High-Resolution Lesion Assessment With OCT

What every interventional cardiologist needs to know about this FDA-approved imaging modality.

BY SAHIL A. PARIKH, MD, AND MARCO A. COSTA, MD, PHD

Cardiovascular optical coherence tomography (OCT) uses light and its reflection to generate high-resolution images of the arterial wall. Although this technology has been available outside of the United States for some time, the recent US Food and Drug Administration approval of the C7-XR OCT device (LightLab Imaging Inc., a St. Jude Medical company, St. Paul, MN) has brought this new technology into the hands of interventional cardiologists across the United States. Thus, OCT is poised to provide a new perspective on intravascular imaging and lesion assessment in the United States. This article elucidates the basic principles of OCT, defines possible calibration and imaging artifacts with OCT, and identifies potential clinical applications of this technology for operators who are unfamiliar with its use.

PRINCIPLES OF OCT

OCT was developed from concepts of light reflectometry, initially in one dimension and then in two dimensions.[1,2] The technique was adopted in a variety of biomedical applications including high-resolution retinal scanning.[3] Intravascular OCT was subsequently developed with a fiber optic wire that both emits near-infrared light (1,250–1,350 nm) and records its reflection while rotating 360°.[4] At these wavelengths, tissue penetration ranges between 1 to 3 mm, in contradistinction to the 4- to 8-mm penetration achieved with intravascular ultrasound (IVUS).[5] Despite the lower penetration depth, OCT has an axial resolution of 12 to 18 µm compared to 150 to 200 µm for IVUS, with a lateral resolution of 20 to 90 µm compared to 150 to 300 µm for IVUS.[5] The biophotonics and physics of OCT are well reviewed elsewhere, but it is generally held that, in a typical human coronary artery, the use of OCT results in a gain in resolution when compared to IVUS (Figure 1).[1,5-9]

To obtain these images, blood must be cleared from the vessel and replaced with a solution with a known index of refraction. Typically, saline or contrast must be injected into the artery to obtain a clear image. Early versions of OCT imaging required balloon occlusion of an artery for up to 30 seconds during image acquisition. However, subsequent generations of OCT technology with faster pullback speeds have reduced image acquisition times to < 3 seconds per artery, which is approximately the same duration as that of a standard coronary injection for diagnostic angiography.[5,10] Naturally, this advance in image acquisition speed obviates the need for long ischemic times to obtain OCT images.

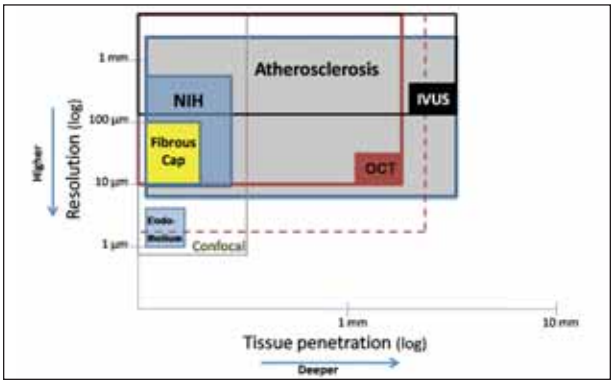

Figure 1. Graphical representation of tissue penetration versus spatial resolution of OCT compared with other imaging methods. The solid boxes represent the maximal resolution and depth achieved with current technologies. The larger, open boxes represent the range of resolution and tissue penetration for each of the technologies. The dashed box illustrates the hypothetical capabilities of future OCT systems. Resolution requirements to accurately detect neointimal hyperplasia observed after drug-eluting stent deployment usually exceed the capabilities of IVUS. Similarly, fibrous cap thickness can only be assessed in vivo by OCT. Atherosclerosis = early and advanced stages of the process; endothelium = single intimal cell layer; fibrous cap = thickness range related to thin-cap fibroatheroma. Reprinted from JACC Cardiovasc Interv, Vol. 2, Bezerra HG, et al. Intracoronary optical coherence tomography: a comprehensive review: clinical and research applications. 1035–1046, Copyright (2009), with permission from Elsevier.[5]

TABLE 1. PHYSICAL CHARACTERISTICS OF OCT VERSUS IVUS

	OCT[a]	IVUS[b]
Energy source	Near-infrared light	Ultrasound (20–45 MHz)
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
Maximum scan diameter, mm	11	15
Tissue penetration, mm	1–2.5	10

[a]Based on specifications of the C7-XR frequency-domain OCT imaging system.
[b]Based on specifications of the current generations of Volcano Corporation (San Diego, CA), Boston Scientific Corporation (Natick, MA), and Terumo Interventional Systems (Somerset, NJ) IVUS systems.
Adapted from Prati F, et al. Expert review document on methodology, terminology, and clinical applications of optical coherence tomography: physical principles, methodology of image acquisition, and clinical application for assessment of coronary arteries and atherosclerosis. Eur Heart J. 2010;31:401–415 with permission from Oxford University Press.[7]

TABLE 2. GENERAL CHARACTERISTICS OF DIFFERENT TISSUES BY OCT[a]

Tissue	Backscattering	Attenuation	General Aspects
Calcium	+	+	Sharp borders, low signal with heterogeneous regions
Lipids	++	+++	Irregular borders, superficial high signal followed by very low signal
Fibrotic	++	+	Homogeneous bright tissue
Red thrombus	+++	+++	Superficial signal rich, low penetration, signal-free shadowing
White thrombus	+++	+	Signal rich, more penetration than for red thrombus
Media layer	+	+	Low-signal region, limited by two signal-rich bands (IEL/EEL)
IEL/EEL	+++	+	High-signal band (~ 20 µm)

Abbreviations: IEL/EEL, internal elastic lamina/external elastic lamina.
[a]+ = low; ++ = moderate; +++ = high.
Reprinted from JACC Cardiovasc Interv., Vol. 2, Bezerra HG, et al. Intracoronary optical coherence tomography: a comprehensive review: clinical and research applications. 1035–1046, Copyright (2009), with permission from Elsevier.[5]

COMMERCIAL OCT SYSTEMS AVAILABLE IN THE UNITED STATES

Although earlier-generation, time-domain OCT systems have been available in Europe, Asia, and South America, the first OCT system approved by the US Food and Drug Administration (granted on May 5, 2010) is the frequency domain C7-XR, with its companion C7 Dragonfly catheter. 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, with the potential to scan up to a 5-cm length of a coronary artery in under 3 seconds.[10,11] Rapid pullback speeds enable short, low-volume bolus injections of contrast to sufficiently clear the selected coronary artery for high-resolution OCT image acquisition. The C7-XR is used with the Dragonfly imaging catheter, a monorail 2.7-F catheter system that is compatible with standard 6-F guide catheters and has a light source in an optical fiber that is encased in a rotating torque wire.

Image acquisition is accomplished after coaxial engagement of the guide catheter, advancement of a standard 0.014-inch coronary guidewire into the distal coronary artery, and advancement of the OCT catheter beyond the area of interest in the vessel. Typically, automated power-injection of contrast (14 mL in the left coronary circulation and 10 mL in the right coronary circulation, as is the protocol in our catheterization laboratory) over 3 seconds will sufficiently clear blood from the vessel to adequately image the vessel with OCT. Contrast is preferred to saline because its viscosity more effectively clears blood from the vessel. Once armed, the C7-XR console will automatically sense clearance of blood from the vessel and will initiate an automated pullback at 10 mm/s.[10] Images will then be displayed on the console unit for consideration by the operator.[10]

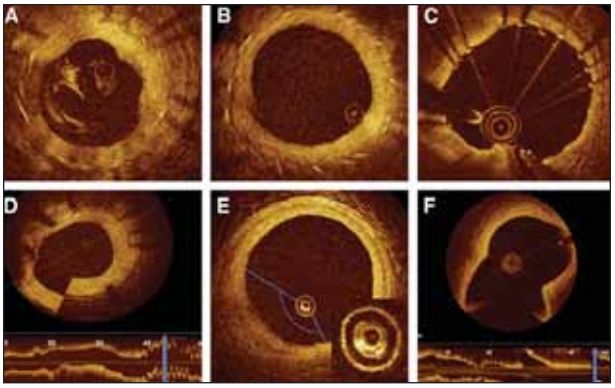

Figure 2. Cross-sectional image of the human coronary artery. Most frequently observed artifacts: incomplete blood displacement resulting in light attenuation (A); an eccentric imaging wire can distort stent strut reflection orientation (note that struts appear to be perpendicular to the lumen, this is known as the "sunflower" or "merry-go-round" effect) (B); saturation artifact, some scan lines have a streaked appearance (C); sew-up artifact: result of 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); fold-over artifact (Fourier-domain OCT system), the longitudinal view shows that the cross section is located at the level of a side branch (blue line) (F). Reprinted from JACC Cardiovasc Interv., Vol. 2, Bezerra HG, et al. Intracoronary optical coherence tomography: a comprehensive review: clinical and research applications. 1035–1046, Copyright (2009), with permission from Elsevier.[5]

Previous generations of OCT have proven to be safe and comparable to IVUS in clinical evaluation.[12-14] However, as with IVUS, the OCT catheter can cause transient occlusion of the vessel in areas of tight stenosis and cause ischemia or injury to the vessel. In addition to the C7-RX system, Terumo Interventional Systems and Volcano Corporation are also developing OCT systems.[5] The differences between OCT and IVUS are depicted in Figure 1 and Table 1.

OCT IMAGE INTERPRETATION: CALIBRATION AND IMAGING ARTIFACTS

Although intravascular imaging principles are familiar to most interventional cardiologists given the prevalence of IVUS, several key features are unique to OCT and should be understood by practitioners who are considering its use. One term that may be new to those uninitiated in OCT imaging is the "Z-offset," which is an operator-adjustable manual image calibration. This parameter is particularly important for obtaining accurate measurements. In the C7-XR system, four crescent-shaped marks in the OCT image delineate the outer boundary of the OCT catheter in situ,

TABLE 3. VESSEL MEASUREMENTS THAT CAN BE MADE WITH OCT[7]

Stenosis	Obstructive lesion comprising > 50% reduction in lumen area
Minimal lumen area	Smallest lumen area within a lesion
Reference lumen area	Lumen area of a proximal or distal segment
Maximum lumen diameter	Largest lumen diameter measured from intimal edge to intimal edge across a target lesion
Minimum lumen diameter	Smallest lumen diameter measured from intimal edge to intimal edge across a target lesion
Lesion length	Measured from longitudinal view with automated pullback
Luminal area stenosis	Decrease in luminal area by a stenosis compared to a reference segment in the same vessel (minimal lumen area divided by reference lumen area)

Adapted from Prati F, et al. Expert review document on methodology, terminology, and clinical applications of optical coherence tomography: physical principles, methodology of image acquisition, and clinical application for assessment of coronary arteries and atherosclerosis. Eur Heart J. 2010;31:401–415 with permission from Oxford University Press.[7]

and proper alignment of these markers coincident with the catheter image will ensure accurate intravascular measurements.[5] Calibration by adjusting the Z-offset is critically important—previous work in our OCT imaging core laboratory has shown that 1% differences in Z-offset calibrations resulted in 12% to 14% differences in vascular area calculations.[5] Thus, during the initial training period with OCT, particular attention must be paid to this parameter.[7]

In addition to calibration concerns, there are several possible imaging artifacts that may be observed in OCT imaging. As with IVUS, there are no substitutes for experience and training. We list some common imaging artifacts for reference here and depict them in Figure 2:

- Residual blood is the most common artifact and can obscure imaging of the vascular wall.
- Nonuniform rotational distortion is a result of rotational bias of the imaging system with resultant image distortion similar to that seen with IVUS.
- Sew-up artifact results in misalignment of subsequent images from pullback.
- Saturation artifact is observed when particularly dense objects, such as stent struts, are imaged and appear bright or "bloom" on OCT imaging.

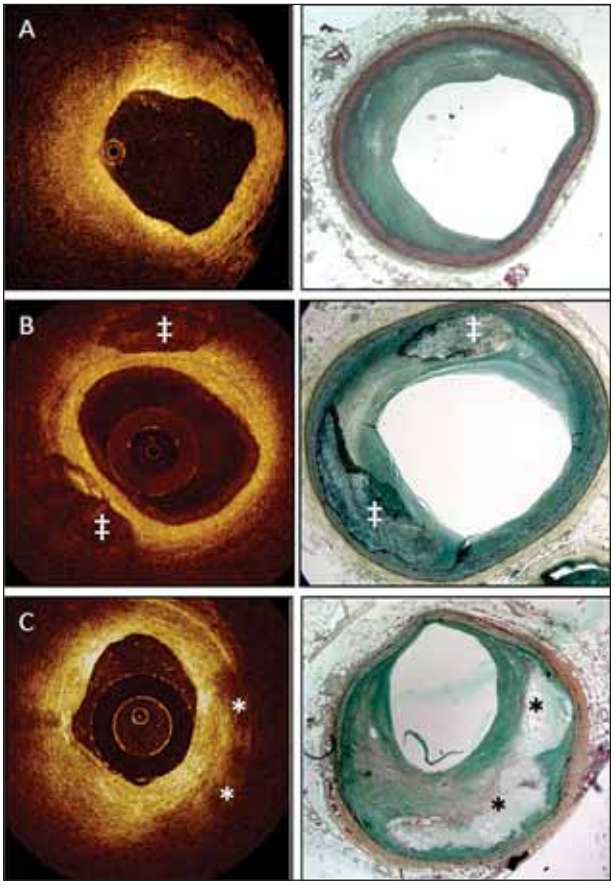

Figure 3. OCT histology correlation. Fibrotic plaque: characterized by high signal (high backscattering) and low attenuation (deep penetration) (A). Predominantly calcified plaque: calcified regions have a sharp border, low signal, and low attenuation permitting deeper penetration (B). Lipid-rich plaque: the lipid core has a diffuse border. High levels of light attenuation result in poor tissue penetration (in contrast to calcified regions). The overlying fibrotic cap can be readily measured; in this case a thick cap (> 200 µm) is present (C). ‡Calcified region; *lipid core. Reprinted from JACC Cardiovasc Interv., Vol. 2, Bezerra HG, et al. Intracoronary optical coherence tomography: a comprehensive review: clinical and research applications. 1035-1046, Copyright (2009), with permission from Elsevier.[5]

- Bubble artifact occurs when tiny bubbles form inside the catheter, distorting the image.
- Fold-over artifact results in signal dropout at the sites of side branches or vessels larger in diameter than the dynamic range of OCT.

Vascular measurements with OCT are similar to those made via IVUS. Some common measurements are listed in Table 2. Although real-world validation has not yet been performed, typically, a minimal luminal area of 4 mm^2 found in an epicardial coronary artery (not the left main) is thought to represent a significant stenosis when OCT imaging is undertaken, as it would be with IVUS.[15]

POTENTIAL CLINICAL APPLICATIONS OF OCT

The images obtained with OCT are often breathtaking. However, from a clinical perspective, these high-resolution images have very practical applications in both preinterventional assessment of atherosclerosis and in guiding interventions. Thus, it is in these two areas that OCT is likely to gain a foothold in clinical practice.

IMAGING OF ATHEROSCLEROSIS

Given the extremely high-resolution of OCT images, diagnostic lesion assessment with this technology can provide startling images of the atherosclerotic plaque. Imaging the various biological components of active atherosclerotic plaque has been reported by many investigators, with each constituent element of the plaque having particular imaging characteristics on OCT (Table 3).[16-22] A great deal of investigation has assessed the role of the thin-capped fibroatheroma in the pathogenesis of acute coronary syndromes.[6,19,23-25] These lesions typically consist of a thin fibrous cap, an inflammatory cell infiltrate at the margins of the cap, and a lipid core.[6] Although OCT cannot always penetrate very deeply into the vascular wall, its luminal resolution provides extremely reliable imaging of the thin fibrous cap, which *may* identify a vulnerable lesion that is at risk for rupture. Although the definition of *vulnerable plaque* is controversial, OCT can identify ruptured plaques with high degrees of accuracy (Figure 3).[5,17,26] Vascular inflammation with macrophage-rich infiltrates have previously been identified with OCT; however, it remains unclear if quantitative assessment of an inflammatory cell burden may be imputed from an OCT image.[11,19,22] Unlike IVUS, the penetration of vascular calcium by light results in images with well-defined boundaries of calcium (Figure 3), and sensitivity and specificity for identification of calcium have been determined to be 96% and 97%, respectively.[17] Finally, although some operators claim to be able to differentiate red from white thrombus, our experience with this is less definitive.[5,27] To summarize, OCT provides extremely high-resolution images of atherosclerotic plaque, particularly the fibrous cap with possible plaque rupture and the presence of calcium, thrombus, and a lipid core. For lesion assessment, these characteristics will demonstrate superior image clarity and accuracy when evaluating coronary stenoses, which should improve decision making when planning percutaneous coronary intervention (PCI) or an alternate therapy.

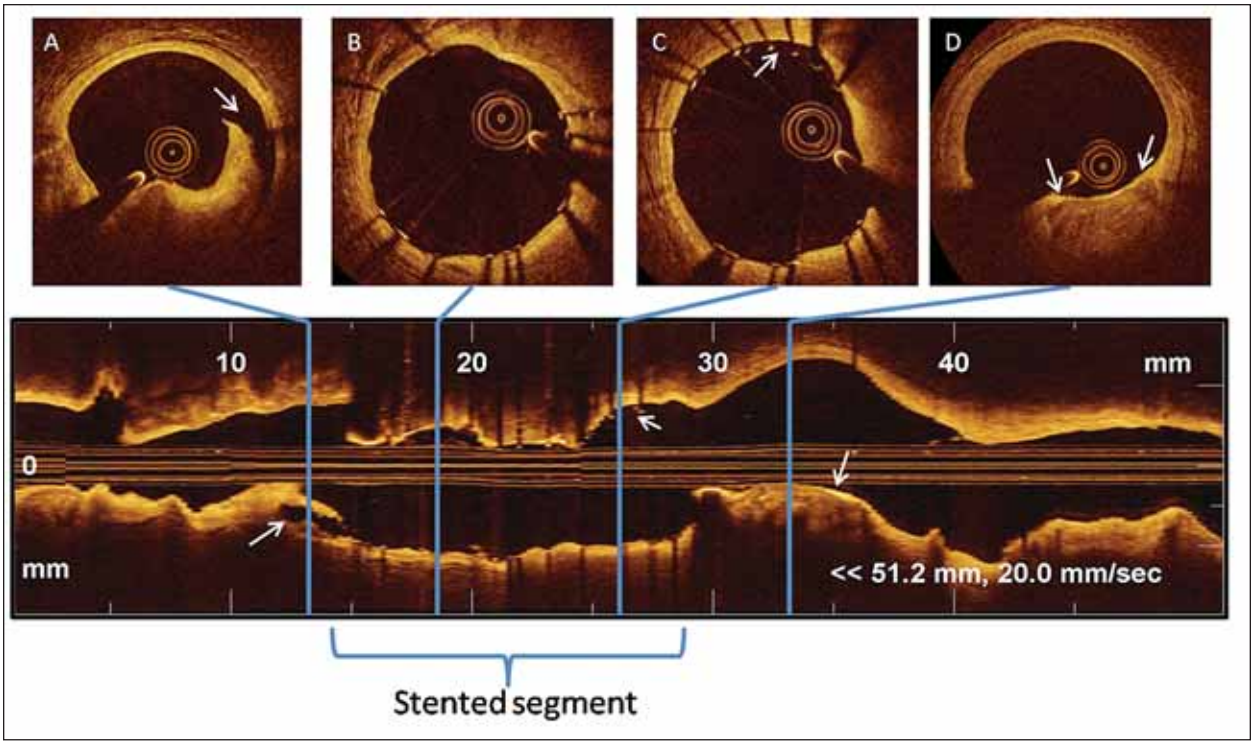

Figure 4. Coronary imaging acquired with a Fourier-domain OCT system. A longitudinal reconstruction (lower panel) and cross-sectional images (upper panels) acquired with a frequency or the C7-XR OCT system at 20 mm/s immediately after stent implantation. Note that a 5-cm coronary segment was imaged with a 3-second contrast injection. Distal edge dissection with corresponding longitudinal view (arrows) (A). Well-expanded and well-apposed stent struts with corresponding longitudinal view (B). Malapposed struts between 11 and 1 o'clock with corresponding longitudinal view (arrows) (C). Proximal calcified plaque with minimal fibrous coverage with corresponding longitudinal view (arrows) (D). Reprinted from JACC Cardiovasc Interv., Vol. 2, Bezerra HG, et al. Intracoronary optical coherence tomography: a comprehensive review: clinical and research applications. 1035–1046, Copyright (2009), with permission from Elsevier.[5]

OCT-GUIDED PCI

During PCI, OCT imaging can be particularly helpful in lesion sizing (both diameter and length), and the added resolution of OCT can identify culprit plaque rupture and stent malapposition, as previously discussed. Better lumen quantification remains the primary advantage of intravascular imaging over angiography in PCI because the sharp contrast between the lumen and the vessel wall obtained with OCT has practical advantages over IVUS. The images are often easier to interpret, and fully automated lumen segmentation reduces guesswork in lesion length determination. The measurements previously mentioned (Table 3) will generally facilitate correct selection of stent diameter and length in PCI. OCT has substantial advantage over IVUS in PCI in its ability to image individual stent struts, both for apposition in the setting of performing an intervention or for reviewing stent coverage after stent placement in the setting of restenosis or thrombosis. Figure 4 depicts a common scenario in interventional cardiology in which a stented segment has both an edge dissection and malapposed struts, both of which were missed on angiography. Further postdilation in this case ensured proper stent apposition and sealing of the edge dissection, which was not previously visible on angiography. In fact, in clinical trials, OCT imaging has increasingly been used to assess stent apposition and individual strut coverage as a safety endpoint.[5,7,28-31] Whether these correlations will further enhance our understanding of the biology of the vascular response to injury remains to be seen.[26,31]

FUTURE APPLICATIONS OF CARDIOVASCULAR OCT

In addition to the research applications of OCT in clinical trials, it is hoped that future applications of OCT will focus on enhanced imaging of atherosclerotic plaque constituents via image processing algorithms. Practically speaking, the advent of bioabsorbable stents will likely mandate the use of OCT because IVUS does not have the resolution or capability of imaging entire polymeric stent struts.[5,32-36] Moreover, contrast-enhanced and molecular OCT remain areas of

active investigation at our institution and others. Finally, the combination of physiologic with anatomic imaging, such as Doppler-like signal processing from the OCT catheters, may well be available in the future.[5] This potent combination of physiology with high-resolution lesion morphometry will likely again transform our understanding of interventional lesion assessment.

CONCLUSION

Given the current state of OCT technology, there appear to be clear advantages over IVUS in the assessment of atherosclerotic plaque morphology and the outcomes of PCI with respect to stent apposition. However, like any new technology, OCT will require a learning curve, and consistent experience with multiple imaging modalities will further improve our ability to reliably obtain and interpret OCT images and optimize treatment of our patients. We welcome OCT into our armamentarium for lesion assessment and look forward to the evolution of this technology and its clinical application. ■

Sahil A. Parikh, MD, is Assistant Professor of Medicine, Case Western Reserve University School of Medicine; Director, Experimental Interventional Cardiology Laboratory at the Harrington-McLaughlin Heart and Vascular Institute, University Hospitals Case Medical Center in Cleveland, Ohio. He has disclosed that he holds no financial interest in any product or manufacturer mentioned herein. Dr. Parikh may be reached at (216) 844-5170; sahil.parikh@uhhospitals.org.

Marco A. Costa, MD, PhD, is Professor of Medicine, Case Western Reserve University School of Medicine; Director, Interventional Cardiovascular Center; Director, Center for Research and Innovation at the Harrington-McLaughlin Heart and Vascular Institute, University Hospitals Case Medical Center in Cleveland, Ohio. He has disclosed that he receives consulting honoraria and research funding from LightLab Imaging, Inc. Dr. Costa may be reached at (216) 844-5840; marco.costa@uhhospitals.org.

1. Barlis P, Schmitt JM. Current and future developments in intracoronary optical coherence tomography imaging. EuroIntervention. 2009;4:529-533.
2. Fujimoto JG, Brezinski ME, Tearney GJ, et al. Optical biopsy and imaging using optical coherence tomography. Nat Med. 1995;1:970-972.
3. Hee MR, Izatt JA, Swanson EA, et al. Optical coherence tomography of the human retina. Arch Ophthalmol. 1995;113:325-332.
4. Fujimoto JG, Boppart SA, Tearney GJ, et al. High resolution in vivo intra-arterial imaging with optical coherence tomography. Heart. 1999;82:128-133.
5. Bezerra HG, Costa MA, Guagliumi G, et al. Intracoronary optical coherence tomography: a comprehensive review clinical and research applications. JACC Cardiovasc Interv. 2009;2:1035-1046.
6. Finn AV, Nakano M, Narula J, et al. Concept of vulnerable/unstable plaque. Arterioscler Thromb Vasc Biol. 2010;30:1282-1292.
7. Prati F, Regar E, Mintz GS, et al. Expert review document on methodology, terminology, and clinical applications of optical coherence tomography: physical principles, methodology of image acquisition, and clinical application for assessment of coronary arteries and atherosclerosis. Eur Heart J. 2010;31:401-415.
8. Guagliumi G, Sirbu V. Optical coherence tomography: high resolution intravascular imaging to evaluate vascular healing after coronary stenting. Catheter Cardiovasc Interv. 2008;72:237-247.
9. Garcia-Garcia HM, Gonzalo N, Regar E, et al. Virtual histology and optical coherence tomography: from research to a broad clinical application. Heart. 2009;95:1362-1374.
10. Takarada S, Imanishi T, Liu Y, et al. Advantage of next-generation frequency-domain optical coherence tomography compared with conventional time-domain system in the assessment of coronary lesion. Catheter Cardiovasc Interv. 2010;75:202-206.
11. Tearney GJ, Waxman S, Shishkov M, et al. Three-dimensional coronary artery microscopy by intracoronary optical frequency domain imaging. JACC Cardiovasc Imaging. 2008;1:752-761.
12. Barlis P, Gonzalo N, Di Mario C, et al. A multicenter evaluation of the safety of intracoronary optical coherence tomography. EuroIntervention. 2009;5:90-95.
13. Prati F, Cera M, Ramazzotti V, et al. Safety and feasibility of a new non-occlusive technique for facilitated intracoronary optical coherence tomography (OCT) acquisition in various clinical and anatomical scenarios. EuroIntervention. 2007;3:365-370.
14. Yamaguchi T, Terashima M, Akasaka T, et al. Safety and feasibility of an intravascular optical coherence tomography image wire system in the clinical setting. Am J Cardiol. 2008;101:562-567.
15. Briguori C, Anzuini A, Airoldi F, et al. Intravascular ultrasound criteria for the assessment of the functional significance of intermediate coronary artery stenoses and comparison with fractional flow reserve. Am J Cardiol. 2001;87:136-141.
16. Jang IK, Bouma BE, Kang DH, et al. Visualization of coronary atherosclerotic plaques in patients using optical coherence tomography: comparison with intravascular ultrasound. J Am Coll Cardiol. 2002;39:604-609.
17. Yabushita H, Bouma BE, Houser SL, et al. Characterization of human atherosclerosis by optical coherence tomography. Circulation. 2002;106:1640-1645.
18. Low AF, Kawase Y, Chan YH, et al. In vivo characterization of coronary plaques with conventional grey-scale intravascular ultrasound: correlation with optical coherence tomography. EuroIntervention. 2009;4:626-632.
19. Raffel OC, Tearney GJ, Gauthier DD, et al. Relationship between a systemic inflammatory marker, plaque inflammation, and plaque characteristics determined by intravascular optical coherence tomography. Arterioscler Thromb Vasc Biol. 2007;27:1820-1827.
20. Kawasaki M, Bouma BE, Bressner J, et al. Diagnostic accuracy of optical coherence tomography and integrated backscatter intravascular ultrasound images for tissue characterization of human coronary plaques. J Am Coll Cardiol. 2006;48:81-88.
21. Jang IK, Tearney GJ, MacNeill B, et al. In vivo characterization of coronary atherosclerotic plaque by use of optical coherence tomography. Circulation. 2005;111:1551-1555.
22. MacNeill BD, Jang IK, Bouma BE, et al. Focal and multi-focal plaque macrophage distributions in patients with acute and stable presentations of coronary artery disease. J Am Coll Cardiol. 2004;44:972-979.
23. Barlis P, Serruys PW, Gonzalo N, et al. Assessment of culprit and remote coronary narrowings using optical coherence tomography with long-term outcomes. Am J Cardiol. 2008;102:391-395.
24. Fujii K, Kawasaki D, Masutani M, et al. OCT assessment of thin-cap fibroatheroma distribution in native coronary arteries. JACC Cardiovasc Imaging. 2010;3:168-175.
25. Kubo T, Imanishi T, Takarada S, et al. Assessment of culprit lesion morphology in acute myocardial infarction: ability of optical coherence tomography compared with intravascular ultrasound and coronary angioscopy. J Am Coll Cardiol. 2007;50:933-939.
26. Bezerra HG, Costa MA. Will intravascular OCT shed light on vascular biology? JACC Cardiovasc Imaging. 2010;3:85-87.
27. Kume T, Akasaka T, Kawamoto T, et al. Assessment of coronary arterial thrombus by optical coherence tomography. Am J Cardiol. 2006;97:1713-1717.
28. Guagliumi G, Sirbu V, Bezerra H, et al. Strut coverage and vessel wall response to zotarolimus-eluting and bare-metal stents implanted in patients with ST-segment elevation myocardial infarction: the OCTAMI (Optical Coherence Tomography in Acute Myocardial Infarction) Study. JACC Cardiovasc Interv. 2010;3:680-687.
29. Kyono H, Guagliumi G, Sirbu V, et al. Optical coherence tomography (OCT) strut-level analysis of drug-eluting stents (DES) in human coronary bifurcations. EuroIntervention. 2010;6:69-77.
30. Abizaid A, Costa JR Jr, Feres F. First nine-month complete invasive assessment (angiography, IVUS and OCT) of the novel NEVO sirolimus eluting stent with biodegradable polymer. Catheter Cardiovasc Interv. In press.
31. Guagliumi G, Musumeci G, Sirbu V, et al. Optical coherence tomography assessment of in vivo vascular response after implantation of overlapping bare-metal and drug-eluting stents. JACC Cardiovasc Interv. 2010;3:531-539.
32. Serruys PW, Ormiston JA, Onuma Y, et al. A bioabsorbable everolimus-eluting coronary stent system (ABSORB): 2-year outcomes and results from multiple imaging methods. Lancet. 2009;373:897-910.
33. Ormiston JA, Serruys PW, Regar E, et al. A bioabsorbable everolimus-eluting coronary stent system for patients with single de-novo coronary artery lesions (ABSORB): a prospective open-label trial. Lancet. 2008;371:899-907.
34. Tanimoto S, Serruys PW, Thuesen L, et al. Comparison of in vivo acute stent recoil between the bioabsorbable everolimus-eluting coronary stent and the everolimus-eluting cobalt chromium coronary stent: insights from the ABSORB and SPIRIT trials. Catheter Cardiovasc Interv. 2007;70:515-523.
35. Okamura T, Garg S, Gutierrez-Chico JL, et al. In vivo evaluation of stent strut distribution patterns in the bioabsorbable everolimus-eluting device: an OCT ad hoc analysis of the revision 1.0 and revision 1.1 stent design in the ABSORB clinical trial. EuroIntervention. 2010;5:932-938.
36. Slottow TL, Pakala R, Okabe T, et al. Optical coherence tomography and intravascular ultrasound imaging of bioabsorbable magnesium stent degradation in porcine coronary arteries. Cardiovasc Revasc Med. 2008;9:248-254.