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Intracoronary imaging using attenuation-compensated optical coherence tomography allows better visualisation of coronary artery diseases

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ABSTRACT

Purpose: To allow an accurate diagnosis of coronary artery diseases by enhancing optical coherence tomography (OCT) images of atheromatous plaques using a novel automated attenuation compensation technique.
Background: One of the major drawbacks of coronary OCT imaging is the rapid attenuation of the OCT signal, limiting penetration in tissue to only few millimetres. Visualisation of deeper anatomy is however critical for accurate assessment of plaque burden in-vivo.
Methods: A compensation algorithm, previously developed to correct for light attenuation in soft tissues and to enhance contrast in ophthalmic OCT images, was applied to intracoronary plaque imaging using spectral-domain OCT.
Results: Application of the compensation algorithm significantly increased tissue contrast in the vessel wall and atherosclerotic plaque boundaries. Contrast enhancement allows a better differentiation of plaque morphology, which is particularly important for the identification of lipid rich fibro atheromatous plaques and to guide decision on treatment strategy.
Conclusion: The analysis of arterial vessel structure clinically captured with OCT is improved when used in conjunction with automated attenuation compensation. This approach may improve the OCT-based interpretation of coronary plaque morphology in clinical practice.
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1. Introduction

Accurate assessment of plaque morphology in-vivo during interventions is critical to guide decision of treatment on a particular lesion. Despite improved axial resolution, reaching up to 10 microns, use of intracoronary OCT for the assessment of plaque contour and identification of plaque composition is limited by the rapid physical attenuation of OCT signal in tissue [1,2]. Typically intravascular OCT has a limited field of view because OCT signal is completely attenuated within a few millimetres. In addition, highly attenuating plaque components create shadow artefacts that can distort the OCT visualisation of deep tissues or mask entirely the atherosclerotic plaque inner structural composition and most external contour (i.e. external elastic lamina or EEL).

Absence of signal in the deepest tissue structures may result in clinical misinterpretation and errors on plaque burden measurements. Because OCT often fails to render deepest tissue structures, its use for guidance of Percutaneous Coronary Interventions (PCIs) has been mainly limited to post-PCI assessment of stent apposition and strut endothelialisation and coverage at follow-up [2]. Contrary to OCT, intravascular ultrasound (IVUS) has a lower axial resolution but can penetrate much deeper into tissue, and remains therefore widely used for pre-stenting assessment of plaque composition and measurement of plaque burden (Fig. 1). While the image quality of OCT is significantly improved, it is still greatly hampered by the presence of shadow artefacts and by poor tissue visibility in the deepest layers. This is also due to signal attenuation, whereby signal strength diminishes as a function of tissue depth. This phenomenon is a barrier to clinical applications of intracoronary OCT and limits its use in the diagnosis and risk management of coronary artery diseases.

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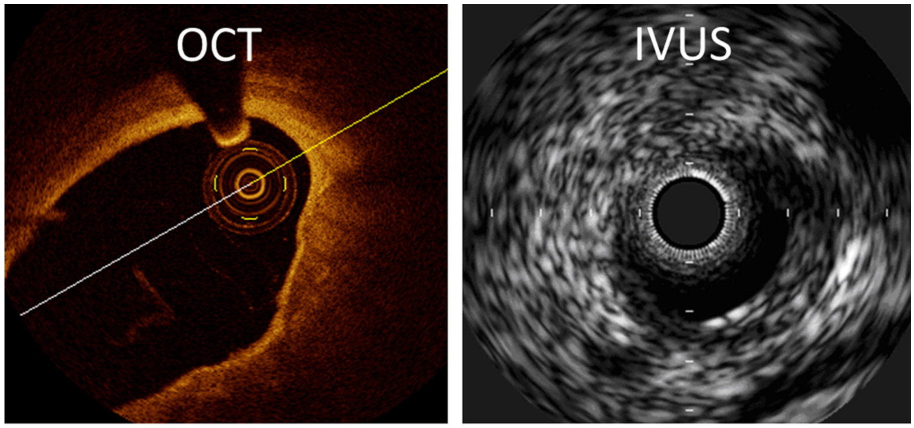

	OCT	IVUS
Resolution	15 µm	100 µm
Penetration	2 mm	10 mm
Requires blood clearance	Yes	No

Fig. 1. Comparison of main characteristics of OCT and IVUS for intravascular imaging assessment. Despite a lower resolution, IVUS has been conventionally used for intravascular assessment of plaque burden and lumen area. OCT produces a significantly higher resolution but is limited by its low penetration depth.

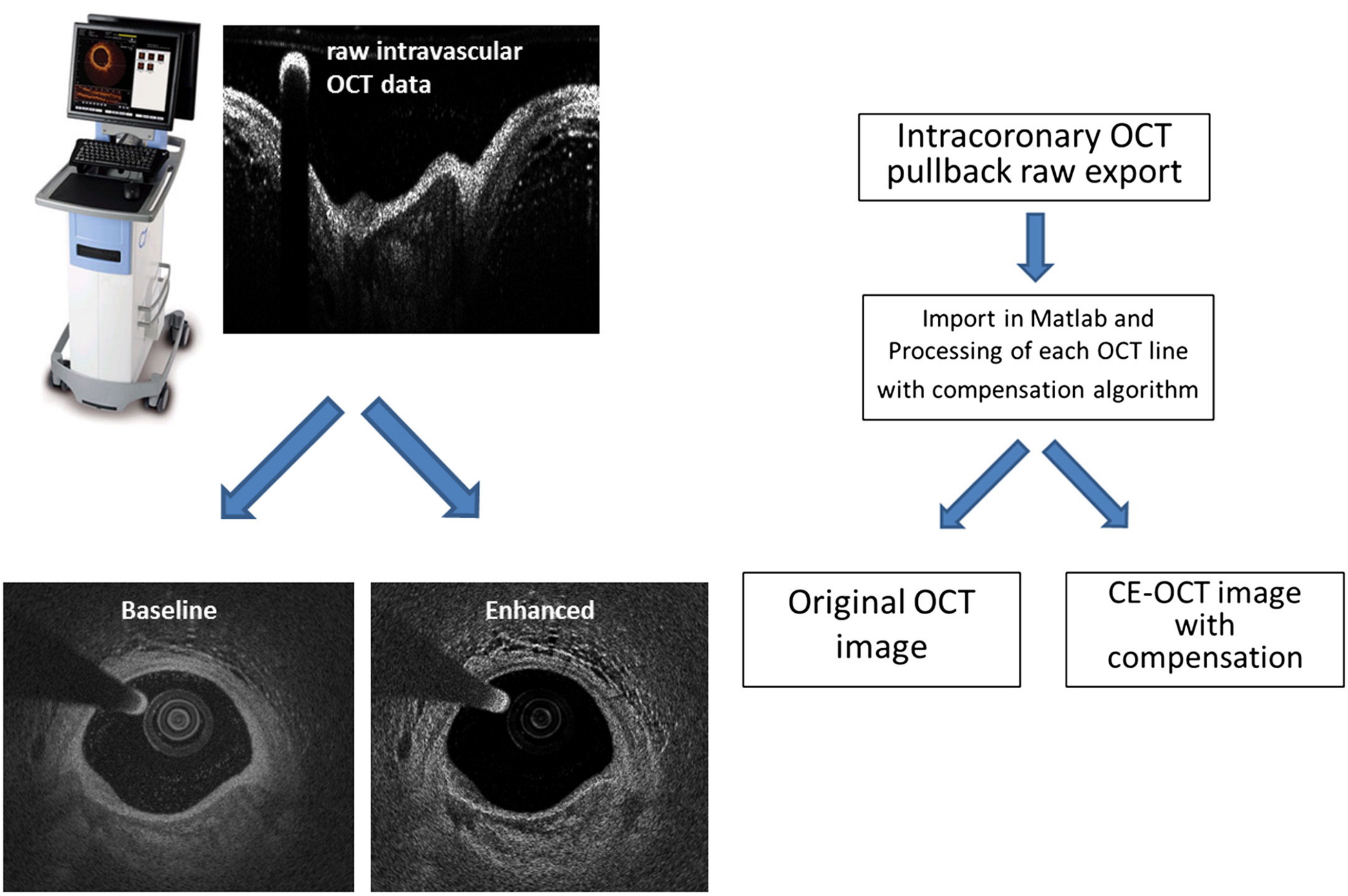

Fig. 2. Flow chart of data processing. Intravascular OCT raw data obtained from the OCT scanner were imported in Matlab and processed with attenuation compensation along each OCT A-Scan. Contrast enhanced results after compensation were plotted in polar representation against baseline OCT plot without compensation.

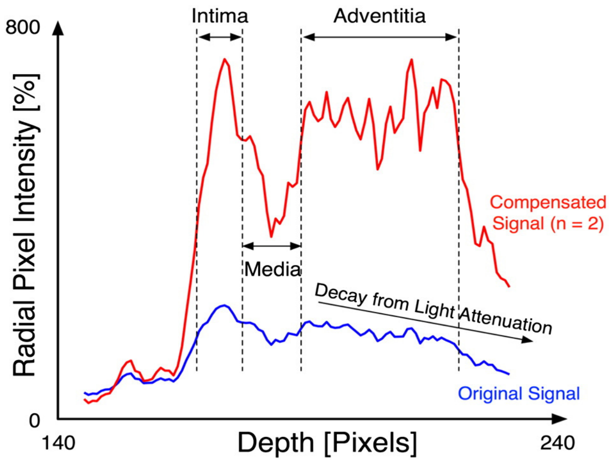

Fig. 3. Illustration of attenuation compensation along an OCT A-line. Intravascular OCT signal (percentage difference from lumen pixel intensity) before (blue line; lumen located on the left) and after compensation (red line). Compensation (with contrast exponent n = 2) is able to drastically enhance the visibility of the three blood vessel layers without signal decay throughout the blood vessel depth. On the contrary, the original signal is affected by poor contrast and signal decay, which is due to light attenuation, thus limiting identification of different vessel/plaque layers.

To address some of the OCT limitations in the case of intravascular imaging, several studies have attempted to quantify signal attenuation from intravascular OCT B-scans to better understand light/plaque interactions and identify plaque content [3–5]. However such methods are not straightforward and not easily implemented, as they require signal fitting to a predefined model (e.g. exponential decay modelling of the A-Scan pixel intensity across biological layers), matching specific vessel conformations.

Inspired from an image post-processing approach to correct for ultrasound attenuation [6], Girard et al. [7,8] have shown that OCT signal attenuation can be modelled into OCT theory, and its effects corrected. This approach was shown to drastically improve the penetration and contrast in ophthalmic OCT images.

In a preliminary study, we suggested that the same post-processing approach could be applied to enhance the quality of normal intravascular OCT images [9]. Here, it is tested in the particular cases of plaque-induced and strut-induced attenuation. Our ultimate goal is to improve the detection of coronary artery plaques using intravascular OCT.

2. Methods and results

OCT pullbacks acquired on a spectral-domain C7 intracoronary OCT system (St Jude Medical, St Paul, MN) were exported in raw format and then imported in Matlab (Mathworks, US) for post-processing as described in Fig. 2. Raw OCT data were processed with the described contrast enhancement compensation algorithm applied along each OCT line. The effect of the compensation algorithm on a particular OCT line is described in Fig. 3. Finally, polar reconstructions of the results after compensation (Enhanced) are obtained for comparison with Baseline OCT images (Fig. 4).

Application of the compensation algorithm on different atheromatous plaque examples are shown on Fig. 5. Rapid attenuation of the OCT signal on the baseline OCT image precludes the correct interpretation of atherosclerotic plaque morphology and plaque burden (Fig. 5, A, C, E).

Compensation increases contrast between different tissue/plaque layers within the vessel wall, revealing internal details within the atherosclerotic plaque structure and external contour that can be critical for interpretation of plaque extend and composition. (Fig. 5, B, D, F).

Such compensation algorithm is also useful to correct for the shadow artefacts created by dense and highly attenuating tissues (Figs 4, 5 and 6). Shadowing from the superficial strip on OCT images is usually interpreted as artefacts caused by macrophages infiltration [2,3,10]. Such artefacts distort OCT image and attenuate signal very rapidly. Correcting for light attenuation can allow better visualisation of the plaque and plaque/EEL boundary hidden behind shadow artefacts (Figs. 4 and 5). In addition, such attenuation correction also increases the field of view in the deepest vessel structure as well as enhancing inter-layer contrast between the atherosclerotic material and normal tissue. It may improve intracoronary examination by OCT by revealing details within the superficial layer of the atherosclerotic plaque and producing sharper contours between the different constituting layers of the arterial vessel. (Fig. 6, C, D).

3. Discussion

Optical Coherence Tomography (OCT) emerged as a promising imaging modality for intravascular assessment of atherosclerosis plaque and guidance of percutaneous interventions. Interpretation of plaque components in OCT can be sometimes difficult and the use of OCT in the assessment of atherosclerotic plaque morphology remains

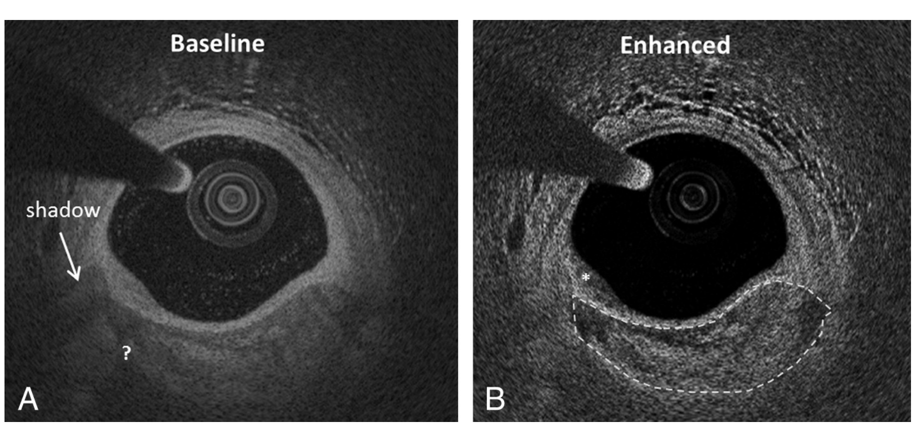

Fig. 4. Comparison of a conventional baseline OCT image (A) with contrast enhanced result after compensation (B). Shadow artefacts (arrow) and OCT signal attenuation limit penetration through the atherosclerotic plaque. The compensation algorithm corrects for the shadow artefacts and improves contrast in the plaque internal structures as well as signal from the deepest tissues.

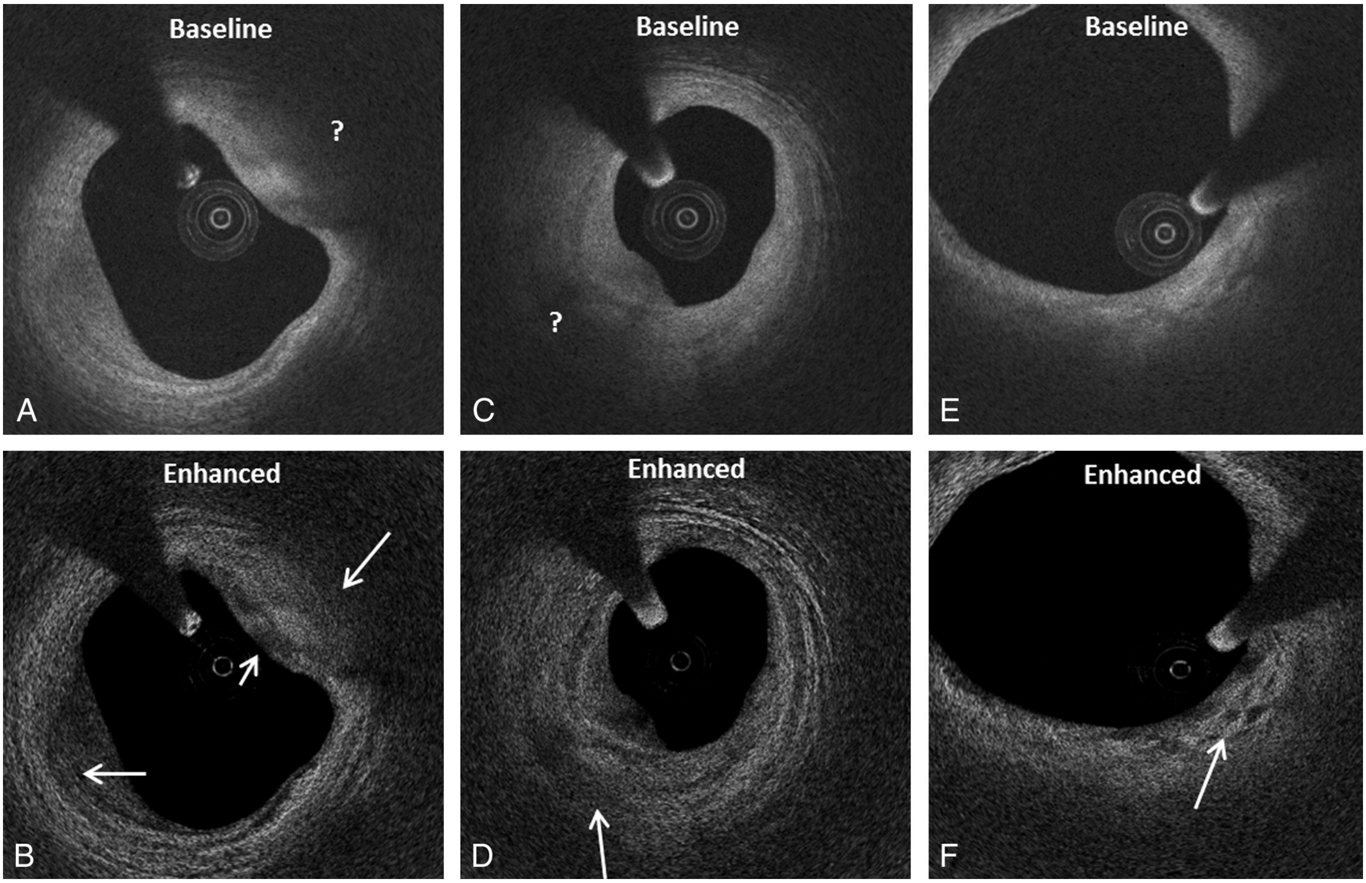

Fig. 5. Comparison of baseline (A, C, E) and compensated contrast enhanced OCT (B, D, F). Intravascular scans showing the impact of the compensation algorithm on OCT results: In the baseline images (A, C, E) external contour of the atheromatous plaque (?) is sometimes not visible because of the rapid OCT light attenuation. After compensation (B, D, F), plaque internal structures and vessel EEL become more visible (arrow).

limited by the rapid attenuation of OCT signal in tissue, limiting signal on deep plaque structure and EEL boundaries.

We applied here a compensation algorithm, initially developed to correct for light attenuation in ophthalmic OCT images, to raw spectral-domain intracoronary OCT data acquired during PCI. Application of the compensation algorithm to multiple patient OCT pullbacks showed that compared with the original baseline OCT image, compensation significantly improves the interpretation of the OCT images by: 1) enhancing plaque and blood vessel layer contrast; 2) removing shadow artefacts from dense structures; and by 3) improving the visibility of the deepest tissue layers and thus allowing better identification of external plaque boundaries.

From our results, it can also be observed, that only a reasonable amount of attenuation, leaving sufficient signal for a possible compensation, can be processed successfully. Despite the stiff nature and the strong attenuating properties of some coronary artery plaques (Figs. 4–6), the proposed compensation approach is able to restore the 'true' profile of the tissues, as far as residual signal can be measured from the deeper structures. The condition for successful compensation is simply the non-complete suppression of the OCT signal in the deepest tissue layers, regardless of the attenuation level.

This compensation approach has a strong potential to improve OCT intracoronary plaque assessment not only by improving deeper tissue visualisation but also by correcting for shadowing OCT artefacts from superficial structures. In particular, Thin-Cap Fibroatheroma (TCFA), characterized by a necrotic core, containing little smooth muscle cells but numerous macrophages with an overlying thin-fibrous cap measuring < 65 microns has been shown to be the main predicator of plaque rupture in Acute Coronary Syndrome [11]. With a resolution on the order of 10 microns, OCT allows precise measurement of cap thickness and identification of Thin-Cap Fibroatheroma (TCFA) and because only OCT can achieve such resolution, OCT has been proposed as the gold standard compared to IVUS for in-vivo measurement of cap thickness and vulnerability to rupture [12]. But pathological studies evaluating atherosclerotic arterial segments obtained at autopsy by OCT and histology demonstrated that intimal macrophages infiltration produces superficial shadowing artefacts on OCT images [3]. Inflammation and macrophage activity are important contributors to plaque vulnerability [11] but such shadowing artefacts can distort OCT images and produce a thin superficial bright appearance masking internal plaque structure, thereby giving an OCT signature falsely similar to TCFA [3,13]. Correcting for superficial shadow artefacts by compensation is therefore also important for accurate OCT measurements of cap thickness and true classification of atherosclerotic plaque as TCFA.

4. Conclusion

The compensation approach of vascular OCT signal studied in this paper and previously validated for ophthalmic OCT, can be used to improve the interpretation of intravascular OCT images and to perform more accurate plaque burden measurements. Such compensated OCT visualisation provided in addition to baseline OCT offers a way to widen potential applications of intravascular OCT instead of IVUS in clinical practice. Future studies will include validations of this compensation algorithm through comparison of compensated OCT with histology sections obtained on human atherosclerotic plaques.

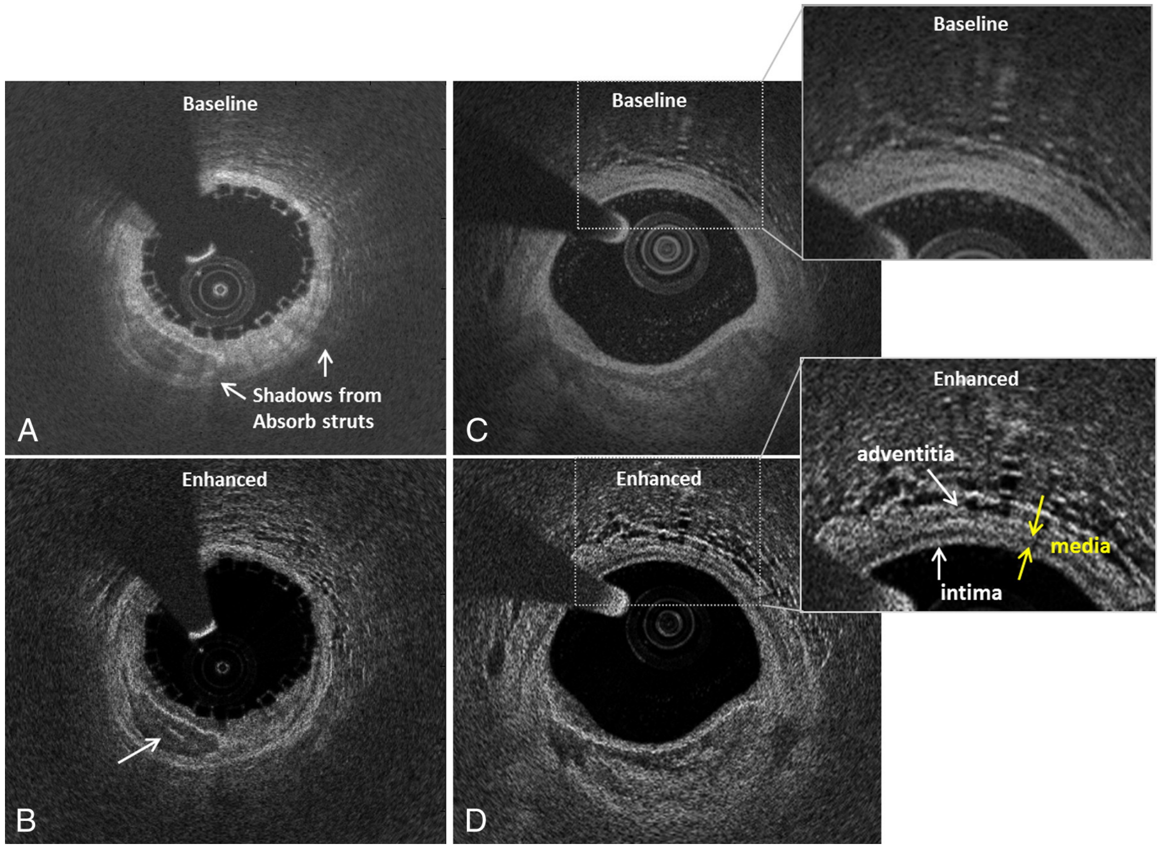

Fig. 6. Comparison of baseline (A, C) and compensated contrast enhanced OCT (B, D). Intravascular scans showing the effect of OCT compensation on shadow artefact created by absorbable stent struts (A, arrows). In addition to enhancing plaque morphology, the attenuation correction also increases the field of view in the deepest vessel adventitial structure as well as the inter-layer contrast between normal tissue layers (C, D).

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