COR ET VASA 54 (2012) E167–E175

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Review – *Special issue: Novel methods in interventional cardiology and cardiac surgery*

Optical coherence tomography in interventional cardiology—Research field or future daily routine?

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ARTICLE INFO

Article history:
Received 29 April 2012
Received in revised form
22 May 2012
Accepted 23 May 2012
Available online 30 May 2012

Keywords:
Optical coherent tomography
Acute coronary syndrome
Coronary morphology

ABSTRACT

Nowadays, optical coherent tomography (OCT) as the most precise morphologic technique is used in the increasing number of cases, both in routine clinical situations and research projects. Huang and co-workers reported the first clinical use of the 2-dimensional OCT in 1991, suggesting the principle of its use both in ophthalmology and interventional cardiology. The method has developed rapidly since that time. Interventional cardiologists benefit from its detailed intravascular imaging ability, providing real-time information of the intracoronary pathology. Researchers acknowledge the resolution, allowing detailed analysis of vessel structure. Its axial resolution level is approximately 10–15 μm, which is far from any other method used in interventional cardiology. The review will address the principle of the method and the main fields of the relatively short history of the OCT use as a routine clinical imaging method. We will summarize the main OCT milestones in the research field and its possible future as well. The review will describe OCT as the method under rapid development that should be considered as a new "gold" or even "platinum" standard for the coronary vessels imaging.

Contents

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http://dx.doi.org/10.1016/j.crvasa.2012.05.007

1. Introduction

Optical coherence tomography (OCT) is the intravascular imaging method, that allows physicians to investigate structure of a vessel in a near to cellular level in vivo. From the time of the first implantation of coronary stent in human in 1986 [1], cardiologists were trying to find ways how to investigate coronary vessels in vivo from inside. The first method used for this purpose was angioscopy [2], method that allows only surface assessment of the vessel. First, truly useful imaging modality for the vessel and stent analysis was intravascular ultrasound (IVUS), developed in 70s [3]. For many years, IVUS was a gold standard for both the vessel wall and stent imaging. However, resolution of IVUS is about ten times lower than the one of OCT and the limitations in the assessment of stents (especially uselessness of IVUS as a tool for the analysis of the stent tissue coverage) are not negligible. The first clinical application of the 2-dimensional OCT was reported by Huang and co-workers in 1991 [4], suggesting the principle of its use both in ophthalmology and interventional cardiology. The method has developed rapidly since that time. Nowadays, OCT is used in the increasing number of cases, both in routine clinical situations and research projects. Interventional cardiologists benefit from its detailed intravascular imaging ability, providing real-time information of the intracoronary pathology. Researchers acknowledge the resolution, allowing detailed analysis of vessel structure. Its axial resolution level is approximately 10–15 μm, which is far from any other method used in interventional cardiology. The review will address the main fields of the relatively short history of the OCT use as a routine imaging method (the first clinical use of OCT in US was performed in May 2010 following the FDA approval) and its future. We will summarize the main OCT milestones in the research field as well. The review will describe OCT as the method under rapid development that should be considered as a new gold standard for the coronary vessels imaging.

2. Principles of coronary OCT

OCT imaging is a light-based intravascular imaging technique. The principle of the image creation is based on the back-scattering of light from the vessel wall structures and the time that light needs to travel from the source to the tissue structure and back. Due to an extreme speed of light, interferometry techniques are needed to measure the back-scattered signal. Current OCT systems use a central wavelength of approximately 1300 nm, which is very close to the infrared light. The main advantage of the OCT method is getting a very detailed picture of the vessel. The axial resolution is 10–15 μm. This high resolution is a result of wave velocity and the bandwidth, both orders of magnitude higher that in the ultrasound medical devices. The lateral resolution 20–40 μm is determined by the imaging optics in the catheter. The tissue penetration of this wavelength is limited to 1–3 mm. Compared to IVUS (tissue penetration of 4–8 mm), the vessel wall penetration of light might be one of the main limitations of the OCT method. However, according to Kume et al. [5], intima-media thickness can be measured more accurately by OCT than IVUS (depending on the vessel diameter).

First commercially available OCT system (M2/M3 TD-OCT Imaging system, LightLab/St. Jude Medical, St. Paul, Minnesota) was based on the older technology, called time-domain OCT (TD-OCT). The system is based on a broadband light source emitting light through the fiberoptic coupler, dividing the signal to two "arms"—one to the tissue, the second one to the reference arm consisting of moving mirror calibrated to produce known echo delays. The main pitfall of this system is a slow speed of the frames acquisition (max. acquisition speed 3 mm/s, mainly due to a limitation of the movement speed of the mirror), which results in need of a complete vessel occlusion with an over-the-wire low-pressure occlusion balloon (Helios, Goodman, Nagoya, Japan). Distal flush ports of the balloon are used to infuse saline or Ringer's lactate to displace blood during the imaging process. Due to safety issues, the manufacturer limited the time of the occlusion to maximum of 30 s. Safety was the reason why FDA never approved TD-OCT system for a clinical use in US, contrary to European Union (EU) countries, where TD-OCT was introduced to the market in 2007.

Newer system, termed frequency or Fourier-domain OCT (FD-OCT) uses fixed mirror instead, because light is emitted by a variable frequency source, called "swept-laser" (Fig. 1). This difference allows the system to be significantly faster (max. acquisition speed 20 mm/s) [6] (Table 1). Thus, no blood flow occlusion is needed with this system, only a continuous flush of the contrast fluid is enough to clear the vessel to gain an uncompromised image.

FD-OCT system $C7_{XR}$ (St. Jude Medical, St. Paul, Minnesota; Fig. 2) was the first FD-OCT system available for the clinical use on the US market. FDA clearance of the method followed in 2010 its former approval in EU, Asia and South America. The system uses 2.7-F imaging catheter C7 Dragonfly™ (St. Jude Medical, St. Paul, Minnesota; Fig. 3), compatible with 0.014" guidewire and 6-F guiding catheters. Detailed description of the imaging procedure is out of the scope of this article and is available elsewhere [7].

The feasibility of the procedure was increased with the introduction of the FD-OCT technology, providing physicians with completely new level of information about vessels and stents in vivo. Despite the undisputed advantages of the OCT as an imaging method, operator using this technique has to be aware of its specific limitations. First of all, there is a certain vessel size range that is suitable for OCT examination. Ideally, the artery diameter should be 2.0–3.75 mm, since the upper limit is based on the maximum scanning diameter of the system. One of the most common causes of distortion of the image is an extreme vessel tortuosity, causing the catheter to be placed significantly eccentric in the lumen [8]. Incomplete blood displacement from the vessel segment leads to the severe attenuation of the image, compromising the analysis as well (Fig. 4). Several types of the artifacts were described [7], although introducing of the FD-OCT system significantly decreased their occurrence. Especially artifacts based on the slow image acquisition of the TD-OCT technique (e.g., "sew-up" artifacts generated due to a movement of the vessel during the one frame data acquisition) are suppressed with the new system.

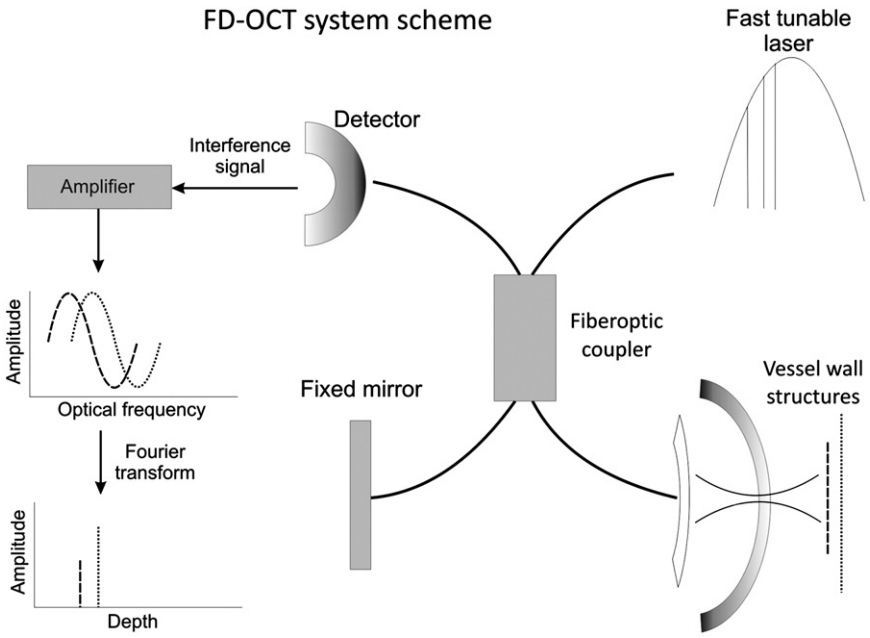

Fig. 1 – Scheme of the FD-OCT system (adapted from JACC Cardiovascular Intervention 2009 Nov;2(11):1035–46).

Table 1 – Comparison of physical characteristics of the TD-OCT, FD-OCT and IVUS systems.

	TD-OCT (M2/M3)[a]	FD-OCT ($C7_{XR}$)[a]	IVUS [b]
Wavelength	1.3 μm	1.3 μm	35–80 μm
Axial resolution	12–15 μm	12–15 μm	100–200 μm
Lateral resolution	90 μm	20–40 μm	200–300 μm
Pullback speed	3 mm/s	20 mm/s	1 mm/s
Frame acquisition rate	20 frames/s	100 frames/s	30 frames/s
Max. scan diameter	6.8 mm	9.7 mm	15 mm
Tissue penetration	1.5–2 mm	2.5 mm	10 mm

[a] Based on specifications of the M2/M3 and $C7_{XR}$ OCT system.
[b] Based on specifications of Volcano, Boston Scientific and Terumo IVUS systems (Modified from Int J Cardiol (2012), http://dx.doi.org/10.1016/j.ijcard.2012.02.013).

One run of the image acquisition (one "pullback") is in the $C7_{XR}$ system fixed to 54 mm. If longer vessel segment analysis is needed, multiple overlapping pullbacks are performed. When more than one pullback is obtained, analyst face a potential problem of the overlapping segments identification. Characteristic identifiable structures (e.g., side branches) are used for this purpose.

Another common cause of an incorrect image analysis is the wrong adjustment of the Z-offset. Calibration of this parameter corrects the difference of the optical path between both (reference and sample) arms [7]. In $C7_{XR}$ TD-OCT system the outer diameter of the semitransparent imaging catheter (0.90 mm) serves as the calibration reference dimension, "zero-point" setting of the system [9]. The Z-offset of the pullback has to be indispensably adjusted before any quantitative measurement is started; otherwise results are significantly compromised.

3. OCT as a research tool

Analysis of the OCT image for the research purposes is a significantly different process comparing to the routine clinical on-line use in a cathlab. Since the beginning of the OCT availability, the cornerstone of the OCT analysis has been in the stent coverage assessment. However, number of suitable clinical situations and study endpoints where OCT was successfully used is constantly rising.

Since 2007 (when TD-OCT was first approved in EU), almost 40 clinical OCT studies focused on the stent coverage assessment have been published [10]. Only few of the trials had randomized design [11–17]. Most of the trials were single-center, which is expected to change in the future, as the availability of the OCT technology is rising in cathlabs. There are several multicenter randomized OCT studies recruiting patients now, e.g., OCTAVIA trial [18].

The offline analysis of the OCT pullbacks is a strenuous work, if performed in a detailed "strut level" way. As the strut level analysis make demands on personnel and time, it is usually performed in one of the OCT corelabs with skilled and experienced team of analysts. Generally, for one stent pullback, the number of struts that have to be analyzed is usually more than one thousand, depending on the thickness of the cross-section for the assessment. The offline analysis has two parts—quantitative and qualitative. Whereas the

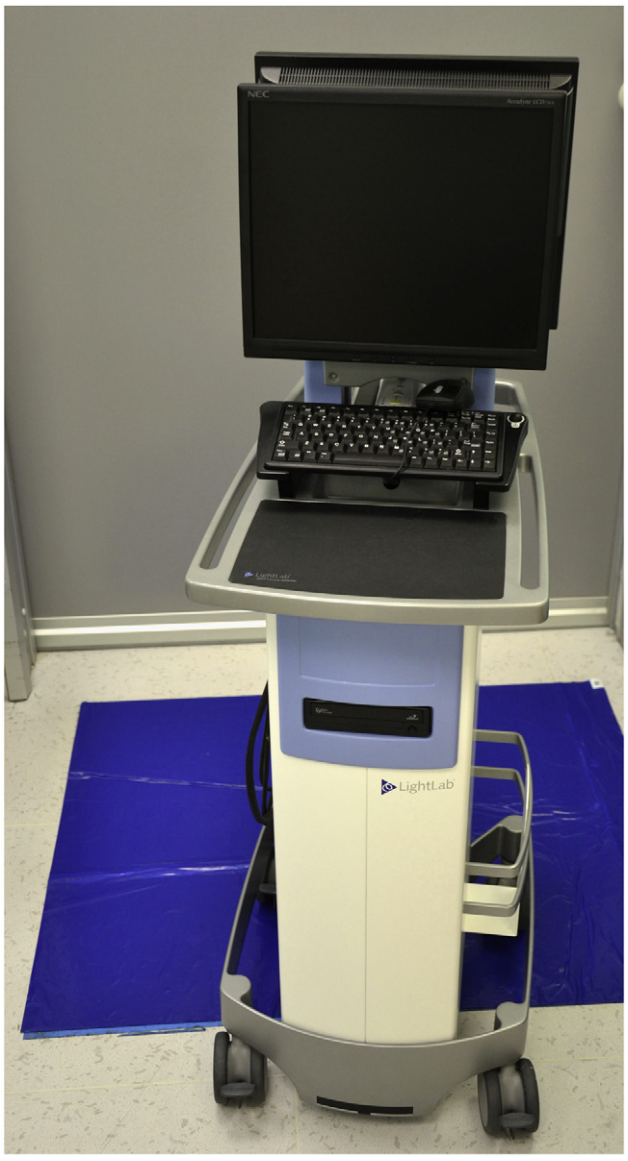

Fig. 2 – St. Jude/Lightlab C7$_{XR}$ FD-OCT system.

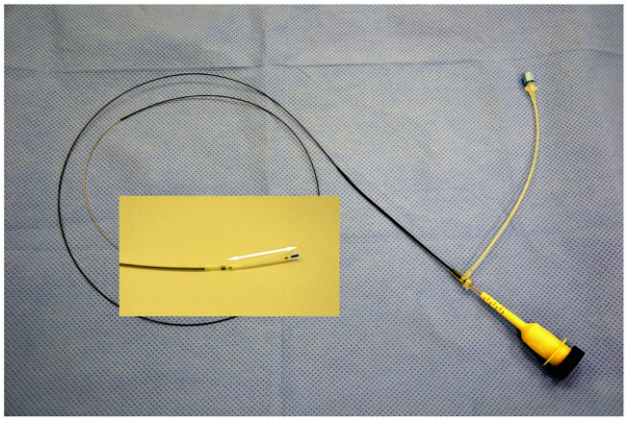

Fig. 3 – C7 Dragonfly™ imaging catheter with the tip in detail—note very short segment (arrows) used for the wire guiding the catheter. The imaging area lies proximally from this part, therefore the wire is found outside of the catheter in the OCT cross-section image.

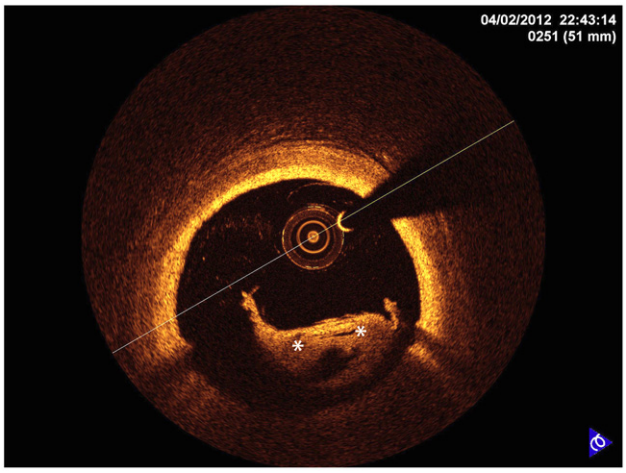

Fig. 4 – Example of the incomplete displacement of blood (asterisks) from the vessel lumen, significantly compromising the image quality.

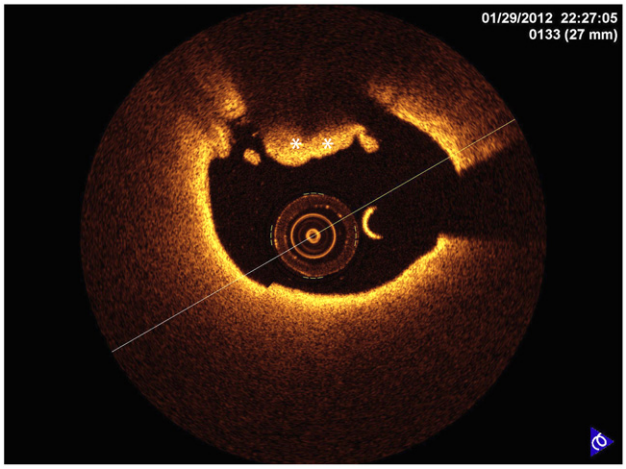

Fig. 5 – Red thrombus (asterisks), characterized by the high backscattering of the border and severe signal attenuation.

qualitative part is based on the characteristics of the structures displayed, the quantitative part is mostly the result of manual tracing of the vessel lumen and stent struts position. For now, no reliable software for the automatic segmentation of the OCT frames commercially exists.

Based on the light backscattering, light attenuation and structure displayed in the OCT pullback, type of the tissue is determined by the qualitative analysis. The recognition of the structure is crucial also for the on-line analysis in the cathlab, as the cardiologist can use the information for the optimal intervention technique choice. There are characteristic patterns for the thrombus recognition, described as the irregular structures inside the lumen with the high backscattering and severe attenuation of signal (red thrombus, Fig. 5) or as the low-backscattering structures (white thrombus) [19]. Lipid plaque is characterized as a signal-attenuated structure with a high backscattering diffuse border, usually with a smooth surface (compared to thrombus, Fig. 6) [20,21]. Calcified plaque is defined as a hyposignal region delineated by a sharp boundary (Fig. 7) [22,23]. Normal physiological vessel

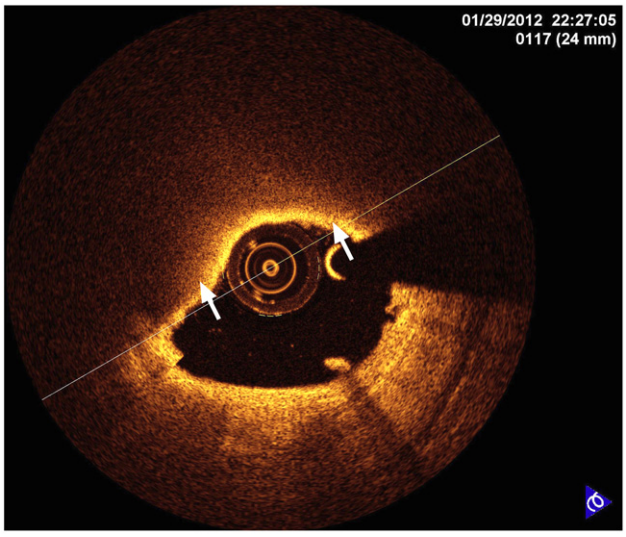

Fig. 6 – Lipid-rich plaque in the severely diseased vessel (white arrows), defined as a signal-attenuated structure with a high backscattering diffuse border, usually with a smooth surface.

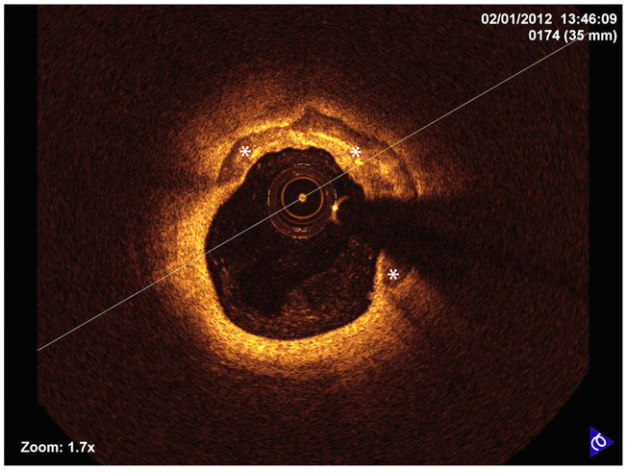

Fig. 7 – Large calcified plaque (asterisks), defined as a hyposignal region delineated by a sharp boundary.

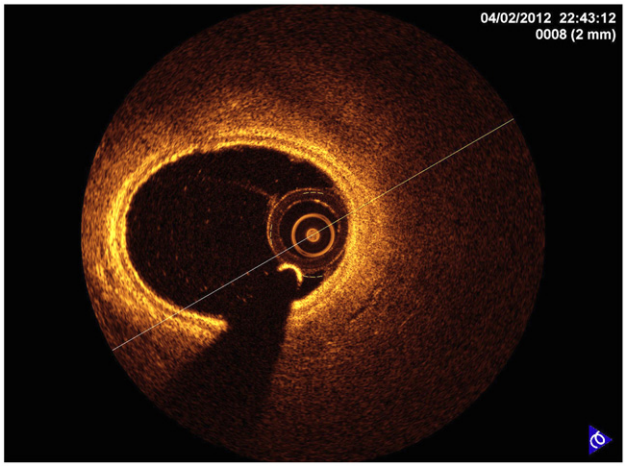

Fig. 8 – Almost normal vessel with no significant disease—three layers wall structure.

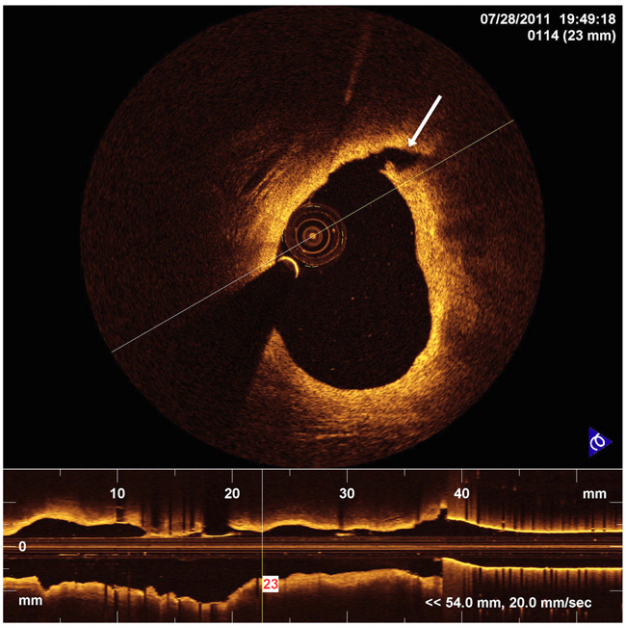

Fig. 9 – Vessel wall dissection in the proximity of the proximal stent edge (arrow).

image is recognized according to the typical 3-layer structure of the wall (Fig. 8). Another structures usually described in the analysis are protruded tissue or dissections [24,25] (Fig. 9).

Strut level analysis is based on the lumen and stent struts position tracing. Surface of stent struts reflects light fully, creating a bright signal, usually named as "blooming". Due to the inability of light to pass through metal struts, a shadow is seen behind the blooming. If baseline examination is performed after the stent placement, struts are described as apposed, malapposed or embedded (according to its position towards the vessel wall). If formerly implanted stent is analyzed during the follow-up period, it can be described as covered, covered-protruding (disturbing lumen contour, but covered), uncovered-apposed, and uncovered-malapposed [26]. Due to a different nominal thickness of the struts in different stents, the type of the stent needs to be known for the proper assessment of the struts. The apposition of the strut is preferably measured as the distance from the inner surface of the strut blooming to the lumen of the vessel, correcting for half of the thickness of the blooming (18 μm) [8,26]. In clinical trials, analysts in corelab are usually blinded to the stent type, thus the real strut position (apposed, malapposed) is revealed after the statistical analysis.

4. OCT as a daily tool

During the regular clinical examination in a cathlab, detailed analysis of the stent struts, as performed offline, is inconceivable. The on-site assessment of the acquired data is limited by the patient presence on the examination table and the necessity to proceed without any needless delay. Therefore, the operator is able to perform only a standard qualitative assessment of the pullback (diameter of the

vessel, location and length of stenosis, intraluminal pathological structures, vessel wall pathology etc.).

Most important information obtained from the pullback is a vessel wall response to the stent implantation. OCT data allows to assess the strut apposition or to analyze acute damage after the stent implantation (e.g., tissue prolapse, intimal rupture, vessel dissections or acute thrombus formation). OCT with its resolution can even detect a fracture of the stent in vivo [27]. In the follow-up period after the stent implantation, OCT is a sovereign method for the strut tissue coverage assessment, including the in-stent restenosis or stent thrombosis.

In the setting of the acute coronary syndrome (ACS), the OCT imaging can provide valuable information about the vessel wall structural pathology, minimal lumen diameter and area and reference areas proximally and distally to the segment that is about to be stented. Ino et al. [28] recently assessed culprit lesion morphology in ACS patients and revealed significant differences in the incidence of plaque rupture, thin-cap fibroatheroma, and red thrombus in ST-segment elevation myocardial infarction (STEMI) patients compared with those with nonST segment ACS. Interesting finding in this study was the difference in the ruptured plaque of which aperture was open-wide against the direction of coronary flow significantly more often in STEMI compared with nonST ACS.

After the stent placement, the OCT image of the strut positions can make the operator to proceed with another intervention (e.g., postdilatation of the lesion, if the stent seems to be malapposed). Obviously, the physician can only estimate, if the struts are apposed to the vessel wall, because he usually cannot perform regular strut level analysis of the stent due to a limited time (however, the nominal stent struts thickness is known in this situation).

Decision making based on the OCT imaging (in fact, OCT guided procedure) is one of the unsolved questions in the cathlab. Only few studies addressed this problem, using OCT either for the angiographically ambiguous lesions [29], or as a complementary method with the fractional flow reserve (FFR) to guide decision making in complex clinical scenarios [30]. Randomized trials are needed, attempting to prove if the OCT imaging brings a real benefit to the patients' care in term of reduced morbidity and mortality.

As the experience has been rising with the OCT systems, as well as the confidence in the method safety and feasibility, novel applications of the OCT imaging appear. The successful imaging of the carotid vessels was reported [31–33]. OCT imaging of the peripheral vessels (both arteries and veins) was described as well [34,35]. One of the uncommon applications of OCT in pulmonary arteries was reported recently [36].

5. Case report

As an example of the routine clinical use of the OCT, we present a case report of the 75 years old male, admitted to our coronary care unit due to a severe chest pain lasting 4 hours. The patient had a history of hypertension, peripheral ischemic disease and ischemic heart disease. He experienced a coronary stenting in different hospital due to the exertional angina 8 months ago. First generation drug eluting stents (DES) were implanted into two vessels—left circumflex (LCX) and right coronary artery (RCA) during the percutaneous intervention (PCI). The patient refers no ischemic symptoms since the time of previous PCI until the day of admission. He claimed that he used prescribed medication regularly (clopidogrel, aspirin, statin, angiotensin II receptor blockers).

ECG revealed a pattern of the inferolateral STEMI and the patient was immediately transferred to the cathlab. Occluded LCX was found as a culprit lesion, treated with thromboaspiration with the extraction of several red thrombi, followed by an immediate TIMI3 flow restoration. OCT revealed residual thrombotic material in the vessel, concentrated in the segment with the malapposed struts of the DES implanted 8 months ago (Fig. 10). The lesion was treated with platelet glycoprotein receptors IIb/IIIa inhibitor and balloon postdilatation, subsequent

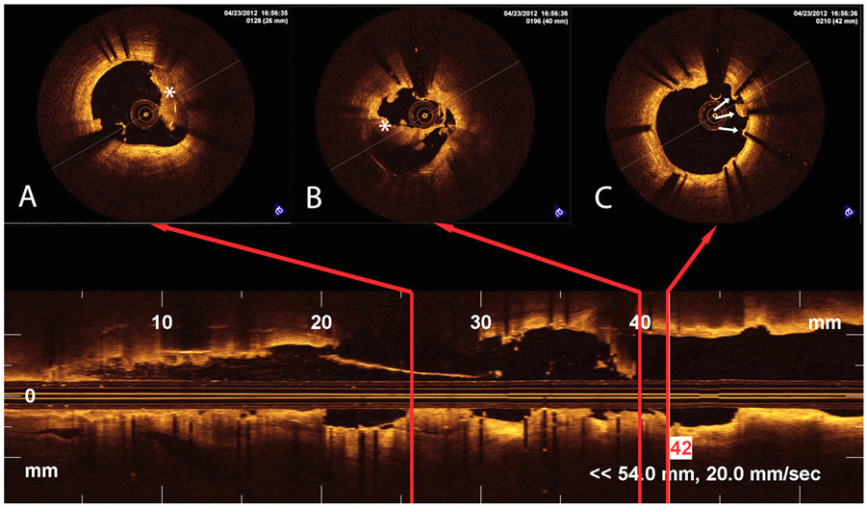

Fig. 10 – Pullback cross-sections after the thromboaspiration in the STEMI patient (see the case report description in the text). (A)—Medial part of the stent, thrombi (asterisk), and malapposed stent struts in the thrombus material. (B)—Proximal part of the stent, thrombus material filling the most of the lumen cross-section. (C)—Close to the proximal edge of the stent, malapposed stent struts (arrows) covered with material (most likely thrombus).

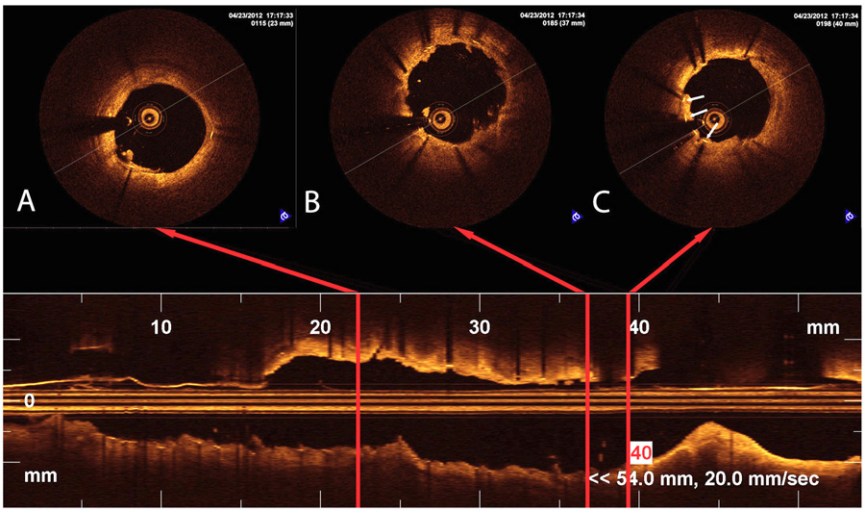

Fig. 11 – Pullback cross-sections (corresponding with the cross-sections in the Fig. 9) after the balloon postdilatation in the STEMI patient (see the case report description in the text). (A)–(C)—Small amount of residual thrombi. (C)—Note the change in the stent apposition after the balloon postdilatation (compared to the baseline image 10C, arrows), still covered with residual material.

OCT record showed a small amount of residual thrombi and acceptable stent apposition (Fig. 11). The physician responsible for the intervention decided not to implant an additional stent due to a satisfactory result of the balloon angioplasty verified by OCT.

The patient was discharged from the hospital on day 5 with no complications. Antiplatelet treatment was switched from clopidogrel to prasugrel. This report shows very clearly how important additional information can bring OCT image in the decision-making process.

6. Future of OCT in the interventional cardiology

As we demonstrated in the previous part of the text, OCT imaging technique is constantly developing and opening new horizons in the coronary interventions. Two other commercial systems are planned to reach the market [37,38]. Development of the software for the 3D reconstruction of the OCT image is probably one of the most competing tasks in the field, with few first reports published on the topic [39,40]. In the near future, introduction of the micro-OCT system is expected [41]. This system should provide extreme image resolution (up to 1 μm). The resolution brings such a level of detail, that the cellular structure of endothelial tissue should be assessable. As each of the intravascular imaging techniques (OCT, IVUS) and FFR has specific indications, advantages and disadvantages, manufacturers try to combine these methods into one compact device. Recently, new system to combine FFR and OCT was approved for the clinical use (ILUMIEN™, St.Jude Medical, St. Paul, MN). Another research target is a semi-automatic or automatic analysis of the vessel. In the future, an ideal system should display 3D reconstruction of the vessel, together with automatically analyzed structures of the vessel wall, their diameters and volumetric assessment.

7. Conclusions

Optical coherence tomography is a high-resolution intravascular imaging technique. Its research application is irreplaceable, but the method is also an excellent routine clinical tool. In hands of skilled and experienced interventional cardiologist OCT extends the borders of the diagnostic options. No other method can provide undisputable quality images in such a detail. The technique is safe and easy to use. The constant development of OCT could overcome its limitations and become a " platinum" standard of the intracoronary imaging in the future. Further research is needed to prove the patients' benefit from the "OCT-guided" procedures. One of the current important limitations of the technique is relatively high price of the imaging catheter.

Acknowledgment

Supported by the Grant of the IGA Ministry of Health of the Czech Republic no. NT/13830 and NS9824-4/2008

REFERENCES

[1] U. Sigwart, J. Puel, V. Mirkovitch, F. Joffre, L. Kappenberger, Intravascular stents to prevent occlusion and restenosis after transluminal angioplasty, New England Journal of Medicine 316 (1987) 701–706.
[2] M.J. Suter, S.K. Nadkarni, G. Weisz, et al., Intravascular optical imaging technology for investigating the coronary artery, JACC Cardiovascular Imaging 4 (2011) 1022–1039.
[3] N. Bom, C.T. Lancée, F.C. Van Egmond, An ultrasonic intracardiac scanner, Ultrasonics 10 (1972) 72–76.
[4] D. Huang, E.A. Swanson, C.P. Lin, et al., Optical coherence tomography, Science 254 (1991) 1178–1181.
[5] T. Kume, T. Akasaka, T. Kawamoto, et al., Assessment of coronary intima–media thickness by optical coherence

tomography: comparison with intravascular ultrasound, Circulation Journal 69 (2005) 903–907.
[6] S.R. Chinn, E.A. Swanson, J.G. Fujimoto, Optical coherence tomography using a frequency-tunable optical source, Optics Letters 22 (1997) 340–342.
[7] H.G. Bezerra, M.A. Costa, G. Guagliumi, A.M. Rollins, D.I. Simon, Intracoronary optical coherence tomography: a comprehensive review clinical and research applications, JACC Cardiovascular Intervention 2 (2009) 1035–1046.
[8] N. Suzuki, G. Guagliumi, H.G. Bezerra, et al., The impact of an eccentric intravascular ImageWire during coronary optical coherence tomography imaging, EuroIntervention 6 (2011) 963–969.
[9] F. Prati, E. Regar, G.S. Mintz, et al., Expert review document on methodology, terminology, and clinical applications of optical coherence tomography: physical principles, methodology of image acquisition, and clinical application for assessment of coronary arteries and atherosclerosis, European Heart Journal 31 (2010) 401–415.
[10] S. Tahara, D. Chamié, M. Baibars, C. Alraies, M. Costa, Optical coherence tomography endpoints in stent clinical investigations: strut coverage, International Journal of Cardiovascular Imaging 27 (2011) 271–287.
[11] G. Guagliumi, G. Musumeci, V. Sirbu, et al., Optical coherence tomography assessment of in vivo vascular response after implantation of overlapping bare-metal and drug-eluting stents, JACC Cardiovascular Intervention 3 (2010) 531–539.
[12] G. Guagliumi, M.A. Costa, V. Sirbu, et al., Strut coverage and late malapposition with paclitaxel-eluting stents compared with bare metal stents in acute myocardial infarction: optical coherence tomography substudy of the harmonizing outcomes with revascularization and stents in acute myocardial infarction (HORIZONS-AMI) trial, Circulation 123 (2011) 274–281.
[13] G. Guagliumi, V. Sirbu, H. Bezerra, et al., Strut coverage and vessel wall response to zotarolimus-eluting and bare-metal stents implanted in patients with ST-segment elevation myocardial infarction: the OCTAMI (optical coherence tomography in acute myocardial infarction) study, JACC Cardiovascular Interventions 3 (2010) 680–687.
[14] G. Guagliumi, V. Sirbu, G. Musumeci, et al., Strut coverage and vessel wall response to a new-generation paclitaxel-eluting stent with an ultrathin biodegradable abluminal polymer: optical coherence tomography drug-eluting stent investigation (OCTDESI), Circular Cardiovascular Interventions 3 (2010) 367–375.
[15] P. Barlis, E. Regar, P.W. Serruys, et al., An optical coherence tomography study of a biodegradable vs. durable polymer-coated limus-eluting stent: a LEADERS trial sub-study, European Heart Journal 31 (2010) 165–176.
[16] T. Adriaenssens, J. Dens, G. Ughi, et al., Optical coherence tomography (OCT) in PCI for in-stent restenosis (ISR): rationale and design of the SEDUCE (safety and efficacy of a drug eluting balloon in coronary artery restenosis) study, EuroIntervention 7 (Suppl K:K) (2011) 100–105.
[17] T.C. Poerner, S. Otto, J. Gassdorf, et al., A prospective randomised study using optical coherence tomography to assess endothelial coverage and neointimal proliferation at 6-months after implantation of a coronary everolimus-eluting stent compared with a bare metal stent postdilated with a paclitaxel-eluting balloon (OCTOPUS Trial): rationale, design and methods, EuroIntervention 7 (Suppl K:K) (2011) 93–99.
[18] 〈www.clinicaltrials.gov〉.
[19] T. Kume, T. Akasaka, T. Kawamoto, et al., Assessment of coronary arterial thrombus by optical coherence tomography, American Journal of Cardiology 97 (2006) 1713–1717.
[20] T. Kume, T. Akasaka, T. Kawamoto, et al., Assessment of coronary arterial plaque by optical coherence tomography, American Journal of Cardiology 97 (2006) 1172–1175.
[21] Y. Miyamoto, H. Okura, T. Kume, et al., Plaque characteristics of thin-cap fibroatheroma evaluated by OCT and IVUS, JACC Cardiovascular Interventions 4 (2011) 638–646.
[22] H. Yabushita, B.E. Bouma, S.L. Houser, et al., Characterization of human atherosclerosis by optical coherence tomography, Circulation 106 (2002) 1640–1645.
[23] T. Kubo, C. Xu, Z. Wang, N.S. Van Ditzhuijzen, H.G. Bezerra, Plaque and thrombus evaluation by optical coherence tomography, International Journal of Cardiovascular Imaging 27 (2011) 289–298.
[24] M. Radu, E. J½rgensen, H. Kelbæk, S. Helqvist, L. Skovgaard, K. Saunamäki, Optical coherence tomography at follow-up after percutaneous coronary intervention: relationship between procedural dissections, stent strut malapposition and stent healing, EuroIntervention 7 (2011) 353–361.
[25] T. Kume, H. Okura, Y. Miyamoto, et al., Natural history of stent edge dissection, tissue protrusion and incomplete stent apposition detectable only on optical coherence tomography after stent implantation, Circular Journal 76 (2012) 698–703.
[26] E.A. Mehanna, G.F. Attizzani, H. Kyono, M. Hake, H.G. Bezerra, Assessment of coronary stent by optical coherence tomography, methodology and definitions, International Journal of Cardiovascular Imaging 27 (2011) 259–269.
[27] P. Barlis, G. Sianos, G. Ferrante, F. Del Furia, S. D'Souza, C. Di Mario, The use of intra-coronary optical coherence tomography for the assessment of sirolimus-eluting stent fracture, International Journal of Cardiology 136 (2009) e16–20.
[28] Y. Ino, T. Kubo, A. Tanaka, et al., Difference of culprit lesion morphologies between ST-segment elevation myocardial infarction and non-ST-segment elevation acute coronary syndrome: an optical coherence tomography study, JACC Cardiovascular Interventions 4 (2011) 76–82.
[29] F. Imola, M.T. Mallus, V. Ramazzotti, et al., Safety and feasibility of frequency domain optical coherence tomography to guide decision making in percutaneous coronary intervention, EuroIntervention 6 (2010) 575–581.
[30] G.T. Stefano, H.G. Bezerra, G. Attizzani, et al., Utilization of frequency domain optical coherence tomography and fractional flow reserve to assess intermediate coronary artery stenoses: conciliating anatomic and physiologic information, International Journal of Cardiovascular Imaging 27 (2011) 299–308.
[31] S. Yoshimura, M. Kawasaki, K. Yamada, et al., OCT of human carotid arterial plaques, JACC Cardiovascular Imaging 4 (2011) 432–436.
[32] B. Reimers, D. Nikas, E Stabile, et al., Preliminary experience with optical coherence tomography imaging to evaluate carotid artery stents: safety, feasibility and techniques, EuroIntervention 7 (2011) 98–105.
[33] M.R. Jones, G.F. Attizzani, C.A. Given, 2nd, Brooks W.H., Costa M.A., Bezerra H.G. Intravascular frequency-domain optical coherence tomography assessment of atherosclerosis and stent-vessel interactions in human carotid arteries. American Journal of Neuroradiology 2012; http://dx.doi.org/10.3174/ajnr.A3016 [Epub ahead of print].
[34] T. Yonetsu, T. Kakuta, T. Lee, et al., Assessment of acute injuries and chronic intimal thickening of the radial artery after transradial coronary intervention by optical coherence tomography, European Heart Journal 31 (2010) 1608–1615.
[35] G.T. Stefano, E. Mehanna, S.A. Parikh, Imaging a spiral dissection of the superficial femoral artery in high resolution with optical coherence tomography—seeing is believing, Catheter Cardiovascular Intervention (2012), http://dx.doi.org/10.1002/ccd.24292 [Epub ahead of print].
[36] S. Tatebe, Y. Fukumoto, K. Sugimura, et al., Optical coherence tomography as a novel diagnostic tool for distal type chronic thromboembolic pulmonary hypertension, Circulation Journal 74 (2010) 1742–1744.

[37] T. Okamura, Y. Onuma, H.M. Garcia-Garcia, et al., First-in-man evaluation of intravascular optical frequency domain imaging (OFDI) of Terumo: a comparison with intravascular ultrasound and quantitative coronary angiography, EuroIntervention 6 (2011) 1037–1045.
[38] G. Guagliumi, V. Sirbu, Optical coherence tomography: high resolution intravascular imaging to evaluate vascular healing after coronary stenting, Catheter Cardiovascular Intervention 72 (2008) 237–247.
[39] V. Farooq, T. Okamura, B.D. Gogas, et al., 3D reconstructions of optical frequency domain imaging to improve understanding of conventional PCI, JACC Cardiovascular Imaging 4 (2011) 1044–1046.
[40] S. Tu, L. Xu, J. Ligthart, et al. In vivo comparison of arterial lumen dimensions assessed by co-registered three-dimensional (3D) quantitative coronary angiography, intravascular ultrasound and optical coherence tomography. International Journal Cardiovascular Imaging 2012; http://dx.doi.org/10.1007/s10554-12-0016-6 [Epub ahead of print].
[41] L. Liu, J.A. Gardecki, S.K. Nadkarni, et al., Imaging the subcellular structure of human coronary atherosclerosis using micro-optical coherence tomography, Nature Medicine 17 (2011) 1010–1014.