Optical Coherence Tomography for Online Guidance of Complex Coronary Interventions

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Decision making on lesion preparation and stent/scaffold optimization are cornerstones of patient outcome. Intravascular imaging recently emerged as a critical modality to achieve better results of stent/scaffold implantation and superior clinical outcomes compared with coronary angiography alone. Optical coherence tomography (OCT), a light-based intravascular imaging modality with high frame rate in acquisition and very high speed pullback, can interrogate the target vessel in a couple of seconds, and immediately display a pristine longitudinal lumen contour with automatic detection of lesion severity, site and lumen/stent areas. Further, OCT provides pivotal information on sites of calcium, with accurate measurements of the minimum distance from the lumen, a major determinant of stent/scaffold underexpansion, malapposition and eccentricity. Finally, to guide the PCI procedure using OCT without operator misjudgment, a real-time point-to-point correspondence between angiographic and OCT images has been recently created. Co-registration of OCT with angiography with direct tableside control of acquisition and analysis enables the operator to plan and map optimal stent/scaffold implantation. To prove the clinical relevance of OCT-guided PCI, simple, standardized interventional planning, including pre- and postprocedural automatic lumen detection metrics, has to be translated into effective treatment flow algorithms. A similar OCT algorithm is being tested in the ongoing prospective, randomized, multicenter ILUMIEN III study, to demonstrate that OCT-guided stent placement is superior to angiography-guided and non-inferior to IVUS-guided stent implantation.

Key Words: Bioresorbable vascular scaffolds; Drug-eluting stents; Lesion preparation; Optical coherence tomography; Percutaneous coronary intervention

Coronary angiography is routinely used to guide the invasive treatment of coronary artery disease (CAD). However, even the most experienced interventionalist, confronted with lesion and patient complexity, may face doubts in decisions based only on the angiographic lumen profile. A number of limitations of coronary angiography (eg, limited planar resolution to inform on complex 3-dimensional anatomy, limited reliability in assessing true area and length dimensions, and low sensitivity in detecting calcium) may affect decisions made during percutaneous coronary interventions (PCI). As well as the increase in age and comorbidities, patients currently undergoing PCI present with multiple, diffuse, calcified lesions, frequently involving bifurcations. Although drug-eluting stents (DES) have significantly reduced rates of restenosis and target vessel revascularization (TVR), DES results are not always as expected, especially in complex lesions. Stent underexpansion remains a major predictor of restenosis and stent thrombosis, even with current generation DES. Finally, current bioresorbable scaffolds (BRS) are less forgiving to suboptimal implantation because of their inherent limitations of mechanical properties. Accordingly, decision making on lesion preparation and assessment of the immediate stent/scaffold results are the cornerstones of patient outcome.

Intravascular imaging has emerged as a critical modality to achieve better results of stent implantation in complex patient and lesion cohorts, with superior clinical outcomes compared with coronary angiography alone. Optical coherence tomography (OCT) is a high-resolution (10–20 μm) light-based intravascular imaging modality that immediately provides after acquisition automatic detection metrics of the coronary lumen and stents across the entire explored vessel. Because of the high frame rate in acquisition and the high-speed pullback, OCT automatically displays a pristine longitudinal lumen contour that is easier to measure and interpret. This review focuses on strategies and the contribution of OCT to guide PCI optimization in complex settings.

Increasing Patient/Lesion Complexity and Accurate Implantation Technique

Lesion preparation guided by OCT has 2 steps to be accomplished: (1) obtain precise and detailed analysis of lesion characteristics and plaque distribution across the vessel before the stent/scaffold implantation and (2) selection of the appropriate...
Lesions makes PCI challenging, often requiring adjuvant techniques to achieve satisfactory stent results. Angiography has low sensitivity (48%) for calcium detection, except for severe calcification, defined as radio-opacities detected before contrast injection. Conversely, calcium is precisely detected by OCT as a signal poor or heterogeneous region with sharply delineated leading, and/or lateral borders (Figure 1A-e, white arrow). Based on pathology, OCT estimates the area of calcification more accurately than intravascular ultrasound (IVUS).

Role of Calcium in Lesion Preparation and Stent/Scaffold Results

OCT can differentiate tissue characteristics based on the polarization properties of light, permitting precise analysis of plaque morphology, composition, and distribution. Calcification strongly correlates with advanced atherosclerosis, increased age and comorbidities. The presence of calcified and rigid lesions makes PCI challenging, often requiring adjuvant techniques to achieve satisfactory stent results. Angiography has low sensitivity (48%) for calcium detection, except for severe calcification, defined as radio-opacities detected before contrast injection. Conversely, calcium is precisely detected by OCT as a signal poor or heterogeneous region with sharply delineated leading, and/or lateral borders (Figure 1A-e, white arrow). Based on pathology, OCT estimates the area of calcification more accurately than intravascular ultrasound (IVUS).
because the light penetrates calcium without shadowing. In addition, OCT allows the operator to distinguish between superficial (close to the intima-lumen interface) and deep calcium (located at the media-adventitia border), with accurate measurement of the minimum distance from the lumen, the thickness of the calcified plate, and circumferential arc distribution. Consequently, OCT may be a more useful clinical tool for quantifying calcified plaques.

Extended calcification as assessed by OCT results in less optimal stent expansion\(^{18,19}\) and more frequent acute incomplete stent apposition.\(^{20}\) Similarly, the use of OCT to guide implantation of BRS has demonstrated that scaffold underexpansion, eccentricity and incomplete strut apposition are more related to the extent and thickness of calcification\(^{21}\) compared with other lesions.\(^{22}\)

**Device Selection in Lesion Preparation**

Rotational atherectomy, cutting or scoring balloon is frequently used because the light penetrates calcium without shadowing. In addition, OCT allows the operator to distinguish between superficial (close to the intima-lumen interface) and deep calcification (located at the media-adventitia border), with accurate measurement of the minimum distance from the lumen, the thickness of the calcified plate, and circumferential arc distribution. Consequently, OCT may be a more useful clinical tool for quantifying calcified plaques.

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used in calcified and fibrocalcific vessels as adjunctive techniques to improve plaque compliance. Rotational atherectomy is recommended for lesion preparation of heavily calcified or severely fibrotic lesions that cannot be crossed by a balloon catheter or adequately dilated before planned stent implantation. Nevertheless, a recent trial assessing the effect of rotational atherectomy on DES implanted in calcified lesions failed to show a lower late lumen loss compared with DES implanted without prior atherectomy. However, in that study calcified lesions were selected based on calcium detection by coronary angiography, suggesting that angiography cannot discriminate lesions that might benefit of rotational atherectomy. Conversely, recent observational studies have demonstrated the importance of intravascular imaging in deciphering calcium distribution, visualizing the mechanism of action and the immediate results of the devices used for preparation of hard lesions. IVUS and OCT studies have confirmed that rotational atherectomy ablates calcium through fissuring or cracking of the calcified segment. In addition, OCT studies conducted in calcified lesions treated with a metallic stent or BRS have demonstrated that calcium close to the lumen is more difficult to expand than deeper calcium, significantly affecting stent/BRS enlargement and the final minimal lumen area (MLA). This setting, cutting or scoring balloons that do not ablate calcium but improve vessel compliance through incisions at the edges between calcified and non-calcified components enable greater stent expansion under controlled dissection.

A routine OCT-guided strategy, liberally using a cutting/scoring balloon in complex calcified lesions treated with BRS, was able to obtain similar postprocedural area stenosis and eccentricity index to those for second-generation DES. Figure 1 and Figure 2 show examples of calcified lesion preparation with different devices and the effect on the final stent result.

Further prospective, randomized OCT studies are needed to identify the most appropriate lesion preparation strategy according to the type and distribution of calcium. A suggested decision-making algorithm based on the current level of evidence is shown in Figure 3.

**Use of Imaging and Novel Automatic Measures to Optimize Stent/Scaffold Placement**

Compared with IVUS, OCT can immediately display a longitudinal view of the investigated vessel at very high resolution, with automatic detection of the luminal border and OCT metrics fully integrated. Based on this view, OCT enables identification of lesion severity and the precise extension of atherosclerotic disease through its automatic detection and display of the MLA (Figure 4).

**Comparing Intracoronary Imaging Metrics With Quantitative Coronary Analysis (QCA)**

It has been recently demonstrated that QCA, compared with frequency domain OCT (FD-OCT), systematically measures a smaller lumen diameter (LD)/area, while IVUS reports larger luminal dimensions than OCT. However, FD-OCT
match, a major predictor of negative outcome.\(^{37}\) (Figure 5). Without access to co-registered data, the segment of the target lesion indicated by OCT was left uncovered by the stent in approximately 70% of PCI cases.\(^{38}\) In addition, ACR helps to detect the most appropriate “landing” site for stenting, which can be quite challenging in diffuse disease, long or tandem lesions, or bifurcated lesions. Finally, ACR may be useful in selecting the appropriate stent/scaffold diameter, which enables precise stent/scaffold placement. Careful selection of the angiographic view to be co-registered is required for appropriate synchronization during OCT pullback. Avoiding angiographic views with vessel foreshortening and overlap, and maintaining cine acquisition during the entire pullback are prerequisites for clinical use of ACR.

To prove the clinical relevance of OCT compared with angiography, simple, standardized interventional planning, including longitudinal view evaluation and automatic lumen measurements, has to be implemented in a treatment flow algorithm that is easy to use in daily practice. In the prospective multicenter, randomized trial, ILUMIEN III OPTIMIZE PCI [OPltical Coherence Tomography Compared to Intravascular Ultrasound and Angiography to Guide Coronary Stent Implantation (NCT02471586)], a novel OCT algorithm for stent optimization was used to prove superiority of imaging guidance compared with angiography alone, as measured by post-PCI minimal stent area (MSA). In the OCT flow algorithm of the ILUMIEN III study, stent diameter and post-dilation balloon diameter were decided by measuring the mean diameter of the phantom dimensions than does IVUS.\(^{32}\) The superior ability of OCT to visualize luminal dimensions compared with IVUS probably resides in the unique level of accuracy in detecting the luminal border and significantly lower observer variability of all metrics of stent deployment.\(^{34}\)

QCA underestimates LD measurements more with ABSORB BVS\(^{TM}\) compared with XIENCE EES\(^{TM}\) as demonstrated by intracoronary imaging.\(^{35,36}\) The relative difference of QCA vs. OCT LD measurements (−9.8% with ABSORB BVS\(^{TM}\) and −4.8% with XIENCE EES\(^{TM}\)) is probably related to the increased protrusion into the lumen of the invisible struts of the BVS, with higher distortion of the lumen profile observed on coronary angiography.

**Co-Registration of OCT With Coronary Angiography**

In the current practice of intracoronary imaging, information is not immediately correlated with images obtained by coronary angiography. Accordingly, any operative decision will visually translate with some degree of ambiguity. To guide PCI procedures using OCT without operator misjudgment, a real-time point-to-point correspondence between the angiographic and OCT images has been developed. OCT-angiography co-registration (ACR) provides better integration of OCT into the PCI workflow with direct tablesided control of acquisition and analysis, enabling the operator to map optimal stent/scaffold implantation. The automatic point-to-point correspondence of OCT with angiography reduces the risk of geographic mismatch, a major predictor of negative outcome.\(^{37}\) (Figure 5). Without access to co-registered data, the segment of the target lesion indicated by OCT was left uncovered by the stent in approximately 70% of PCI cases.\(^{38}\) In addition, ACR helps to detect the most appropriate “landing” site for stenting, which can be quite challenging in diffuse disease, long or tandem lesions, or bifurcated lesions. Finally, ACR may be useful in selecting the appropriate stent/scaffold diameter, which enables precise stent/scaffold placement. Careful selection of the angiographic view to be co-registered is required for appropriate synchronization during OCT pullback. Avoiding angiographic views with vessel foreshortening and overlap, and maintaining cine acquisition during the entire pullback are prerequisites for clinical use of ACR.

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recently in the USA. BRS implanted in complex lesions require more accurate lesion preparation to achieve optimal expansion, compared with current DES.

Although OCT guidance of BRS shares similar procedural steps with those used for metallic stents, important additional imaging requirements should be considered during implantation of current generation BRS (Table), which are less forgiving to suboptimal implantation because of their inherently different mechanical properties. At present, the most widely used and studied BRS is the everolimus-eluting bioresorbable vascular scaffold (Absorb BVS, Abbott Vascular, Santa Clara, CA, USA), composed of poly-L-lactic acid-based polymer, 154 μm strut thickness), which resorbs in approximately 3–5 years. Previous large-scale, prospective, randomized trials have shown the Absorb BVS can be successfully and safely used for revascularization of coronary artery stenosis with low risk of repeat revascularization, comparable to current generation DES. However, the acute gain and minimal LD measured after the procedure in those trials (ABSORB II, III, ABSORB JAPAN, ABSORB CHINA) was significantly smaller.

The ILUMIEN III study randomized 450 patients to angiography or IVUS- or OCT-guided PCI. The study enrollment was completed early April 2016. The primary efficacy end-point (post-PCI MSA) will be presented shortly and will substantiate or reject the mechanistic benefit of OCT-guided stent placement.

Post-dilation with non-compliant high-pressure balloons can be effective only when lesion preparation is appropriately done, especially in the presence of fibrocalcific lesions. By contrast, when adequate lesion preparation fails, even use of super high-pressure non-compliant balloons (OPN NCTM, SIS Medical AG, Winterthur, Switzerland, rated burst pressure of 35 atm) might not be able to achieve adequate stent/scaffold expansion (Figure 6).

OCT Guidance in BRS Procedures

A novel, promising BRS technology has been recently approved and introduced for the treatment of CAD in Europe and more

Figure 5. OCT with online angiographic co-registration system. Angiography shows multiple stenoses in the mid and distal LAD (A). Cine angiography acquired during OCT pullback is on the left side of the OCT display system and a white marker represents the OCT lens position on coronary angiography (B, C). OCT longitudinal view is on the lower panel of the display (B, C) and the cross-sectional view is on the right side of the upper panel. Each cross-sectional view corresponds to the white marker on angiography and to the vertical line in the longitudinal view (B, C). Luminal dimensions of the 2 lesions are calculated and automatically displayed (middle panel), into the automatic detection lumen border cartoon (mid-LAD: MLA=1.15 mm², Ø=1.20 mm, %AS=84.0% (B); distal LAD: MLA=1.39 mm², Ø=1.32 mm, %AS=69.0% (C)). After lesion preparation with a semicompliant balloon 2.5/15 mm, 2 EES 2.75/28 mm and 3.0/24 mm were implanted in the distal and proximal lesions, respectively. The post-stent OCT lumen profile shows stent underexpansion (MLA 3.14 mm² %AS 34.9%) and a mean EEL diameter 2.80 mm at the distal site (D). Therefore, an additional post-dilation with a 2.75/20 mm non-compliant balloon was performed (14 atm). After post-dilation, the OCT lumen profile shows well-expanded stents at both the distal (MLA 4.55 mm², %AS 9.1%) and proximal lesions (MLA 6.59 mm², %AS 9.9%) (E). %AS, percent area stenosis; EES, everolimus-eluting stent; LAD, left anterior descending artery; MLA, minimal lumen area; OCT, optical coherence tomography; Ø, mean diameter.
OCT Guidance for Complex PCI

Preparation and post-scaffold detection and correction of under-expansion and malapposition, may be more relevant during BRS implantation than with metallic DES.

Complex fibrocalcific lesions are more challenging to be treated with BRS. As the scaffold struts are not visible on fluoroscopy or cineangiography, only IVUS or OCT can confirm apposition of the struts against the vessel wall and the fully expanded scaffold. In addition, fibrocalcific plaque underlying the scaffold significantly reduces the depth of penetration of the struts compared with all other lesion types, with poor embedding, more protrusion and more difficult coverage.

Small, retrospective studies and several case reports have suggested meticulous lesion preparation facilitates BRS implantation compared with DES.

Further, a higher rate of scaffold thrombosis has been reported in single- and multicenter observational studies and in a recent meta-analysis. These results were obtained with a quite low rate of post-dilation and marginal use of intracoronary imaging, preferentially after scaffold placement. When optimal implantation technique, including lesion preparation, systematic post-dilation with high-pressure non-compliant balloons and liberal use of intracoronary imaging, was recommended, the Absorb BVS demonstrated safety and good clinical outcomes in large, real-world registries (IT-DISAPPEAR, RAI Registry, France-Absorb). Thus, careful lesion assessment by OCT and OCT-guided procedural strategies that include effective lesion preparation and post-scaffold detection and correction of under-expansion and malapposition, may be more relevant during BRS implantation than with metallic DES.

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Table. Key Points for Use of Imaging With BRS Implantation Compared With DES

1. Perform meticulous lesion preparation, especially in diffuse, fibrocalcific lesions (do not hesitate to use debulking devices)
2. Do not hesitate to perform pre-intervention intravascular imaging, to assist sizing (more difficult to be optimized after deployment) and avoid underexpansion
3. Avoid mismatch with reference vessel (oversizing leads to more frequent MACE; undersizing leads to more frequent malapposition and scaffold thrombosis)
4. Avoid implanting BRS in too small vessel (mean reference vessel EEL diameter <2.5 mm)
5. Perform ACR to avoid or minimize overlap in cases of multiple BRS implantation
6. Always perform post-stent dilation with NC high-pressure balloon (max. BRS+0.5 mm) to achieve strut embedment without scaffold disruption
7. Confirm accurate automatic measurement of MSA, %DS, and scaffold asymmetry
8. When crossing a newly deployed scaffold with imaging catheters, exercise care to avoid disrupting the scaffold geometry

ACR, OCT-angiography co-registration; BRS, bioresorbable scaffold; DES, drug-eluting stent; EEL, external elastic lamina; MACE, major adverse cardiac event; MSA, minimum stent area; NC, non-compliant; %DS, percent diameter stenosis.

Figure 7. OCT-guided strategy in BRS implantation. Preprocedural OCT pullback performed in the mid-proximal Lcx (A). OCT images show diffuse fibrocalcific lesions with 180–360° calcification (A-c to A-f). Reference mean EEL diameter of 3.08 mm and 3.56 mm at the A-a and A-f sites, respectively. According to the OCT data, lesion preparation with a scoring balloon Lacrosse NSETM 3.0/13 mm was performed in the middle and proximal LCx (at 4 atm and 12 atm, respectively). After lesion preparation, OCT images (B) show the expanded vessel with cracking of the calcified segments and a limited dissection (B-a to B-e). Two BVS AbsorbTM (3.5/28 mm and 3.5/18 mm) were implanted with minimum overlap and post-dilation with non-compliant balloons (3.5/15 mm, 18 atm and 4.0/15 mm, 12 atm, in the distal and proximal scaffold, respectively). In the postprocedural OCT images (C), the automatic lumen detection view shows limited residual area stenosis (17%), with well-apposed struts (C-a to C-e) observed in the cross-sectional views. AS, percent diameter stenosis; BRS, bioresorbable vascular scaffold; EEL, external elastic lamina; EES, everolimus-eluting stent; LAD, left anterior descending artery; LCx, left circumflex artery; LM, left main trunk; MLA, minimal lumen area; OCT, optical coherence tomography; Ø, mean lumen diameter.
tion in lesions with severe calcification.\textsuperscript{54,55} In this setting, OCT-guided strategies may provide further benefit to appropriate selection of device type and size (Figure 7). However, to definitely establish the safety and efficacy of BRS in complex lesions with severe calcification and the merit of OCT guidance to optimize scaffold implantation, large randomized studies of those types of lesion are required.

**Positioning of Multiple Scaffolds in Diffuse Disease**

Based on pathology and clinical data, major concerns have been addressed about the use of overlapping BRS when multiple scaffolds need to be implanted. The increased strut thickness with an overlapping technique might be associated with a higher incidence of periprocedural myocardial infarction, acute/subacute scaffold thrombosis, and restenosis compared with current DES.\textsuperscript{56,57} As a consequence, the overlapping segment should be minimized and scaffold-to-scaffold placement is recommended when multiple BRS implantation is required to fully cover the lesion. The use of OCT with online angiographic co-registration enables minimization of the number of struts overlapping (on average 0.9 mm vs. 2.2 mm; P=0.02), and can be particularly effective in fine-tuning the relative position of the invisible scaffolds compared with angiography alone.

**Conclusions**

The increasing level of patient/lesion complexity being treated by interventional cardiologists today requires a much higher standard of procedural precision and safety compared with the past. The informative role of intracoronary imaging has been changed with the introduction of novel OCT systems that allow immediate and accurate automatic lumen measurements, coupled with synchronized point-to-point co-registration with angiography. By this means, less subjective interpretation and more quantification are immediately integrated into the PCI flow, to plan and adapt the appropriate interventional strategy. Lesion preparation, accurate stent/scaffold placement, and optimal post-dilatation are key issues that may benefit from OCT guidance. However, the superiority of OCT-guided procedures compared with angiography guidance remains to be demonstrated in large, prospective studies.

**Conflict of Interest**

G.G. has received consulting fees from Boston Scientific, St. Jude Medical, and Goodman; has received grant support through the Hospital from Abbott Vascular. There is no other potential conflict of interest relevant to this article.

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