small calcium deposit within the fibrous cap. Coronary lesions with these vulnerable plaque features detected by OCT are associated with attenuated plaques on IVUS, yellow plaques on angioscopy, low-density plaques on computed tomography (CT), high-intensity plaques on T1-weighted magnetic resonance imaging (MRI), and ^{18}F -sodium fluoride (^{18}F -NaF) positive uptake plaques on ^{18}F -NaF positron-emission tomography (6). OCT-derived TCFA are the potential predictors of subsequent plaque progression and lumen narrowing (7). Patients with OCT-derived lipid-rich

plaques had a high risk of future adverse cardiovascular events such as cardiac death, acute myocardial infarction, and coronary revascularization (8).

Guidance of PCI

As compared with IVUS, OCT provides more accurate measurements of coronary lumen diameter and lesion length, which is useful in determining the stent size (9,10). OCT is also much more sensitive in detecting inadequate stent findings such as intrastent tissue protrusion, stent malapposition, stent edge dissection, and intrastent thrombus, which is helpful in optimizing stent implantation (11). Moreover, recently developed new stent optimization software such as OCT/angiography co-registration, three-dimensional (3D) navigation (Fig. 2), and stent apposition indicator (Fig. 3) enhances ease of use, simplifies interpretation and allows us to literally visualize a better outcome of PCI.

Follow-up of stent

The high resolution of OCT enables us to investigate neointimal coverage of coronary stents, late acquired stent malapposition, and neoatherosclerosis (defined as a development of atherosclerosis in neointima) which are associated with future stent failure. The follow-up after PCI by OCT helps to understand vessel healing in the stent-treated lesion and guide discontinuation of dual antiplatelet therapy.

Limitations

OCT has two main disadvantages when compared with IVUS. First, OCT has a relatively shallow penetration depth ($\approx 2\text{ mm}$) depending on the tissue types. OCT is not appropriate for the visualization of whole vessel and the evaluation of arterial

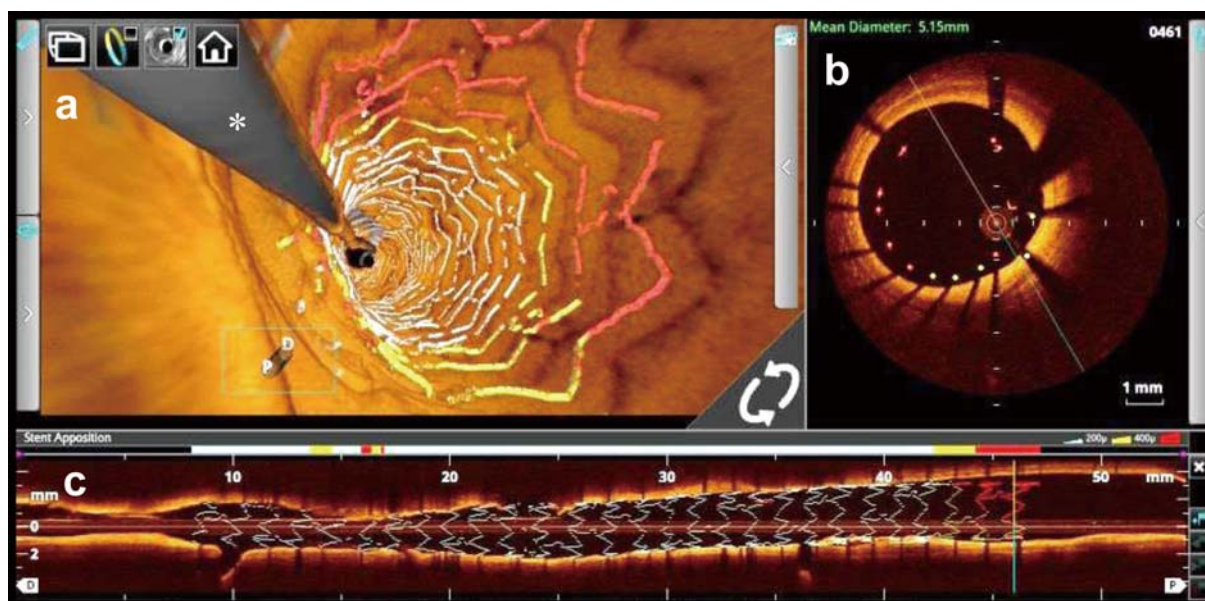


Fig. 3 Stent apposition indicator.

Images were obtained by using OPTIS™ Metallic Stent Optimization Software (Abbot Vascular Inc., St. Paul, Minnesota, USA). [a] 3D flythrough view. [b] Cross-sectional view. [c] Longitudinal-mode with apposition indicator bar. The distance between the leading edge of the stent and vessel surface is measured automatically. According to its distance, the stent struts are color-coded through red ($>400\mu\text{m}$), yellow ($200\text{--}400\mu\text{m}$) or silver ($<200\mu\text{m}$). Asterisks: guide wire; D: distal, P: proximal, and 3D: three-dimensional.

remodeling. Second, the OCT image acquisition requires blood removal by flashing contrast media through a guiding catheter. The totally occluded lesions, ostial coronary arteries, patients with renal dysfunctions are not good candidates for OCT.

Future development

There are several technology challenges in intravascular OCT. A new form of OCT, termed μ OCT that has a resolution of $1\mu\text{m}$, provides clear pictures of cellular and subcellular features associated with atherogenesis (12). Heartbeat OCT, working at 4000 frames/s and 100 mm/s pullback speed, allows visualization of a long segment of coronary artery in less than one cardiac cycle (13). Hybrid IVUS-OCT includes the deeper tissue penetration of IVUS and the superior contrast, resolution and near-field image quality of OCT (14). Hybrid near-infrared spectroscopy (NIRS)-OCT measures the wavelength-dependent interaction of near-infrared light with plaque tissue and allows better characterization of lipid-rich plaque (15). Combination of OCT and near-infrared fluorescence (NIRF)/near-infrared autofluorescence (NIRAF) enables the precise detection of macrophages and thrombi through the emission of light from a tissue that has absorbed near-infrared light (16, 17).

Conclusions

OCT allows visualization of coronary vessel microstructure with an extraordinary high resolution. OCT is a promising

technology to assess coronary atherosclerosis and to guide PCI.

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Conflicts of interest

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