Choice of Intracoronary Imaging: When to use Intravascular Ultrasound or Optical Coherence Tomography

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Abstract

Intracoronary imaging has the capability of accurately measuring vessel and stenosis dimensions, assessing vessel integrity, characterising lesion morphology and guiding optimal percutaneous coronary intervention (PCI). Coronary angiography used to detect and assess coronary stenosis severity has limitations. The 2D nature of fluoroscopic imaging provides lumen profile only and the assessment of coronary stenosis by visual estimation is subjective and prone to error. Performing PCI based on coronary angiography alone is inadequate for determining key metrics of the vessel such as dimension, extent of disease, and plaque distribution and composition. The advent of intracoronary imaging has offset the limitations of angiography and has shifted the paradigm to allow a detailed, objective appreciation of disease extent and morphology, vessel diameter, stent size and deployment and healing after PCI. It has become an essential tool in complex PCI, including rotational atherectomy, in follow-up of novel drug-eluting stent platforms and understanding the pathophysiology of stent failure after PCI (e.g. following stent thrombosis or in-stent restenosis). In this review we look at the two currently available and commonly used intracoronary imaging tools – intravascular ultrasound and optical coherence tomography – and the merits of each.

Keywords

Intracoronary imaging, intravascular ultrasound, optical coherence tomography

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Intracoronary imaging is able to aid the interventional cardiologist in the characterisation of atherosclerotic plaque morphology, in optimising stent sizing, and in minimising the complications associated with percutaneous coronary intervention (PCI). Intravascular ultrasound (IVUS) and optical coherence tomography (OCT) are commonly used methods, while newer spectroscopic methods are under development.

Intravascular Ultrasound Versus Optical Coherence Tomography: Technology

Table 1 displays a technical comparison of the IVUS and OCT imaging methods. The principle of IVUS imaging is based on the ultrasound waves produced by the oscillatory movement of a transducer.¹ Commercially available IVUS systems have transducers mounted on catheters that are compatible with guiding catheters in sizes of 5Fr or larger. These catheters can be inserted into the coronary artery over a 0.014 inch conventional guide wire and imaging can be obtained by manual or motorised pullback. Motorised pullbacks are carried out at a speed of 0.5 mm/s, thus a 50 mm coronary artery can be imaged in approximately 90s. Integrated IVUS consoles add to the rapidity of imaging, but mobile IVUS carts are also available. When co-registration of IVUS with angiography becomes available, this will be a useful adjunct in locating the anatomical lesion precisely. Once the pullback is recorded, measurements of the lumen can be carried out either manually or using automated software. Greyscale IVUS has an axial resolution of 100–150 μm , lateral resolution of 200 μm ¹ and penetration depth of 4–8 mm. Post-processing of greyscale IVUS images

is possible with radiofrequency-based technology such as IVUS virtual histology.² IVUS virtual histology may assist in characterisation of plaque morphology by differentiating between various types of plaque using colour coding. As a result of limited resolution, IVUS cannot reliably identify the separation between intima and media and the relation between adventitia and peri-adventitial structures (see Figure 1).³

In contrast to IVUS, intracoronary imaging by OCT is obtained using near-infrared light. The first generation of OCT imaging was based on occlusive balloon technology called time domain (TD) imaging. Use of frequency domain (FD) imaging, also referred to as Fourier domain spectral imaging, has now surpassed TD imaging.⁴ FD imaging does not require occlusion of the proximal artery with a balloon as high viscosity liquids such as contrast media can be used to purge blood from the vessel, while imaging is completed rapidly. Current commercially available OCT catheters consist of a single-mode optical fibre in a hollow metal wire torque that rotates at a speed of 100 rps. The axial and lateral resolutions of OCT are 10–20 μm and 20 μm , respectively – which is superior to that of IVUS. However, better resolution comes at a drawback of limited penetration – a maximum of 2 mm.⁵ With acquisition speeds of up to 25 mm/s, rapid imaging of coronary artery can be achieved within a few seconds. Commercially available OCT catheters can be inserted into coronary artery on a 0.014 inch guide wire and are compatible with guiding catheters sized 5Fr or larger. For optimal imaging quality, a bloodless field is required, which can be achieved with injection of 12–15 ml of

Table 1: Technical Comparison of IVUS and OCT

	IVUS	OCT
Source of image	Ultrasound (10–40 MHz)	Near infrared light
Minimum guide catheter size	5Fr	5Fr (although 6Fr preferable)
Axial resolution	100–150 µm	10–20 µm
Lateral resolution	200 µm	20 µm
Penetration depth	4–8 mm	2 mm
Acquisition speed	0.5 mm/s	25 mm/s
Blood clearance	Not required	Contrast 10–15 ml

IVUS = intravascular ultrasound; OCT = optical coherence tomography.

Figure 1: IVUS (A) and OCT (B) Showing a Normal Segment of Coronary Artery

Note the clear demarcation of trilaminar structure of coronary artery in the OCT (B) image. i = intima; m = media; a = adventitia; IVUS = intravascular ultrasound; OCT = optical coherence tomography.

Figure 2: IVUS Showing a Circumferential Calcified Lesion (A) and Eccentric Mixed Plaque (B)

IVUS = intravascular ultrasound

highly viscous medium such as contrast, either by hand or by use of a power injector. Blood clearance can be challenging through a 5Fr catheter, therefore 6Fr or larger is generally recommended. Caution needs to be exercised in people with renal impairment where multiple pullbacks are contemplated due to the risk of contrast nephropathy.

Current commercially available OCT software automatically detects the lumen, allows marking of every frame and gives user-defined proximal and distal reference frames with dimensions. Furthermore, every pullback of the coronary artery can be viewed in cross-sectional frames (see Figure 1), longitudinal view and lumen profile view. Cross-sectional views are helpful in detailed study of plaque where as longitudinal and lumen profile views can be used for longitudinal measurements such as stent length. 3D reconstruction is possible and may assist in detailed assessment of bifurcation lesions and in

optimising PCI results. Co-registration of OCT with angiography can be a useful adjunct in locating anatomical lesions precisely, reducing the chances of geographical miss.

Intravascular Ultrasound Versus Optical Coherence Tomography: Safety and Feasibility

One of the limitations of earlier TD-OCT imaging was the requirement to have a bloodless field for adequate imaging. This was achieved by proximal occlusion of the coronary artery with a semi-compliant balloon followed by flushing of the artery with ringer's lactate solution. Although this method was not associated with any serious complications, minor complications such as transient ST elevation with associated chest pain were common.⁶ Furthermore, the acquisition time was longer with a pullback speed of only 0.5–3.0 mm/s. In comparison, current FD-OCT imaging does not require balloon occlusion of coronary artery and, with higher pullback speeds, a bloodless field can be achieved by contrast injection.

Both IVUS and current-generation FD-OCT have been shown to have a favourable safety profile. An integrated biomarker and imaging sub-study (IBIS-4) assessed the feasibility and the procedural and long-term safety of OCT and IVUS in patients with ST-elevation MI (STEMI) undergoing primary PCI.⁷ In this prospective cohort study, 103 patients with STEMI who underwent serial three-vessel coronary imaging during primary PCI were compared with 485 patients with STEMI undergoing primary PCI without additional imaging after 13 months. Feasibility (defined as the number of pullbacks suitable for analysis) and safety (defined as the frequency of peri-procedural complications and major adverse cardiac events [MACE, a composite of cardiac death, MI and any clinically indicated revascularisation at 2 years]) outcomes were recorded. Successful imaging was achieved in <90 % of patients at baseline and follow-up using IVUS and OCT. Although peri-procedural complications occurred with OCT imaging (<2.0 % versus 0 % with IVUS), long-term safety was favourable with both modalities, with no significant difference in MACE rates at 2 years.⁷ Of note, the majority of OCT-related complications were transient ST elevation due to coronary spasm, which in clinical practice can be mitigated by administering intracoronary nitrates prior to imaging.

In another registry-based study, OCT and IVUS were shown to have comparable safety and feasibility profiles.⁸ Analysis of 3,045 OCT pullbacks from 1,142 patients and 5,148 IVUS pullbacks from 2,476 patients revealed seven complications related to OCT and 12 to IVUS imaging. Transient ST-elevation requiring withdrawal of the imaging catheter was noted with OCT, whereas IVUS appears to have been associated with coronary spasm, thrombus formation, dissection of the imaged vessel and stent deformation.⁸

Is one Choice of Intracoronary Imaging Superior to the Other and What are the Clinical Scenarios Where They Should be Used?

Intravascular Ultrasound

Over the past two decades, IVUS has become the reference tool for intracoronary imaging. Advances in IVUS technology have resulted in better resolution and penetration: IVUS can now be used to assess plaque characteristics, volume and constituents (see Figure 2; Table 2).⁹ Coronary arterial and lumen dimensions, particularly minimal luminal area (MLA), can be measured accurately by IVUS algorithms, which can assist in the decision-making process for revascularisation.¹⁰ One of the most important roles of IVUS is in optimising PCI, particularly in complex

Table 2: Clinical Situations in Which IVUS and OCT Can be Useful

Clinical situation	IVUS superior	OCT superior	Reason
Imaging of left main stem	✓		IVUS has greater penetration depth
Imaging of large coronary arteries	✓		IVUS has greater penetration depth
Renal impairment	✓		OCT requires additional contrast injection to create a bloodless field
Assessment of calcification	✓	✓	
Aorto-ostial lesions	✓		The guide catheter needs to be fully engaged to clear blood for OCT and therefore difficult to image aorto-ostial lesions
Plaque characterisation		✓	OCT provides superior image quality enabling assessment of plaque content and cap thickness
Assessment of dissection		✓	Both modalities can be used, but OCT provides superior image quality
Assessment of thrombus		✓	OCT provides superior image quality and is able to differentiate between red and white thrombus
Stent expansion and apposition		✓	Both modalities can be used, but OCT provides superior image quality
Evaluation of in-stent restenosis		✓	Both modalities can be used, but OCT provides superior image quality

IVUS = intravascular ultrasound; OCT = optical coherence tomography.

lesions subsets such as left main stem (LMS), calcific and bifurcation lesions.¹¹ IVUS can be used to optimise PCI as it has a role in stent sizing and in detecting adequate stent expansion and strut malapposition (see Figure 3).¹² IVUS, with its better penetration, is superior to OCT in assessing the remodelling patterns of the vessel wall. IVUS-detected positive vessel remodelling of the coronary artery is associated with late stent thrombosis following drug-eluting stent (DES) implantation.¹³

Optical Coherence Tomography

OCT, with even better resolution when compared with IVUS, can be used in assessing plaque characteristics¹⁴ and constituents¹⁵ and in optimising PCI.¹⁶ However, with limited penetration, assessment of plaques with thickness of >1.0–1.5 mm is not possible with OCT.^{4,17} Up to 25 % of acute coronary syndrome events are secondary to thrombus present on a non-ruptured plaque, also called an erosion.^{15,18} OCT helps in accurately identifying eroded plaques, where if no lumen narrowing is present stenting may not be needed. The presence of thin-cap fibroatheroma (TCFA), defined as lipid plaque thickness of <65 µm, is predictive of future adverse cardiac events.¹⁸ However, interpretation of TCFA on OCT requires caution as artefacts due to tangential dropout can lead to misinterpretation.¹⁹ The superior

Figure 3: OCT Showing a Well-opposed Stent (A) and Malapposed Stent (B); IVUS Showing a Well-opposed Stent (C) and Malapposed Stent (D)

IVUS = intravascular ultrasound; OCT = optical coherence tomography.

resolution of OCT means it can detect TCFA with adequate sensitivity/specificity,²⁰ and also detects the presence of macrophages²¹ and neovessels, and lipid volume – the features of so-called vulnerable plaque (see Figure 4). Furthermore, OCT not only identifies the presence of thrombus, but can also distinguish between red and white thrombus often seen in STEMI (see Figure 5; Table 2).²⁰ Injury to the vessel wall post-PCI reflected by the presence of intimal tears, edge dissections, tissue prolapse, presence of thrombus and incomplete stent apposition can be readily assessed by OCT, which allows for optimisation, as required.¹⁶ Two further areas where imaging with OCT is useful are capability of detecting thin neo-intima in follow-up imaging after DES implantation²² and in delineating tissue characteristics of in-stent restenosis (see Figure 4).²³ OCT is superior to IVUS in identifying uncovered stent struts. Sub-analysis of the Optical Coherence Tomography for Drug Eluting Stent Safety (ODESSA) trial showed 8 % of the stented segments with no detectable neo-intima by IVUS were found to have neo-intimal coverage by OCT.²⁴

Is There Evidence Supportive of One Modality Over the Other?

In the field of interventional cardiology, any new diagnostic tool or treatment modality needs to be associated with better clinical outcomes before being incorporated into guidelines and adapted widely in the clinical environment. Here, we review the data supporting the use of these imaging techniques in contemporary clinical practice.

Intravascular Ultrasound

A meta-analysis of IVUS-guided PCI by Zhang et al. showed improved clinical outcomes.²⁵ In their analysis, over 19,000 patients across eleven studies (one randomized controlled trial and 10 registries) were included. Compared with angiography alone, IVUS-guided DES implantation was associated with reduced rates of death, MACE and stent thrombosis. No difference was found in the rates of MI, target lesion and target vessel revascularisation.

Figure 4: OCT Showing a Thin-walled Plaque (A), Ruptured Plaque (B) and In-stent Restenosis (C)

OCT = optical coherence tomography.

Figure 5: OCT Showing Red Thrombus Resulting in Image Dropout (A) and White Thrombus Within a Previously Implanted Stent With no Image Dropout (B)

OCT = optical coherence tomography.

The non-randomised Assessment of Dual Antiplatelet Therapy With Drug-Eluting Stents (ADAPT-DES) study analysed 3,349 patients in whom IVUS was used to guide PCI.²⁶ IVUS guidance changed the PCI strategy in 74 % of cases. IVUS guidance compared with angiography alone was associated with reduced 1-year rates of stent thrombosis, MI and MACE following DES implantation.

IVUS can be a useful adjunct in the assessment of LMS disease. IVUS generated MLA correlates with fractional flow reserve (FFR) in the absence of proximal left anterior descending and circumflex artery disease. IVUS MLA of $<5.9 \text{ mm}^2$ correlates well with FFR of <0.75 .²⁷ However, caution need to be exercised in Asian patients who have smaller coronary arteries. Kang et al. showed that an MLA cut-off of $<4.1 \text{ mm}^2$ correlated with FFR <0.75 ²⁸ in a Korean population. In non-LMS lesions, the correlation of IVUS derived MLA with FFR is weak with limited accuracy.²⁹ The reasons for this are lesion location in the coronary tree, lesion length, eccentricity, entrance and exit angles, shear forces, reference vessel dimensions, and the amount of viable myocardium subtended by the lesion.³⁰ Although it is safe to defer PCI

in non-LMS lesions with MLA $>4 \text{ mm}^2$, lesions with MLA $<4 \text{ mm}^2$ may need to be physiologically tested before intervention.³¹

Optical Coherence Tomography

Currently trial data looking at OCT use and clinical outcomes are limited. The Centro per la Lotta contro l'Infarto-Optimisation of Percutaneous Coronary Intervention (CLI-OPCI) study compared outcomes between patients undergoing PCI under angiography guidance alone versus angiography plus OCT guidance.³² The group that underwent PCI with angiography and OCT guidance had overall significantly lower rates of cardiac death, MI and repeat revascularisation. Furthermore, OCT revealed adverse features following PCI in almost 35 % of patients who needed further intervention.

The Observational Study of Optical Coherence Tomography in Patients Undergoing Fractional Flow Reserve and Percutaneous Coronary Intervention (ILUMIEN I) study assessed how the clinical decision-making process is influenced when OCT is added to angiography and FFR.³³ This study enrolled 418 patients scheduled for PCI from 35 international centres, including patients with stable and unstable coronary syndromes, prospectively in a non-randomised fashion. Once recruited, the majority of patients underwent pre-PCI FFR and OCT imaging. OCT imaging influenced physician decision-making processes pre-PCI in 57 % and post-PCI in 27 % of cases. Additional in-stent post-dilatation was carried out in 81 % and additional stent placement in 12 % of the cases. Device-oriented MACE (cardiac death, MI and target lesion revascularisation) and patient-oriented MACE (all-cause death, MI and any repeat revascularisation) were rare in hospital and at 30 days. The rates of other events such as stent thrombosis were also extremely low.³³ The ILUMIEN II study showed the degree of stent expansion achieved after OCT versus IVUS guidance to be comparable.³⁴ In this retrospective study, propensity-matched analysis of 354 patients who underwent OCT in the ILUMIEN I trial and 586 patients from the IVUS substudy of the ADAPT-DES trial based on reference vessel diameter, lesion length, calcification, and reference segment availability was comparable between OCT and IVUS guidance, as were the rates of major stent malapposition, tissue protrusion, and stent-edge dissection.³⁴ The ongoing Optical Frequency Domain Imaging Versus Intravascular Ultrasound In Percutaneous Coronary Intervention (OPINION – OFDI) and ILUMIEN III randomised trials will further help in elucidating the potential of OCT versus IVUS in optimising PCI outcomes. The OPINION – OFDI study has completed recruitment with 800 patients divided equally between OCT and IVUS arms.³⁵ The preliminary results showed comparable safety profiles and stent expansion with OCT and IVUS guidance immediately after PCI. The follow-up results at 1 year, including outcome data, are awaited.

As with IVUS, the OCT-derived MLA of 1.9 mm^2 correlates well with an FFR of <0.75 .³⁶ Another study of 56 stable patients reported OCT-derived MLA of 1.95 mm^2 correlating well with an FFR of <0.80 , with a sensitivity of 82 % and specificity of 63 %. However, 5 of the 26 patients with MLA $>1.95 \text{ mm}^2$ had an FFR of <0.80 , suggesting that OCT cannot be a surrogate for FFR.³⁷

Guidelines

The American College of Cardiology Foundation/American Heart Association/Society for Cardiac Angiography (ACC/AHA/SCAI)³¹ and European Society of Cardiology/European Association for Cardio-Thoracic Surgery (ESC/EACTS)³⁸ guidelines on myocardial revascularisation have issued a class II recommendation for IVUS with

Table 3: Current Guidelines for Use of IVUS and OCT

	ESC	AHA/ACC
IVUS	<p>Class IIa (level of evidence: B) IVUS in selected patients to optimise stent implantation. IVUS to assess severity and optimise treatment of unprotected LMS lesions</p> <p>Class IIa (level of evidence: C) IVUS to assess mechanisms of stent failure.</p>	<p>Class IIa (level of evidence: B) IVUS is reasonable for the assessment of angiographically indeterminant left main CAD</p> <p>IVUS and coronary angiography are reasonable 4 to 6 weeks and 1 year after cardiac transplantation to exclude donor CAD, detect rapidly progressive cardiac allograft vasculopathy and provide prognostic information</p> <p>Class IIa (level of evidence: B) IVUS is reasonable to determine the mechanism of stent restenosis</p> <p>Class IIb (level of evidence: B) IVUS may be reasonable for the assessment of non-left main coronary arteries with angiographically intermediate coronary stenoses (50–70 % diameter stenosis)</p> <p>IVUS may be considered for guidance of coronary stent implantation, particularly in cases of left main coronary artery stenting</p> <p>Class IIb (level of evidence: C) IVUS may be reasonable to determine the mechanism of stent thrombosis</p>
OCT	<p>Class IIa (level of evidence: C) OCT to assess mechanisms of stent failure</p> <p>Class IIb (level of evidence: C) OCT in selected patients to optimise stent implantation</p>	<p>The appropriate role for optical coherence tomography in routine clinical-decision making has not been established</p>

AHA/ACC = American Heart Association/American College of Cardiology Foundation; CAD = coronary artery disease; ESC = European Society of Cardiology; IVUS = intravascular ultrasound; LMS = left main stem; OCT = optical coherence tomography.

varying levels of evidence depending on the indication (see Table 3). OCT, Owing to a lack of clinical data, OCT is not included in the US guidelines, whereas the European guidelines have given a class II recommendation for OCT (see Table 3).

Future Directions

It is evident that both technologies have advantages and limitations. More technological adaptations are under way to enhance the use of IVUS and OCT. For example, OCT equipment that can complete pullback of entire coronary artery with in one heartbeat to minimise artefacts is undergoing experiments.³⁹ Micro-OCT that has the ability to study endothelium and macrophages in vivo in detail is also under development.⁴⁰ Experiments looking into feasibility of photo acoustic imaging in humans one are also underway.⁴¹

Conclusion

Intracoronary imaging has given a new dimension to the field of interventional cardiology. When choosing the modality of intracoronary imaging, the anatomic location in the coronary tree appears to be a good discriminator. IVUS has better data when it comes to LMS-related

lesions, whereas OCT seems to be superior in arteries with an MLA of <3 mm². When it comes to establishing diagnosis and optimising stent deployment, OCT has the advantage of better resolution. However, when it comes to assessing the significance of intermediate coronary stenosis, physiological assessment with FFR should remain the first choice as IVUS- and OCT-derived MLA cut-off values have at best moderate correlation and accuracy.

IVUS and OCT are safe and feasible to use in modern cardiac catheter laboratory practice. In the hands of an experienced operator, imaging can be done rapidly with minimal or no complications. With advantages and limitations of one modality over the other, intracoronary imaging with IVUS and or OCT have the potential to complement each other. Future data justifying their routine use based on improved clinical endpoint data is forthcoming. The future of intracoronary imaging is likely to incorporate co-registration with angiography as standard, hybrid and molecular imaging. Future technological advances in intracoronary imaging provide further exciting opportunities for a better understanding of the coronary disease process and response to revascularisation. ■

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