https://doi.org/10.48047/AFJBS.6.2.2024.4546-4561

African Journal of Biological Sciences

Journal homepage: http://www.afjbs.com

Research Paper Open Access

Evaluation of Stent Expansion and Stent Failure in Diabetic Patients

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Article History

Volume 6, Issue 2, Apr-Aug 2024

Received: 15 May 2024

Accepted: 20 July 2024

Published: 27 July 2024

doi:10.48047/AFJBS.6.2.2024.4546-4561

Abstract: Diabetic patients represent a high-risk population for coronary artery disease (CAD) and subsequent stent implantation. This abstract summarizes findings from a study evaluating stent expansion and failure rates in diabetic versus non-diabetic patients undergoing percutaneous coronary intervention (PCI). The study aimed to determine if inherent differences in vascular biology or procedural factors contribute to disparities in stent outcomes. We retrospectively analyzed a large cohort of patients who underwent PCI with drug-eluting stents (DES) or bare-metal stents (BMS), stratifying them by diabetic status (type 1, type 2, or non-diabetic). Detailed angiographic and clinical data, including stent diameter, lesion length, vessel characteristics, procedural techniques, and post-procedural follow-up, were collected. Our analysis revealed a significantly higher incidence of suboptimal stent expansion in diabetic patients compared to their non-diabetic counterparts. This was particularly pronounced in patients with longer lesions and calcified vessels, challenging the optimal deployment of stents. Furthermore, diabetic patients exhibited a statistically significant increase in the rate of stent thrombosis, restenosis, and target lesion revascularization (TLR) within the first year post-PCI. Multivariable regression analysis adjusted for confounding factors like age, gender, lesion complexity, and stent type, consistently demonstrated diabetes mellitus as an independent predictor of both inadequate stent expansion and increased stent failure. The increased risk persisted regardless of stent type (DES or BMS), although the absolute risk reduction associated with DES remained evident in both groups. The heightened risk of suboptimal stent expansion in diabetics may be attributed to several factors, including increased vascular stiffness, impaired endothelial function, and chronic inflammation, all hallmarks of diabetic vasculopathy. These findings highlight the need for meticulous procedural planning and optimized stent selection in diabetic patients. Further investigation is required to explore the role of novel imaging modalities and advanced stent designs in mitigating these challenges. Ultimately, a better understanding of the mechanistic underpinnings of impaired stent expansion in diabetic patients is crucial for improving PCI outcomes and reducing morbidity and mortality in this vulnerable population. Future strategies should focus on personalized approaches to PCI tailored to the specific vascular characteristics and clinical profiles of individual diabetic patients.

Keywords: *Stent Expansion, Stent failure, Diabetic patients*

Introduction.

Coronary artery disease (CAD) affects millions of people all over the world and is the most prevalent form of cardiovascular disease being a major public health problem. In the developed world, its impact on the health of individuals has decreased over the last decades because of the proper identification and introduction of new primary and secondary prevention strategies of modifiable risk factors. Patients with CAD may need revascularization procedures. However, even with these improvements, the mortality rate is substantially higher than that in the general population [1].

IVUS has played a pivotal role in the development of interventional cardiology. Compared with angiography, it has superior imaging capabilities that enriched our knowledge about the anatomical, pathophysiologic, diagnostic and interventional era of CAD [1].

Physical principles of IVUS imaging

Ultrasound images are produced when a piezoelectric crystalline material in the transducer expands and contracts to produce sound wave beams after being electrically excited. Sound waves beams travel to hit a tissue which reflects them again to the transducer that converts the electrical impulse into an image. There are two fields; the near field in which the beam remains fairly parallel for a distance with greater image quality and resolution or the far field when the beam diverges [2].

IVUS as a Diagnostic Tool

Despite the routine use of angiography in guiding percutaneous coronary intervention (PCI), it has many limitations and it is very difficult to accurately assess lesion severity, anatomy, clinical significance and optimal stent deployment. This is because the 2D nature of fluoroscopic imaging of angiography provides only a lumen profile and there is significant inter-observer variability in visual interpretation due to many factors including contrast streaming artifact, vessel overlap, complex anatomy, equipment quality and variability, and poor resolution [3].

In this regard and to overcome some of the angiography limitations, intravascular imaging modalities are developed and technical evolution has occurred to help decide PCI strategy including lesion preparation, stent sizing, and stent optimization. Significant observational and randomized trial evidenced that these modalities improve the outcome after PCI. Specifically, many studies have demonstrated that intravascular imaging-guided PCI is associated with lower rates of target lesion revascularization (TLR), target vessel revascularization (TVR), stent thrombosis, major adverse cardiac events (MACE), and cardiovascular (CV) death compared to coronary angiography-guided PCI [4]. Vascular ultrasound (IVUS) is one the most commonly used modalities for intravascular imaging in addition to optical coherence tomography (OCT) [5].

IVUS equipment and acquisition system

The IVUS acquisition system consists of:

a) Console: provides electrical signals to the transducer, receives and processes the reflected signals then displays them as a grayscale reconstruction of the vessel wall. In addition, it offers tools for quantitative analysis, data exporting in various formats, and archiving. b) Pullback device: To obtain the image, the imaging catheter is manually advanced beyond the lesion of interest in coronary artery and is then pulled back, manually or with an automatic pullback system, at a speed of 0.5–1 mm/s. Automatic system enables longitudinal image display and accurate length measurements. c) Imaging Catheter: Currently, IVUS catheters are 150 cm long and have can go through 5–6-French guiding catheter. At the catheter tip, there is a miniature transducer which contains piezoelectric crystals, the source of ultrasound waves. d) IVUS transducers: two types that differ in the transmit-receive modes for monitoring ultrasound waves (Table 3). e) Mechanical or rotating transducer: (Boston Scientific) consist of a single transducer housed in a protective sheath and operated by an external motor drive unit. The transducer sends and receives ultrasound signals during circumferential rotation (1800 rpm) to form the cross-sectional image. The ideal resolution for a 20 to 40 MHz IVUS transducer, is 80-100 microns axially and 200 to 250 microns laterally and the compatible imaging

catheters 40 MHz or 60 MHz and are 5F or 6F. The transducer is housed by a plastic sheath and a syringe is employed to flush saline water inside the sheath to get rid of air bubbles and acquire high-quality IVUS images [6].

Electronic or solid-state transducer: (Volcano) also known as phased array system. It has a transducer with 64 elements that are circumferentially mounted around the tip of the catheter and sequentially activated with different time delays to produce an ultrasound beam that sweeps around the vessel circumference. The catheter works at a central frequency of 20 MHz and is 5F compatible [7].

Table 1: Types of IVUS transducers [8]

	Solid state transducer	***Mechanical transducer***
Transducer	Multiple, fixed and sequentially firing	Single, rotating
Catheter	5F	6F
Flexibility	Flexible, easy to pass through tortuous vessels	Rigid, more difficult to pass through tortuous vessels
Artifact	Ring-down artifact	No uniform rotational distortion
Monorail segment	Short, limited track-ability in complex lesions	LONG, better track-ability in complex coronary anatomy
Guide wire location	Central , eliminating guide wire artifact	on the side of the transducer, producing guidewire artifact in the image
Transducer location	The transducer is housed at 25 mm from the tip, which makes it unsuitable for CTO imaging	shorter distance from the catheter tip to the transducer offers advantage in chronic total occlusion (CTO) intervention
Outer sheath housing around the transducer	Does not have outer sheath so that no air trapping is present around the catheter and it does not need saline flushing.	Present and allows precise and controlled pullback but needs frequent saline flushing to overcome air trapping and image quality distortion
Rotating elements	No rotating elements are present hence non-uniform rotational deformity (NURD) does not occur	present and cause NURD
Central frequency	lower frequency and the resultant poor near- field resolution produces ring down artifact (bright halos surrounding the catheter) and loss of imaging details close to the surface of the catheter	higher frequency offers better resolution and high-quality images

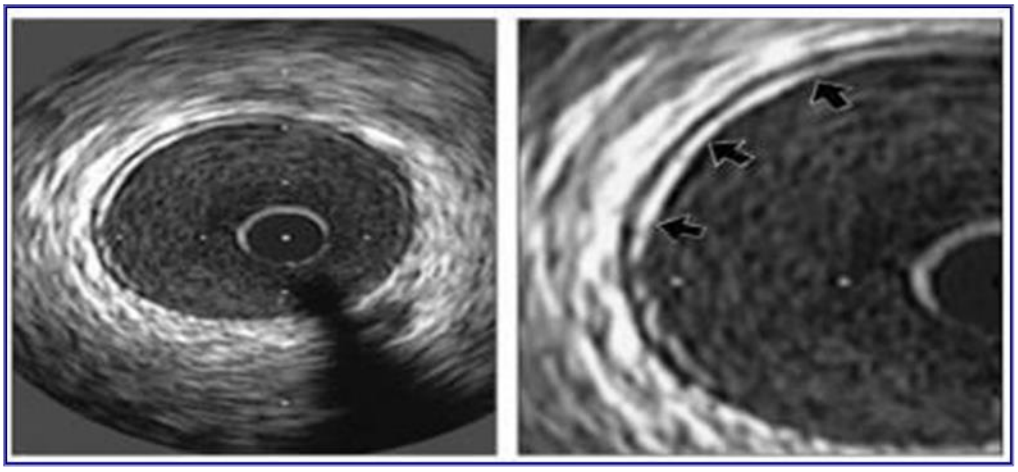

Figure 1: Normal anatomy by IVUS. In zoomed image (right), thin intimal leading edge is highlighted by arrows. Scale is 1 mm between markers [9].

Interpretation of IVUS image

Interpretation of IVUS image requires the recognition of two interfaces: blood/intimal (lumen) and medial/adventitial interface, which gives rise to a three-layered appearance of coronary wall (bright, dark, bright) (Figure 6). IVUS require measurements to be performed at the leading edge of boundaries, never the trailing edge [10].

1. Reference Segment Measurements • Proximal reference: the largest lumen 10 mm prior to the same segment of the stenosis with no major intervening side branches. It may not be the site with the least plaque.
   • Distal reference: the largest lumen 10 mm after the same segment of a stenosis with no intervening branches. It may not be the site with the least plaque. • Average reference lumen size: The average measurement of lumen size at the distal and proximal reference site [11].
2. Lumen measurements • Lumen CSA: The area surrounded by the luminal border. • Minimum lumen diameter: The narrowest diameter through the central part of the lumen. • Maximum lumen diameter: The widest diameter through the central part of the lumen. • Lumen Eccentricity: maximum - minimum lumen diameter / maximum lumen diameter. • Lumen area stenosis: similar to the angiographic % stenosis. Reference - minimum lumen CSA /reference lumen CSA. The reference segment used should be defined (proximal, distal, largest, or average) [12].
3. External elastic membrane (EEM) measurements: • EEM cross-sectional area (CSA): The area surrounded by the EEM margins. Cannot be measured reliably at sites where large side branches originate or in the setting of extensive calcification extensive than 90° of arc because of acoustic shadowing.
4. • Minimum and maximum EEM diameter: The narrowest and widest diameters through the central part of the EEM area, respectively [13].

Qualitative Assessment

A. Atheroma morphology • Soft (echo lucent) plaques (Figure 4): It has low echogenicity resulting from high lipid content in a mostly cellular lesion with minimal collagen and elastin. However, a zone of more reduced echogenicity may also be attributable to a necrotic zone within the plaque, an intramural hemorrhage, or a thrombus [14].

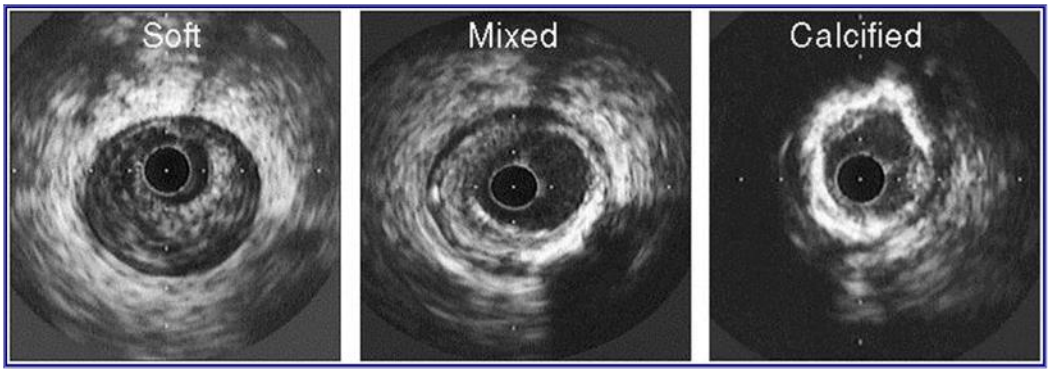

Figure 2: Shows different morphology of plaque by IVUS [15].

• Fibrous plaques: the majority of atherosclerotic lesions that have an intermediate echogenicity between soft and highly • Calcific: it is highly echogenic leading acoustic shadowing • Mixed: contain mixture of tissue subtype and can be described as fibro-calcific or fibro-fatty • Thrombus: a layered, lobulated, or pedunculated echo-lucent presumptive intraluminal mass that is affected by blood flow speckling. • Intimal hyperplasia: very low echogenicity tissue that characterizes early in-stent restenosis. The intimal hyperplasia of late in-stent restenosis often appears more echogenic [16].

B. Dissections and other complications after intervention Intravascular ultrasound is commonly employed to detect and direct the treatment of dissections and their types as well as other complications after intervention [17].

C. Ambiguous Lesions.

Common IVUS artifacts

Artifacts may affect the quality of image, be misinterpreted as pathologies or limit identification of the true tissue structures that may lead to unnecessary interventions. The common artifacts are [18]:

1. Post-acoustic Shadowing: occurs with (Severe Calcified Lesions, Metal Stent Struts, and Guidewires) [7].
   • Severe calcified lesions: calcium causes poor penetration and reflection of ultrasound beam with occurrence of shadowing obscuring evaluation of the underlying plaque. • Metal stent struts: cause a sunburst shadowing pattern. • Guidewires: cause shadowing especially at bifurcations [19].
2. Non-uniform rotational deformity (NURD): is related to mechanical systems and results from uneven drag or friction on the drive cable that disturbs its smooth rotation leading to image distortion and concealing the structures especially in cases of tortuous vessels, tight stenosis, heavy calcification, small guiding catheter.
3. Ring-down artifact: It is a near-field artifact related to the solid-state catheters. It looks like luminal halos of various thickness surrounding IVUS catheter and precludes its visibility and assessment. It can be electronically overcome by suppressing the ring-down function.
4. Reverberation artifacts: repeated false echo reflections that occur between the transducer and a strong reflecting surface when ultrasound waves bump on that reflective surface.
5. Air bubble artifact: It is specific to mechanical catheters. Small air bubbles trapped in the protective sheath leads to poor image quality. Careful preparation by flushing the catheter with saline can eliminate this artifact.
6. Blood speckles: May obscure interpretation especially when IVUS is passed across tight stenosis. Contrast or saline flush during imaging displaces blood and reveals the interface clearly [16].

X-Ray Dependent Stent Imaging

Adequate stent positioning and apposition onto the vessel wall are the keys to the procedural success and patient safety. Stent assessment with conventional X-ray images is extremely challenging due to their low radio-opacity and their increased motion. The ideal method to evaluate stent deployment and apposition is to perform IVUS that provides cross-sectional images of the vessel, depicting the stent, the vessel wall and enables quantitative length and area measurements [20].

Unfortunately, the routine use of IVUS is impractical as it would add obvious time and cost to the procedure. It is only used in 4.5% of the cases in Europe, 14% in the USA and 60% in Japan where it is reimbursed. The x-Ray dependent techniques that enable stent visualization during the normal workflow of an angioplasty procedure cannot directly assess the apposition of the stent onto the vessel wall, but they can provide relevant images for visualizing stent irregularities, enabling lesion treatment and potentially measuring stent expansion [21].

Digital Stent Enhancement (DSE)

Historical Overview and Definition

Stent boost (SB) or enhanced stent imaging (ESI) is the enhancement stent edge radiologically by digital processing of the regular X-ray image sequences [22]. This technique is now available in most angiographic devices and operates through identifying the two markers of a balloon present inside and move in synchrony with the metallic struts during the respiratory and cardiac cycle. Several frames from a cine loop, centered on the balloon's markers, are then superimposed, thus providing a clear image of the stent [21].

Advantages

Stent boost is a quick, safe and inexpensive maneuver that permits the visualization of a high-quality image of the deployed stent without the need for specific training of the operator or staff or significant increase in radiation exposure or procedural time (3 to 4-second runs). It is then advantageous for evaluating the need for post-dilation, ensuring proper stent positioned, and in assessing the result after high-pressure inflation [23].

Acquisition and image quality

The first step in performing DSE is shooting a short X-ray sequence (15 fps) while keeping the delivery balloon in place. This enables showing the stent while its motion is induced by the heartbeat and the breathing of the patient. The visibility of the stent is limited like in any regular X-ray sequence. Motion-compensated image integration is the mainstay of DSE that enables a significant reduction of the noise at the same time of preserving the motion-compensated details of the image components (Fig. 5). Studies obviated that stent visibility is greatly improved by this technique [24].

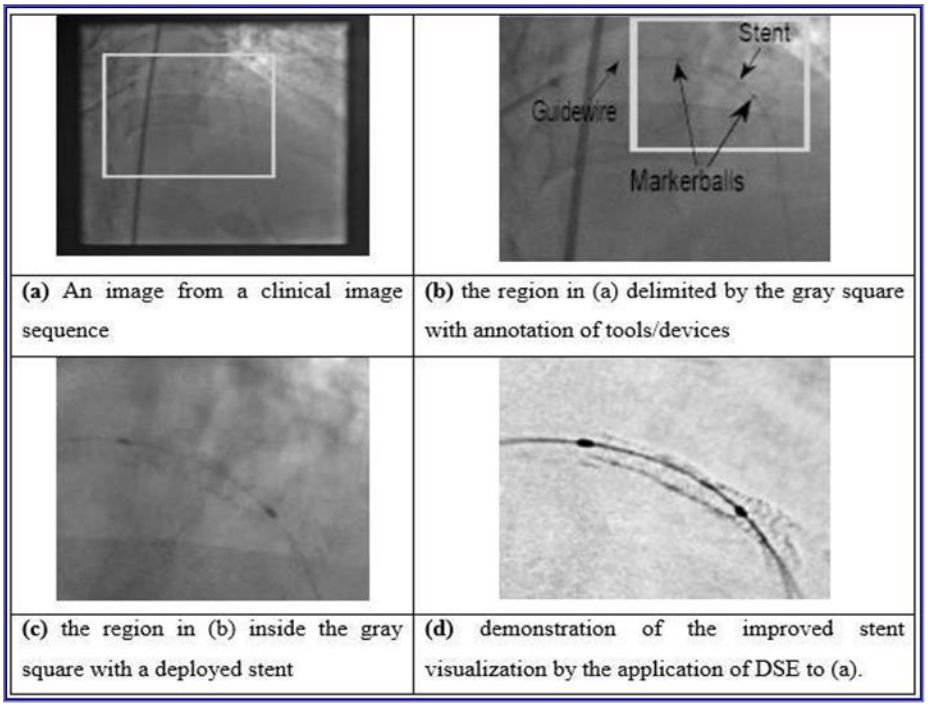

Figure 3: Stent visualization enhancement in X-ray image sequences [25].

From the clinician's standpoint, the value of a DSE technique depends upon three factors: improvement in image quality, limited user interaction and reasonable execution time. In order to get high-quality pictures, several technical expedients should be adopted [22]:

• Narrow the field around the stent. • Ensure absence of balloon movement inside the stent. • Exclude other radiopaque structures from the field view. • Put the stent on a relatively radiolucent background devoid of the spine or diaphragm (holding patient breath keep diaphragm away and minimize movement). • Position the C-arm perpendicular to the long axis of the stent to minimize foreshortening. • Taking 2 orthogonal views of the stent [26].

Stent Boost in clinical trials

SB predicted inadequate findings of IVUS with 100% specificity, 33% sensitivity, and 81% agreement. Although the low sensitivity, the specificity is optimally high to make it the first line for evaluation after stent implantation if IVUS is not used routinely [27].

Quantitative Coronary Analysis (QCA)

Quantitative coronary arteriography (QCA) has been used extensively for years as a reliable tool in clinical research to assess changes in vessel dimensions, but also as a tool to provide evidence to the interventionist

prior to and after an intervention and at follow-up when necessary [28]. Despite the routine use of angiography in guiding PCI (Figure 9), it has many limitations and it is very difficult to accurately assess lesion severity, anatomy, clinical significance and optimal stent deployment and expansion. This is because the 2D nature of fluoroscopic imaging of angiography provides only a lumen profile and there is significant inter-observer variability in visual interpretation due to many factors including contrast streaming artifact, vessel overlap, complex anatomy, equipment quality and variability, and poor resolution [22].

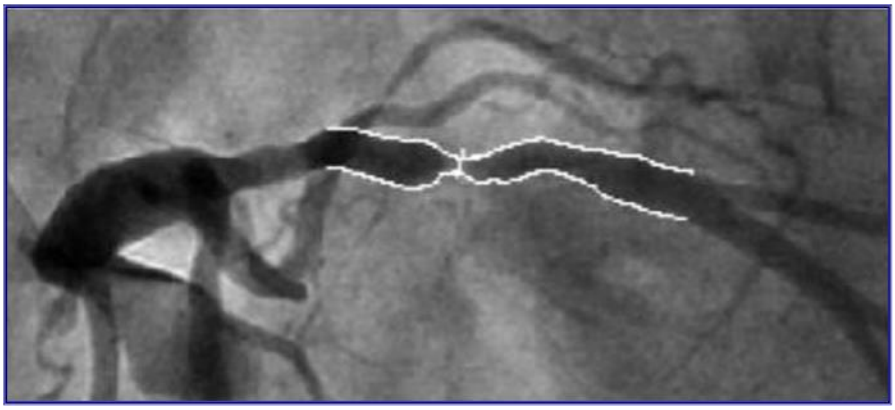

Figure 4: QCA analysis of coronary vessel angiogram [29].

Stent Failure in Diabetic Patients

Stent Failure

In parallel with the remarkable evolution of PCI and the development of DESs, there were many progressing advances in intracoronary imaging modalities (ICI); Intravascular ultrasound (IVUS) and Optical coherence tomography (OCT). Those have enriched our knowledge about the identification of different mechanisms of stent failure (restenosis or stent thrombosis), guided appropriate treatment, minimized the risk of subsequent stent failure events and raised awareness of the potential device-related concerns [30].

Diabetes mellitus is defined as a syndrome, a group of disorders characterized by hyperglycemia and glucose intolerance, caused by either insulin deficiency or impaired insulin function, or a combination of the two [31]. It is associated with a shorter life expectancy, major morbidity from diabetes-related microvascular complications, an increased risk of macrovascular consequences (ischemic heart disease, stroke, and peripheral vascular disease), and a worse quality of life. Type II diabetes is caused by a combination of pathogenetic mechanisms. These include mechanisms that damage pancreatic beta cells, resulting in insulin deficiency, and others that result in insulin resistance [32].

In-stent restenosis

Restenosis after angioplasty and stent implantation has been historically considered the most significant problem ranges from 3% to 20% with DES and 16% and 44% with BMS. This occurs mostly between 3 to 20 months after stent placement [33]. Although DESs have dramatically reduced the rates of restenosis and target lesion revascularization in diabetic patients (TLR) compared with BMS, a low non-negligible rate of in-stent restenosis (ISR) after DES still exists because of the relatively huge number of patients revascularized using DES. That was predominant in longer lesions and smaller vessel diameters [34].

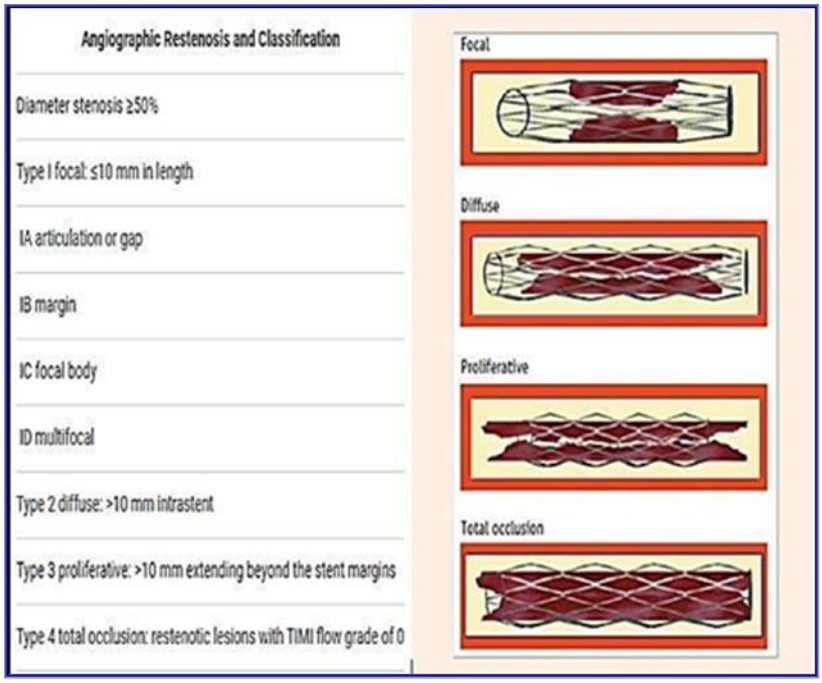

Figure 5: Classification of ISR [35].

This system was primarily created concerning BMS-ISR, but it also has prognostic value in DES-ISR [36]. Differing from BMS, DES tends to possess a more focal pattern of ISR, except in diabetics, where the ISR tends to be more confined to the stent edges. Focal ISR (Mehran pattern I) [37] has been associated with a lower rate of ISR. Identifiable causes of ISR include intimal hyperplasia, chronic stent under expansion, stent fracture, and new atherosclerosis. The first three abnormalities can be readily detected by IVUS or OCT, the latter by OCT. Early-ISR has been shown to be caused by new intimal hyperplasia, whereas new atherosclerosis represents the main mechanism of late-ISR [38].

Stent Thrombosis (ST):

ST is a life-threatening hazard of PCI. The reported incidence is up to 0.4–0.6% per year, which appears to be lower with newer-generation DES. The majority of ST patients present with acute myocardial infarction and rates of mortality following presentation are as high as 20–40% [39].

Table 2: Academic Research Consortium definition of ST [40].

Timing of ST after stent implantation (combined acute and subacute are also considered early ST)
Acute: between 0 and 24 h
Subacute: between 24 h and 30 days
Late: between 30 days and 1 year
Very late: after 1 year
Definite ST
Angiographic confirmation: intrastent thrombus (or within 5 mm of stent edge)
Target vessel occlusion
Probable ST
Acute MI in the target vessel territory
Possible ST
Any unexplained death in a patient with prior DES implantation

ST is characterized by post-mortem or angiographic evidence of recently formed thrombus within a previous stent [33]. Thrombus aspirates from patients presenting with ST have been studied and shown a mix of thrombotic and inflammatory components including fibrin fragments, platelet-rich thrombus, and leukocytes of both neutrophil and eosinophil lineage [41]. Common morphologic abnormalities found in patients with acute to subacute stent thrombosis include stent malposition (also referred to as incomplete stent apposition) and stent under expansion [42]. Edge dissections may also contribute to stent thrombosis by affecting target segment inflow and outflow [43].

Presentation of stent failure in diabetic patients

Due to the gradual and slow progression of ISR compared with stent thrombosis, the majority of ISR presents as progressive recurrent angina. The presumed time for symptoms to develop due to DES-ISR is 3 to 12 months after stent placement [44].

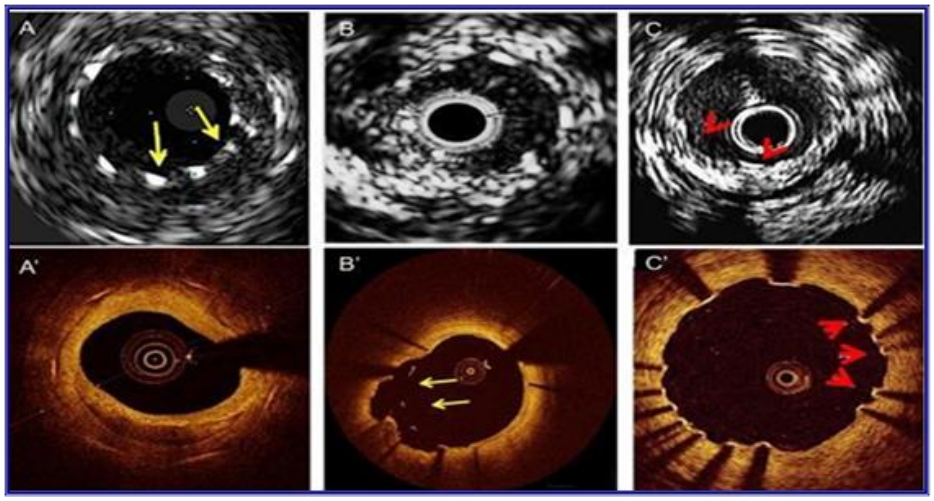

Figure 6: The leading causes of stent thrombosis visualized by intracoronary imaging modalities. Panel A and A': show malapposition at IVUS and at OCT (respectively). Panel B and B': show neo-atherosclerosis at IVUS and OCT, respectively. Panel C and C': example of uncovered struts (red arrowheads) at IVUS and OCT, respectively [42].

BMS stent, on the other hand, develop ISR symptoms nearer with a documented mean period of 6 months post-PCI. BMS-ISR presented as MI in 3.5%-20% of patients. DES-ISR resembles that of BMS with approximately 1%-20% presenting with MI and 16%-66% of patients presenting [45].

Mechanisms of stent failure in diabetic patients:

• Intimal hyperplasia: aggressive new intimal hyperplasia and smooth muscle hypertrophy are the predominant mechanisms in the ISR process. • Stent under expansion: due to the potential for intrastent restenosis and stent thrombosis, stent under-expansion is a risk factor for a poor prognosis. At the target lesion level, it is frequently caused by an increased calcium burden. Diabetes enhances dystrophic calcification and so stent failure

• Neo-atherosclerosis is histologically characterized by an accumulation of lipid-laden foamy macrophages with or without necrotic core formation and/or calcification within the new intima. Neo-atherosclerosis seems to occur in months to years following stent placement and rapidly and more frequently in DES when compared with BMS. In-stent new atherosclerosis has emerged as an important contributing factor to both late ST and late ISR. • Edge dissection: Intracoronary imaging can be used also to detect the presence of stent edge dissection as well as its extension helps identify less extensive edge dissections missed by IVUS. Edge dissection is a precipitating mechanism of stent thrombosis and dissections >200 μm at the distal stent edge emerged as an independent predictor of major adverse cardiovascular events (MACE) [46]. Minor edge dissections are unlikely to be clinically significant and possibly do not require correction by stent [47]. • Malapposition:

Malposition is defined as a lack of contact of stent struts with the vessel wall (space occupied by blood can be detected between the stent struts and the arterial intima). It can occur either in the acute, post-procedural period, or it may develop later. One OCT study showed that maximum incomplete stent apposition (ISA) distance <270 μm after stent implantation appeared grossly covered and spontaneously re-apposed in 100% of cases at follow-up, whereas maximum ISA distances >850 μm resulted in persisting malposition and grossly delayed coverage in 100% of cases. Malapposed struts should be avoided following stent implantation and should be corrected with post-dilation [48].

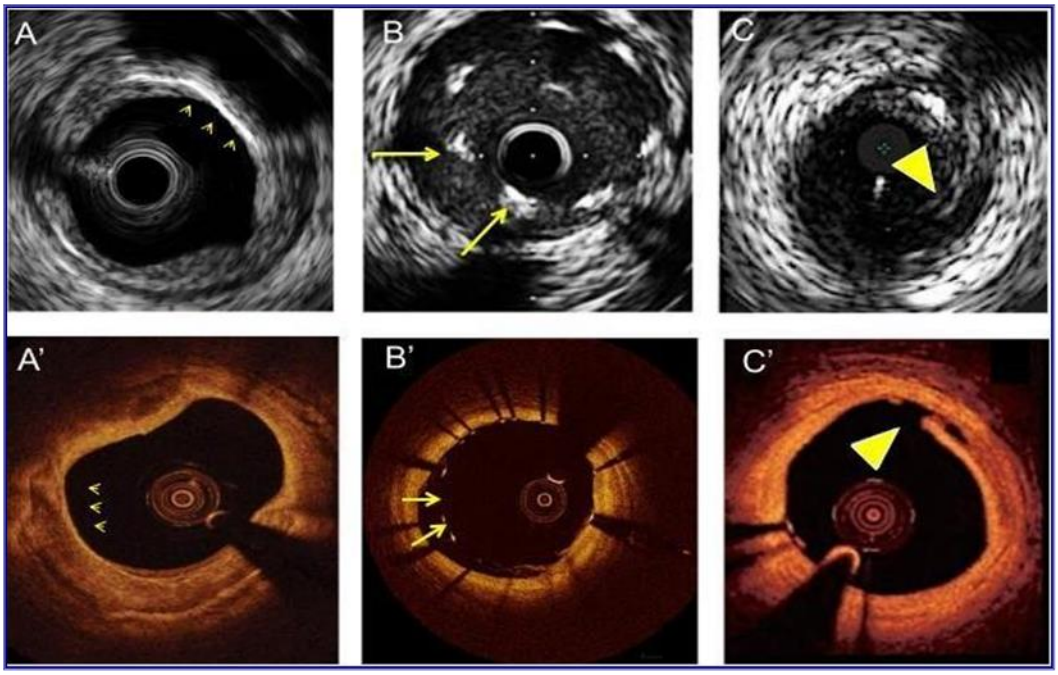

Figure 7: Features visualized by intravascular coronary imaging. Panel A and A': example of calcifications (yellow arrowheads) at IVUS and OCT, respectively. Panel B and B': show incomplete stent apposition (ISA) at IVUS and OCT, respectively. Panel C and C': show stent edge dissection (flap indicated by yellow arrowhead) at IVUS and OCT, respectively. IVUS and OCT images are taken from different coronaries of different patients. Malapposition usually occurs in arteries that have significant tortuosity and fluctuations of reference arterial lumen diameter within the treated segment or with the use of undersized stents and is thought to predispose to stent thrombosis. It is difficult to be judged angiographically (except in very few extreme cases) [49].

Stent Under Expansion

Stent under expansion (SU) is a powerful predictor of long-term stent patency and correlates with unfavorable clinical outcomes [50]. A common cause of MACE in both the acute setting, where up to 25% of patients with stent thrombosis have stent under expansion, and in the chronic setting where stent under expansion is implicated in in-stent restenosis in 55% of lesions [51].

Definitions of optimal stent expansion

Stent expansion may be expressed by the minimum stent cross-sectional area measurement and is categorized as absolute expansion or relative expansion; compared with the predefined reference area, which can be the proximal, distal, largest, or average reference area in principle [45]. The greater the absolute stent expansion, the better as well as the lower risk of stent failure, so it appears to be a better predictor of future stent patency than relative expansion failure [52].

Causes of stent under expansion

Under expansion can be caused by both technique/operator-related factors (small balloon size, insufficient balloon pressure, and short duration of inflation) and lesion-related factors (vessel size; plaque volume; and

plaque composition, especially fibrocalcific and calcific lesions) [53]. Stent under expansion may be caused by the presence of underlying heavily calcified lesions that prevent adequate stent expansion despite the use of large balloon size, high dilation pressures and long [54].

How to achieve optimal stent expansion

If stents remain constrained following implantation despite appropriate inflation pressure, typical conventional treatment options are often limited to high-pressure noncompliant balloon inflation. Options described for the management of stent under expansion include very high-pressure balloons (OPN), laser atherectomy, and rotational atherectomy, that is, "stent ablation". When conventional non-compliant balloons have failed, the OPN, noncompliant, very high-pressure balloon (rated burst pressure 35 atm.) has been shown to be an effective, safe alternative with a described efficacy rate in resistant calcified coronary lesions of 92.3% [55].

Management of stent under expansion

I. Proper lesion preparation Intravascular imaging is advocated to guide lesion assessment and efficacy of calcium modification prior to stent implantation as well as to treat under-expanded stents especially in the presence of significant calcification [56]. OCT-dependent calcium scoring systems to predict stent under expansion and identify predictors of calcium fracture have been used to ensure adequate lesion preparation and confirm adequate stent expansion [57].

II. Proper measurement and assessment of expanded stents for detection of under expansion [48]: a) X-ray stent imaging: • QCA angiography. • Digital stent enhancement. b) Intracoronary imaging modalities: • IVUS. • OCT.

III. Proper treatment of detected under expansion.

1. Stent deployment at higher pressures (≥14 Atm.) With its semi-compliant balloon to attain the principle "media to media" stent expansion. Prolonged inflation time for >25 sec has a significant impact on stent expansion and is recommended.
2. High-pressure non-compliant balloon: To improve the minimum stent area and achieve uniform volumetric stent expansion. A very high-pressure (rated burst pressure 35 Atm.,) noncompliant balloon, the OPN®NC plain rapid exchange PTCA catheter, has been shown to be an effective (92.3%), safe alternative in resistant calcified coronary lesions when conventional non-compliant balloons have failed.
3. Cutting Balloon: Cutting balloons have been designed to create an advantage of reducing balloon slippage during inflation due to the stabilizing effect of the blades. They possess several advantages for the treatment of severe calcified lesions, allowing a larger luminal gain at lower pressure compared to balloon angioplasty alone as well as preventing late recoil owing to the incisions made by the blades [46].
4. Laser atherectomy: Is based on the principle of photo-ablation (utilizes short wavelength high-energy ultraviolet light), converting occlusive material into microbubbles which are immediately dissolved in the blood. It has demonstrated to be effective in improving stent expansion when high-pressure noncompliant balloon inflation was unsuccessful, but has a peri-procedural MI rate of 7.1%, risk of transient slow flow of 7.1%, and ST elevation rate of 3.6%.
5. Rotational Atherectomy (e.g. Rotablator®): A technique that uses a small grinder inserted inside the coronary arteries to ablate the plaque. It has a differential cutting mechanism effective in the ablation of hard calcified lesions during high-speed rotation while soft tissues (such as the normal arterial wall) are deflected so that they escape ablation.
6. Intravascular lithotripsy (IVL): IVL is a safe, feasible, and effective novel tool for calcium modification in de novo coronary lesions by emitting high-energy sonic waves that fracture both intimal and medial calcification, but pass traumatically through the surrounding non-calcified tissue [51].

References

1. Terashima, M., Kaneda, H., Honda, Y., Shimura, T., Kodama, A., Habara, M., & Suzuki, T. (2021). Current status of hybrid intravascular ultrasound and optical coherence tomography catheter for coronary imaging and percutaneous coronary intervention. Journal of Cardiology, 77(5), 435–443.

2. Akl, E., Pinilla-Echeverri, N., Garcia-Garcia, H. M., Mehta, S. R., Dan, K., Kuku, K. O., Courtney, B. K., & Sheth, T. (2022). First in-human evaluation of a novel intravascular ultrasound and optical coherence tomography system for intracoronary imaging. Catheterization and Cardiovascular Interventions, 99(3), 686–698.

3. Nagaraja, V., Kalra, A., & Puri, R. (2020). When to use intravascular ultrasound or optical coherence tomography during percutaneous coronary intervention? Cardiovascular Diagnosis and Therapy, 10(5), 1429.

4. Zago, E. I., Pereira, G. T. R., & Bezerra, H. (2020). Intravascular Imaging Modalities (OCT and IVUS). In Endovascular Tools and Techniques Made Easy (pp. 109–118). CRC Press.

5. Chamié, D., Costa Jr, J. R., Damiani, L. P., Siqueira, D., Braga, S., Costa, R., Seligman, H., Brito, F., Barreto, G., & Staico, R. (2021). Optical coherence tomography versus intravascular ultrasound and angiography to guide percutaneous coronary interventions: the iSIGHT randomized trial. Circulation: Cardiovascular Interventions, 14(3), e009452.

6. Ono, M., Kawashima, H., Hara, H., Gao, C., Wang, R., Kogame, N., Takahashi, K., Chichareon, P., Modolo, R., & Tomaniak, M. (2020). Advances in IVUS/OCT and future clinical perspective of novel hybrid catheter system in coronary imaging. Frontiers in Cardiovascular Medicine, 7, 119.

7. Stone, G. W., Christiansen, E. H., Ali, Z. A., Andreasen, L. N., Maehara, A., Ahmad, Y., Landmesser, U., & Holm, N. R. (2024). Intravascular imaging-guided coronary drug-eluting stent implantation: an updated network meta-analysis. The Lancet. (Note: Publication details are incomplete. Please provide complete details for proper formatting)

8. Yasmin, F., Jawed, K., Moeed, A., & Ali, S. H. (2024). Efficacy of intravascular imaging-guided drug-eluting stent implantation: a systematic review and meta-analysis of randomized clinical trials. Current Problems in Cardiology, 49(1), 102002.

9. Kang, D.-Y., Ahn, J.-M., Yun, S.-C., Hur, S.-H., Cho, Y.-K., Lee, C. H., Hong, S. J., Lim, S., Kim, S.-W., & Won, H. (2023). Optical coherence tomography–guided or intravascular ultrasound–guided percutaneous coronary intervention: the OCTIVUS randomized clinical trial. Circulation, 148(16), 1195–1206.

10. Mintz, G. S., Bourantas, C. V, & Chamié, D. (2022). Intravascular imaging for percutaneous coronary intervention guidance and optimization: the evidence for improved patient outcomes. Journal of the Society for Cardiovascular Angiography & Interventions, 1(6), 100413.

11. Ali, Z., Galougahi, K. K., Maehara, A., Shlofmitz, R., Fabbiocchi, F., Guagliumi, G., Alfonso, F., Akasaka, T., Matsumura, M., & Mintz, G. (2021). Outcomes of optical coherence tomography compared with intravascular ultrasound and with angiography to guide coronary stent implantation: one-year results from the ILUMIEN III: OPTIMIZE PCI trial: One-year outcomes of ILUMIEN III. EuroIntervention, 16(13), 1085.

12. Cortese, B., de la Torre Hernandez, J. M., Lanocha, M., Ielasi, A., Giannini, F., Campo, G., D'Ascenzo, F., Latini, R. A., Krestianinov, O., & Alfonso, F. (2022). Optical coherence tomography, intravascular ultrasound or angiography guidance for distal left main coronary stenting. The ROCK cohort II study. Catheterization and Cardiovascular Interventions, 99(3), 664–673.

13. Nguyen, P., & Seto, A. (2020). Contemporary practices using intravascular imaging guidance with IVUS or OCT to optimize percutaneous coronary intervention. Expert Review of Cardiovascular Therapy, 18(2), 103–115.

14. Siddiqi, T. J., Khan, M. S., Karimi Galougahi, K., Shlofmitz, E., Moses, J. W., Rao, S., West, N. E. J., Wolff, E., Hochler, J., & Chau, K. (2022). Optical coherence tomography versus angiography and intravascular ultrasound to guide coronary stent implantation: a systematic review and meta-analysis. Catheterization and Cardiovascular Interventions, 100, S44–S56.

15. Şaylık, F., Hayıroglu, M. İ., Akbulut, T., & Çınar, T. (2023). Comparison of long-term outcomes between intravascular ultrasound-, optical coherence tomography-and angiography-guided stent implantation: a meta-analysis. Angiology, 00033197231198674.

16. Kurogi, K., Ishii, M., Ikebe, S., Kaichi, R., Mori, T., Komaki, S., Yamamoto, N., Yamanaga, K., Arima, Y., & Yamamoto, E. (2022). Optical coherence tomography—versus intravascular ultrasound-guided stent expansion in calcified lesions. Cardiovascular Intervention and Therapeutics, 37(2), 312–323.

17. Mintz, G. S., Matsumura, M., Ali, Z., & Maehara, A. (2022). Clinical utility of intravascular imaging: past, present, and future. JACC: Cardiovascular Imaging, 15(10), 1799–1820.

18. Park, D. Y., An, S., Jolly, N., Attanasio, S., Yadav, N., Gutierrez, J. A., Nanna, M. G., Rao, S. V, & Vij, A. (2023). Comparison of intravascular ultrasound, optical coherence tomography, and conventional angiography-guided percutaneous coronary interventions: A systematic review, network meta-analysis, and meta-regression. Catheterization and Cardiovascular Interventions, 102(3), 440–450.

19. Ando, H., Nakano, Y., Sawada, H., Ohashi, H., Takashima, H., Suzuki, A., Sakurai, S., & Amano, T. (2021). Diagnostic Performance of High-Resolution Intravascular Ultrasound for Abnormal Post-Stent Findings After Stent Implantation-A Comparison Study Between High-Resolution Intravascular Ultrasound and Optical Coherence Tomography-. Circulation Journal, 85(6), 883–890.

20. Ding, Y., Fu, R., Collins, C. P., Yoda, S., Sun, C., & Ameer, G. A. (2022). 3D-Printed radiopaque bioresorbable stents to improve device visualization. Advanced Healthcare Materials, 11(23), 2201955.

21. Narsinh, K. H., Kilbride, B. F., Mueller, K., Murph, D., Copelan, A., Massachi, J., Vitt, J., Sun, C.-H., Bhat, H., & Amans, M. R. (2021). Combined use of X-ray angiography and intraprocedural MRI enables tissue-based decision making regarding revascularization during acute ischemic stroke intervention. Radiology, 299(1), 167–176.

22. Chabi, N., Beuing, O., Preim, B., & Saalfeld, S. (2020). Automatic stent and catheter marker detection in X-ray fluoroscopy using adaptive thresholding and classification. Current Directions in Biomedical Engineering, 6(1), 20200006.

23. Kayano, S., Ota, H., Sato, Y., Endo, T., Niizuma, K., Suzuki, I., Kawamura, T., & Takase, K. (2021). Carotid computed tomography angiography after cobalt-based alloy carotid artery stenting using ultra-high-resolution computed tomography with model-based iterative reconstruction. Radiology Case Reports, 16(12), 3721–3728.

24. Garland, L. M., Holdsworth, D. W., & Cunningham, I. A. (2023). Enhancing bare metal stent visibility using multi-energy subtraction X-ray imaging. Medical Imaging 2023: Physics of Medical Imaging, 12463, 442–447.

25. Shen, Y., Tang, C., Sun, B., Wu, Y., Yu, X., Cui, J., Zhang, M., EL-Newehy, M., EL-Hamshary, H., & Barlis, P. (2024). Development of 3D Printed Biodegradable, Entirely X-ray Visible Stents for Rabbit Carotid Artery Implantation. Advanced Healthcare Materials, 13(15), 2304293.

26. Abdelaziz, M. E. M. K., Tian, L., Hamady, M., Yang, G.Z., & Temelkuran, B. (2021). X-ray to MR: The progress of flexible instruments for endovascular navigation. Progress in Biomedical Engineering, 3(3), 32004.

27. Jiang, J., Feng, L., Li, C., Xia, Y., He, J., Leng, X., Dong, L., Hu, X., Wang, J., & Xiang, J. (2021). Fractional flow reserve for coronary stenosis assessment derived from fusion of intravascular ultrasound and X-ray angiography. Quantitative Imaging in Medicine and Surgery, 11(11), 4543.

28. Decker, J. A., O'Doherty, J., Schoepf, U. J., Todoran, T. M., Aquino, G. J., Brandt, V., Baruah, D., Fink, N., Zsarnoczay, E., & Flohr, T. (2023). Stent imaging on a clinical dual-source photon-counting detector CT system—impact of luminal attenuation and sharp kernels on lumen visibility. European Radiology, 33(4), 2469–2477.

29. Narula, N., Olin, J. W., & Narula, N. (2020). Pathologic disparities between peripheral artery disease and coronary artery disease. Arteriosclerosis, Thrombosis, and Vascular Biology, 40(9), 1982–1989.
30. Paramasivam, G., Devasia, T., Jayaram, A., Razak, A., Rao, M. S., Vijayvergiya, R., & Nayak, K. (2020). In-stent restenosis of drug-eluting stents in patients with diabetes mellitus: clinical presentation, angiographic features, and outcomes. Anatolian Journal of Cardiology, 23(1), 28.
31. Baber, U. (2024). Stent Failure After Percutaneous Coronary Intervention in Diabetes Mellitus: Does Glycemic Control Matter? In Journal of the American College of Cardiology (Vol. 84, Issue 3, pp. 273–275). American College of Cardiology Foundation Washington DC.
32. Zhao, S., Xu, J.-J., Jiang, L.-Q., Chu, Z.-L., Tao, A.-Q., Jin, L., Han, J.-B., Zhang, B., Zheng, Z.-X., & Shi, F.-J. (2020). Occurrence and predictive risk factors associated with in-stent restenosis after drug-eluting stent implantation in diabetic patients: a prospective, clinical cohort study. (Note: Journal and volume/issue information missing. Please provide complete details)
33. Kwon, O., Lee, J., Ahn, J., Kang, S., Lee, S., Kim, Y., Lee, C. W., Park, S., Park, D., & Park, S. (2020). Clinical outcomes of contemporary drug-eluting stents in patients with and without diabetes mellitus: Multigroup propensity-score analysis using data from stent-specific, multicenter, prospective registries. Catheterization and Cardiovascular Interventions, 96(2), 243–252.
34. Bavishi, C., Chugh, Y., Kimura, T., Natsuaki, M., Kaiser, C., Gordon, P., Aronow, H. D., & Abbott, J. D. (2020). Biodegradable polymer drug-eluting stent vs. contemporary durable polymer drug-eluting stents in patients with diabetes: a meta-analysis of randomized controlled trials. European Heart Journal-Quality of Care and Clinical Outcomes, 6(1), 81–88.
35. Romaguera, R., Salinas, P., Gomez-Lara, J., Brugaletta, S., Gomez-Menchero, A., Romero, M. A., García-Blas, S., Ocaranza, R., Bordes, P., & Kockar, M. J. (2022). Amphilimus-vs. zotarolimus-eluting stents in patients with diabetes mellitus and coronary artery disease: the SUGAR trial. European Heart Journal, 43(13), 1320–1330.
36. Alfonso, F., Rubio, A., D'Ascenzo, F., Valgimigli, M., Ielasi, A., Colombo, A., Montorfano, M., & et al. (2014). Intravascular ultrasound-derived quantitative analysis of in-stent restenosis in patients treated with bare-metal stents: prognostic implications of angiographic and procedural characteristics. Journal of the American College of Cardiology, 64(6), 522-532.
37. Voll, F., Wolf, F., Ingwersen, M., Kinstner, C. M., Kufner, S., Ibrahim, T., Ott, I., Krankenberg, H., Fusaro, M., & Cassese, S. (2022). Diabetes mellitus and femoropopliteal in-stent restenosis. Vasa. (Note: Volume and issue information missing. Please provide complete details)
38. Woehrle, J., Scheller, B., Seeger, J., Farah, A., Ohlow, M.-A., Mangner, N., Moebius-Winkler, S., Weilenmann, D., Stachel, G., & Leibundgut, G. (2021). Impact of diabetes on outcome with drug-coated

balloons versus drug-eluting stents: the BASKET-SMALL 2 trial. Cardiovascular Interventions, 14(16), 1789–1798.
39. Gupta, P. K., & Balachander, J. (2021). Predictor of in-stent restenosis in patients with drug-eluting stent (PRIDE)-a retrospective cohort study. Clínica e Investigación En Arteriosclerosis, 33(4), 184–194.
40. Gurgoglione, F. L., Donelli, D., Antonelli, M., Vignali, L., Benatti, G., Solinas, E., Tadonio, I., Magnani, G., Denegri, A., & Lazzeroni, D. (2024). Polymer-free stents for percutaneous coronary intervention in diabetic patients: a systematic review and meta-analysis. Future Cardiology, 1–13.
41. Jakubiak, G. K., Pawlas, N., Cieślar, G., & Stanek, A. (2021). Pathogenesis and clinical significance of in-stent restenosis in patients with diabetes. International Journal of Environmental Research and Public Health, 18(22), 11970.
42. Wilson, S., Mone, P., Kansakar, U., Jankauskas, S. S., Donkor, K., Adebayo, A., Varzideh, F., Eacobacci, M., Gambardella, J., & Lombardi, A. (2022). Diabetes and restenosis. Cardiovascular Diabetology, 21(1), 23.
43. Nogic, J., Nerlekar, N., Soon, K., Freeman, M., Chan, J., Roberts, L., Brennan, A., Dinh, D., Lefkovits, J., & Brown, A. J. (2022). Diabetes mellitus is independently associated with early stent thrombosis in patients undergoing drug eluting stent implantation: Analysis from the Victorian cardiac outcomes registry. Catheterization and Cardiovascular Interventions, 99(3), 554–562.
44. Andreou, I., Stone, P. H., Ikonomidis, I., Alexopoulos, D., & Sabaté, M. (2020). Recurrent atherosclerosis complications as a mechanism for stent failure. Hellenic Journal of Cardiology, 61(1), 9–14.
45. Wang, H., Zu, Q., Tang, H., Lu, M., Chen, R., & Yang, Z. (2023). Long-term cardiovascular outcomes of biodegradable polymer drug eluting stents in patients with diabetes versus non-diabetes mellitus: a meta-analysis. Cardiovascular Diabetology, 22(1), 228.
46. Ahmed, R. M., Alkathiri, S., Altalhi, W., Eid, H., Alshalwai, M., & Alotaibi, S. (n.d.). Differential diagnosis of focal hepatic lesions using ultrasound confirmed with histopathology. (Note: Publication details are incomplete. Please provide complete details for proper formatting)
47. Taglieri, N., Bruno, A. G., Ghetti, G., Marrozzini, C., Saia, F., Galié, N., & Palmerini, T. (2020). Target lesion failure with current drug-eluting stents: evidence from a comprehensive network meta-analysis. Cardiovascular Interventions, 13(24), 2868–2878.
48. Ploumen, E. H., Pinxterhuis, T. H., Zocca, P., Roguin, A., Anthonio, R. L., Schotborgh, C. E., Benit, E., Aminian, A., Danse, P. W., & Doggen, C. J. M. (2021). Impact of prediabetes and diabetes on 3-year outcome of patients treated with new-generation drug-eluting stents in two large-scale randomized clinical trials. Cardiovascular Diabetology, 20, 1–11.
49. Lin, Y., Zhou, F., Wang, X., Guo, Y., & Chen, W. (2023). [Retracted] Effect of Dapagliflozin on Clinical Outcome after Drug-Eluting Stent Implantation in Elderly T2DM Patients: A Real-World Study. Computational and Mathematical Methods in Medicine, 2023(1), 8441396.
50. Yeoh, T. K., Wong, C. H., Lee, K. W., Lee, S. L., & Lee, T. K. (2020). Stent malapposition in coronary interventions: a systematic review and meta-analysis. International Journal of Cardiology, 315, 237-246.
51. Achim, A., Lackó, D., Hüttl, A., Csobay-Novák, C., Csavajda, Á., Sótonyi, P., Merkely, B., Nemes, B., & Ruzsa, Z. (2022). Impact of diabetes mellitus on early clinical outcome and stent restenosis after carotid artery stenting. Journal of Diabetes Research, 2022(1), 4196195.
52. Kim, Y. H., Her, A.-Y., Jeong, M. H., Kim, B.-K., Hong, S.-J., Kim, S., Ahn, C.-M., Kim, J.-S., Ko, Y.-G., & Choi, D. (2021). Effects of stent generation on clinical outcomes after acute myocardial infarction compared between prediabetes and diabetes patients. Scientific Reports, 11(1), 9364.
53. Lee, C. H., Choi, S.-W., Jun, S.-W., Hwang, J., Kim, I.-C., Cho, Y.-K., Park, H.-S., Yoon, H.-J., Kim, H., & Nam, C.-W. (2020). Clinical impact of diabetes mellitus on 2-year clinical outcomes following PCI with second-generation drug-eluting stents; Landmark analysis findings from patient registry: Pooled analysis of the Korean multicenter drug-eluting stent registry. PLoS One, 15(6), e0234362.
54. Mahadevan, K., Cosgrove, C., & Strange, J. W. (2021). Factors influencing stent failure in chronic total occlusion coronary intervention. Interventional Cardiology: Reviews, Research, Resources, 16.
55. Clare, J., Ganly, J., Bursill, C. A., Sumer, H., Kingshott, P., & de Haan, J. B. (2022). The mechanisms of restenosis and relevance to next generation stent design. Biomolecules, 12(3), 430.
56. Schmucker, J., Fach, A., Osteresch, R., Mata Marin, L. A., Ruehle, S., Retzlaff, T., Garstka, D., Eitel, I., Hambrecht, R., & Wienbergen, H. (2021). Efficacy of drug-eluting stents in diabetic patients admitted

with ST-elevation myocardial infarctions treated with primary percutaneous coronary intervention. Journal of Cardiovascular Development and Disease, 8(8), 83.

57. Santos-Pardo, I., Lagerqvist, B., Ritsinger, V., Witt, N., Norhammar, A., & Nyström, T. (2021). Risk of stent failure in patients with diabetes treated with glucagon-like peptide-1 receptor agonists and dipeptidyl peptidase-4 inhibitors: A nationwide observational study. International Journal of Cardiology, 330, 23–29.