

Optical Coherence Tomography Basics

An overview of OCT systems, current clinical applications, and the future of this breakthrough in imaging technology.

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Optical coherence tomography (OCT) is a novel, catheter-based, invasive imaging modality based on near-infrared light rather than ultrasound, generating high-resolution images of the arterial wall. This system allows for unparalleled imaging resolution of the coronary artery wall, including plaque characterization, assessment of coronary stent strut apposition, neointimal coverage, vascular proliferative response, complications related to percutaneous coronary intervention (PCI) (ie, focal dissection or thrombus formation), and information regarding the time course of stent dissolution for bioabsorbable stents. We discuss the advantages and limitations of this new imaging modality, with specific emphasis on its current clinical and research applications in intracoronary image generation, as well as future directions of the technology.

INTRAVASCULAR OCT SYSTEMS

OCT was initially applied in clinical settings for high-resolution scanning of the retina.¹ This technique was later adopted for intravascular OCT with a fiber optic wire that both emits light and records the reflection while simultaneously rotating and being pulled back along the length of the artery.² Because of the shorter wavelength of infrared light compared to ultrasound, OCT has a 10-fold higher axial and lateral image resolution (10–20 μm) than conventional intravascular ultrasound (IVUS) (150–200 μm) and is therefore able to provide superior arterial wall image quality (Table 1).³ Thus, OCT has recently been approved by the US Food and Drug Administration for human intracoronary imaging and provides a new perspective for intravascular imaging and lesion assessment for interventional cardiologists.

The intravascular OCT laser light source uses a bandwidth in the near-infrared with wavelengths ranging from 1,250 to 1,350 nm.² Using these wavelengths, tissue penetra-

tion is limited to 1 to 3 mm as compared to 4 to 8 mm achieved by IVUS, with the exception of calcified lesions in which sound has a limited penetration depth.³ Although longer wavelengths provide better deep tissue penetration, the optimal wavelength used in an arterial vessel is also defined by minimizing tissue absorption of light to allow more photons in the returning signal. The light reflection is also maximal at regions in the arterial wall with the greatest differences in the refractive index—mechanisms that are not relevant during IVUS. The axial resolution, determined by the light wavelength, usually ranges from 12 to 18 μm compared with 150 to 200 μm for IVUS, and the lateral resolution in catheter-based OCT is typically 20 to 90 μm as compared with 150 to 300 μm for IVUS.³

Light is split, and half is aimed at the arterial wall while the other half is aimed at a mirror at an equal distance as the arterial wall. The returning light from both the arterial wall and the mirror interfere with each other, hence the term “interferometer,” resulting in the creation of an image or A scan. Multiple A scans are acquired as the image wire rotates, and a full revolution creates a com-

TABLE 1. PHYSICAL CHARACTERISTICS OF CURRENTLY AVAILABLE FD OCT VERSUS IVUS SYSTEMS

	OCT	IVUS
Energy source	Near-infrared light	Ultrasound
Wavelength (μm)	1.3	35–80
Resolution (μm)	10–15 (axial), 40–90 (lateral)	100–200 (axial), 200–300 (lateral)
Frame rate (frames/s)	100–200	30
Pullback rate (mm/s)	10–20	0.5–1
Tissue penetration (mm)	1–2.5	10

plete cross-section of the vessel wall. A second factor affecting image formation, which is similar with IVUS, is the time it takes for emitted light to travel back from the target tissue to the lens, producing an “echo time delay.” Further discussion of the physics of OCT is beyond the scope of this article. However, it is important to mention that compared to the initial time-domain (TD) OCT systems, newer generations of intravascular OCT systems, termed “frequency-domain” or “Fourier-domain” (FD) OCT, allow the simultaneous detection of reflections from all echo time delays, resulting in a much faster system for image acquisition.⁴ It is this last advance that has allowed widespread application of OCT to the catheterization laboratory, where an entire coronary artery can be interrogated with a single flush. There are two types of FD OCT systems, which differ in their method of data generation: optical frequency domain imaging, also known as “swept OCT,” and spectral-domain OCT.

OCT DEVICE DESCRIPTION, IMAGE ACQUISITION, AND SAFETY

Even though the earlier-generation TD OCT systems have been available for quite some time, the FD OCT C7-XR system with its C7 Dragonfly catheter (LightLab Imaging, Inc., a St. Jude Medical, St. Paul, MN) has recently been approved by the US Food and Drug Administration as the first OCT system in North America. The C7-XR system consists of an intravascular OCT catheter, an imaging engine, and a computer. This system is equipped with a tunable laser light source with a sweep range of 1,250 to 1,350 nm. The C7-XR is used with the Dragonfly imaging catheter, a monorail 2.7-F catheter system that is compatible with standard curve 6-F guide catheters and has a light source in an optical fiber that is encased in a rotating torque wire. The imaging catheter can be delivered over a conventional 0.014-inch coronary guidewire. The OCT catheter is withdrawn proximal to the analyzed segment using an automated pullback system during simultaneous contrast infusion at a rate of approximately 4 mL/s.

The infrared light is unable to penetrate red blood cells and, in fact, scatters off the red cells. Thus, OCT imaging must be performed in a blood-free environment. Although proximal balloon occlusion of the coronary artery was required to create a blood-free environment during image acquisition with the earlier TD systems, accelerated pullback speeds of newer FD OCT systems permit the use of a single, high-rate bolus injection of contrast (approximately 4 mL/s) to produce a blood-free environment, thus eliminating the need for balloon occlusion.^{5,6} Contrast is preferred over saline because its greater viscosity more effectively clears blood from the

vessel being imaged and delays the return of blood as well. The C7-XR system acquires images at a rate of 100 frames/s at a pullback speed of up to 10 to 20 mm/s. Thus, a 5-cm length of a coronary artery can be scanned in less than 3 seconds. Once activated, the C7-XR console will automatically sense the clearance of blood from the vessel lumen and initiate an automated pullback at 10 mm/s.⁷ The images will be displayed on the console unit for interpretation by the operator.

Besides the C7-RX system, Terumo Interventional Systems (Somerset, NJ) is developing an FD OCT system with a 2.4-F shaft. Volcano Corporation (San Diego, CA) has a third-generation FD OCT system under development with a rapid-exchange nitinol-hybrid drive shaft.⁸ The goal of all these devices is to scan the proximal two-thirds of the coronary artery in as little as 1 second using the Low Volume OCT imaging system (Volcano Corporation). Developing the Low Volume OCT imaging system will be the key to allowing interventional cardiologists to acquire OCT images during a routine coronary angiographic injection. This extremely low flush volume is expected to allow for optimal imaging while maximizing patient safety, clinical utility, and ease of use for the physician and staff.

The potential procedural risks that are associated with use of OCT have been shown to be comparable to IVUS in clinical evaluations thus far.⁹⁻¹³ Transient events, such as chest discomfort and ST changes, were observed without hemodynamic instability in some patients. The advantages of the new FD OCT as compared to TD OCT have been further supported by studies showing lower mean procedure time, less ischemic changes, and fewer ischemic symptoms.⁷

IMAGE INTERPRETATION AND ARTIFACTS

Operator-adjustable manual calibration, so-called Z-offset, carries critical importance for accurate measurements. For the C7-XR system, four crescent-shaped marks in the OCT image delineate the outer boundary of the OCT catheter. The proper alignment of these markers with the catheter image is important for manual image calibration.³ This is important because even a small difference in Z-offset calibration can result in significant differences in vascular measurements.¹⁴

There are some imaging artifacts that every operator using OCT needs to be familiar with. Some of these artifacts, which are also common with IVUS use, are shown in Figure 1:

- Residual blood can obscure imaging of the wall and can mistakenly be labeled as red thrombus.
- Nonuniform rotational distortion similar to IVUS occurs as a result of variation in the rotational speed

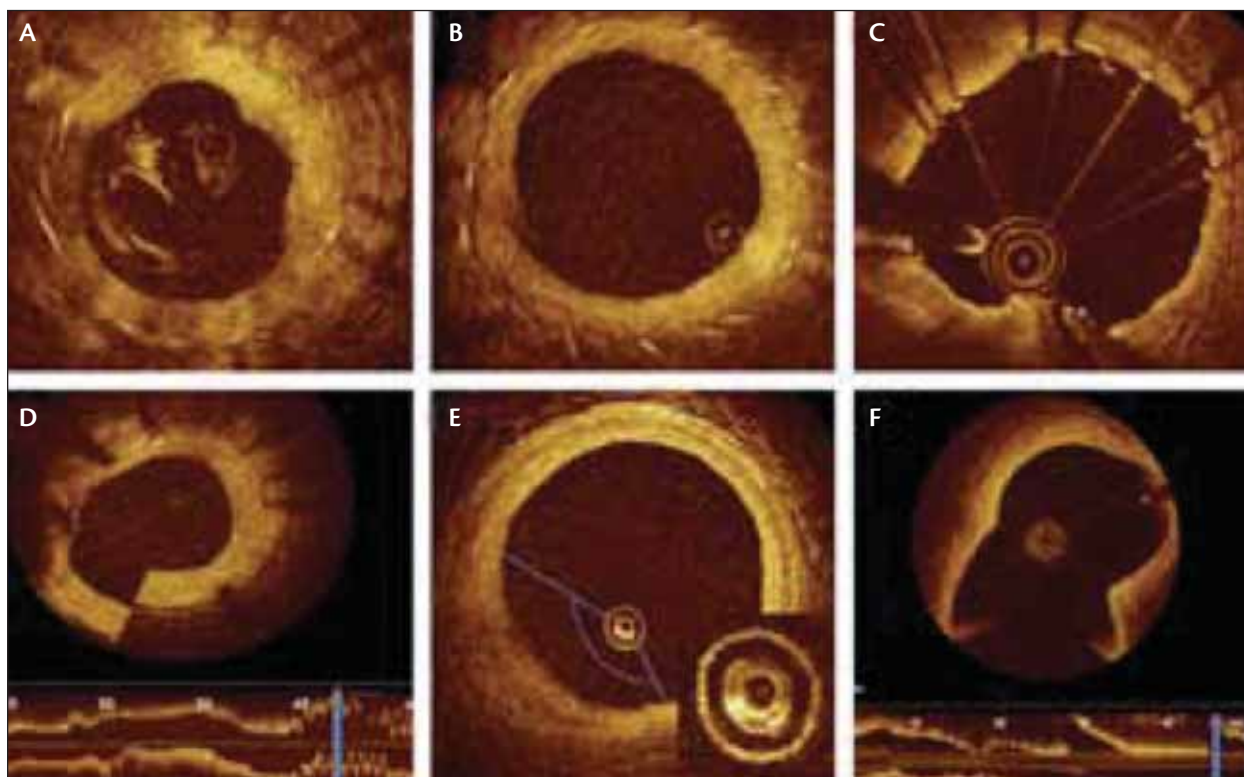


Figure 1. Cross-sectional image of the human coronary artery. Most frequently observed artifacts: incomplete blood displacement resulting in light attenuation (A); an eccentric imaging wire can distort stent strut reflection orientation (note that struts appear to be perpendicular to the light source, this is known as the “sunflower” effect) (B); saturation artifact—some scan lines have a streaked appearance (C); sew-up artifact due to rapid wire or vessel movement along one frame formation, resulting in misalignment of the image (D); air bubbles formed inside the catheter produce an attenuated image along the corresponding arc. Detail reveals the bubbles (bright structures) between 5 and 9 o’clock (E). With fold-over artifact (FD OCT system), the longitudinal view shows that the cross-section is located at the level of a side branch (blue line) (F). Reprinted with permission from Bezerra HG et al. *JACC Cardiovasc Interv.* 2009;2:1035–1046.³

of the spinning optical fiber, although there is evidence that it is less significant with OCT.

- Sew-up artifact occurs as a result of misalignment of the lumen border from subsequent images during pullback.
- Saturation artifact is the result of light reflection from a highly specular surface, such as stent struts, that produce signal amplitudes exceeding the dynamic range of the data acquisition system.
- Fold-over artifact occurs when the structural signals are reflected outside the system’s field of view as dropouts and typically occur in large vessels or distant side branches.
- Bubble artifact from small bubbles inside the imaging catheter can produce attenuated images.
- Sunflower effect occurs as a result of eccentric OCT catheter positions and can artifactually turn stent struts toward the light source, creating the mistaken impression of poor strut apposition to the vessel wall.

Most of the vascular measurements with OCT are very similar to IVUS (minimal lumen diameter, minimal lumen area, reference lumen diameter, reference lumen area lesion length, etc.).

OCT IN ATHEROSCLEROSIS IMAGING

Despite the lack of prospective studies, it is generally accepted that acute coronary syndromes are primarily caused by rupture of an inflamed thin-capped fibroatheroma (TCFA).¹⁵⁻¹⁸ TCFA is characterized by three key components: a large lipid core, inflammatory cell infiltration, and a thin fibrous cap (Figure 2).¹⁹ The criterion for TCFA on OCT is a lipid-rich plaque (lipid core occupying > 40% of the vessel wall) with fibrous cap thickness < 65 μm .¹⁵⁻¹⁸ Although TCFA tend to localize within the proximal segment of the left anterior descending artery, they are evenly distributed throughout the entire left circumflex and right coronary arteries.²⁰ Multiple OCT-derived TCFA have been observed

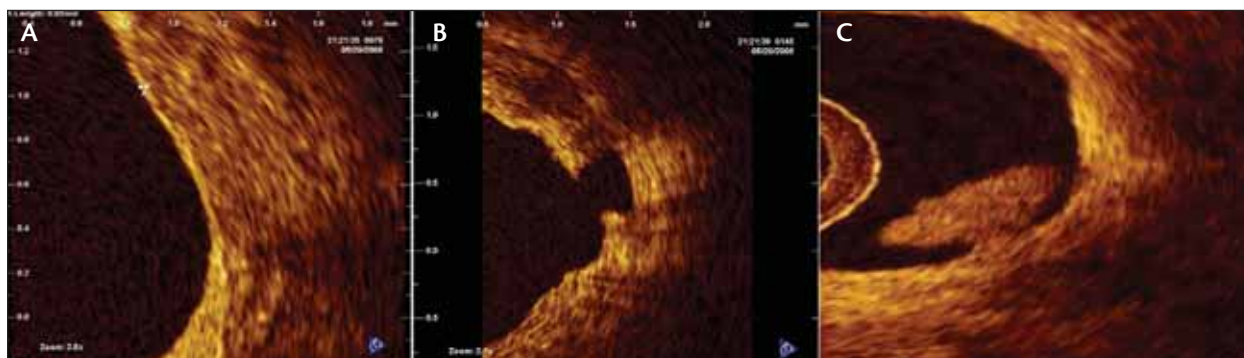


Figure 2. OCT imaging of TCFA in the pathogenesis of acute coronary syndromes. TCFA is characterized by a thin fibrous cap and a large lipid core (A). So-called volcanic erupted base of a ruptured plaque is imaged in a patient who presented with acute coronary syndrome (B). Intraluminal thrombus is noted with plaque rupture in a patient presenting with a non-ST-elevation myocardial infarction (C).

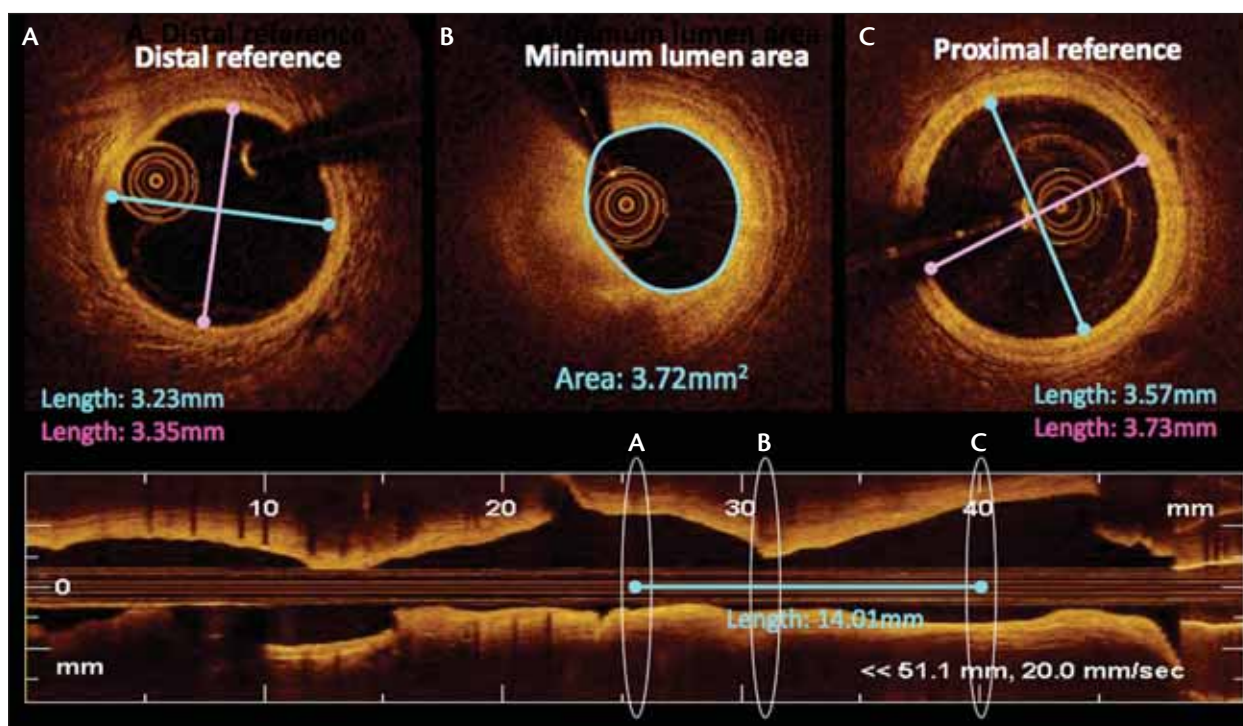


Figure 3. FD OCT measurements at preintervention. FD OCT is a powerful modality to guide PCI. OCT can provide accurate reference vessel diameter, minimum lumen area, and lesion length. OCT images with sharp depiction of the boundaries between lumen and vessel wall has practical advantages over IVUS. The OCT images are easier to interpret, and fully automated lumen segmentation reduces the guesswork in lesion determination. This will facilitate correct selection of stent diameter and length in PCI.

in up to 38% of patients with acute myocardial infarction in infarct- and noninfarct-related lesions.²¹ In patients taking statins, fibrous cap thickness has been shown to increase compared to controls using OCT as the imaging tool.²²

The interface between the fibrous cap and the lipid pool produces a bright OCT reflection. However, because of both the imaging depth limitation of OCT and light

being absorbed by the arterial wall components, OCT has difficulty defining the full extent of the lipid pool and vascular remodeling. On the other hand, in contrast to ultrasound, light can penetrate calcium, and OCT studies reported a sensitivity of 96% and specificity of 97% to detect calcified nodules and probably microcalcifications, which are also key markers for plaque vulnerability and lesion complexity for PCI.^{23,24}

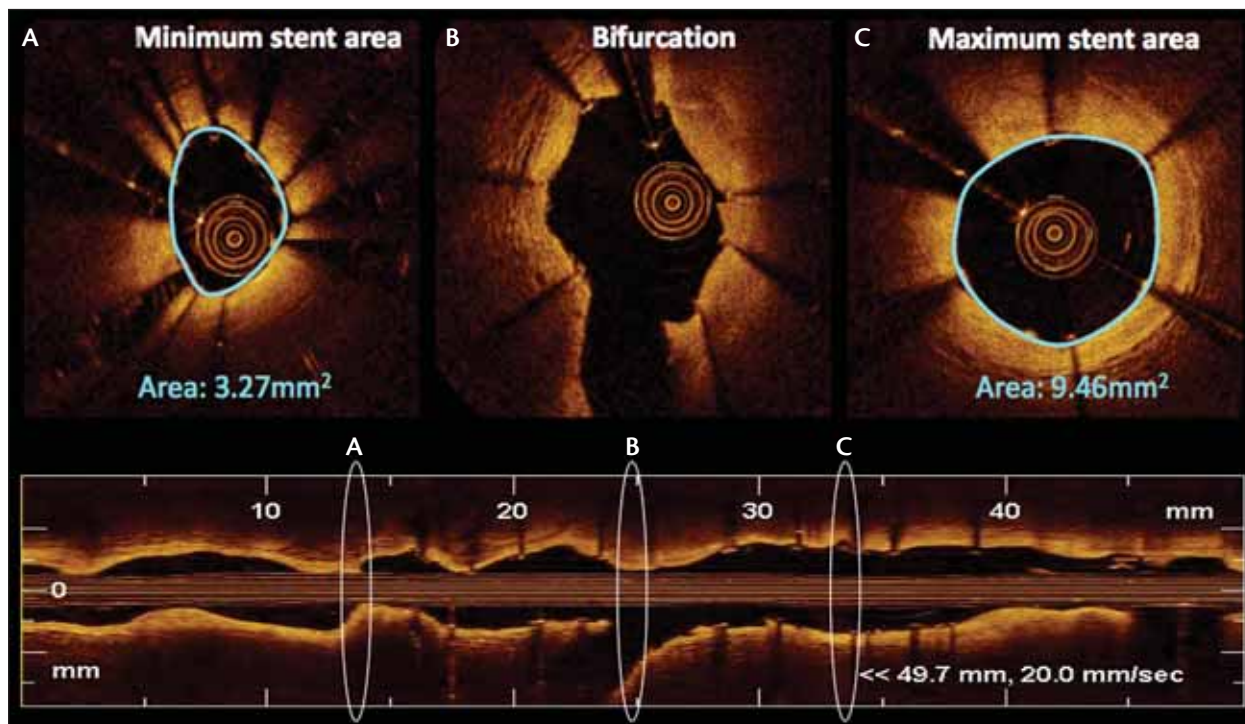


Figure 4. FD OCT measurements postintervention. OCT can provide minimum and maximum stent areas after stent deployment and assist with the decision of whether postdilation for optimal stent deployment and stent apposition to the vessel wall has been achieved. The bifurcation ostium from the main vessel can also be visualized.

Vascular inflammation with macrophage-rich infiltrates has previously been identified with OCT by our group and others; however, it remains unclear if quantitative assessment of an inflammatory cell density may be determined using OCT images.²⁵⁻²⁷ Previous studies also suggested that it is possible to identify thrombus by OCT and even discriminate between red and white thrombus, as confirmed by histopathologic correlation.²⁸ The clinical implications of these findings will have to be determined in prospective clinical trials.

OCT IN CORONARY INTERVENTION

OCT image guidance during PCI can be helpful in both lesion assessment (plaque rupture, stent malapposition, etc.) as well as in optimal sizing of the stent (reference vessel diameter, lesion length). Additional measurements, such as minimal lumen area (Figure 3), percent lumen stenosis, stent apposition, stent expansion, minimal stent cross-section area, lumen gain, late lumen loss, and residual stenosis are all based on the proper evaluation of the lumen/vessel/stent interface and thus are available to OCT.²⁹⁻³² OCT images with sharp depiction of the boundaries between lumen and vessel wall has practical advantages over IVUS. The OCT images are easier to interpret, and fully automated lumen segmentation reduces the guesswork in lesion

determination. This should facilitate correct selection of stent diameter and length in PCI (Figure 4). Although real-world validation has not yet been performed, typically, a minimal luminal area of 4 mm² found in an epicardial coronary artery, excluding the left main, is thought to represent a significant lesion when OCT imaging is undertaken, as it would be with IVUS.³³ However, there is concern that (1) OCT generates smaller lumen measurements than IVUS, in part due to balloon occlusion with TD OCT systems, and (2) more recent IVUS studies are showing that a 4-mm² cutoff may be too liberal.

The ability of OCT to penetrate and delineate calcium in the vessel wall also makes it well suited to guide complex interventional strategies in vessels with superficial calcification. Incomplete stent apposition (ISA) has been implicated as a potential factor in the development of late stent thrombosis.³⁴ Compared to IVUS, OCT has been shown to have a higher sensitivity for imaging individual stent struts and malapposed strut assessment.^{35,36} ISA may occur either acutely at the time of stent deployment or later as a consequence of vessel remodeling. In fact, in current clinical stent trials, OCT imaging has increasingly been used to assess stent apposition and individual strut coverage with intimal

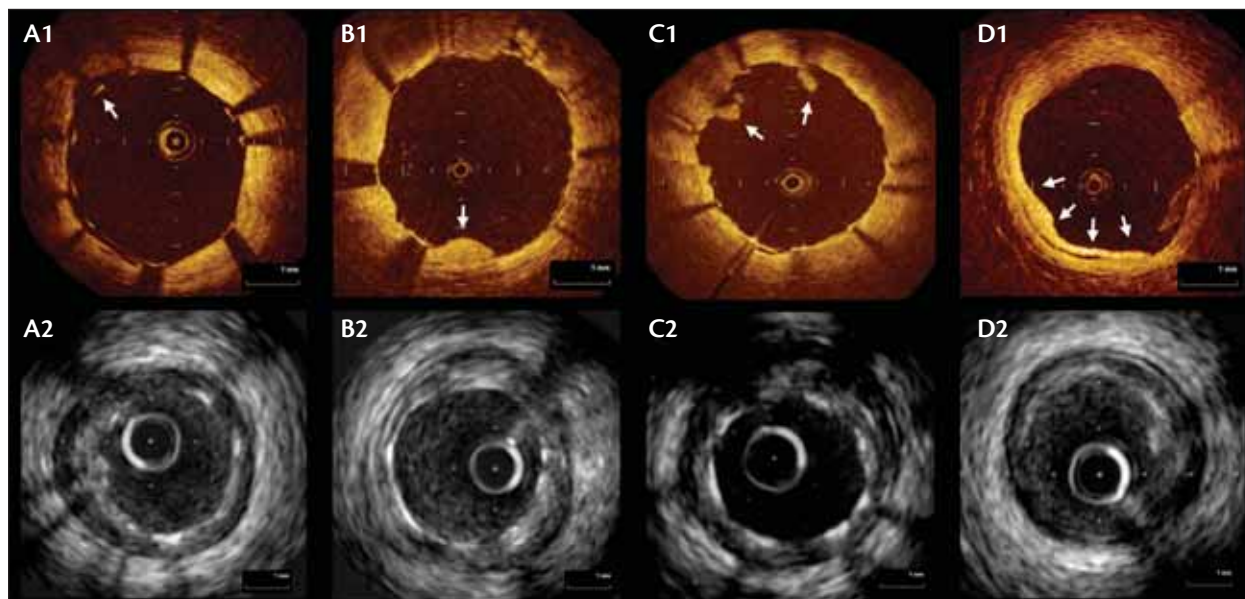


Figure 5. OCT and IVUS images of stented lesions. OCT-visualized inadequate stent strut apposition (A1; arrows). It was not shown clearly on IVUS (A2). Tissue protrusion between stent struts was observed in OCT image (B1; arrow). It was not evident in the IVUS image (B2). Intracoronary thrombi were identified as intraluminal pedunculated masses without shadow by OCT (C1; arrows). They were not detected by IVUS (C2). Coronary dissection at the site of the stent edge was demonstrated by OCT (D1; arrows). IVUS documented dissection (5 o'clock) and clot (2 o'clock) (D2). Reprinted with permission from Kubo T et al. *JACC Cardiovasc Imaging*. 2008;1:475–484.¹¹

hyperplasia as a safety endpoint.^{37–41} Histological studies have revealed that IVUS does not have adequate resolution to detect the thinnest layer of tissue coverage, and the perception that lack of neointimal hyperplasia by IVUS is synonymous to an uncovered strut needs to be reconsidered.⁴² Some studies have shown that up to 40% of struts may remain malapposed despite optimal high-pressure postdilation.⁴³ Late ISA and uncovered struts are more common in patients with ST-elevation myocardial infarction.⁴⁴ The entrapment of thrombus within the stented segment during primary PCI, which later resolves, has been proposed as the mechanism underlying this important observation. The impact of these observations on patient care has not yet been determined.

Despite its high resolution, OCT is limited in detecting strut coverage that may only be composed of single endothelial cells because a normal endothelial coverage is beyond the resolution of OCT. OCT has also enabled the detection of procedural complications, such as edge dissection, that are not detectable with conventional IVUS or coronary angiography (Figure 5).^{45,46} OCT also has a higher sensitivity than IVUS for detecting tissue prolapse after stenting, although clinical significance of this observation remains to be determined.^{47,48}

FUTURE IMPLICATIONS

Although OCT has emerged as a new intracoronary imaging modality with high resolution, no large-scale prospective studies have shown a relationship between OCT findings and clinical outcomes to date. At present, OCT is the only imaging technology with a resolution high enough for detection of TCFA and studying its progression and regression in patients with coronary atherosclerosis. On the other hand, OCT is certainly becoming an integral tool to study emerging stent technologies, such as bioabsorbable stents and polymers, and intimal thickness of other experimental stents. IVUS does not have the resolution or capability of imaging polymeric stent struts dissolution or strut intimal thickness. Also, neointima thickness covering drug-eluting stents has important clinical implications for predicting late stent thrombosis and for determining the optimal duration of dual-antiplatelet therapy.

CONCLUSION

OCT is a new imaging modality that allows for high-resolution assessment of the coronary artery lumen, coronary stent strut apposition, neointimal coverage thickness, vascular proliferative response, and PCI-related complications, such as focal dissection or thrombus formation. Imaging with OCT appears to have several advantages over IVUS in

the assessment of atherosclerotic plaque morphology and outcomes of poor stent apposition. However, similar to the earlier days with IVUS, we will continue to learn more about this technique, which will require further studies to reliably obtain and interpret OCT images, leading to a better understanding of vulnerable plaque and the optimization of treatment algorithms for our patients. ■

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