Current Cardiovascular Imaging Reports (2019) 12: 35
https://doi.org/10.1007/s12410-019-9513-5

INTRAVASCULAR IMAGING (A TRUESDELL, SECTION EDITOR)

Mechanisms of Stent Failure: Lessons from IVUS and OCT

Poonam Velagapudi[1] · Majid Asawaeer[1] · Andrew M. Goldsweig[1] · Fawaz Alenezi[2] · Yiannis Chatzizisis[1] · Herbert D. Aronow[3] · J. Dawn Abbott[3]

Published online: 18 July 2019

Abstract

Purpose of Review Despite significant advances in stent design and procedural technique, stent failure remains the "Achilles' heel" of percutaneous coronary intervention (PCI). It is important to understand the mechanism of stent failure to prevent major adverse events and improve clinical outcomes.

Recent Findings Two-dimensional angiography alone is insufficient for elucidating the etiology of stent failure. Intracoronary imaging modalities, including intravascular ultrasound (IVUS) and optical coherence tomography (OCT) have evolved to guide optimal stent placement during PCI, and have enabled identification of the etiology behind stent failure.

Summary In this review, we discuss the mechanisms of stent failure, use and limitations of intracoronary imaging (IVUS and OCT) to assess its etiology, and future directions for its use in patients undergoing coronary stent implantation.

Keywords Stent failure · Percutaneous coronary intervention · Intravascular ultrasound · Optical coherence tomography · In-stent restenosis · Stent thrombosis

Introduction

Stent failure, comprised of in-stent restenosis (ISR) and stent thrombosis (ST), is a well-known complication of percutaneous stent implantation [1•]. The factors associated with ISR include neointimal hyperplasia, neoatherosclerosis (NA), stent fracture, and stent underexpansion [2, 3], while risk of ST is associated with suboptimal stent deployment, including inappropriate stent sizing, edge dissection, stent malapposition, NA, and uncovered stent struts [4, 5] (Fig. 1). Traditionally, two-dimensional angiography has been used to assess plaque characteristics, vessel dimensions and adequacy of stent expansion, but its use is limited to visualization of the coronary lumen. Intracoronary imaging with IVUS or OCT has evolved as an effective imaging modality for identifying the mechanism of stent failure and for optimizing acute procedural results and improving clinical outcomes of percutaneous stent implantation [6••].

This article is part of the Topical Collection on *Intravascular Imaging*

✉ J. Dawn Abbott
jabbott@lifespan.org

Majid Asawaeer
majid.asawaeer@unmc.edu

Andrew M. Goldsweig
andrew.goldsweig@unmc.edu

Fawaz Alenezi
fawaz.enezi@duke.edu

Yiannis Chatzizisis
y.chatzizisis@unmc.edu

Herbert D. Aronow
herbert.aronow@lifespan.org

[1] University of Nebraska Medical Center, Omaha, NE, USA

[2] Duke University Medical Center, Durham, NC, USA

[3] Division of Cardiovascular Medicine, Department of Internal Medicine, Brown University, Providence, RI, USA

Mechanism/Pathophysiology of Stent Failure

Percutaneous coronary intervention (PCI) has evolved over the past 40 years. Bare metal stents (BMS) reduced vessel recoil associated with balloon angioplasty, but these benefits were offset by ST [1•] and the occurrence of neointimal hyperplasia several months after PCI leading to ISR [7]. This led to the development of first-generation drug-eluting stents (DES) with a durable polymer and anti-proliferative drug to reduce ISR [8]. However, there was an increase in late and

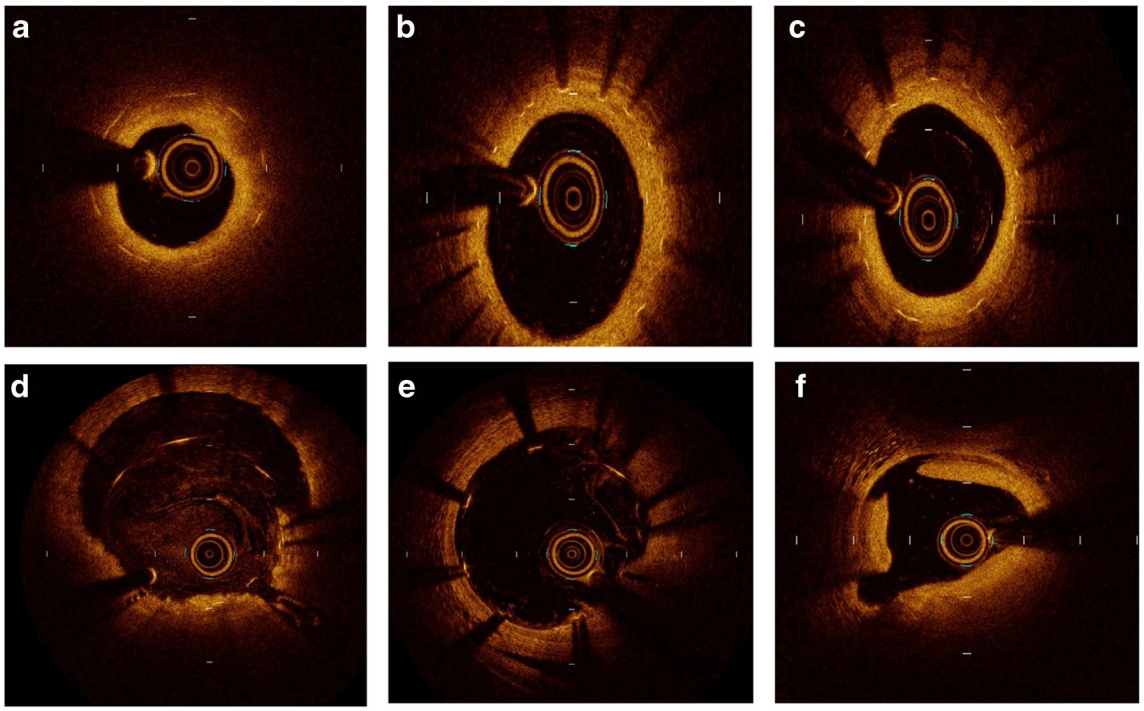

Fig. 1 OCT images showing neointimal hyperplasia (**a**, **b**, **c**), stent malapposition (**d**, **e**) and distal edge dissection (**f**)

very late ST due to delayed re-endothelialization [8] secondary to chronic inflammation and hypersensitivity reactions due to the durable polymer [9]. Thus, second-generation DES with different drugs and release kinetics, more biocompatible and bioresorbable polymers, and thinner stent struts were developed, leading to an incremental decrease in the rates of ISR and ST. [10, 11] To promote recovery of endothelial function and vascular remodeling and thereby reduce the risk of late and very late ST caused by DES, bioresorbable vascular scaffolds were developed [12]. These devices provide transient mechanical support along with antirestenotic drug delivery, but ultimately, are completely resorbed. However, due to late scaffold thrombosis, the first generation of these devices has not been broadly adopted in clinical practice, remains investigational, and is not approved by the US Food and Drug Administration.

In-stent Restenosis

Neointimal hyperplasia and negative vascular remodeling are the pathophysiological processes underlying ISR [13]. There are several predictors for ISR including diabetes, small vessel diameter, longer lesion length, multiple stents, and chronic total occlusion (CTO) [14, 15]. Final luminal diameter and degree of stent expansion are major determinants of ISR as demonstrated by studies involving IVUS and angiography. Factors such as stent fracture and NA are other notable causes [16, 17]. However, these factors are underappreciated with standard 2-dimensional angiography and typically require IVUS or OCT for detection [18]. OCT has a 10-fold higher image resolution than IVUS (OCT 10 μm and IVUS 100 μm) as it uses light that has a shorter wavelength than sound, thereby increasing its ability to detect differences in tissue composition, cell density, and orientation [19, 20]. OCT can therefore more clearly identify certain causes of late stent failure including NA and uncovered stent struts, which are associated with ST. [3, 21]

Stent and Scaffold Thrombosis

Intracoronary imaging studies using IVUS [22–24] and OCT [4, 25, 26] have identified multiple factors associated with ST (Table 1). Due to the ability to differentiate thrombus from other tissue components, OCT is often preferred over IVUS for evaluation of ST. [6••] Therapy for ST can be tailored towards OCT findings; however, there are no prospective trials to support this strategy [6••]. An important consideration to note is that malapposition, though a common finding after stent implantation, was not found to be clinically significant in a large OCT follow-up study [30] and may not require treatment unless there is associated under expansion [31].

Bioresorbable vascular scaffolds (BVS) with completely resorbable polymers after drug elution for a year were developed with the goal of reducing late events secondary to chronic inflammation and incomplete endothelialization secondary to permanent polymers of DES [32]. However,

Table 1 Selected studies demonstrating the mechanism of stent thrombosis by intracoronary imaging

Study	*N*	Intracoronary imaging	Type of stent failure	Mechanisms of stent thrombosis
Alfonso, 2004 [22]	50	IVUS	Early ST ($n = 12$); BMS	Underexpansion, malapposition, edge dissection, inflow-outflow disease
Choi, 2011 [23]	464 (349 DES, 115 BMS)	IVUS	Early ST ($n = 12$); all DES* Late/VLST ST ($n = 4$) all DES*	Minimum lumen area (MLA) < 5 mm2, residual stenosis, edge dissection, or tissue protrusion
Lee, 2010 [24]	30 (23 DES, 7 BMS)	IVUS	VLST ($n = 30$)	Malapposition and disease progression more common with DES, neointimal rupture more common with BMS
Adriaenssens, 2017 [27]	231 (110 BMS, 121)	OCT	Early ST ($n = 62$, 28.6%) Late/VLST ($n = 155$, 71.4%)	Uncovered struts (66.7%) were most common finding for acute ST; uncovered struts (61.7%) and underexpansion (25.5%) in subacute ST; uncovered struts (33.3%), severe restenosis (19.1%) for late ST; neoatherosclerosis (31.3%) and uncovered struts (20.2%) for VLST.
Souteyrand, 2016 [26]	120 (47 BMS, 71 DES)	OCT	Early ST ($n = 5$) Late ST ($n = 7$) VLST ($n = 90$)	Malapposition (31%) and neoatherosclerosis (28%) were more common in late and VLST; malapposition (48%) and underexpansion (26%) were more common in early ST.
Prati, 2015 [4]	63 (48 BMS, 15 DES)	OCT	Subacute ST ($n = 21$)	Higher proportion of stent edge dissection (52.4% vs. 9.5%), underexpansion (42.8% vs. 16.7%) were more common in subacute ST compared with controls.
Taniwaki, 2016 [25]	64 (all DES)	OCT	VLST ($n = 64$)	Common causes for VLST included malapposition (35%), neoatherosclerosis (28%), uncovered struts (12%), and stent underexpansion (7%).
Sotomi, 2017 [28]	43 (all BVS)	OCT/IVUS	Early ScT ($n = 17$) Late ScT ($n = 26$)	Early ScT was associated with malapposition (24%), device underexpansion (12%), incomplete lesion coverage (18%); late ScT late and VLScT were associated with malapposition (35%), scaffold discontinuity (31%), scaffold underexpansion (15%), peristrut low-intensity area (19%), uncovered struts (15%), restenosis (8%), incomplete lesion coverage (12%), and scaffold recoil (12%).
Yamaji, 2017 [29]	36 (all BVS)	OCT	VLScT	VLScT was associated with scaffold discontinuity (42.1%), malapposition (18.4%), neoatherosclerosis (18.4%), scaffold recoil (10.5%), uncovered struts (5.3%), and edge-related disease progression (2.6%)

*Paclitaxel-eluting stents; VLST, very late ST; ScT, scaffold thrombosis; VLScT, very late scaffold thrombosis

scaffold thrombosis remains a problem [33] with intracoronary imaging trials demonstrating multiple underlying associated factors [[3, 28])] (Table 1). In porcine models, a complete resorption of the poly(L-lactide) (PLLA) Absorb scaffold (Abbott, Chicago, IL) occurred within 3 years [34]. However, very late scaffold thrombosis (ScT) associated with preserved box-shaped appearance was noted to occur as late as 44 months at an advanced stage of scaffold resorption secondary to scaffold discontinuity and restenosis during the resorption process [35]. It is important to note that scaffold discontinuity related to late resorption has no clinical significance if scaffold structures are not protruding into the lumen [30, 35]. Protrusion of scaffold structures into the lumen can occur during implantation due to excessive stretching and fracture of polymer, or late/very late during resorption due to excessive biomechanical stress or iatrogenic mechanical causes such as disruption by catheters, thus making the case for prolonged dual antiplatelet therapy and careful instrumentation of these scaffolds [32, 36]. Since IVUS is less sensitive than OCT in the detection of strut disruption or discontinuity, OCT is the imaging modality of choice for evaluating ScT, particularly when overexpansion or oversizing is suspected [30, 37]. Table 1 demonstrates selected studies evaluating the mechanism of stent failure in bioresorbable vascular scaffolds.

Intra-procedural Predictors of Stent Failure

Stent Sizing OCT and IVUS use can decrease the incidence of long-term stent failure. Current data show that post-PCI minimal stent area (MSA) is the most reliable predictor of both ISR and ST. [38, 39] Small post-procedural MSA (smallest ≤ 5.0 mm2 and intermediate 5.0–6.7 mm2), creatinine clearance, prior stroke, CTO, and lesion SYNTAX score were independent predictors of target lesion revascularization (TLR) at 2 years in the SYNTAX II trial [40]. A 5.5-mm^2 MSA cutoff value for the prediction of angiographic ISR can be used for sirolimus-eluting stents (sensitivity 72.2% and specificity 66.3%), 5.3 mm^2 for zotarolimus-eluting stents (sensitivity 56.7% and specificity 61.8%), < 5.4 mm^2 for everolimus-eluting stents (sensitivity 60.0% and specificity 60.0%), and 5.7 mm^2 for paclitaxel-eluting stents (PES) [(38, 41]].

During IVUS-guided DES implantation, plaque burden 5-mm proximal or distal to the stent edge < 50%, MLA > 5.0 mm^2, or 90% of the MLA at the distal reference segments, and no edge dissection that involves the media with a length > 3 mm correlate with significantly improved clinical outcome including reduced target vessel failure (TVF) at 1 year in an all-comers population [42]. In a RCT, including 1,448 patients, IVUS guidance for left main PCI also was associated with a significant reduction in ST (RR, 0.48; $P = 0.01$) compared with angiographic guidance [42].

In an OCT registry, OCT-MSA (< 5 mm^2 for DES and < 5.6 mm^2 for BMS) was an independent predictor of TLR, cardiac death, ST, and myocardial infarction (MI) [39]. OCT-guided stenting showed improved procedural outcomes, in-hospital events, and long-term survival compared with traditional angiography-guided stent implantation [43]. This can be attributed to the ability of OCT to delineate the neointimal patterns and NA in ISR, which can guide the choice of treatment [44]. OCT imaging revealed that, compared to BMS, DES are more likely to develop NA with ISR [45].

Post-dilation using the distal lumen as a reference appears to be an effective way to prevent stent under expansion. IVUS can detect the external elastic membrane diameter of the vessel wall, while OCT fails to detect the vessel wall accurately. However, both IVUS and OCT can be used to measure the vessel wall using the lumen-based approach. Despite the unique advantages of each modality, the MLA measured by OCT is about 10% smaller than the MLA measured by IVUS. In addition, the reference site lumen measurement appears to be smaller with OCT, which can impact stent sizing. The OPINION study, a prospective randomized study including 829 patients comparing IVUS vs. OCT, demonstrated a significantly higher average stent size when applying lumen-based stent sizing (2.99 ± 0.39 mm vs. 2.92 ± 0.39 mm, $p = 0.0005$) [46•]. There was no significant difference in in-stent (1.6% vs. 1.6%, $p = 1.0$) or in-segment restenosis rates (6% vs. 6.2%, $p = 1.0$) between both groups at 8-month follow-up [46•]. The ILUMIEN III trial compared 450 patients between IVUS and OCT and demonstrated that the minimum stent area with OCT was non-inferior to IVUS or angiography (5.79 mm^2 vs. 5.89 mm^2 vs. 5.49 mm^2) respectively [47]. However, data regarding post-PCI OCT measurement to predict physiological ischemia or clinical outcomes are still limited pending results from the ongoing large-scale randomized ILUMIEN IV study (NCT03507777), which is expected to be completed by July 31, 2022.

Strut apposition refers to the proximity of stent struts to the arterial wall, while stent malapposition refers to stent under expansion and lack of contact with the vessel wall. Stent malapposition can occur immediately following the procedure or chronically due to vascular inflammation and vessel remodeling.

OCT-guided PCI using the ILUMIEN III: OPTIMIZE PCI protocol [47] establishes stent length, diameter, and expansion, resulting in safe and similar MSA to that of IVUS-guided PCI. Early vascular healing post-DES placement contributes to a reduction in both the presence and severity of stent malapposition. However, malapposition that exceeds 400 μm is associated with a higher chance of long-term persistent malapposition and impaired vascular remodeling [48]. A meta-analysis by Hassan revealed that the risk of late acquired stent malapposition is strongly increased after DES implantation compared with BMS and is associated with late and very late ST. [49]

OCT guidance showed improved strut coverage at 3 months compared with angiography-guided DES implantation with an average 2.8% absolute reduction in the percentage of uncovered struts [48]. The larger the acute incomplete stent apposition, the greater is the likelihood of persistent stent malapposition and delayed healing on follow-up [50]. IVUS and OCT complement each other in the diagnosis and elucidation of incomplete stent apposition mechanisms. OCT-detected uncovered stent struts and positive vessel remodeling detected on IVUS were associated with late ST after PCI [51].

Longitudinal stent deformation leads to increased risk of ST and ISR [52]. The introduction of cobalt-chromium and platinum-chromium alloys in stents, along with a reduced number of fixed links between stent cells, are potential risk for longitudinal stent deformation [52]. IVUS and OCT can delineate protrusion of struts and affirm malapposition of struts caused by longitudinal deformation [53].

Longitudinal geographical miss (*GM*) is defined as an angioplasty-injured or diseased segment not covered by a stent. GM is associated with an increased risk of TLR and a 3-fold increase in myocardial infarction at 1 year [54]. Intracoronary imaging using IVUS and OCT can precisely identify the landing zone and facilitate appropriate length selection.

Tissue protrusion (*TP*) defined as extrusion of atherothrombotic material beyond the stent margins is hard to

appreciate on angiography while up to 34% of stented lesions displayed tissue protrusion on IVUS [55]. While presence of TP on IVUS did not show a significant difference in long-term major adverse cardiac events including cardiac death, MI, or target vessel revascularization at 1 year [56] or cardiac death, MI, or ST at 2 years [55] compared to those without, it was an independent predictor of acute and subacute ST. [56, 57] OCT enables more accurate visualization of tissue protrusion when compared with IVUS [47]. Irregular but not smooth or disrupted fibrous tissue protrusion was identified as an independent OCT predictor of 1-year device-oriented clinical endpoints driven by TLR [39]. Irregular protrusion reflective of moderate to severe vessel injury can be associated with thrombus [39] and has a high likelihood of medial disruption which is known to be associated with increased risk of occlusive DES restenosis [58].

Edge dissection involves intimal disruption at the stent margin and can occur in 5–23% of stent implantation. Edge dissections were associated with increased rates of in-hospital (11.9 vs. 5.2%, $P = 0.017$) and 1-month MACE (13.4 vs. 6.0%, $P = 0.013$), with similar 6-month trends [59]. Following DES implantation, residual edge dissection, particularly with a smaller effective lumen area, was associated with TLR at 1 year [60]. The presence of large, calcified, and/or attenuated plaques; residual plaque eccentricity; greater stent expansion; lumen-to-stent-edge-area ratio; and stent edge symmetry are predictors of edge dissections [61]. Both IVUS and OCT are excellent tools for identification of edge dissection. Edge dissection with a lateral extension of $> 60°$ and length of > 2 mm identified by IVUS have been correlated with adverse events including early ST. [62] OCT has a higher resolution than IVUS and can identify less extensive edge dissections as demonstrated in the ILUMIEN III trial, which showed a two-fold higher identification of edge dissections compared with IVUS [47].

Intramural hematomas occur due to dissection into the vessel media with blood accumulation due to lack of reentry and can lead to higher rates of NSTEMI, need for repeat revascularization, and sudden death post PCI [63]. In one study, intramural hematomas were identified by IVUS in up to 6.7% of PCIs and a third of IVUS-identified hematomas were missed on standard angiography [63]. However, OCT due to its higher resolution may better characterize intramural hematomas including assessment of the vessel wall and exclusion of atheroma [64].

Slow flow during PCI is another phenomenon that can occur in up to 16% of PCI and can be transient or permanent. OCT and IVUS can be utilized to decrease the incidence of slow flow by using a ratio of stent diameter to a vessel diameter of 0.71 or more following stent implantation PCI [65].

Current Recommendations, Limitations, and Future Directions for Use of Intracoronary Imaging In-Stent Failure

Both IVUS and OCT can readily identify stent under expansion and stent fracture, while OCT is preferred for identifying NA [3] and ST. [6••] Where thrombus burden is large, IVUS may be preferred since light attenuation may impair OCT evaluation of stent struts and the outer vessel wall [6••]. The 2011 ACCF/AHA/SCAI guidelines for PCI [66] and 2014 ESC guidelines on myocardial revascularization [67] give a class IIa recommendation for intracoronary imaging using IVUS/OCT to determine the mechanism of stent failure. This recommendation is further supported by an expert consensus document of the European Association of Percutaneous Cardiovascular Interventions that also maintains a similar class IIa recommendation for identifying the mechanism of stent failure [6••].

Despite the benefits of IVUS and OCT in establishing the factors predictive of stent failure and in optimizing stent implantation, there remain limitations to their use. First, although IVUS has been around for several decades, the use of OCT has only become prevalent in the past few years. Interventional cardiologists trained prior to the introduction of this technology may not be versatile with its use. The learning curve associated with image acquisition and interpretation can be overcome by attending courses and appropriate mentoring from experts familiar with this technology. Second, the time and costs involved in the use of intracoronary imaging must be weighed against the possible benefits of its use. Currently, there are limited data that stent optimization using intracoronary imaging improves long-term clinical outcomes in all comers. However, there is no doubt that this technology is beneficial in a subset of higher risk patients. Third, it may be challenging to pass the IVUS or OCT catheters in coronaries with excessive tortuosity, calcium, and bifurcation lesions, where their use may be of the most benefit. Evolving technology using high-resolution imaging, low-profile wires and sheaths, micro-OCT catheters, molecular analysis, and integration with coronary angiography can overcome this limitation and facilitate widespread use. Finally, complications with the use of intracoronary imaging can occur, but these are relatively rare and decrease with operator experience. Future studies should aim to create catheters that are more deliverable and cost-effective, and fellowship programs should ensure that all trainees are proficient with these devices.

Conclusions

Intracoronary imaging is an important tool in understanding the factors predictive of stent failure to guide appropriate

therapy and improve clinical outcomes. The operator must understand the advantages and limitations of the two imaging modalities and use them to optimize treatment. Future studies evaluating the role of intracoronary imaging for stent failure are necessary.

Compliance with Ethical Standards

Conflict of Interest All authors declare no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:
- • Of importance
- •• Of major importance

1.• Torrado J, Buckley L, Durán A, et al. Restenosis, stent thrombosis, and bleeding complications. J Am Coll Cardiol. 2018;71:1676. **This study provides a thorough description regarding restenosis, stent thrombosis and bleeding complications post-PCI**.
2. Goto K, Zhao Z, Matsumura M, Dohi T, Kobayashi N, Kirtane AJ, et al. Mechanisms and patterns of intravascular ultrasound in-stent restenosis among bare metal stents and first- and second-generation drug-eluting stents. Am J Cardiol. 2015;116:1351–7.
3. Kang S-J, Mintz Gary S, Akasaka T, et al. Optical coherence tomographic analysis of in-stent neoatherosclerosis after drug–eluting stent implantation. Circulation. 2011;123:2954–63.
4. Prati F, Kodama T, Romagnoli E, Gatto L, di Vito L, Ramazzotti V, et al. Suboptimal stent deployment is associated with subacute stent thrombosis: optical coherence tomography insights from a multicenter matched study. From the CLI Foundation investigators: the CLI-THRO study. Am Heart J. 2015;169:249–56.
5. the PI, the PI, the PI, et al. Mechanisms of stent thrombosis analysed by optical coherence tomography: insights from the national PESTO French registry. Eur Heart J. 2016;37:1208–16.
6.•• Group ESCSD, Koskinas KC, Räber L, et al. Clinical use of intracoronary imaging. Part 1: guidance and optimization of coronary interventions. An expert consensus document of the European Association of Percutaneous Cardiovascular Interventions. Eur Heart J. 2018;39:3281–300. **This expert consensus document is a must read for guidance on optimization of coronary interventions.**
7. Stone Gregg W, Ellis Stephen G, Cox David A, et al. One-year clinical results with the slow-release, polymer-based, paclitaxel-eluting TAXUS stent. Circulation. 2004;109:1942–7.
8. Kirtane AJ, Gupta A, Iyengar S, Moses JW, Leon MB, Applegate R, et al. Safety and efficacy of drug-eluting and bare metal stents: comprehensive meta-analysis of randomized trials and observational studies. Circulation. 2009;119:3198–206.
9. Finn Aloke V, Nakazawa G, Joner M, et al. Vascular responses to drug eluting stents. Arterioscler Thromb Vasc Biol. 2007;27:1500–10.
10. Ellis SG, Colombo A, Grube E, Popma J, Koglin J, Dawkins KD, et al. Incidence, timing, and correlates of stent thrombosis with the polymeric paclitaxel drug-eluting stent. J Am Coll Cardiol. 2007;49:1043–51.
11. Stone GW, Rizvi A, Newman W, Mastali K, Wang JC, Caputo R, et al. Everolimus-eluting versus paclitaxel-eluting stents in coronary artery disease. N Engl J Med. 2010;362:1663–74.
12. Kang S-H, Chae I-H, Park J-J, et al. Stent thrombosis with drug-eluting stents and bioresorbable scaffolds. J Am Coll Cardiol Intv. 2016;9:1203.
13. Alfonso F, Byrne RA, Rivero F, Kastrati A. Current treatment of in-stent restenosis. J Am Coll Cardiol. 2014;63:2659–73.
14. Foley DP, Melkert R, Serruys PW. Influence of coronary vessel size on renarrowing process and late angiographic outcome after successful balloon angioplasty. Circulation. 1994;90:1239–51.
15. Violaris AG, Melkert R, Serruys PW. Long-term luminal renarrowing after successful elective coronary angioplasty of total occlusions. A quantitative angiographic analysis. Circulation. 1995;91:2140–50.
16. de Feyter PJ, Kay P, Disco C, Serruys PW. Reference chart derived from post-stent-implantation intravascular ultrasound predictors of 6-month expected restenosis on quantitative coronary angiography. Circulation. 1999;100:1777–83.
17. Serruys PW, Kay IP, Disco C, Deshpande NV, de Feyter PJ. Periprocedural quantitative coronary angiography after Palmaz-Schatz stent implantation predicts the restenosis rate at six months: results of a meta-analysis of the BElgian NEtherlands Stent study (BENESTENT) I, BENESTENT II Pilot, BENESTENT II and MUSIC trials. Multicenter Ultrasound Stent In Coronaries. J Am Coll Cardiol. 1999;34:1067–74.
18. Raber L, Mintz GS, Koskinas KC, et al. Clinical use of intracoronary imaging. Part 1: guidance and optimization of coronary interventions. An expert consensus document of the European Association of Percutaneous Cardiovascular Interventions. Eur Heart J. 2018;39:3281–300.
19. Waksman R, Kitabata H, Prati F, Albertucci M, Mintz GS. Intravascular ultrasound versus optical coherence tomography guidance. J Am Coll Cardiol. 2013;62:S32–40.
20. Maehara A, Matsumura M, Ali ZA, Mintz GS, Stone GW. IVUS-guided versus OCT-guided coronary stent implantation: a critical appraisal. J Am Coll Cardiol Img. 2017;10:1487–503.
21. Lee S-Y, Hong M-K. Stent evaluation with optical coherence tomography. Yonsei Med J. 2013;54:1075–83.
22. Alfonso F, Suárez A, Angiolillo DJ, Sabaté M, Escaned J, Moreno R, et al. Findings of intravascular ultrasound during acute stent thrombosis. Heart. 2004;90:1455–9.
23. Choi SY, Witzenbichler B, Maehara A, Lansky AJ, Guagliumi G, Brodie B, et al. Intravascular ultrasound findings of early stent thrombosis after primary percutaneous intervention in acute myocardial infarction: a Harmonizing Outcomes with Revascularization and Stents in Acute Myocardial Infarction (HORIZONS-AMI) substudy. Circ Cardiovasc Interv. 2011;4:239–47.
24. Lee CW, Kang S-J, Park D-W, Lee SH, Kim YH, Kim JJ, et al. Intravascular ultrasound findings in patients with very late stent thrombosis after either drug-eluting or bare-metal stent implantation. J Am Coll Cardiol. 2010;55:1936–42.
25. Taniwaki M, Radu Maria D, Zaugg S, et al. Mechanisms of very late drug-eluting stent thrombosis assessed by optical coherence tomography. Circulation. 2016;133:650–60.
26. Souteyrand G, Amabile N, Mangin L, Chabin X, Meneveau N, Cayla G, et al. Mechanisms of stent thrombosis analysed by optical coherence tomography: insights from the national PESTO French registry. Eur Heart J. 2016;37:1208–16.
27. Adriaenssens T, Joner M, Godschalk TC, Malik N, Alfonso F, Xhepa E, et al. Optical coherence tomography findings in patients with coronary stent thrombosis: a report of the PRESTIGE Consortium (Prevention of Late Stent Thrombosis by an

Interdisciplinary Global European Effort). Circulation. 2017;136: 1007–21.
28. Sotomi Y, Suwannasom P, Serruys PW, Onuma Y. Possible mechanical causes of scaffold thrombosis: insights from case reports with intracoronary imaging. EuroIntervention. 2017;12:1747–56.
29. Yamaji K, Ueki Y, Souteyrand G, Daemen J, Wiebe J, Nef H, et al. Mechanisms of very late bioresorbable scaffold thrombosis: the INVEST registry. J Am Coll Cardiol. 2017;70:2330–44.
30. Onuma Y, Serruys PW, Muramatsu T, et al. Incidence and imaging outcomes of acute scaffold disruption and late structural discontinuity after implantation of the absorb everolimus-eluting fully bioresorbable vascular scaffold. J Am Coll Cardiol Intv. 2014;7:1400.
31. Mintz GS. Why are we so concerned with acute incomplete stent apposition? Eur Heart J – Cardiovasc Imaging. 2014;16:110–1.
32. Stone GW, Granada JF. Very late thrombosis after bioresorbable scaffolds. J Am Coll Cardiol. 2015;66:1915–7.
33. Lipinski MJ, Escarcega RO, Baker NC, et al. Scaffold thrombosis after percutaneous coronary intervention with ABSORB bioresorbable vascular scaffold. J Am Coll Cardiol Intv. 2016;9:12.
34. Otsuka F, Pacheco E, Perkins LE, et al. Long-term safety of an everolimus-eluting bioresorbable vascular scaffold and the cobalt-chromium XIENCE V stent in a porcine coronary artery model. Circ Cardiovasc Interv. 2014;7:330–42.
35. Räber L, Brugaletta S, Yamaji K, O'Sullivan CJ, Otsuki S, Koppara T, et al. Very late scaffold thrombosis. J Am Coll Cardiol. 2015;66: 1901–14.
36. Ali ZA, Karimi Galougahi K, Maehara A, Shlofmitz RA, Ben-Yehuda O, Mintz GS, et al. Intracoronary optical coherence tomography 2018: current status and future directions. J Am Coll Cardiol Intv. 2017;10:2473–87.
37. Gomez-Lara J, Brugaletta S, Diletti R, et al. Agreement and reproducibility of gray-scale intravascular ultrasound and optical coherence tomography for the analysis of the bioresorbable vascular scaffold. Catheter Cardiovasc Interv. 2012;79:890–902.
38. Doi H, Maehara A, Mintz GS, Yu A, Wang H, Mandinov L, et al. Impact of post-intervention minimal stent area on 9-month follow-up patency of paclitaxel-eluting stents: an integrated intravascular ultrasound analysis from the TAXUS IV, V, and VI and TAXUS ATLAS Workhorse, Long Lesion, and Direct Stent Trials. JACC Cardiovasc Interv. 2009;2:1269–75.
39. Soeda T, Uemura S, Park SJ, Jang Y, Lee S, Cho JM, et al. Incidence and clinical significance of poststent optical coherence tomography findings: one-year follow-up study from a multicenter registry. Circulation. 2015;132:1020–9.
40. Katagiri Y, De Maria GL, Kogame N, et al. Impact of post-procedural minimal stent area on 2-year clinical outcomes in the SYNTAX II trial. Catheter Cardiovasc Interv. 2019;93:E225–e234.
41. Song HG, Kang SJ, Ahn JM, Kim WJ, Lee JY, Park DW, et al. Intravascular ultrasound assessment of optimal stent area to prevent in-stent restenosis after zotarolimus-, everolimus-, and sirolimus-eluting stent implantation. Catheter Cardiovasc Interv. 2014;83: 873–8.
42. Zhang J, Gao X, Kan J, Ge Z, Han L, Lu S, et al. Intravascular ultrasound versus angiography-guided drug-eluting stent implantation: the ULTIMATE trial. J Am Coll Cardiol. 2018;72:3126–37.
43. Jones DA, Rathod KS, Koganti S, Hamshere S, Astroulakis Z, Lim P, et al. Angiography alone versus angiography plus optical coherence tomography to guide percutaneous coronary intervention: outcomes from the Pan-London PCI Cohort. JACC Cardiovasc Interv. 2018;11:1313–21.
44. Xhepa E, Byrne RA, Rivero F, et al. Qualitative and quantitative neointimal characterization by optical coherence tomography in patients presenting with in-stent restenosis. Clin Res Cardiol. 2019.
45. Nakamura D, Yasumura K, Nakamura H, Matsuhiro Y, Yasumoto K, Tanaka A, et al. Different neoatherosclerosis patterns in drug-eluting- and bare-metal stent restenosis- optical coherence tomography study. Circ J. 2019;83:313–9.
46.• Kubo T, Shinke T, Okamura T, Hibi K, Nakazawa G, Morino Y, et al. Optical frequency domain imaging vs. intravascular ultrasound in percutaneous coronary intervention (OPINION trial): one-year angiographic and clinical results. Eur Heart J. 2017;38: 3139–47. **This randomized trial showed non-inferiority of OCT to IVUS for target vessel failure 12 months post PCI**.
47. Ali ZA, Maehara A, Genereux P, et al. Optical coherence tomography compared with intravascular ultrasound and with angiography to guide coronary stent implantation (ILUMIEN III: OPTIMIZE PCI): a randomised controlled trial. Lancet (London, England). 2016;388:2618–28.
48. Lee SY, Kim JS, Yoon HJ, Hur SH, Lee SG, Kim JW, et al. Early strut coverage in patients receiving drug-eluting stents and its implications for dual antiplatelet therapy: a randomized trial. J Am Coll Cardiol Img. 2018;11:1810–9.
49. Hassan AK, Bergheanu SC, Stijnen T, et al. Late stent malapposition risk is higher after drug-eluting stent compared with bare-metal stent implantation and associates with late stent thrombosis. Eur Heart J. 2010;31:1172–80.
50. Gutierrez-Chico JL, Wykrzykowska J, Nuesch E, et al. Vascular tissue reaction to acute malapposition in human coronary arteries: sequential assessment with optical coherence tomography. Circ Cardiovasc Interv. 2012;5:20–9 s1-8.
51. Guagliumi G, Sirbu V, Musumeci G, Gerber R, Biondi-Zoccai G, Ikejima H, et al. Examination of the in vivo mechanisms of late drug-eluting stent thrombosis: findings from optical coherence tomography and intravascular ultrasound imaging. JACC Cardiovasc Interv. 2012;5:12–20.
52. Hanratty CG, Walsh SJ. Longitudinal compression: a "new" complication with modern coronary stent platforms–time to think beyond deliverability? EuroIntervention. 2011;7:872–7.
53. Kereiakes DJ, Popma JJ, Cannon LA, Kandzari DE, Kimmelstiel CD, Meredith IT, et al. Longitudinal stent deformation: quantitative coronary angiographic analysis from the PERSEUS and PLATINUM randomised controlled clinical trials. EuroIntervention. 2012;8:187–95.
54. Costa MA, Angiolillo DJ, Tannenbaum M, Driesman M, Chu A, Patterson J, et al. Impact of stent deployment procedural factors on long-term effectiveness and safety of sirolimus-eluting stents (final results of the multicenter prospective STLLR trial). Am J Cardiol. 2008;101:1704–11.
55. Qiu F, Mintz GS, Witzenbichler B, Metzger DC, Rinaldi MJ, Duffy PL, et al. Prevalence and clinical impact of tissue protrusion after stent implantation: an ADAPT-DES intravascular ultrasound substudy. JACC Cardiovasc Interv. 2016;9:1499–507.
56. Hong YJ, Jeong MH, Choi YH, Song JA, Kim DH, Lee KH, et al. Impact of tissue prolapse after stent implantation on short- and long-term clinical outcomes in patients with acute myocardial infarction: an intravascular ultrasound analysis. Int J Cardiol. 2013;166:646–51.
57. Cheneau E, Leborgne L, Mintz GS, Kotani JI, Pichard AD, Satler LF, et al. Predictors of subacute stent thrombosis: results of a systematic intravascular ultrasound study. Circulation. 2003;108:43–7.
58. Nakano M, Otsuka F, Yahagi K, Sakakura K, Kutys R, Ladich ER, et al. Human autopsy study of drug-eluting stents restenosis: histomorphological predictors and neointimal characteristics. Eur Heart J. 2013;34:3304–13.
59. Biondi-Zoccai GG, Agostoni P, Sangiorgi GM, Airoldi F, Cosgrave J, Chieffo A, et al. Incidence, predictors, and outcomes of coronary dissections left untreated after drug-eluting stent implantation. Eur Heart J. 2006;27:540–6.
60. Kobayashi N, Mintz GS, Witzenbichler B, et al. Prevalence, features, and prognostic importance of edge dissection after drug-

eluting stent implantation: an ADAPT-DES intravascular ultrasound substudy. Circ Cardiovasc Interv. 2016;9:e003553.

61. Liu X, Tsujita K, Maehara A, Mintz GS, Weisz G, Dangas GD, et al. Intravascular ultrasound assessment of the incidence and predictors of edge dissections after drug-eluting stent implantation. JACC Cardiovasc Interv. 2009;2:997–1004.
62. Choi S-Y, Witzenbichler B, Maehara A, Lansky AJ, Guagliumi G, Brodie B, et al. Intravascular ultrasound findings of early stent thrombosis after primary percutaneous intervention in acute myocardial infarction. Circ Cardiovasc Interv. 2011;4:239–47.
63. Maehara A, Mintz GS, Bui AB, Castagna MT, Walter OR, Pappas C, et al. Incidence, morphology, angiographic findings, and outcomes of intramural hematomas after percutaneous coronary interventions: an intravascular ultrasound study. Circulation. 2002;105:2037–42.
64. Johnson TW, Smith D, Strange JW, Bucciarelli-Ducci C, Lowe R, Baumbach A. Spontaneous multivessel coronary intramural hematoma. JACC Cardiovasc Imaging. 2012;5:1070.
65. Watanabe Y, Sakakura K, Taniguchi Y, Yamamoto K, Wada H, Fujita H, et al. Determinants of slow flow following stent implantation in intravascular ultrasound-guided primary percutaneous coronary intervention. Heart Vessel. 2018;33:226–38.
66. Levine GN, Bates ER, Blankenship JC, Bailey SR, Bittl JA, Cercek B, et al. 2011 ACCF/AHA/SCAI guideline for percutaneous coronary intervention: a report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines and the Society for Cardiovascular Angiography and Interventions. J Am Coll Cardiol. 2011;58:e44–122.
67. Windecker S, Kolh P, Alfonso F, et al. 2014 ESC/EACTS Guidelines on myocardial revascularization: the Task Force on Myocardial Revascularization of the European Society of Cardiology (ESC) and the European Association for Cardio-Thoracic Surgery (EACTS)Developed with the special contribution of the European Association of Percutaneous Cardiovascular Interventions (EAPCI). Eur Heart J. 2014;35:2541–619.