Fundamentals and role of intravascular ultrasound in percutaneous coronary intervention

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Abstract: Intravascular ultrasound (IVUS) is a catheter-based invasive imaging modality that has become an essential adjunctive tool to percutaneous coronary intervention (PCI) over the past 20 years. Clinical applications of IVUS in PCI include assessment of lesion severity, characterizing plaque morphology, optimization of acute stent results and clarification of mechanisms of stent failure. Numerous meta-analyses of large observational and randomized studies support the role of IVUS-guided PCI in reducing short and long-term adverse outcomes, including mortality and stent failure, particularly in patients receiving drug-eluting stents (DESs) and in complex lesion subsets. The current review provides a summary of the fundamental aspects and current clinical roles of IVUS in coronary intervention.

Keywords: Intravascular ultrasound (IVUS); percutaneous coronary intervention (PCI); drug eluting stent

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Introduction

Supported by a wealth of randomized and observational data, intravascular ultrasound (IVUS) has established itself as an invaluable adjunctive tool to contemporary coronary angiography and percutaneous coronary interventions (PCI). Indeed, in the current drug-eluting stent (DES) era, IVUS-guided PCI has consistently been shown to reduce hard clinical endpoints of mortality, target lesion revascularization, stent thrombosis and myocardial infarction (MI), across various lesion subsets and device generations (1,2). Recently, the 2-year exploratory analysis of the SYNTAX II study (3), where IVUS was used in 84% of cases, re-affirmed earlier observations that this “state-of-the-art” PCI strategy utilizing modern adjunctive tools such as IVUS, can achieve superior clinical outcomes compared to angiography-guided PCI and even coronary artery bypass grafting (CABG).

However, despite a firmly established evidence base and guideline endorsements, utilization of IVUS in routine interventional practice remains highly heterogenous and is underscored by substantial variability in regional practices and individual operator experience (4). Cost remains a major factor in many countries. Appropriate knowledge exchange, stronger guideline-driven indications and reimbursement for IVUS use are key to improving its clinical penetration. The purpose of this review is to provide a concise summary on the clinical applications of grayscale IVUS and to highlight its extraordinary potential to enhance interventional practice.

Image evaluation: the fundamentals

The principles of IVUS are analogous to other forms of ultrasound imaging: piezo-electric crystals generate ultrasound pulses under electric current, and reflected echoes from tissue structures are used to produce monochrome images in grayscale. More reflective or
echogenic structures such as fibrous tissue and calcifications produce brighter signals, whereas echo-lucent structures such as lipid collections generate low-intensity signals. As with all ultrasound techniques, measurements on IVUS images are obtained from leading-edge to leading-edge as a standard approach.

The spatial resolution of IVUS is dependent on the wavelength and beam-width of the ultrasound pulses. The lower the wavelength and narrower the beam width, the better the axial and lateral resolution, respectively. Both variables can be altered by varying the frequency of the transducer. Frequency is related to wavelength by the equation: \( c = f\lambda \), where \( c \) is the speed of sound which is constant, \( f \) is frequency and \( \lambda \) is wavelength. Therefore, as frequency increases, wavelength and beam-width are reduced, increasing axial and lateral resolution. Tissue penetration is another factor that is determined by frequency. As frequency is increased, penetration distance is decreased. These factors need to be considered when selecting the IVUS catheter.

There are two main types of conventional IVUS catheters used in clinical practice today: mechanical rotational single transducer probe (annular-array) with a typical sound frequency of 40-45 MHz (such as OptiCross™, Boston Scientific, USA), and phased-array probe with multiple fixed transducers with a typical sound frequency of 20 MHz (such as Eagle Eye™, Philips Volcano, USA) (Figure 1). Image pull-backs can be performed manually or automatically with a typical pull-back speed of 0.5 mm/s. Catheters range from 2.6–3.5 French and can therefore be placed through 5 or 6 French guiding catheters, depending on the IVUS catheter used (5) (Table 1). The typical axial resolution for commonly used systems is ~80–100 μm and lateral resolution is ~200–250 μm, whereas tissue penetration is ~6–12 mm (6). More recently, high-definition IVUS with transducer frequency of 60 MHz has also become available, allowing for superior axial resolution <40 μm. To put this into context, modern thin-strut stents typically have a strut thickness of 60–80 μm.

Image artifacts are frequently encountered and important to recognize. Many IVUS artifacts are also present in other forms of ultrasound imaging and have similar underlying principles. These include: reverberation artifacts, acoustic shadowing and ring-down artifacts. A more unique IVUS artifact is the non-uniform rotational

![Figure 1 Types of IVUS catheters. (A) Mechanical rotational or annular array with a rotational transducer; (B) phased-array with multiple fixed transducers. IVUS, intravascular ultrasound.](image)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Boston Scientific OptiCross</th>
<th>Philips Volcano Eagle Eye</th>
<th>Philips Volcano Revolution</th>
<th>Philips Volcano Refinity</th>
<th>Acist Kodama</th>
<th>Terumo ViewIT*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transducer frequency</td>
<td>40 MHz (60 MHz HD version also available)</td>
<td>20 MHz</td>
<td>45 MHz</td>
<td>45 MHz</td>
<td>60 MHz</td>
<td>40 MHz</td>
</tr>
<tr>
<td>Distal shaft profile</td>
<td>3.1 F</td>
<td>3.3 F</td>
<td>3.2 F</td>
<td>3.0 F</td>
<td>3.2 F</td>
<td>2.6 F</td>
</tr>
<tr>
<td>Proximal shaft profile</td>
<td>3.1 F</td>
<td>2.9 F</td>
<td>3.5 F</td>
<td>3.0 F</td>
<td>3.6 F</td>
<td>3.2 F</td>
</tr>
<tr>
<td>Transducer to tip length</td>
<td>20 mm</td>
<td>10 mm (2.5 mm for short-tip version)</td>
<td>30 mm</td>
<td>20.5 mm</td>
<td>20 mm</td>
<td>29 mm</td>
</tr>
<tr>
<td>Guiding catheter compatibility</td>
<td>≥5 F</td>
<td>≥5 F</td>
<td>≥6 F</td>
<td>≥5 F</td>
<td>≥6 F</td>
<td>≥5 F</td>
</tr>
<tr>
<td>Comments</td>
<td>Rotational (annular array), OptiCross HD has highest IVUS axial resolution</td>
<td>Phased-array, plug-and-play, no preparation required, virtual-histology, Chromaflo</td>
<td>Rotational</td>
<td>Rotational</td>
<td>Rotational</td>
<td>Rotational, excellent crossing profile</td>
</tr>
</tbody>
</table>

* not available outside of Japan. HD, high-definition; IVUS, intravascular ultrasound.
Figure 2 Examples of IVUS artifacts. (A) Acoustic shadowing behind calcific plaque (Asterix); (B) ring-down artifact seen as a bright ring around the IVUS catheter (arrow); (C) reverberation artifact seen as multiple equidistant reflections from calcium (multiple arrows); (D) NURD (non-uniform rotational distortion) is seen between 7 to 12 o’clock (curved dotted arrow). IVUS, intravascular ultrasound.

distortion (NURD) (Figure 2), which is exclusive to the mechanical rotational IVUS systems. This often occurs as a result asymmetric friction due to bends in the artery and guiding catheter or over-tightening of Tuohy-Borst on the catheter resulting in cyclic geometric distortion of the image (6). Since air reflects ultrasound before it can reach tissue structures, air-bubble artifacts can degrade and potentially obliterate the IVUS image, hence meticulous catheter preparation with flushing is mandatory prior to imaging. Therefore, catheter flushing during pullbacks is conceptually a coronary artery air embolism risk, which is best avoided by re-flushing outside the body. A detailed discussion of the various types of ultrasound artifacts is beyond the scope of this review.

Lesion assessment

Significance of stenosis

The DEFER, FAME and FAME 2 trials, all with long-term follow-up data, not only established fractional flow reserve (FFR) as the standard of reference for assessing the hemodynamic significance of coronary stenoses, but also cemented the paradigm that angiographic and physiologic assessments of stenosis severity are poorly correlated (7-9). By extension, it should not come as a surprise that IVUS minimal lumen area (MLA) measurements, a purely anatomic assessment, is also only a modest correlate of FFR. This is not to say, however, that there is no role for IVUS in this context, especially in the case of left main coronary
Non-calcific plaques can be broadly grouped into soft or hard. Soft plaques are lipid-rich and therefore echolucent. Hard plaques are fibrous plaques which have greater echogenicity than the surrounding adventitia, but do not typically cause bright echoes and acoustic shadowing characteristic of calcific plaques (Figure 3). Mixed plaques are also seen and these can be fibro-calcific or fibro-fatty (6). Characterizing plaque types with IVUS may have useful clinical implications and provide important insights. For instance, hard plaques may prompt the use of cutting balloons, and soft plaques, although easier to compress with stenting, are independent predictors of in-stent restenosis (16). In fact, highly lipid-rich plaques, especially within large positively-remodelled vessels, are associated with microembolization and no-reflow after PCI in the setting of acute MI (17).

Quantification of plaque burden or percent atheroma volume, a concept distinct from luminal stenosis, can also be achieved with IVUS. Plaque burden is defined as the ratio of atheroma area to the vessel external elastic lamina (EEL) area, where the atheroma area is given by the difference between the EEL area and the lumen area (Figure 4). The extent of baseline plaque burden and its progression has been shown to have a direct relationship with long-term major adverse cardiovascular events (MACE) (18). The PROSPECT study showed that in patients presenting with acute coronary syndromes (ACS), non-culprit lesion plaque burden of ≥70% was associated with long-term MACE (19). Although predominantly done in the research setting, radiofrequency plaque analysis with virtual histology IVUS can aid in the detection of thin-cap fibroatheromas (TCFA). Indeed, large plaque burden (≥70%) TCFAs have also been shown to strongly predict MACE, even within 6 months, and are higher risk than smaller TCFAs (20).

**Guidance of stent implantation**

Through optimization of acute stent results, IVUS-guided PCI has consistently been shown to improve clinical outcomes. Apart from understanding plaque characteristics and modification, IVUS can also aid in identifying optimal stent landing zones, selecting appropriate stent sizes, and minimizing stent under-expansion and mal-apposition.

**Pre-stenting**

Post-interventional residual plaque burden has long been acknowledged as a powerful independent predictor of restenosis (21), and this is particularly true where the residual plaque burden at the stent margins is >50% (22). This is further corroborated by the observation that angiographically “normal” coronary arteries still tend to have an average plaque burden of 50% (23). Therefore, a step-wise approach to optimal stent landing, aiming for an IVUS derived normal segment or if not possible then a plaque burden of <50%, has been proposed and widely adopted (24).

A correct understanding of plaque distribution can also have important implications for pre-intervention planning,
Figure 3 Appearance of different plaque types on IVUS. (A) Normal; (B) soft plaque (arrows); (C) hard plaque (arrows); (D) calcific plaque (arrows). IVUS, intravascular ultrasound.

Figure 4 Deriving plaque burden. EEL, external elastic lamina.

given the limitations of two-dimensional angiography, particularly in key anatomic locations such as the LMCA bifurcation. Indeed, we have come to understand from IVUS analyses that atherosclerotic LMCA disease frequently manifests as diffuse axial plaque involving the distal bifurcation, and the overwhelming majority of distal LMCA bifurcation lesions extend into the proximal left-anterior-descending artery (25). Furthermore, eccentric plaque distribution can be defined using an IVUS eccentricity index (ratio of maximum to minimum plaque plus media thickness), which may be useful in planning certain procedures such as directional atherectomy, particularly given that angiographic assessment of lesion eccentricity is not a reliable predictor of eccentric plaque distribution (26).

Given the superior tissue penetration of IVUS,
true vessel sizing and detection of positive or negative remodelling is possible, even in larger vessels, allowing for appropriate stent sizing. Different sizing approaches can be used and tend to vary among studies and clinicians. These include, with increasing aggressiveness, lumen, mid-wall or EEL based sizing. The European Association of Percutaneous Cardiovascular Interventions (EAPCI) recommends a practical approach using the mean diameter of the distal vessel reference. Specifically, if a conservative lumen-based sizing is adopted, then the stent size may be up-rounded by 0–0.25 mm, whereas if a more aggressive EEL-based sizing is chosen, the stent size may be rounded down to the nearest 0.25 mm stent size (27).

Post-stenting

Several abnormal post-PCI IVUS features have been identified as predictors of stent thrombosis, including stent under-expansion, persistent mal-apposition (but not isolated acute mal-apposition), large edge dissections, and tissue prolapse (28-30). Among these, stent under-expansion, with a resultant smaller minimum stent area (MSA), was most clearly established as a major determinant of early and late stent failure. The MUSIC study inaugurated a formal IVUS criteria for optimal stent result after bare-metal stent (BMS) PCI. In this prospective observational IVUS study of 155 stable patients, all 3 proposed criteria for optimized stent deployment were attained in 81% of patients (Table 2). These patients were treated with single agent aspirin only after stenting, despite which the overall stent thrombosis rate was 1.3% at 6 months (31). Many subsequent IVUS studies of BMS PCI also applied this or similar criteria, but with highly variable rates of actually satisfying these. For instance, in the AVID trial, the largest of such trials, where 800 stable patients were randomized to angiography or IVUS-guided therapy, a simplified IVUS criteria for optimal stent placement was used, but only achieved in 48% of IVUS patients (36). In contrast, in the randomized TULIP trial of 150 stable patients, a similar simplified IVUS criteria was used and was achieved in 89% of IVUS patients (32). Despite this variability, studies were mostly still in favor of IVUS. A meta-analysis of randomized IVUS-guided BMS PCI studies concluded that IVUS-guidance improves the MSA and thereby reduces restenosis, repeat revascularization and MACE (37).

### Table 2 Various IVUS criteria for optimal stent deployment

<table>
<thead>
<tr>
<th>MUSIC (BMS) (31)</th>
<th>TULIP (BMS) (32)</th>
<th>RESIST (BMS) (33)</th>
<th>Moussa (BMS) (34)</th>
<th>AVIO (DES) (35)</th>
<th>Modern (DES)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Complete strut apposition</td>
<td>1. Complete strut apposition</td>
<td>1. MSA &gt;80% average reference lumen CSA</td>
<td>1. MSA &gt;55% average vessel CSA (measured at media/plaque boundary)</td>
<td>1. MSA &gt;70% of CSA of chosen non-compliant balloon (diameter of the balloon is chosen on the basis of the average media-to-media diameters of the vessel at different points of themal-apposition if stented area)</td>
<td>1. MSA &gt;5.5 mm² for non-LMCA; MSA &gt;7 mm² for distal LMCA and &gt;8 mm² for proximal LMCA</td>
</tr>
<tr>
<td>2. Symmetrical stent expansion: minimum/maximum lumen diameter ≥0.7</td>
<td>2. MLD &gt;80% average reference lumen diameter</td>
<td>2. MSA &gt; distal reference lumen CSA</td>
<td>2. MSA &gt;80% average reference lumen CSA</td>
<td>2. MSA &gt;80% average reference lumen CSA</td>
<td>2. MSA &gt;80% average reference lumen CSA</td>
</tr>
<tr>
<td>3. Adequate stent expansion</td>
<td>3. MSA &gt; distal reference lumen CSA</td>
<td>3. MSA &gt; distal reference lumen CSA</td>
<td>3. Avoid extensive dissections and extensive tissue prolapse</td>
<td>3. Avoid extensive dissections and extensive tissue prolapse</td>
<td>3. Avoid extensive dissections and extensive tissue prolapse</td>
</tr>
</tbody>
</table>

- If MSA <9 mm² then MSA ≥90% average reference lumen area or ≥100% of minimum reference lumen area
- If MSA >9 mm² then MSA ≥80% average reference lumen area or ≥90% of minimum reference lumen area

**BMS**, bare metal stent; **DES**, drug-eluting stent; **MSA**, minimum stent area; **MLD**, minimum lumen diameter; **CSA**, cross-sectional area; **LMCA**, left-main coronary artery.
XPL and ULTIMATE only fulfilling pre-defined criteria in approximately 50% of patients (38,39). Furthermore, these criteria often differed widely between studies and were sometimes poorly defined. Nevertheless, studies were largely consistent in that even “sub-optimal” IVUS-guided DES PCI still leads to more aggressive post-dilatation and a larger MSA, and improves clinical outcomes and hard endpoints compared to angiography-guided PCI.

A universal, evidence-based, practical and more consistently achievable IVUS criteria for optimal PCI is still clearly desirable. Observations from earlier generation DES studies suggested that an MSA <5.0–5.5 mm² in non-LMCA, <6 mm² in ostial LAD, <7 mm² in distal LMCA and <8 mm² in LMCA trunk best predicted subsequent adverse events (40–42). While large residual stent edge dissections and tissue protrusion also predicted subsequent stent thrombosis, acceptable limits are less precisely characterized. Based on available data, extensive dissections with >60° arc, >2 mm longitudinal extension, or involving the media or adventitia should be avoided (29,43,44). Any dissection or tissue protrusion resulting in an MLA of >4 mm² is also considered extensive and should be considered as a suboptimal result (43). In contrast, the clinical relevance of acute stent mal-apposition, although undesirable, is much more ambiguous. The EAPCI recommends avoiding and if possible, correcting extensive acute stent mal-apposition >0.4 mm with longitudinal extension >1 mm (27). Table 2 summarizes the above as the generally accepted modern IVUS criteria for optimal DES PCI.

Complex lesion subsets

Clinical benefits of IVUS may be even more pronounced in complex interventions. In the MAIN-COMPARE study, where IVUS-guided stenting was used in over 77% of PCI patients, notwithstanding that BMS were used in nearly a third of cases, PCI for unprotected LMCA was comparable to CABG with regards to all-cause death and a composite endpoint of death, MI or stroke at 10 years (45). In a propensity score matching analysis of 201 matched pairs of PCI patients from MAIN-COMPARE, IVUS guided DES PCI impressively resulted in approximately 60% reduction in all-cause mortality at 3 years compared to angiography guidance (46). In non-LMCA bifurcation lesion PCI, a propensity score matching analysis of 487 pairs of patients from a Korean registry showed that IVUS-guided DES PCI was also associated with a significantly lower incidence of death or MI compared to angiography guidance only (47). Furthermore, in bifurcation PCI, a pre-intervention side-branch ostium MLA of >2.4 mm² is sensitive in predicting a side-branch FFR ≥0.80 after main branch cross over stenting (48). Therefore, IVUS pull-back examination is recommended in bifurcation PCI, and especially in LMCA lesions where defining the anatomy is extremely useful when deciding on the side-branch strategy.

Intravascular imaging is an indispensable tool for chronic total occlusion (CTO) PCI, with IVUS being the most commonly used imaging modality (49). Applications include resolving proximal cap ambiguity (commonly from a side-branch), delineating proximal cap morphology, confirming the location of wires with respect to the true lumen, and IVUS-guided wiring (50). Specific advantages of IVUS include the lack of need for antegrade injections, ability to provide real-time 3-dimensional orientation, and the availability of short-tip catheters. In a series of 31 patients with one or more native vessel CTO, where 22 patients had previously failed PCI attempts, IVUS-guided reverse controlled antegrade and retrograde tracking allowed successful CTO recanalization in all cases (51). A novel 3-dimensional antegrade wiring technique using real-time IVUS has also been developed which has been shown to improve success rate and reduce procedure time of antegrade wiring compared to conventional method (52). In the randomized trial setting, the CTO-IVUS study demonstrated a reduction in 12-month MACE with IVUS-guided CTO intervention compared to angiography-guidance only (53), and the AIR-CTO trial, although under-powered for clinical outcomes, showed a reduction in late lumen loss also in favor of IVUS-guided CTO intervention (54).

Research utility

In the early 1990s, IVUS studies taught us that the risk of early stent thrombosis was more attributable to inadequate stent expansion rather than inadequate peri-procedural anticoagulation, and the use of high-pressure post-dilatations significantly reduced stent thrombosis rates (55). Furthermore, early IVUS observations provided us with the understanding that restenosis after balloon angioplasty is due to vessel wall negative remodeling rather than cellular proliferation (56), hence the success of stent implantation in reducing restenosis. The use of IVUS in the REVERSAL, ASTEROID and more recently GLAGOV study provided the insight that intensive lipid-lowering treatment reduced
plaque progression and may even promote regression (57-59). Second generation IVUS techniques such as radiofrequency tissue characterization and near-infrared spectroscopy are able to provide even more detailed information about plaque progression and its response to various treatments, as well as detection of vulnerable plaques and evaluation of stent performance. In the ABSORB study for instance, IVUS radiofrequency analysis allowed better understanding of changes in plaque tissue composition over time (60). As technologies and therapies continue to evolve, IVUS will undoubtedly remain a valuable tool in research.

Safety

As with any other forms of vessel instrumentation, IVUS examination is not without risks. These can range from vessel dissection to perforation and other potentially life-threatening complications. The most common complication may be vascular spasm, hence the routine administration of intra-coronary nitrates prior to imaging, and major complication rates, such as dissections, acute occlusion and ventricular arrhythmias occur in approximately 0.1% of cases (61). The often crucial peri-interventional information provided by IVUS, as well as other potential benefits such as reduced contrast use and radiation, should contextualize this minor increase in acute clinical risk.

IVUS versus optical coherence tomography (OCT)

A comparison between IVUS and OCT is often made and clinicians may prefer one imaging modality over the other. In reality, OCT and IVUS utilize different technologies to produce intracoronary images. Although the ILUMIEN 3 study suggests that OCT-guided PCI is at least equal to IVUS-guided PCI in achieving a satisfactory MSA (62), each modality has its own advantages and disadvantages and therefore, the two should be considered complimentary. For example, OCT has superior axial resolution (10–20 μm) and has the ability to better delineate calcified plaques without artifacts, whereas IVUS has greater tissue penetration and is better at assessing vessel remodeling. Furthermore, the need for increased contrast use in OCT means that IVUS is favored in patients with renal impairment. In addition, forceful injection of contrast can extend and enlarge a dissection plane, limiting the use of OCT in CTO PCI. Table 3 summarizes the clinical scenarios which may favor one modality over the other.

Table 3 IVUS versus OCT

<table>
<thead>
<tr>
<th>Favors IVUS</th>
<th>Favors OCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aorto-ostial lesions</td>
<td>Thrombus detection</td>
</tr>
<tr>
<td>CTO PCI</td>
<td>Better detection of finer details due to superior resolution (such as edge dissections, strut malapposition, tissue protrusion)</td>
</tr>
<tr>
<td>Renal impairment</td>
<td>visualization and characterization of calcified plaques</td>
</tr>
<tr>
<td>Large vessels (&gt;3.75 mm diameter)</td>
<td>Automated measurements</td>
</tr>
<tr>
<td>Real-time imaging</td>
<td></td>
</tr>
</tbody>
</table>

CTO, chronic total occlusion; PCI, percutaneous coronary intervention.

Conclusions

Despite clear evidence for benefit, IVUS use in PCI is still not class I recommendation in current guidelines (Table 4). Considerations were given to the significant observational data contribution in the meta-analyses and possible treatment selection bias, but the reality may be a combination of this and other factors, such as cost barriers and a perceived increase in duration and complexity of the procedure. As PCI continues to encompass increasingly complex patient and disease subsets, IVUS will become a more integral part of coronary interventions (Table 5). Furthermore, IVUS is a useful tool for research, from evaluating efficacy of various invasive or non-invasive treatments, to understanding mechanisms of stent failure. Second generation techniques such as radiofrequency tissue characterization, near-infrared spectroscopy and iMap have also matured beyond the research setting in being able to quantify individual plaque components and detecting vulnerable plaque. Device technologies will continue to evolve and hopefully further improve ease of use in practice. The important role of IVUS in contemporary PCI is indisputable, and its underutilization is rapidly becoming inexcusable.
Table 4 Current guideline recommendations on use of IVUS

<table>
<thead>
<tr>
<th>AHA/ACC</th>
<th>ESC</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIa B</td>
<td></td>
</tr>
<tr>
<td>Assess the severity of unprotected LMCA lesions</td>
<td>Assess the severity of unprotected LMCA lesions</td>
</tr>
<tr>
<td>4–6 weeks and 1 year after cardiac transplantation to exclude donor CAD, detect rapidly progressive allograft vasculopathy, and provide prognostic information</td>
<td>Optimise treatment of unprotected LMCA lesions</td>
</tr>
<tr>
<td>Optimise stent implantation in selected patients</td>
<td>Optimise stent implantation in selected patients</td>
</tr>
<tr>
<td>IIa C</td>
<td></td>
</tr>
<tr>
<td>Determine mechanism of stent restenosis</td>
<td>Detect stent-related mechanical problems leading to restenosis</td>
</tr>
<tr>
<td>IIb B</td>
<td></td>
</tr>
<tr>
<td>Assessment of non-LMCA with angiographically intermediate stenoses</td>
<td></td>
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<tr>
<td>Guidance of coronary stent implantation, particularly in cases of LMCA stenting</td>
<td></td>
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<tr>
<td>IIb C</td>
<td></td>
</tr>
<tr>
<td>Determine mechanism of stent thrombosis</td>
<td></td>
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</tbody>
</table>

LMCA, left-main coronary artery; CAD, coronary artery disease.

Table 5 Uses of IVUS in contemporary PCI

<table>
<thead>
<tr>
<th>Indications</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lesion assessment</td>
<td></td>
</tr>
<tr>
<td>Indeterminate lesions</td>
<td>FFR gold-standard</td>
</tr>
<tr>
<td>Plaque characterization</td>
<td>Plaque morphology, composition, vulnerable plaque</td>
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<td>Plaque burden</td>
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<tr>
<td>Plaque distribution</td>
<td>Eccentricity index</td>
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<td>Stenting</td>
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<td>Stent sizing</td>
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<td>Stent length</td>
<td></td>
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<tr>
<td>Landing zone assessment</td>
<td></td>
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<tr>
<td>IVUS-marking and real-time deployment</td>
<td>Obtains optimal angiographic view for deployment</td>
</tr>
<tr>
<td>Stent expansion</td>
<td>Note various criteria</td>
</tr>
<tr>
<td>Strut apposition</td>
<td></td>
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<td>Edge dissection</td>
<td></td>
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<td>Tissue protrusion</td>
<td></td>
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<tr>
<td>Mechanisms of stent failure</td>
<td></td>
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<tr>
<td>Neointimal hyperplasia</td>
<td></td>
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<tr>
<td>CTO PCI</td>
<td></td>
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<tr>
<td>Resolving proximal cap ambiguity</td>
<td>Often using a side-branch</td>
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<tr>
<td>Delineating proximal cap morphology</td>
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<tr>
<td>Confirming proximal cap puncture</td>
<td></td>
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<tr>
<td>Wire location with respect to true lumen</td>
<td></td>
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<tr>
<td>IVUS-guided wiring and 3-dimensional wiring</td>
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</table>

FFR, fractional flow reserve; CTO, chronic total occlusion; PCI, percutaneous coronary intervention.
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None.

Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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