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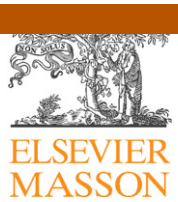

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REVIEW

Optical coherence tomography: From physical principles to clinical applications

Tomographie par cohérence optique : des principes physiques aux applications cliniques

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Summary Optical coherence tomography is a new endocoronary imaging modality employing near infrared light, with very high axial resolution. We will review the physical principles, including the old time domain and newer Fourier domain generations, clinical applications, controversies and perspectives of optical coherence tomography.

MOTS CLÉS
Angioplastie percutanée ;
Athérosclérose ;
Tomographie par cohérence optique ;
Syndrome coronaire aigu

Résumé La tomographie par cohérence optique est une modalité d'imagerie récente endocoronaire utilisant la lumière infrarouge, caractérisée par une haute résolution. Dans cet article, on discute les principes physiques en discutant l'ancienne et la nouvelle génération de tomographie par cohérence optique, *time domain* et *Fourier domain* respectivement.

Abbreviations: FD-OCT, Fourier domain optical coherence tomography; IVUS, intravascular ultrasound; OCT, optical coherence tomography; TD-OCT, time domain optical coherence tomography.

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Introduction

Optical coherence tomography (OCT) is a new imaging modality, used for the first time by Huang et al. in 1991 in vitro on the human peripapillary region of the retina and coronary arteries [1]. OCT is based on near infrared light; an optical beam is directed at the tissues, most of the light scatters and only the small portion of this light that reflects from subsurface features is collected and forms the image by yielding spatial information about tissue microstructure. The critical advantage of OCT over ultrasonography and magnetic resonance imaging is due to its micrometer resolution (about 10—15 μm of tissue axial resolution) [2].

Physical principles and acquisition systems

OCT uses low coherent near infrared light. The wavelength used is around 1300 nm to minimize energy absorption in the light beam caused by protein, water, haemoglobin and lipids [3]. The physics principle that allows the filtering of scattered light is optical coherence [4]. A light source emits a low-coherence, laser light wave. The light wave reaches a beam splitter or a partial mirror, which splits the light wave in half. One part of the light wave travels to a reference mirror, where it reflects directly back towards the beam splitter. The second part travels to the sample tissue. Depending on the optical properties of the tissue, some amount of light may be absorbed, refracted or reflected [5—8]. Reflection occurs when there is a region of sharp refractive index mismatch; therefore the velocity of light is not considered constant when it passes through different media. Light travels faster in a medium of low refractive index compared to a medium of high refractive index. The amount of reflection depends on the level of mismatch, the angle and the polarization of the incident angle. The reflected portion of the light travels back towards the beam splitter, where it meets with the reference light wave. The interaction between these two light waves is the basis on which OCT produces images [7]. When two light waves of the same wavelength and constant phase difference meet, they are combined through superposition; this phenomenon is called interference. If the light waves are in phase, they add together in constructive interference; if they are out of phase, they cancel each other out in destructive interference [7]. When the sample and reference light waves meet, they either intensify or diminish depending on how the sample light interacts with the tissue [8]. A detector uses the light or dark pattern produced to create a pixel for that specific region [6]. OCT cross-sectional imaging is achieved by performing successive axial measurements of back-reflected light at different transverse positions. After scanning a whole area, a full image of the tissue may be produced.

The major limitation of intracoronary OCT is blood attenuation due to the backscattering properties of red blood cells, thus we need to displace blood from the field of view.

There are two OCT systems: the first-generation system or time domain OCT and the new-generation system or Fourier domain OCT.

Table 1 Physical properties of optical coherence tomography and intravascular ultrasound.

	IVUS	OCT
Wavelength (μm)	35—80	1.3
Energy source	Ultrasound	Infrared
Penetration (mm)	10	1—2.5
Axial resolution (μm)	100—200	15—20
Lateral resolution (μm)	200—300	20—40

IVUS: intravascular ultrasound; OCT: optical coherence tomography.

Time domain OCT

Time domain OCT (TD-OCT) uses an occlusive technique that requires stopping of the coronary blood flow by soft balloon inflation [3,9,10]. The pullback speed of TD-OCT ranges between 1 and 5 mm/s [11—15]. TD-OCT uses a broadband light source containing a moving mirror that allows scanning of each depth position in the image, pixel by pixel. This mechanical scanning process limits the rate at which images can be acquired [3].

TD-OCT is limited by the risk of balloon injury, a balloon-vessel size mismatch, a long diseased lesion exceeding 30 mm, the inability to visualize ostial or very proximal lesions and the inability to study the left main coronary artery.

Fourier domain OCT

The development of the new-generation or Fourier domain OCT (FD-OCT) enables high-speed pullbacks (10—25 mm/second) during image acquisition, allowing the visualization of long coronary segments in a much reduced acquisition time and without the need for transient occlusion of the coronary artery. The non-occlusive technique requires simultaneous flushing with a viscous iso-osmolar solution through the guiding catheter [2]. The fluid infused requires a viscosity higher than that of blood; non-occlusive OCT image acquisition using iodixanol 320 is the standard flushing solution [2,11,12,15]. The amount of iodixanol 320 used for OCT pull-back is usually 3-fold greater than that required for standard coronary iodixanol 320.

FD-OCT uses a wavelength-swept laser as the light source and the reference mirror is fixed. This change in technology results in a better signal-to-noise ratio and faster sweeps, allowing a dramatically faster image acquisition and pull-back speed than TD-OCT [3,16,17]. Presently, the maximum imaging speed that can be achieved with FD-OCT is limited by digital data transfer and storage [18].

OCT versus intravascular ultrasound

Many trials have compared OCT with intravascular ultrasound (IVUS) for tissue characterization of human coronary plaques. OCT is mainly limited by its penetration depth. Within its penetration depth OCT has much higher sensitivity and specificity for characterizing calcification, fibrosis, lipid

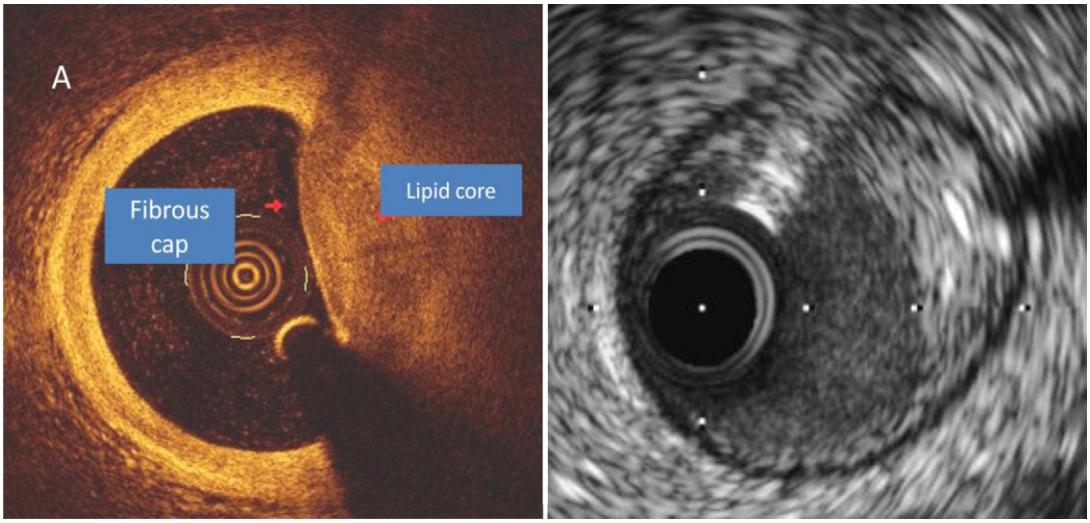

Figure 1. Higher optical coherence tomography resolution and sensitivity for plaque definition.

pool intimal hyperplasia [19,20], fibrous cap erosion and rupture, intracoronary thrombus and thin cap fibroatheroma [21] (Fig. 1), for the detection of stent endothelialization, strut coverage and stent apposition and expansion, and for lumen border visualization and measurement of correct lumen area [22]. As for IVUS, the critical lumen area for intermediate lesions is 4 mm^2 [2]. Measurements of lumen diameter and lumen area obtained with OCT and IVUS were highly correlated, although OCT measurements were found to be 7% smaller [2]; these findings may be more relevant in small vessels. Compared with OCT, IVUS tends to underestimate stent tissue coverage [23]. Table 1 shows the physical properties of IVUS and OCT.

Clinical applications

Coronary plaque classification

OCT was validated in vitro for atherosclerotic plaque characterization on a large post-mortem specimen in 2002 [24] and later in vivo human studies confirmed the ability of OCT to characterize the plaque [20]: fibrous plaques are characterized by a homogeneous rich signal; fibrocalcific plaques reveal signal-poor regions with sharply delineated borders; lipid-rich plaques show diffusely bordered signal-poor regions (lipid is present in two quadrants in any of the images within a plaque); vulnerable plaques are characterized by a thin-capped fibroatheroma, defined as a fibrous cap thickness < 70 μm (Fig. 1), within a lipid-rich plaque; microchannels are defined as no-signal tubuloluminal structures without a connection to the vessel lumen, recognized on three consecutive cross-sectional OCT images [2,14], and are seen with increased neovascularization of atherosclerotic plaque (Fig. 2). Fig. 3 shows a typically stable and calcified coronary plaque with thick fibrous cap.

Acute coronary syndromes

In the setting of acute coronary syndromes, OCT is feasible and can yield, in addition to plaque description, the following information [21,25,26]: plaque rupture, identified by the presence of fibrous cap discontinuity and a cavity formation within the plaque (Fig. 4); plaque erosion, characterized by loss of the endothelial lining with lacerations of the superficial intimal layers and without 'trans-cap' ruptures; intracoronary thrombus (a red thrombus is visualized as a hypersignal protruding in the lumen, with a signal-free posterior shadowing due to attenuation of the optical beam by red blood cells; a white thrombus does not contain red blood cells and can be thus fully visualized with OCT [Fig. 5]).

Percutaneous coronary intervention and stent implantation

Another domain of interest for endocoronary OCT is percutaneous transluminal angioplasty and stent implantation. OCT was able to assess in-stent restenosis, in-stent thrombosis and strut coverage in bioresorbable everolimus stents at 6

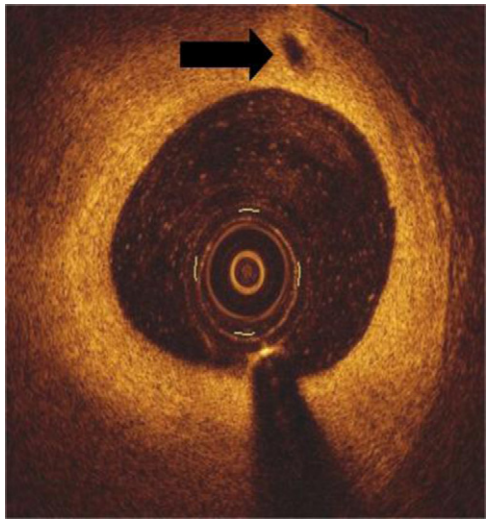

Figure 2. Neo-channels (black arrow) could be visualized within the plaque in some of our acute coronary syndrome patients.

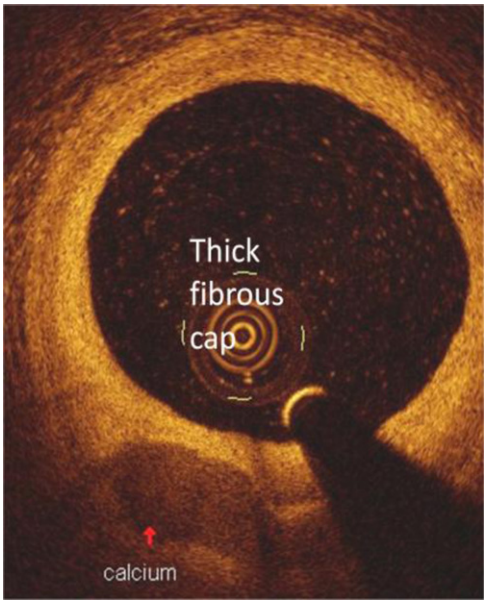

Figure 3. A typically stable coronary plaque, calcified with a thick fibrous cap.

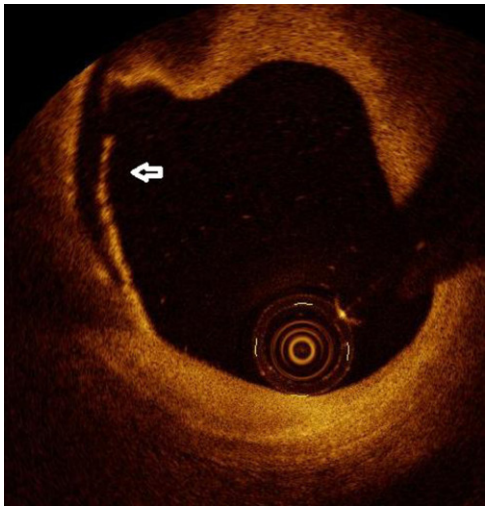

Figure 4. A plaque rupture site (arrow) with cavity formation within the plaque.

months and 1 and 3 years [27—29]. The vascular response (stent apposition and endothelialization) after drug-eluting stent and bare-metal stent implantation between stable and unstable angina pectoris patients was also successfully assessed by OCT [30—33]. OCT analysed the impact of stent strut thickness and the design of different drug-eluting stents on acute stent strut apposition [34]. Vessel injury (tissue prolapse, luminal protrusion and intrastent dissection) after stent implantation can be detected by OCT [35,36]. Fig. 6 shows an example of strut malapposition revealed with OCT.

The reproducibility of quantitative OCT for stent analysis has been studied and showed excellent inter- and intraobserver variability for strut count, strut apposition and strut tissue coverage measurements [37].

Indications and clinical implications

Before or after stent implantation?

When OCT is performed in the setting of percutaneous angioplasty, it is to be done as for IVUS, before stent implantation, to accurately measure the vessel dimensions and cross-sectional areas, and after stent implantation, to detect good stent expansion and apposition short term and good stent endothelialization long term.

For stable angina patients or during acute coronary syndrome?

OCT is helpful in some stable angina patients for assessing the atherosclerotic plaque burden and detecting markers of plaque instability, which should indicate the need for aggressive medical therapy as well as percutaneous angioplasty and stent implantation. Most interesting is the use of OCT in the setting of acute coronary syndrome, especially

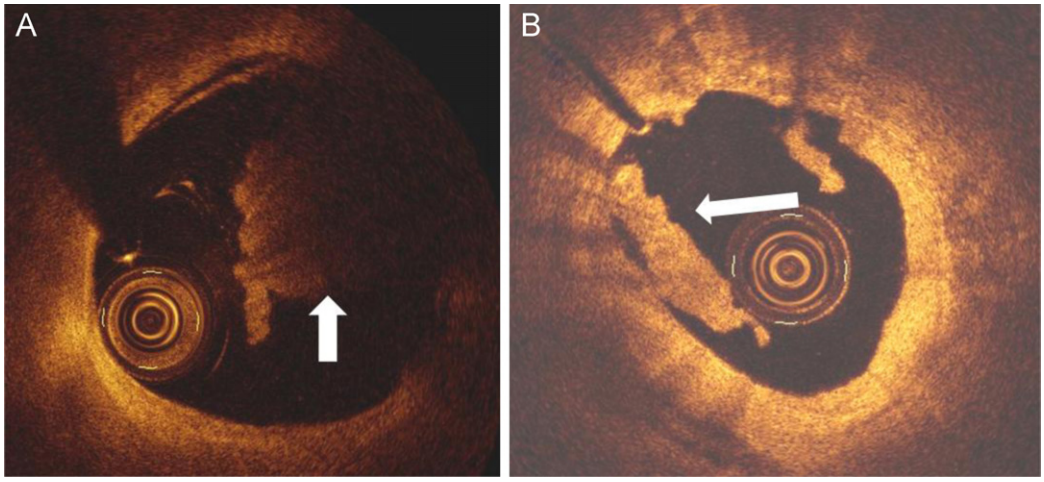

Figure 5. (A) A red thrombus with a signal-free posterior shadowing; (B) A white thrombus fully visualized.

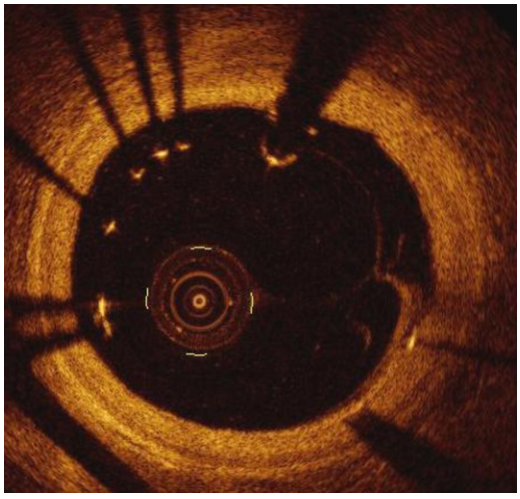

Figure 6. Localized malapposition of a drug-eluting stent.

to detect and measure the thrombus burden and analyse the underlying plaque.

Implications

OCT can potentially lead to a change in strategies, especially in the setting of acute myocardial infarction. Regarding the recently developed minimally invasive strategy for acute myocardial infarction, consisting of a conservative strategy after thrombus aspiration in Myocardial Infarction and TIMI grade III flow restoration, OCT can document and support this strategy by showing the thrombus component of the residual luminal narrowing and by studying the underlying plaque. This can avoid or delay systematic stent implantation in a prothrombotic context.

Controversies

Haemorrhagic components appear as signal-poor OCT regions, thus distinguishing haemorrhage from lipid necrotic pools is difficult [2]. Validation studies of angiogenesis identification are still lacking, although there is a general consensus that OCT should be able to identify microvessels [2,14]. OCT is a costly technique that is not available in all catheterization centres but it appears to be cost effective, although there are still no international guidelines regarding OCT, because the large OCT trials studied its diagnostic impact; recently, trials studying therapeutic decisions guided by OCT have been published and others are still ongoing. The lack of international guidelines is mainly due the fact that this is a recently developedimaging modality.

Perspectives

In vivo intracardiac OCT imaging on a swine model through percutaneous access was able to acquire high-quality OCT images [38]. OCT assessed depolarization-related artefacts induced by the birefringence of myocardium and readily evaluated catheter-tissue contact. This is a critical step toward image-guided radiofrequency ablation in a clinical setting, indicating that OCT could be a promising technique for in vivo guidance of radiofrequency ablation.

Transplant allograft vascular disease is characterized by diffuse concentric fibrointimal proliferation. Coronary angiography underestimates the extent of the disease. OCT has the potential to become an appropriate imaging tool for monitoring the effects of preventive treatments and disease progression [2].

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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