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Geometry-based pressure drop prediction in mildly diseased human coronary arteries

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ABSTRACT

Pressure drop ($\triangle p$) estimations in human coronary arteries have several important applications, including determination of appropriate boundary conditions for CFD and estimation of fractional flow reserve (FFR). In this study a $\triangle p$ prediction was made based on geometrical features derived from patient-specific imaging data.

Twenty-two mildly diseased human coronary arteries were imaged with computed tomography and intravascular ultrasound. Each artery was modelled in three consecutive steps: from straight to tapered, to stenosed, to curved model. CFD was performed to compute the additional $\triangle p$ in each model under steady flow for a wide range of Reynolds numbers. The correlations between the added geometrical complexity and additional $\triangle p$ were used to compute a predicted $\triangle p$. This predicted $\triangle p$ based on geometry was compared to CFD results.

The mean $\triangle p$ calculated with CFD was 855 ± 666 Pa. Tapering and curvature added significantly to the total $\triangle p$, accounting for $31.4 \pm 19.0\%$ and $18.0 \pm 10.9\%$ respectively at $Re = 250$. Using tapering angle, maximum area stenosis and angularity of the centerline, we were able to generate a good estimate for the predicted $\triangle p$ with a low mean but high standard deviation: average error of 41.1 ± 287.8 Pa at $Re = 250$. Furthermore, the predicted $\triangle p$ was used to accurately estimate FFR ($r = 0.93$).

The effect of the geometric features was determined and the pressure drop in mildly diseased human coronary arteries was predicted quickly based solely on geometry. This pressure drop estimation could serve as a boundary condition in CFD to model the impact of distal epicardial vessels.

1. Introduction

Atherosclerosis is a cardiovascular disease, characterized by plaque buildup in the vessel wall. A subset of atherosclerotic plaques, referred to as vulnerable plaques, contain a necrotic core, covered by a thin fibrous cap often infiltrated by inflammatory cells (Stary et al., 1995). Rupture of the fibrous cap is the main cause of myocardial infarctions (Falk et al., 1995). In previous studies we showed a close association between high wall shear stress (WSS) and plaque weakening in human coronary arteries (Gijsen et al., 2008, 2011). Furthermore cap ruptures are often observed in the upstream region of the plaque (De Weert et al., 2009; Fukumoto et al., 2008; Gijsen et al., 2013) where WSS presumably is high. The combination of high WSS and a thin fibrous cap is therefore potentially a valuable parameter to identify the risk for coronary plaque rupture.

WSS distribution in human coronary arteries can be obtained by combining 3D lumen reconstruction methods with computational fluid dynamics (CFD) (Kim et al., 2010; Slager et al., 2000; Stone et al., 2012; Van der Giessen et al., 2010). Both lumen reconstruction and CFD are time consuming, especially if a large part of the coronary tree is included in the analysis. However, if WSS would serve as a risk stratification tool to be determined during an intervention, it needs to be calculated rapidly. To reduce the computational time CFD can be restricted to a 3D region of interest, e.g. a coronary bifurcation containing an atherosclerotic plaque. Appropriate boundary conditions should be defined to replace the proximal and distal regions. In steady flow simulations in a bifurcation region, the flow ratio over the side branches highly influences the WSS distribution (Van der Giessen et al., 2011) and it is determined by the pressure drop in the vessels distal to the bifurcation. This pressure drop is composed of an epicardial part and a microvascular part. In this study we focus on the epicardial part. The goal of our study was to develop a pressure drop estimate based on geometry which can be used as a boundary condition to replace the proximal and distal regions in CFD. We chose to investigate mildly diseased vessels, because although they are left untreated, the regions around a plaque are often affected by atherosclerosis as well (Mollet et al., 2005). The lumen of the epicardial coronary tree can be imaged with biplane angiography and reliable 3D lumen reconstructions (Schuurbiers et al., 2009) can be generated in real time (Girasis et

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al., 2011; Tu et al., 2012). This 3D lumen data can potentially serve to estimate the pressure drop in the epicardial vessels.

Real time image based pressure drop estimation in stenosed epicardial vessels can also be useful to determine the fractional flow reserve (FFR). FFR is an important indicator for the hemodynamic significance of a coronary stenosis (Pijls et al., 1996). It is defined as the pressure drop over the stenosis for minimal myocardial resistance. Treatment of the stenosis is warranted if the FFR is below 0.8 (Tonino et al., 2010). During an intervention the FFR is measured with a pressure catheter. With an image based estimate of the pressure drop in a stenosed vessel it is also possible to calculate the FFR instead of measuring it.

Young and Tsai measured the pressure drop over idealized concentric and eccentric stenoses in a straight tube for a wide range of flow conditions (Young and Tsai, 1973a, 1973b). They found a good relationship between the measured pressure drop and the Reynolds number, stenosis length and severity. Gould et al. (1982) applied the relationship to compare the measured pressure drop in coronary arteries to the ones predicted from angiographic data with moderate success. One of the reasons for this is that the relationship developed by Young and Tsai is based on idealized stenoses, while in vivo data show that lesions are much more complex.

This study sets out to find a new estimation of the pressure drop in human coronary arteries using imaging data. The method is based on stepwise adding a complexity to the geometry. The geometrical complexity is increased in three steps, where each additional geometrical feature leads to an increase in pressure drop. The added geometrical feature is subsequently correlated to the additional pressure drop it causes. The image based pressure drop was primarily investigated as a potential boundary condition in CFD, but is in this study it was also applied to predict FFR.

2. Material and methods

2.1. Patient selection

We investigated the coronary arteries of 33 patients from a subpopulation of the PROSPECT trial (Clinicaltrial.gov identifier NCT00180466; (Stone et al., 2011)). The patients were treated for an acute myocardial infarction or unstable angina. The coronary arteries were imaged with multi slice computed tomography (MSCT) and intravascular ultrasound (IVUS). Accurate 3D reconstructions of 54 mildly diseased arteries were generated based on a previously developed method (Van der Giessen et al., 2010). Mildly diseased segments were selected because the aim of the study was to investigate regions proximal and distal to a plaque. These regions do not have a significant stenosis but are often affected as well and are considered mildly diseased (Mollet et al., 2005). To ensure a significant pressure drop, 22 segments were selected (9 × LAD, 9 × LCx, 4 × RCA) with a maximum diameter stenosis of 4 × 20–30%, 5 × 30–40%, 10 × 40–50%, 1 × 50–60% and 2 × 60–70%.

2.2. Coronary artery models

Four models of each artery were generated to investigate the effect of the geometrical features on the pressure drop. In each subsequent model a geometrical complexity was added and a feature describing this change in geometrical complexity was correlated to the change in pressure drop it caused (Fig. 1, right panel). First, a straight cylindrical model was created with the radius equal to the inlet radius of the 3D reconstruction. Second, a linearly tapered model was generated. The inlet radius, the outlet radius and the length were based on the full 3D reconstruction. Third, in the stenosed model, the lumen contours obtained with IVUS replaced the lumen of the tapered model. Finally, a curved model was created by adding the centerline obtained with MSCT, which resulted in the complete 3D reconstruction of the artery. The models were generated using in-house developed image processing techniques (Mevislab, Bremen, Germany).

2.3. CFD

The pressure drop in each model was calculated with CFD. A tetrahedral mesh with linear elements was generated for all geometries (Gambit, Ansys, anonsburg, U.S.). Mesh refinement studies resulted in an element size of 1.25×10^{-2} mm. The Navier–Stokes equations were solved using standard numerical techniques (FIDAP, Ansys, Canonsburg, U.S.). The pressure drop was calculated under steady flow conditions for inlet Reynolds numbers (*Re*) ranging from 5 to 300, with increments of 5 between 5 and 50 and increments of 25 above that. To mimic the coronary flow conditions we extended the inlet with five times the radius (VMTK, www.VMTK.org) and prescribed plug flow. The outlets were stress free. A typical result of the CFD can be seen in Fig. 1 (left panel), which shows the pressure drops at the different *Re* in the four geometrical models of an artery.

2.4. Modeling the pressure drop

Previous studies already analyzed the typical shape seen in the results of Fig. 1 (Young and Tsai, 1973a). At low flow ($Re < 40$), the pressure loss is a linear function of the average velocity (i.e. the linear domain). At higher flow, the pressure drop is also influenced by convective losses, causing a non-linear pressure drop (i.e. the non-linear domain). Previous studies found that the pressure drop can be described by a second order polynomial

$$\triangle p = \gamma v + \varepsilon v^2 \quad (2.1)$$

here γ and ε are geometry dependent parameters related to the linear and non-linear domain and v the mean velocity at the inlet. If a correlation can be found between these parameters and geometry, the pressure drop in a vessel can be calculated based on geometry.

In addition to Eq. (2.1), an expression for the pressure drop in the linear domain for a tapered vessel can be derived. Similarly to the Poiseuille–Hagen derivation, we assumed that the flow is fully developed and axisymmetric, but now with the boundary conditions

$$v_z = 0 \text{ at } r = \frac{r_0 - r_i}{L} + r_i \quad (2.2)$$

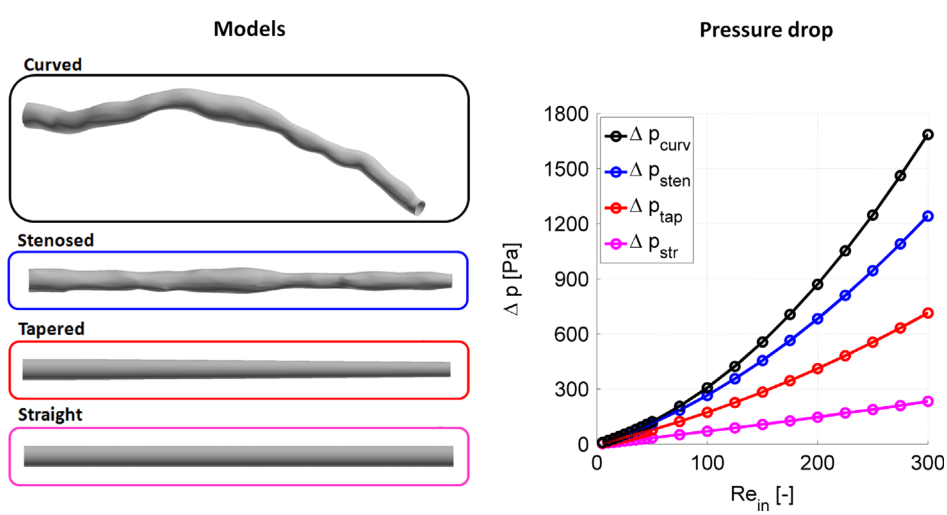

Fig. 1. For each patient specific coronary artery four models with increasing complexity were generated, a straight, tapered, stenosed and curved model (left panel). In each model the pressure drop was calculated using CFD for Reynolds numbers ranging from 0 to 300 (right panel).