High-quality reconstruction of coronary bifurcations is crucial in the evaluation of lesions, dedicated bifurcation stents, and stent techniques. Although 3-dimensional (3D) X-ray angiography restores natural bending of vascular structures, optical coherence tomography (OCT) provides an ultra–high resolution of the vessel wall morphology and stents at baseline and follow-up. We present a new method for 3D fusion of the 2 imaging modalities combined with flow simulation at the target bifurcation. A 63-year-old woman was admitted for percutaneous coronary intervention attributable to severe stenosis (Figure 1A) in the left anterior descending artery (LAD) at the bifurcation of the first diagonal branch (D1). The target bifurcation was reconstructed in 3D (Figure 1B) using a dedicated 3D QCA software package (QAngio XA 3D Research Edition 1.0, Medis Specials, Leiden, The Netherlands). Fusion of the 2 OCT pullbacks acquired in the LAD and in the D1 with the 3D QCA (Figure 1D and Video 1 in the online-only Data Supplement) was performed using QAngioOCT Advanced Edition (Medis Specials). The entire fusion procedure can be summarized in a few major steps as follows: (1) isocenter offset in the angiographic acquisition was corrected; (2) lumen edges at the bifurcation were automatically detected in the 2 angiographic projections; (3) automated reconstruction and modeling techniques were performed, resulting in a 3D lumen surface and a so-called reference surface, ie, the normal lumen as if the disease was not present; (4) the spatial correspondence, including alignment and angulation, of the OCT images with respect to the...
3D angiographic reconstruction was determined based on the common carina position and the segmented OCT contours; (5) the OCT pullbacks were transformed and fused with the 3D angiographic reconstruction using the spatial correspondence. Quantifications by 3D QCA and by OCT were seamlessly integrated after the fusion. In this case, diameter stenosis by 3D QCA is 62% in the LAD and 63% in the D1, respectively. The bifurcation angle between LAD and D1 is 43°, and the bifurcation core volume1 is 24.82 mm³. Minimum lumen area (MLA) by OCT is 1.01 mm² at the LAD ostium and 0.80 mm² at the D1 ostium, respectively.

The reconstructed geometry was exported to the commercially available ANSYS FLUENT software for numeric analysis. A total of 2.7 million tetrahedral cells were generated from the lumen obtained from OCT in the natural bent version. Steady flow was assumed, and the mean pressures measured at the inlet and outlets by Radi PressureWire (St. Jude Medical, Inc, St. Paul, MN) during maximal hyperemia were used to perform flow simulation using computation fluid dynamics. Simulated flow velocity and pressure distribution are presented in Figure 2B and 2C. Some recirculation flows were observed distal to the tight stenosis. At the minimum lumen area position, the average simulated flow velocity is 2.05 m/s in the LAD and 1.56 m/sec in the D1, respectively. The simulated pressures along the reconstructed arterial centerlines of LAD (Figure 2, M1) and the D1 (Figure 2, M2) have sharper pressure gradient than the true measured pressure gradient (Figure 2, M3 and M4) represented by fractional flow reserve.3 The motorized fractional flow reserve pullbacks were performed using a conventional pullback device at a constant speed of 1 mm/s during steady state maximal hyperemia induced by adenosine IV at 140 μg/kg per min.

The patient was treated by implanting a 3.0/2.5 mm Tryton-Side Branch Stent (Tryton Medical, Inc, Newton, MA) in the D1 along with a 3.0x22 mm drug-eluting stent in the LAD. Good angiographic result was achieved after final kissing balloon inflation (Figure 1C). Fusion of X-ray angiography and OCT was performed. The bifurcation angle changed slightly to 44°, whereas the bifurcation core volume increased to 51.29 mm³. Lumen area by OCT increased to 5.79 mm² at the LAD ostium and to 3.11 mm² at the D1 ostium, respectively. Three-dimensional OCT (Figure 1E and Video II in the online-only Data Supplement) shows good stent apposition, but minor distortion of the drug-eluting stent (arrow in Figure 1E’), at the cross-sections opposite to the D1 ostium, likely attributable to the response of a large plaque rich of calcification (arrow in Figure 1D).

This is the first time that in vivo coronary bifurcation was reconstructed in super resolution using fusion of X-ray angiography and OCT images acquired in the 2 branches. The reconstruction of such highly informative anatomic details combined with flow simulation is feasible inside the catheterization laboratories. So far, lack of correspondence between the anatomy-derived stenosis severity and its functional significance has been demonstrated in many studies. The combined/integrated evaluation of both anatomy and functional data have gained significant interests. Intracoronary physiological parameters, such as fractional flow reserve,
myocardial resistance, and hyperemic stenosis resistance, are useful in addressing the possible mechanisms underlying the relation between anatomy and function from different perspectives. Thus, the simultaneous presentation of these parameters could help the interpretation of the coronary physiology. However, this would require the measurement of both pressure and flow, ideally by simultaneous tracing. In current practice, good-quality measurement of both pressure and flow is often time-consuming and less cost-effective. Computation fluid dynamics might be used as a surrogate to obtain flow or pressure data. However, an accurate anatomic model is essential in this scenario. The complementary nature of X-ray angiography and OCT imaging enhances the need to integrate these 2 modalities, especially for bifurcation imaging, where ostial overlap is often present in X-ray angiography. In addition to generating an anatomic model for computation fluid dynamics, the fusion of X-ray angiography and OCT also provides an unsurpassed spatial resolution of the lesion morphology at the bifurcation, allowing to tailor the procedural strategy carefully before the intervention and to assess the procedural success.

Despite all aforementioned clinical potentials, it should be well stressed that the presented technology has several limitations. At present, OCT image acquisition cannot be performed in small branches, which can sublet a portion of the flow if presented at the interrogated vessels, resulting in less realistic flow simulation. In addition, arterial lumen dimensions change slightly over the cardiac cycle, and this cannot be identified by the current OCT systems using standard clinical settings. Last, but not the least, coronary flow is pulsatile in nature and the assumption of steady flow might be oversimplified. Therefore, a larger series is warranted to provide further insight into the correlation between the simulated and the measured flow dynamics.

Disclosures
Dr Tu is employed by Medis medical imaging systems bv and has a research appointment at the Leiden University Medical Center (LUMC). Dr Reiber is the CEO of Medis medical imaging systems bv and has a part-time appointment at LUMC as professor of Medical Imaging.

References

Key Words: computation fluid dynamics ◼ fractional flow reserve ◼ image processing ◼ left anterior descending artery ◼ optical coherence tomography
In Vivo Flow Simulation at Coronary Bifurcation Reconstructed by Fusion of 3-Dimensional X-ray Angiography and Optical Coherence Tomography

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Supplemental Material

Video 1. Fusion of X-ray angiography and OCT in 3D prior to stent deployment.

Video 2. Fusion of X-ray angiography and OCT in 3D after kissing balloon inflation.