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Impact of Side Branch Modeling on Computation of Endothelial Shear Stress in Coronary Artery Disease

Coronary Tree Reconstruction by Fusion of 3D Angiography and OCT

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ABSTRACT

BACKGROUND Computational fluid dynamics allow virtual evaluation of coronary physiology and shear stress (SS). Most studies hitherto assumed the vessel as a single conduit without accounting for the flow through side branches.

OBJECTIVES This study sought to develop a new approach to reconstruct coronary geometry that also computes outgoing flow through side branches in hemodynamic and biomechanical calculations, using fusion of optical coherence tomography (OCT) and 3-dimensional (3D) angiography.

METHODS Twenty-one patients enrolled in the DOCTOR (Does Optical Coherence Tomography Optimize Revascularization) fusion study underwent OCT and 3D-angiography of the target vessel (9 left anterior descending, 2 left circumflex, 10 right coronary artery). Coronary 3D reconstruction was performed by fusion of OCT and angiography, creating a true anatomical tree model (TM) including the side branches, and a traditional single-conduit model (SCM) disregarding the side branches.

RESULTS The distal coronary pressure to aortic pressure (Pd/Pa) ratio was significantly higher in TMs than in SCMs (0.904 vs. 0.842; $p < 0.0001$). Agreement between TM and SCM in identifying patients with a Pd/Pa ratio $\leq$0.80 under basal flow conditions was only $k = 0.417$ ($p = 0.019$). Average SS was 4.64 Pascal lower in TMs than in SCMs ($p < 0.0001$), with marked differences in the point-per-point comparison, ranging from -60.71 to 7.47 Pascal.

CONCLUSIONS True anatomical TMs that take into account the flow through side branches are feasible for accurate hemodynamic and biomechanical calculations. Traditional SCMs underestimate Pd/Pa and are inaccurate for regional SS estimation. Implementation of TMs might improve the accuracy of SS and virtual fractional flow reserve calculations, thus improving the consistency of biomechanical studies. (J Am Coll Cardiol 2015;66:125–35) © 2015 by the American College of Cardiology Foundation.

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ABBREVIATIONS AND ACRONYMS

3D = 3-dimensional

CFD = computational fluid dynamics

FFR = fractional flow reserve

OCT = optical coherence tomography

Pd/Pa = distal coronary pressure to aortic pressure ratio

PCI = percutaneous coronary intervention

QCA = quantitative coronary angiography

SCM = single-conduit model

SS = shear stress

TM = tree model

Intracoronary shear stress (SS) is a potent stimulus for the endothelium, thus playing a relevant role in atherogenesis and plaque distribution within the vessel (1,2). Regions exposed to low SS are more prone to plaque progression, whereas in regions exposed to high SS atherogenesis is minimal (1,3,4). Uneven regional distribution of SS might explain the uneven distribution of atheroma plaques in specific anatomic coronary settings, such as curved vessels or bifurcations (2,5–7).

SEE PAGE 136

SS also modulates the neointimal vascular response after stenting, which drives the neointimalization of the device. The local level of SS is inversely related to the thickness of neointima and oscillatory SS enhances a hyperplastic neointima (8). This association has been consistently described in bare metal stents (9), drug-eluting stents (10,11), and bioresorbable scaffolds (12). The mechanism has been mainly attributed to anatomical or procedural scenarios that promote uneven distribution of SS forces, such as curved stented segments (11), bifurcational stenting techniques (12–15), undersizing, and malapposition (16–20). Moreover, SS promotes platelet activation and thrombosis (21–23) through von Willebrand factor binding to glycoprotein (GP) Ib and GP IIb/IIIa receptors (21–23). Therefore, it should be regarded as potentially prothrombogenic in the presence of malapposition, undersizing, or any kind of protruding struts.

Regional mapping of SS might be an excellent predictor of both plaque progression and outcomes after stenting. It could potentially be used to guide the intervention, including the decision about the need for optimization after stent deployment, but the complex and time-consuming method of calculation of SS has hitherto prevented the implementation of SS in the clinical routine. Additionally, a recent review has challenged the SS hypothesis on atherogenesis, indicating inconsistencies between different studies, and unravelling that the more refined level of quantitative point-by-point comparison, the poorer the association between low SS and atheroma (24). A possible source for inaccuracy that could explain this inconsistency is the influence of side branches in SS calculations: most previous biomechanical studies have estimated SS using the geometric reconstruction of the main vessel and have assumed it as a watertight conduit without flow losses through side branches (2,4–6,8,9,11,20,21,23,25,26). However, several recent studies using computational fluid dynamics (CFDs) have indicated that the impact of lost flow in side branches is not negligible and might affect substantially the accuracy of the SS estimation (27,28).

Co-registration software enabling the spatial combination of 3-dimensional (3D) angiography and optical coherence tomography (OCT) represents a realistic opportunity to calculate intracoronary biomechanics routinely in the catheterization lab in an accurate and time-efficient manner (29–31). For the current study we developed a novel method for calculation of SS that takes into account the flow lost through side branches, on the basis of the reconstruction of the coronary tree anatomy by fusion of 3D-OCT of the main vessel and 3D-angiography of the side branches. The impact of side branches on the accuracy of SS calculation is then evaluated in a clinical sample of real-world patients and compared to classical single-conduit methods.

METHODS

STUDY POPULATION. The Does Optical Coherence Tomography Optimize Revascularization (DOCTOR) fusion study was a prospective, single-arm, pilot study whose primary aim was exploring the feasibility of OCT-angiography co-registration and its potential to guide the percutaneous coronary intervention (PCI) (31). The current biomechanical study corresponds to the patients recruited in DOCTOR fusion. Patients were enrolled in a single center (Aarhus University Hospital, Skejby, Denmark). All patients who were referred for elective or urgent PCI between February 2013 and September 2013 were screened. Exclusion criteria included lesion length > 40 mm (visually estimated), > 2 lesions requiring PCI, serum creatinine >100 μmol/l, ST-segment elevation myocardial infarction within 7 days, cardiogenic shock, or severely tortuous vessels. The study was conducted according to the Declaration

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