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To cite this article: D G Katritsis *et al* 2010 *Phys. Med. Biol.* **55** 1395

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Vortex formation and recirculation zones in left anterior descending artery stenoses: computational fluid dynamics analysis

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Received 20 October 2009, in final form 22 December 2009

Published 11 February 2010

Online at stacks.iop.org/PMB/55/1395

Abstract

Flow patterns may affect the potential of thrombus formation following plaque rupture. Computational fluid dynamics (CFD) were employed to assess hemodynamic conditions, and particularly flow recirculation and vortex formation in reconstructed arterial models associated with ST-elevation myocardial infarction (STEMI) or stable coronary stenosis (SCS) in the left anterior descending coronary artery (LAD). Results indicate that in the arterial models associated with STEMI, a 50% diameter stenosis immediately before or after a bifurcation creates a recirculation zone and vortex formation at the orifice of the bifurcation branch, for most of the cardiac cycle, thus allowing the creation of stagnating flow. These flow patterns are not seen in the SCS model with an identical stenosis. Post-stenotic recirculation in the presence of a 90% stenosis was evident at both the STEMI and SCS models. The presence of 90% diameter stenosis resulted in flow reduction in the LAD of 51.5% and 35.9% in the STEMI models and 37.6% in the SCS model, for a 10 mmHg pressure drop. CFD simulations in a reconstructed model of stenotic LAD segments indicate that specific anatomic characteristics create zones of vortices and flow recirculation that promote thrombus formation and potentially myocardial infarction.

(Some figures in this article are in colour only in the electronic version)

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1. Introduction

Intracoronary ultrasound studies have suggested that plaque rupture itself may not necessarily lead to clinical events (Hong *et al* 2004, Maehara *et al* 2002, Rioufol *et al* 2002). A high incidence of multiple plaque ruptures remote from the culprit lesion has been reported in patients with acute coronary syndromes (ACS) (Hong *et al* 2004), and plaque ruptures have also been identified in patients with stable angina or asymptomatic ischaemia (Maehara *et al* 2002). Therefore, vulnerable plaque rupture may be a frequent event that only occasionally leads to ACS. It has been suggested that it is not the composition of the plaque, i.e. the size of the underlying lipid pool or necrotic core, that leads to post-plaque rupture thrombus formation and ACS, but rather the thrombogenicity of the resulting cavity (Fujii *et al* 2003). Mechanical and flow parameters may contribute to plaque rupture and subsequent thrombosis in this respect. There has been evidence that platelet deposition is correlated to flow patterns such as flow separation and recirculation (Bluestein *et al* 1997, Raz *et al* 2007). However, the potential effect of local hemodynamic factors on thrombus formation in the coronary arterial tree is not known.

We have previously shown that a combination of specific anatomic parameters predispose to vulnerable plaque development, rupture of the plaque and consequent thrombosis (Katritsis *et al* 2008, 2009). In the present study, we hypothesized that at sites of coronary artery occlusion, hemodynamic conditions such as flow recirculation predispose to the development of occlusive thrombus formation and ST-elevation myocardial infarction (STEMI). Computational fluid dynamics (CFD) simulations were employed for assessment of flow characteristics and particularly vortex formation and recirculation in models reconstructing segments of the left anterior descending artery (LAD) with STEMI-related occlusion or stable stenosis.

2. Materials and methods

2.1. Geometric models

Geometric models of coronary arteries were obtained from previous analyses of patients who presented with an anterior STEMI and had a patent LAD, either due to thrombolysis or spontaneous recanalization, at time of angiography. Angiograms of patients with stable coronary stenoses (SCS) and a significant LAD stenosis were reconstructed in the three-dimensional (3D) space and analysed for the provision of control geometric models. Details of our methodology that aimed at ensuring as much representative models as possible have been published elsewhere (Katritsis *et al* 2009). In brief, angiograms were obtained in standard projections and diastolic images from two 'perpendicular views' (view angulation greater than 30°) were 3D reconstructed in the study core laboratory (Coronary Flow Research Unit at Athens Euroclinic). Three-dimensional reconstruction was accomplished with the use of a reconstruction algorithm developed by our group (Andriotis *et al* 2008).

The following geometric features of coronary lesions were extracted from the reconstructed arterial trees: lesion length, distance of most stenotic site from the ostium of LAD, LAD reference diameter and LAD curvature at the lesion site. The following features regarding bifurcation branches were also extracted for all proximal and distal to the lesion bifurcations: distance of the bifurcation from the most stenotic site, bifurcation take-off angle and bifurcation diameter at its orifice. This analysis provided detailed quantitation of all geometric features of the reconstructed arterial trees. Details and data derived have been previously presented (Katritsis *et al* 2009). A bifurcation branch was considered to be on the

Table 1. Averaged geometric features for the three most prevalent angiographic settings.

	STEMI 1 (<i>n</i> = 19)	STEMI 2 (<i>n</i> = 27)	SCS (<i>n</i> = 35)
Lesion length (mm)	19.0	16.1	9.7
Lesion reference diameter (mm)	3.0	3.0	2.7
Side branch 1 diameter (mm)	2.9	3.3	3.0
Side branch 1 take-off angle (°)	79	86	80
Side branch 2 diameter (mm)	1.9	2.2	1.6
Side branch 2 take-off angle (°)	60	82	80
Side branch 3 diameter (mm)	1.4	1.5	1.5
Side branch 3 take-off angle (°)	60	73	80
Side branch 4 diameter (mm)	1.4	1.4	1.2
Side branch 4 take-off angle (°)	62	70	75
Side branch 1–side branch 2 distance (mm)	20.4	12.7	17.8
Side branch 2–side branch 3 distance (mm)	14.1	n/a	8.5
Side branch 2–most stenotic site distance (mm)	n/a	17.2	n/a
Side branch 3–most stenotic site distance (mm)	4.1	n/a	10.1
Most stenotic site–side branch 3 distance (mm)	n/a	4.0	n/a
Most stenotic site–side branch 4 distance (mm)	20.3	n/a	13.7
Side branch 3–side branch 4 distance (mm)	n/a	17.8	n/a
Angulation of lesion (°)	154	151	163

STEMI: ST-elevation myocardial infarction.

SCS: stable coronary stenosis.

n/a: not applicable.

culprit lesion if its orifice was between the proximal and distal non-diseased segments of the artery. The geometric features of 19 cases of STEMI with a bifurcation on the lesion before the site of maximum stenosis were averaged to obtain a representative geometry designated as STEMI 1. Accordingly, the geometric features of 27 cases of STEMI with a bifurcation on the lesion after the site of maximum stenosis and 35 cases of SCS without bifurcations on the lesion were averaged and designated as STEMI 2 and SCS, respectively. These three averaged representative geometries were selected as coronary models to be further studied in CFD simulations in order to evaluate hemodynamic conditions in respect to flow circulation at critical areas. The geometric features of the three models are described in table 1. For each model, three cases were considered: an unrestricted model and three models with increasing degree of diameter stenosis of 20%, 50% and 90% (figure 1). The rationale was to evaluate flow conditions in both tight and non-significant stenoses since vulnerable plaques are often associated with positive arterial remodelling that results in angiographically subcritical lesions. The studied coronary models were considered stationary and the vessel walls were considered rigid.

2.2. CFD analysis

Numerical grids for 12 total cases were constructed with tetrahedral and wedge elements (figure 2) using the commercial grid generator software Gambit. Each numerical grid consisted of approximately 2 million cells with varying grid density. Denser grid nodes have been placed near the wall boundary of the arterial tree as well as at the bifurcation points. Simulations

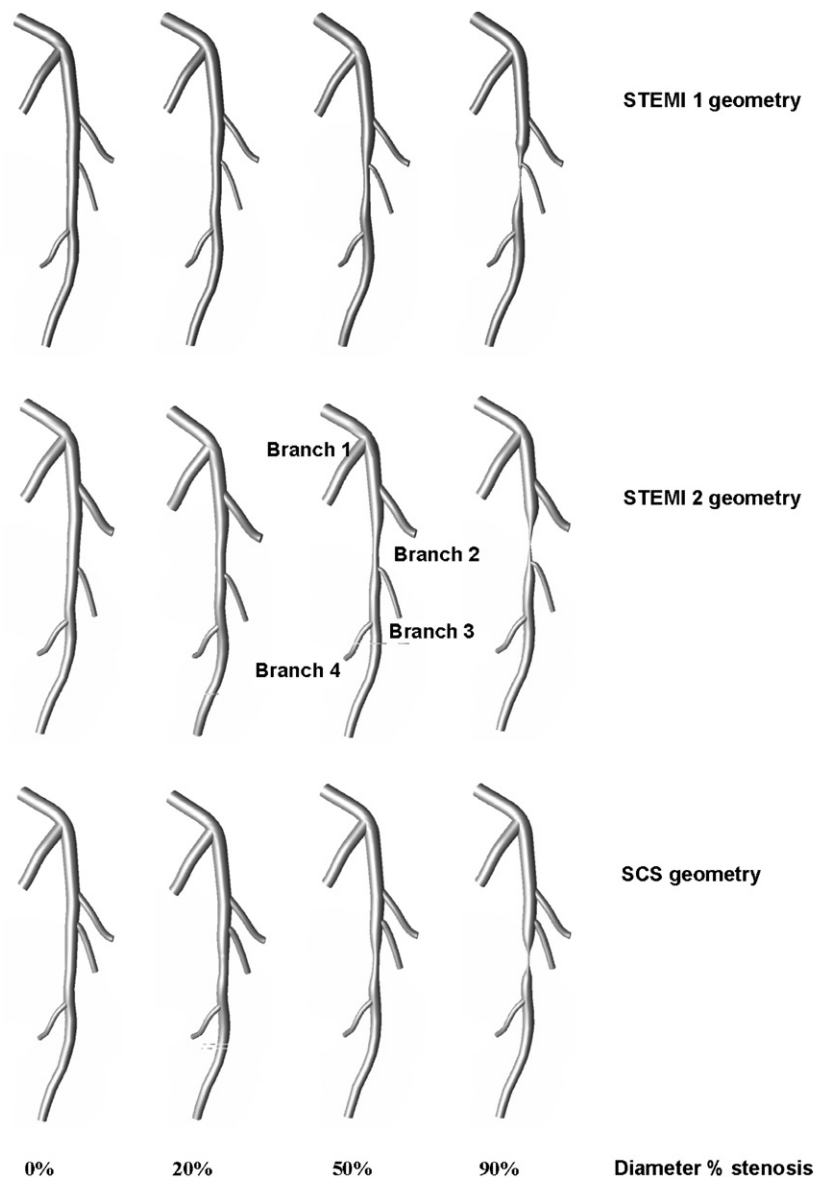


Figure 1. Simplified, three-dimensional arterial models of representative 3D anatomic geometries derived from analysis of angiograms from all patients in the myocardial infarction (STEMI) and stable coronary artery stenosis (SCS) groups, with varying degree of diameter % stenosis (no stenosis, 20%, 50% and 90%). On-lesion bifurcation before and after culprit plaque were seen mainly in patients with STEMI, and lesions without bifurcation were seen mainly in patients with SCS.

have also been performed with lower/higher number of cells in order to make sure that with the number of cells finally adopted for the parametric study, grid independence has been achieved.

The in-house CFD flow solver (GFS) has been used in this study (Giannadakis *et al* 2008, Strotos *et al* 2008, Theodorakakos *et al* 2008, Tonini *et al* 2008). The fluid model

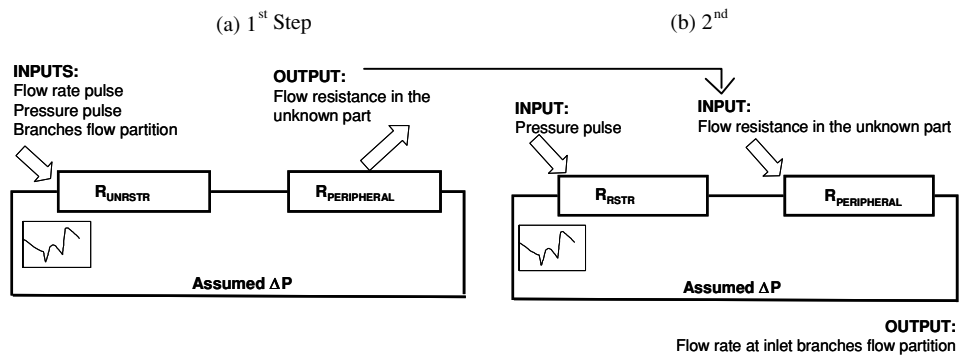
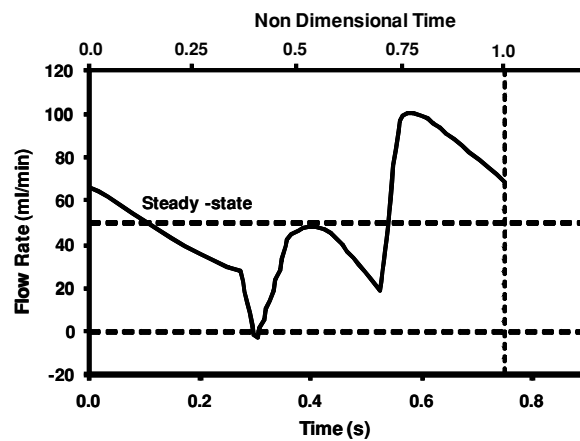
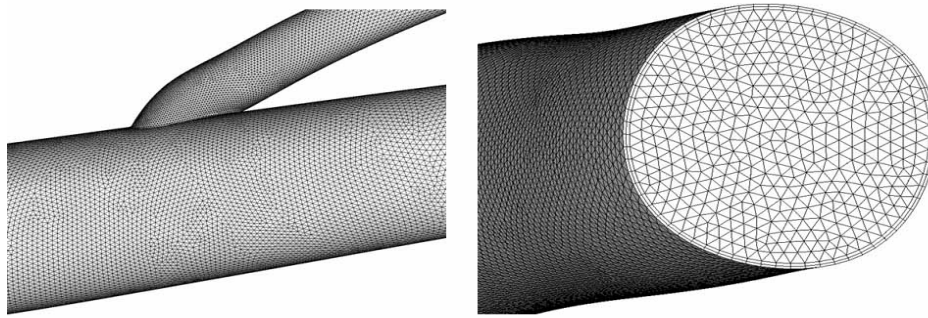


Figure 2. Upper panel: details of the numerical grid. Middle panel: phasic coronary blood flow rate used as an input for the arterial tree. Lower panel: schematic diagram of the equivalent electric circuit of pressure losses (a) in the unrestricted and (b) the restricted geometry. R_{UNRSTR} is the flow resistance in the simulated arterial branch without the stenosis, R_{RSTR} is the flow resistance in the simulated arterial branch with the stenosis and $R_{PERIPHERAL}$ is the flow resistance of the remaining blood flow circuit for an assumed ΔP (steady state simulations for assumed ΔP 10 and 20 mmHg).

solves numerically the time-averaged form of the full Navier–Stokes equations describing the laminar or turbulent motion of a fluid using fully unstructured numerical grids. These equations are written for an arbitrary coordinate system and for Cartesian velocity components as follows.

Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{u} = 0 \quad (1)$$

where ρ is the density, t the time and \vec{u} the velocity vector.

Momentum conservation equation:

$$\begin{aligned} \frac{\partial \rho \vec{u}}{\partial t} + \nabla \cdot (\rho \vec{u} \otimes \vec{u} - \bar{S}) &= 0 \\ \bar{S} &= - \left(P + \frac{2}{3} \mu \nabla \cdot \vec{u} \right) \bar{I} + \mu (\nabla \otimes \vec{u} + (\nabla \otimes \vec{u})^T) \end{aligned} \quad (2)$$

where \bar{S} is the stress tensor, P is the pressure, μ is the viscosity of the fluid and \bar{I} is the unit tensor. The discretization method is based on the finite volume approach and the pressure is computed with a method resembling the PISO algorithm (Bressloff 2001, Issa 1986); a second-order spatial discretization scheme has been used. For simulating non-Newtonian fluid flow, different models for the molecular viscosity can be found in the literature. Shibeshi and Collins have shown that blood at rest requires a yield stress to start flowing (Shibeshi and Collins 2005). The power law does not take into account this characteristic feature. The Casson model, however, takes into consideration this behaviour of blood, and this was the reason that this model was chosen to be used in the present study. In this model the blood viscosity is given by the equation

$$\mu = \frac{\tau_0}{\dot{\gamma}} + \frac{\sqrt{\eta \cdot \tau_0}}{\sqrt{\dot{\gamma}}} + \eta \quad (3)$$

where τ_0 is the yield stress and η is the Casson rheological constant (Johnston *et al* 2004). Widely accepted values for these constants are 0.005 Pa for τ_0 and 0.0035 Pa s for η (Bressloff 2001). The maximum value for the viscosity used is 0.01 Pa s (Shibeshi and Collins 2005). Furthermore, $\dot{\gamma}$ is the shear rate. The relationship between $\dot{\gamma}$ and the rate of deformation \bar{D} is expressed as

$$\dot{\gamma} = \sqrt{\frac{1}{2} \cdot \sum_i \sum_j (D_{ij} \cdot D_{ji})}. \quad (4)$$

The rate of deformation tensor \bar{D} can be expressed as

$$\bar{D} = \frac{1}{2} \cdot [\nabla \otimes \vec{u} + (\nabla \otimes \vec{u})^T]. \quad (5)$$

The shear stress tensor $\bar{\tau}$ is related to viscosity μ and the rate of deformation \bar{D} according to the relation

$$\bar{\tau} = \mu \cdot \bar{D}. \quad (6)$$

At the inlet, a pre-described pulse of the blood flow rate and pressure has been assumed (Berne and Levy 2001); (figure 2) and corresponds to a typical flow rate variation during the cardiac cycle. At the walls, no slip condition is applied. For the conditions at the exit of each branch, again the mass flow rate is prescribed using the following procedure which can be realized schematically in figure 2. A total pressure drop is assumed for the whole arterial system which includes the known geometry in which the flow will be simulated and the remaining

unknown fluid circuit. Two known geometries are considered. The first one represents a non-stenotic artery, while the second is the actual geometry with the stenosis. For arterial trees without stenosis arteries typically adapt to maintain a normal WSS through a compensatory mechanism (Glagov *et al* 1998). The WSS for laminar steady flow in a straight tube may be estimated by the following equation:

$$\tau_{\text{wall}} = \frac{32 \cdot \mu \cdot Q}{\pi \cdot D^3} \quad (7)$$

where Q is the volumetric flow rate, μ is the blood viscosity and D is the conduit diameter. Thus, the volumetric flow rate through each branch can be assumed to be analogous to the third power of the conduit diameter D . In order to estimate the percentage of flow rate that enters each branch after a bifurcation, the following procedure is employed, similar to that proposed by Chen *et al* (2005). First, the vessels' diameters are measured just before and after the bifurcation. Then, the pressure drop in each of the branches present in the unrestricted geometric model can be estimated, while at the same time the pressure drop in the remaining unknown flow circuit present at the end of the branches considered can be computed by a simple subtraction from the assumed total pressure head. This allows estimation of the flow resistance in the unknown circuit. This flow resistance of the unknown circuit is then assumed to be the same also for the restricted arterial tree. Steady-state calculations are then performed for the restricted arterial tree using the same total pressure drop values but at the same time knowing the flow resistance of the unknown arterial circuit. An iterative process is employed in which the flow for each branch is recalculated so that the total pressure drop remains the same. This eventually leads to a reduced total flow rate due to the increased pressure drop that the stenosis causes. Since the method cannot be employed for pulsatile pressure input, during the time steps of the transient flow simulation, the pressure drop through each branch is linearly interpolated from the values obtained from the steady-state simulations. A large number of 36 cases have been simulated for obtaining the flow rate distribution in each of the branches considered in the reconstructed arterial trees, for different pressure drops and different degrees of stenoses.

2.3. Quantitation of flow patterns

For quantifying the expected variations between the geometries investigated, two parameters were plotted: (i) the total flow rate reduction induced by the stenosis relative to that of the unrestricted arterial tree, in each branch considered and (ii) the temporal variation of area blockage percentage of each branch along the length of every arterial tree. This parameter is calculated on cross sections normal to the branch direction and along its length and it is defined as the percentage of area having velocity vectors facing in the direction opposite to the flow exit. It can be interpreted as the percentage of cross-sectional area blocking the flow through it due to the formation of a recirculation zone. It has to be further noted that the value of this coefficient is smaller than the actual equivalent diameter of the recirculation zone. The latter is not possible to be defined here due to the 3D shape of the simulated vessels; however, for axisymmetric sudden contraction geometries, the area of the recirculation zone can be approximately 1.5 times larger than the blockage area as defined here.

3. Results

3.1. Flow distribution

3.1.1. No significant stenosis. Figure 3 shows the flow distribution inside the STEMI 1 case for the unrestricted geometry and the one with the 20% stenosis, respectively; the time instance

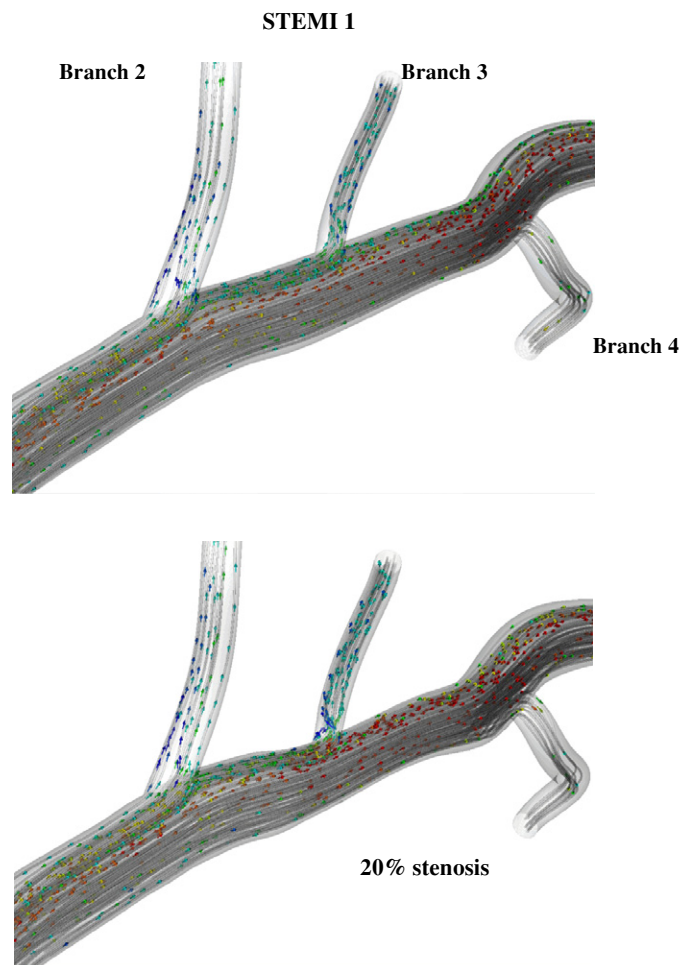


Figure 3. Flow distribution in STEMI 1 geometry at normalized time 0.75, which corresponds to maximum flow rate, for a normal lumen (upper panel) and a 20% stenosis (lower panel). No recirculation zones are noted. STEMI: ST-elevation myocardial infarction.

corresponds to normalized time of approximately 0.75 which, as can be seen in figure 2, is the time of the peak flow rate through the simulated geometry. It can be seen that for the unrestricted geometry, even at the maximum flow rate, no major recirculation is formed along the main branch as well as at the entry into the bifurcation branches considered. When a small degree of stenosis is introduced, a weak recirculation starts to appear at the entry of branch 3, at selective time instances. Still, this is very weak and appears only occasionally.

3.1.2. Significant stenosis. Figure 4 shows a close-up picture of flow recirculation at the orifice of branch 3 for the STEMI 1 case by introducing a 50% stenosis on the main branch. Restricting the flow downstream of the bifurcation point results in the formation of a strong recirculation zone. Such vortex formation is also present for the STEMI 2 but not for the SCS geometry. Analysis of the flow lines over the whole cardiac cycle indicates that for most of the cardiac cycle, the flow is not significantly affected by this geometry. This is fundamentally different from the flow distribution developing within the STEMI 1 and 2 geometries. More

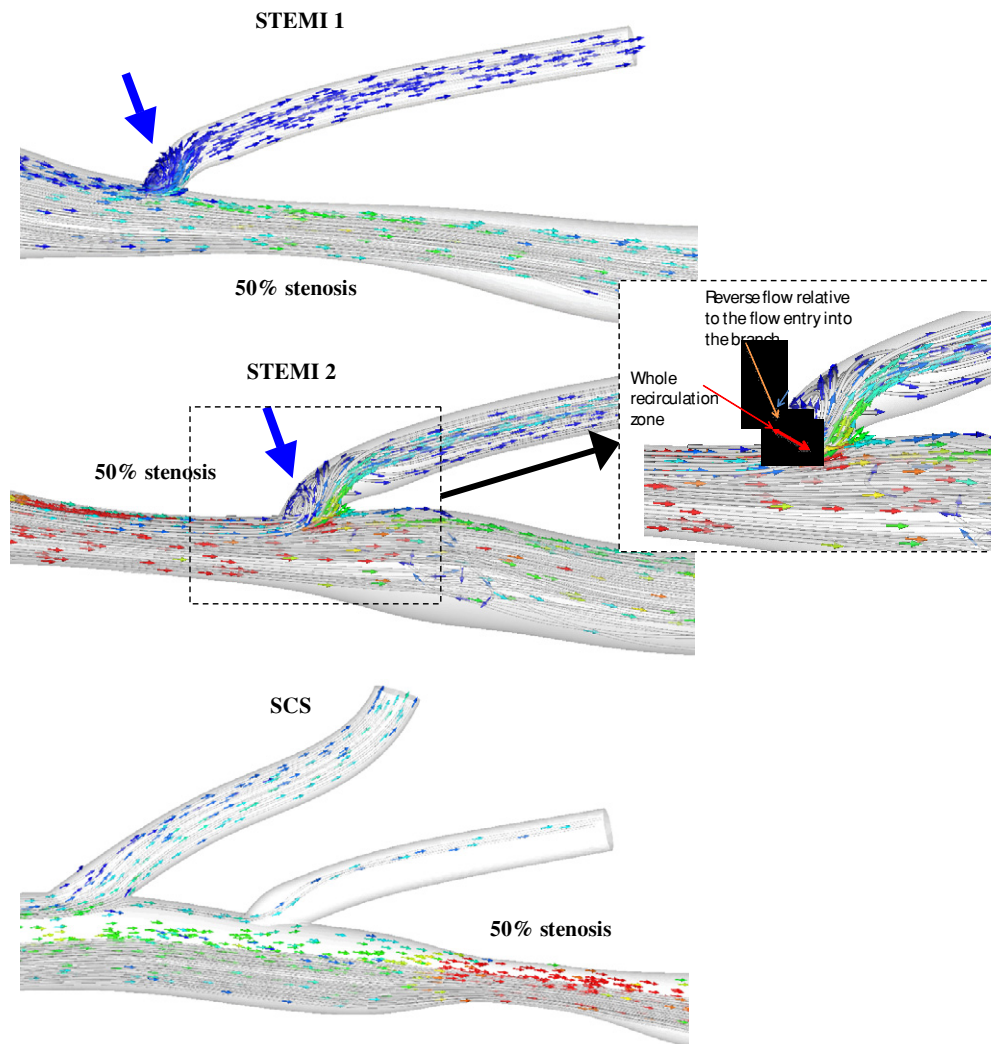


Figure 4. Typical flow distribution for geometries with 50% diameter stenosis investigated at normalized time 0.5. There is flow recirculation at the ostium of the side branch in both STEMI geometries (blue arrows), whereas no recirculation is seen in the SCS model. In STEMI 2 geometry, the recirculation vortex virtually blocks the entry into the branch (details in the enlarged image). STEMI: ST-elevation myocardial infarction, SCS: stable coronary stenosis.

severe flow recirculations are formed with increasing degree of stenosis on the main branch. Figure 5 refers to the 90% stenosis of the STEMI 2 geometry. It can be seen that the flow is practically blocked not only at the entry of branch 3, but also just downstream of the stenosis along the main branch. The 90% stenosis case causes severe flow recirculation not only in the STEMI 1 and 2 cases, but this time also in the post-stenotic lumen of the SCS model.

3.2. Quantitative analysis of recirculation and flow reduction

Table 2 shows the percentage of inflow reduction relative to that of the unrestricted arterial tree for the 50 and 90% degree of stenosis, respectively, for all three groups of geometries considered for the two total pressure drops of 10 and 20 mm of Hg. All 50% stenosis cases

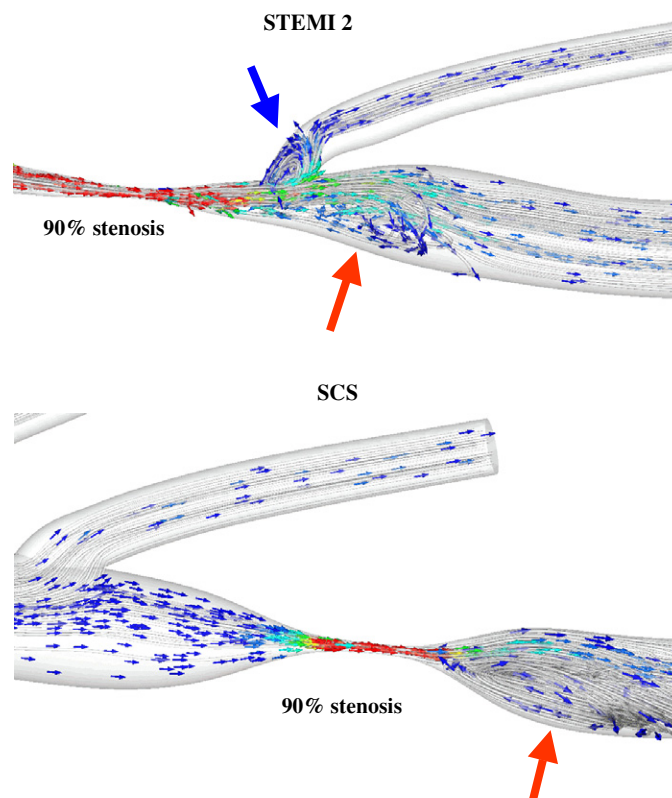


Figure 5. Typical flow distribution for geometries with 90% diameter stenosis investigated at normalized time 0.5. In the STEMI 2 geometry, flow recirculation occurs in both main (red arrow) and side branch (blue arrow) after the stenosis. In the SCS geometry, recirculation is also seen in the post-stenotic lumen of the main branch (red arrow) despite the absence of bifurcation. STEMI: ST-elevation myocardial infarction; SCS: stable coronary stenosis.

result only to a very small reduction of the fluid quantity flowing through the whole arterial tree. The 90% stenosis results in a significant variation, which still is not proportional to the introduced area reduction. The flow distribution of individual branches reveals that immediately after the stenosis the LAD lumen and the adjacent bifurcation branch (branch 3) exhibit a significant flow reduction, up to 80% in comparison with the unrestricted case (table 2).

Figure 6 shows contour plots of the non-dimensional time history of the area blockage percentage along their normalized length for the various cases considered and specific branches. This percentage can be interpreted as the percentage of cross-sectional area of the vessel occupied by flow recirculation, thus it is quantitative measure of the restriction induced flow recirculation. All contour plots show a horizontal low value zone at around normalized time 0.4. This feature is attributed exclusively to pre-described blood flow conditions and not to coronary anatomy. Indeed, this time corresponds to the time instant where the flow used as input for the simulations reverses direction. The fact that it covers the whole length of the branch is due to the boundary conditions used, which consider incompressible fluid and rigid wall arteries; as a result, when negative flow is pre-specified as input, the flow distribution is affected almost in the whole arterial tree.

Table 2. Inflow reduction (percentage) relative to the inflow of the unrestricted arterial tree for the 50% and 90% stenoses for all three cases and two pressure drops (~0 indicates a negligible change).

		STEMI 1 geometry				STEMI 2 geometry				SCS geometry			
		Total inflow	Branch 3	Branch 4	Outflow	Total inflow	Branch 3	Branch 4	Outflow	Total inflow	Branch 3	Branch 4	Outflow
50% stenosis	10 mmHg	2.4	1.1	3.9	3.8	~0	~0	~0	~0	0.8	~0	1.6	1.7
	20 mmHg	1.2	0.6	2.0	2.0	~0	~0	~0	~0	0.4	~0	0.8	0.9
90% stenosis	10 mmHg	51.5	0.4	85.2	84.6	35.9	81.6	81.2	81.1	37.6	~0	84.4	84.3
	20 mmHg	46.7	0.5	77.1	76.7	33.1	74.9	74.8	74.8	34.3	~0	77.0	76.8

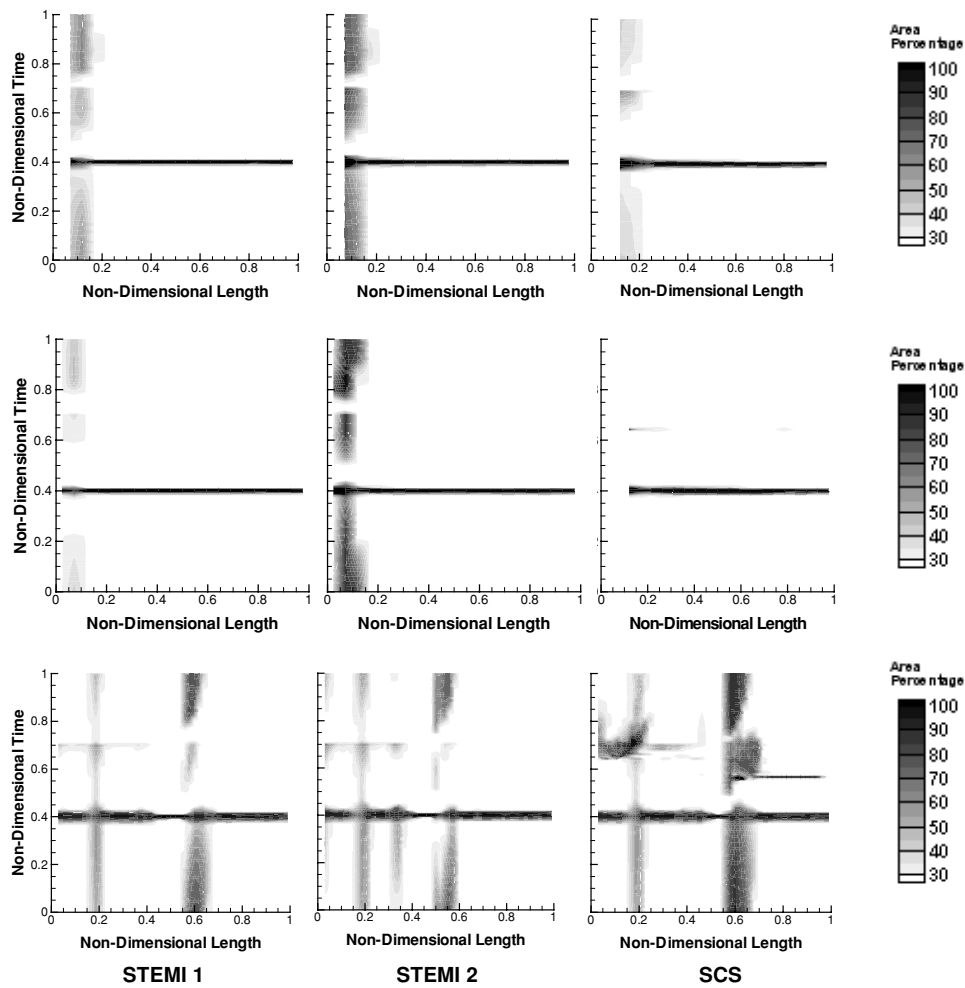


Figure 6. Upper panel: contour plot of the area blockage percentage time history along the length of branch 3, for the 50% stenosis case in STEMI 1, STEMI 2 and SCS geometry. Middle panel: contour plot of the area blockage percentage time history along the length of branch 3, for the 90% stenosis case in STEMI 1, STEMI 2 and SCS geometry. Lower panel: contour plot of the area blockage percentage time history along the length of main branch for the 90% stenosis case in STEMI 1, STEMI 2 and SCS geometry. The vertical lines B1, B2, B3 and B4 indicate the locations of the four branches along the LAD, while S indicates the location of maximum stenosis and t_1 and t_2 correspond to the time of minimum flow rate shown in figure 2(b). STEMI: ST-elevation myocardial infarction, SCS: stable coronary stenosis.

The upper panel of figure 6 refers to branch 3 of STEMI 1, STEMI 2 and SCS, respectively, using the 50% stenosis, while the corresponding results for the 90% cases are shown in the middle panel of figure 6. The results indicate that at the initial part of branch 3 and up to a dimensional length of 1.5 mm, a recirculation zone is present for most of the cardiac cycle. The blockage levels can be as low as 30%, implying that more than 70% of the flow area is occupied by a recirculation zone. This circulation is stronger for the case of 50% stenosis of the STEMI 1 geometry; similar levels are also calculated for the 90% stenosis of the STEMI 2

arterial tree configuration. Thus, although the flow rate reduction through that branch for the 50% stenosis is not very significant compared to the unrestricted case, the actual liquid velocity distribution allows for the formation of a relatively large area where the flow stagnates; the implication of that may be critical compared to the SCS geometry where such a behaviour is not observed as can be seen in the same figures.

Similar sets of results for the main branch are presented in the lower panel of figure 6, for the 90% stenosis case and for all three groups of geometries. The turning of the flow into the first bifurcation, which is found approximately at a normalized distance of 0.2, results to some flow recirculation. A strong recirculation zone however, is found after the stenosis. There, blockage values can be as low as 30% for all three groups for almost the whole cardiac cycle, indicating similar flow behaviour with respect to flow stagnation independently of the position of the bifurcations in relation to the point of maximum stenosis.

4. Discussion

Thrombus formation is thought to begin with an event such as plaque rupture or vessel damage, resulting in the exposure of active tissue factor on the vessel wall (Fuster *et al* 1992). To attract and bind platelets to injured or malfunctioning endothelium, the von Willebrand factor (vWf), a long chain molecule, mediates the interaction between platelets and a vascular lesion (Goto *et al* 1995, Ikeda *et al* 1997). Platelets have various receptors for vWf, some of which are activated by mechanical stimuli, such as high shear stress. Individual platelets adhere to altered vascular surfaces and are activated, after which the integrin IIb–IIIa can bind plasma proteins, notably fibrinogen, vWF and fibronectin; these adhesive substrates immobilized on the membrane surface then recruit additional platelets, resulting in aggregation and thrombus growth (Ruggeri 2002). The relationship between hemodynamic factors and thrombus formation due to platelet deposition has been previously investigated in various experimental and computational CFD studies (Bluestein *et al* 1997, Raz *et al* 2007, Pivkin *et al* 2006, Miyazaki and Yamaguchi 2003). These studies showed that slowly recirculating flow due to core jet flow patterns through a stenosis promote aggregation of platelets and platelet-activating factors. Also, blood stagnation occurring at areas with disturbed flow may facilitate the accumulation of blood thrombogenic factors close to the wall (Feldman *et al* 2002). Since adhesion of platelets to a surface is greatly enhanced by prior activation (Wurzinger *et al* 1985), this mechanism offers an explanation for the increased platelet deposition at the recirculation zone; platelets that are already activated by the high shear stresses at the throat and along the shear layer between the jet and the slowly recirculating vortices are brought into contact by the contracting streamlines on the slower side of this shear layer. Once trapped in the recirculation zone, the motion of the platelets along the curved streamlines with components perpendicular to the wall bring them into contact with the wall along the reattachment point and the slowly recirculating flow adjacent to the wall (Wurzinger *et al* 1985). Formation of vortices has also been associated with the presence of side branches under pulsating flow conditions similar to those of coronary circulation (Chakravarty and Sen 2008). The results of these previous studies indicate that thrombus formation after atheromatic plaque rupture is promoted by vortex formation due to recirculating flow.

Our study provides evidence that specific anatomic features of the coronary structure at the vicinity of atherosclerotic plaque are related to vortex formation. If the hemodynamic conditions at the vicinity of a plaque are favourable, then potential plaque rupture will lead to occlusive thrombus formation and subsequent myocardial infarction. This might partially explain why many plaques along the coronary tree rupture but few lead to myocardial infarction due to occlusive thrombus formation. Results indicate that in all cases of our study when a

non-significant arterial stenosis is introduced, recirculation starts to appear at the orifice of the pre-stenotic arterial branch although it is weak and evident only at selective time instances. This observation is in line with previous evidence (Chakravarty and Sen 2008). However, when the diameter stenosis becomes 50%, there is evident differentiation between models with and without a post-stenotic bifurcation, since a strong recirculation zone is formed at the orifice of the post-stenotic bifurcation branch, whereas flow is not significantly affected in the absence of bifurcation. This phenomenon may possibly be relevant to thrombus formation since post-stenotic flow conditions favour platelet aggregation, particularly when previously activated by the elevated shear stresses of the stenotic region. The observation that myocardial infarctions often occur at sites of mild-to-moderate stenoses (Ambrose *et al* 1988, Little *et al* 1988) could be considered in this context. Minor plaques creating non-significant stenoses might be prone to rupture with a subsequent creation of mild to moderate obstruction that given the right hemodynamic conditions might lead to thrombosis. When these conditions are not met, ruptured plaques do not evolve into coronary occlusions. When stenosis severity increases, flow recirculation also increases. In extremely tight stenosis (90% in our study), flow is practically blocked just downstream of the stenosis along the main branch due to severe recirculation, even in the absence of a bifurcation. This suggests that even if a presumably stable coronary lesion becomes extremely tight it can lead to thrombotic occlusion after plaque rupture. This observation is also in keeping with previous evidence that significant, complex lesions are prone to develop total occlusions (Kaski *et al* 1995) and postmortem examinations demonstrating that ruptured plaques leading to acute coronary syndrome more likely occur within the segment of significant stenosis (Falk 1983, Qiao and Fishbein 1991, Richardson *et al* 1989).

According to our model, the presence of bifurcations creates vortexes mainly at the ostium of the side branch. Therefore, since the recirculation zone of vortex shedding causes platelet aggregation there, one might expect the thrombosis to occur in the arterial branch, not the parent artery. However, the postmortem pathology of fatal infarctions may show thrombus within the ruptured plaque itself regardless of branching patterns. A plausible explanation for this phenomenon is that post-MI, when no recanalization occurs, as was the case in our patients from whom the experimental coronary models were derived, the side branch on the infarct site usually gets thrombosed, and thus renders itself non-identifiable, or subtotally occluded. Thus, thrombosis might start at the ostium of the side branch and extend towards the main branch where it causes the major infarct.

The presence of bifurcations may also predispose to the development of myocardial infarction via diverse mechanisms. Bifurcating branches along the main coronary arteries have been shown to cause flow disturbances and alter local hemodynamic conditions that favour both the development of atherosclerosis and plaque vulnerability (Theodorakakos *et al* 2008, Asakura and Karino 1990, Papafaklis *et al* 2007, Soulis *et al* 2006). Atherosclerotic lesions are known to develop at specific regions, such as arterial curvatures and bifurcations, where disturbed flow and conditions of low or even oscillatory shear stress initially occur (Iwami *et al* 1998, VanderLaan *et al* 2004).

Low shear stress induces lesions with a vulnerable plaque phenotype and creates the condition for plaque rupture and subsequent thrombosis even in non-significant stenosis (Cheng *et al* 2006, Chatzizisis *et al* 2008). In addition, a highly localized circumferential wall stress concentration of approximately 9 to 14 times the proximal circumferential wall stress occurs at bifurcation sites (Salzar *et al* 1995), which undergo a larger deformation during cyclic flexion of the coronary artery, yielding a higher circumferential stress than those further to bifurcations (Wu *et al* 2003).

5. Study limitations

Models of arterial segment reconstruction were derived from specific anatomic patterns identified in the LAD of patients with an antero-septal STEMI. STEMI, however, can also be seen with different anatomic conditions. Thus, our results cannot be generalized for all STEMI settings. The STEMI lesions are examined after the plaque rupture and MI, so these lesions would likely look different if examined before the STEMI. In our models all lesions were assumed to be axisymmetric, whereas asymmetric coronary lesions are frequently observed. Unfortunately, in humans it is not possible to identify and study culprit coronary segments, which develop thrombotic occlusion, before the actual event. At the inlet, a typical pulse of the blood flow rate and pressure during the cardiac cycle has been assumed. Finally, the studied coronary segments were considered only at diastole and thus stationary, and the vessel walls were considered rigid.

6. Conclusion

CFD predictions indicate that flow disturbances and particularly flow recirculation and vortex formation caused by stenotic lesions of the left anterior descending coronary artery are not identical in models derived from arterial segments with thrombotic occlusion or stable lesions. Specific anatomic conditions identified at sites of coronary occlusions, such as the presence of bifurcation branches, create local hemodynamic conditions that promote thrombus formation and may affect the clinical outcome of coronary plaque rupture.

Acknowledgment

The study was supported by a grant from the S Niarchos Foundation. Dr DGK has received research grants from Boston Scientific and Johnson and Johnson.

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