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A computational fluid–structure interaction analysis of coronary Y-grafts

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ABSTRACT

Coronary artery disease is one of the leading causes of death worldwide. The stenotic coronary vessels are generally treated with coronary artery bypass grafts (CABGs), which can be either arterial (internal mammary artery, radial artery) or venous (saphenous vein). However, the different mechanical properties of the graft can influence the outcome of the procedure in terms of risk of restenosis and subsequent graft failure. In this paper, we perform a computational fluid–structure interaction (FSI) analysis of patient-specific multiple CABGs (Y-grafts) with the aim of better understanding the influence of the choice of bypass (arterial vs venous) on the risk of graft failure. Our results show that the use of a venous bypass results in a more disturbed flow field at the anastomosis and in higher stresses in the vessel wall with respect to the arterial one. This could explain the better long-term patency of the arterial bypasses experienced in the clinical practice.

1. Introduction

Coronary artery bypass graft (CABG) surgery, the standard procedure to treat advanced coronary artery disease, consists in bypassing a blocked portion of a coronary artery in order to restore the proper blood flow to the heart. The incidence of CABG operation is significant in the Western countries. For example, in the USA the number of CABG operations was about 250,000 in 2006 (0.09% of the population) and it is expected to increase by over 50% between 2006 and 2025 [1]. The bypass used for the procedure is typically autologous, i.e., harvested from the patient's own body. In case of patients with isolated left anterior descending (LAD) coronary artery disease, the recommended treatment is the use of the left internal mammary artery (LIMA) bypass, due to its excellent long-term patency rate [2]. For patients with multivessel coronary disease, together with LIMA, other types of grafts are used to bypass the remaining coronary occlusions [3]. In particular, arterial or venous grafts may be used either as a conventional *free* (i.e., connected proximally to the aorta and distally to the diseased coronary vessel) or *composite* (i.e., connected proximally to the first graft, usually the LIMA, and distally to the diseased coronary artery) bypasses. In the latter case, two of the most common choices for the second graft are the radial artery (RA) and the saphenous vein (SV), which are typically attached with a Y anastomosis to the LIMA graft to form a *composite Y-graft* [4,5]. RA and SV grafts have both advantages and disadvantages (see [5] for a review) and today there is still controversial evidence regarding the best choice. As a matter of fact, several clinical trials have demonstrated better long-term patency rates for arterial conduits (see e.g. [6–8]), however SV remains one of the most widely used graft because of its accessibility, sufficient length, ease of use, and in those cases where the radial artery cannot be used (e.g. when the Allen's test[1] shows inadequate collateral hand perfusion or in presence of a non-severe coronary artery stenosis) [10–12].

The main factor affecting graft patency is the development of intimal hyperplasia (IH) at the anastomosis between the graft and the coronary artery. IH is the progressive intimal thickening due to abnormal proliferation of smooth muscle cells in the tunica

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[1] This test analyzes possible abnormal circulation in the radial artery. It is based on occluding both arterial arteries by means of an external pressure and by comparing the color of hands after the quick opening of the fingers [9].

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intima of the vessel wall, which results in the reduction of the lumen of the graft and may eventually lead to restenosis and graft failure [13–15]. Although the underlying mechanisms of IH development have not been completely elucidated yet, suggested hypotheses are the presence of hemodynamic disturbances (e.g., stagnation and recirculation regions) and localized stress concentrations in the graft wall, especially in the region of the anastomosis [16–19]. In particular, extensive IH formation typically occurs when a compliance mismatch between the graft and the host coronary artery is present.

Many computational studies have addressed the problem of finding a possible correlation between hemodynamics in CABGs and IH development (see [20] for a review of recent numerical investigations). Most of them focused on the quantification of hemodynamic parameters to explore the theory of IH development due to the disturbed fluid-dynamics (see e.g. [21,22]). Only a few authors have attempted to study the influence of mechanical factors like internal wall stresses on IH. In these studies, accurate models of the vessel wall mechanics were considered. For instance, some authors prescribed a given internal pressure to surrogate the blood dynamics [23].

Within this context, the fluid–structure interaction (FSI) between blood and the vessel walls should provide a better quantification of the internal wall stresses and at the same time would allow to assess also the fluid-dynamic factors. However, no numerical FSI simulations in patient-specific CABG geometries have been made so far. Furthermore, despite the ever-increasing clinical interest in the use of composite Y-grafts and the search for the best graft to be used (RA vs SV), no numerical investigations have been made to compare the effects of the graft choice on the resulting fluid-dynamic and mechanical factors that may contribute to the failure of the graft.

The purpose of this work is to investigate the possible causes of graft failure in patient-specific multiple Y-CABGs, with particular attention to the fluid-dynamics and wall mechanics resulting from different choices (arterial vs venous). With this aim, we perform a computational FSI analysis in three patients with multivessel coronary disease and treated with a Y-graft. In particular, we characterize different grafts by changing their mechanical properties (Young's modulus) and geometric characteristics (diameter). Since the risk of graft failure is related to the degree of coronary stenosis [24,25], for each case we consider three possible degrees (50%, 70%, 90%) to assess the fluid-mechanic and mechanical factors in relation to the severity of the stenosis.

2. Materials and methods

2.1. Patients dataset

In this study, we consider three patients (P1, P2 and P3 in the following) with severe multivessel coronary artery disease who underwent off-pump CABG surgery with a composite Y-graft. In particular, these patients featured two stenoses, one in LAD and another one in a second coronary vessel, see Table 1 for details. In what follows, we refer to these as *LAD stenosis* and *second stenosis*. The patients were treated with a LIMA bypass to restore LAD perfusion and with a second graft (radial artery for P1 and P2 and saphenous vein for P3), proximally attached to LIMA, to bypass the second stenosis, see Fig. 2, top.

The follow-up study, based on three-dimensional Contrast Enhanced Computed Tomography (3D-CE-CT), was performed with a Philips Brilliance CT 64-slice system with the following main acquisition parameters: slice thickness 0.67 mm, slice spacing 0.33 mm, reconstruction matrix 512 × 512 pixels, final resolution 0.45 mm × 0.45 mm × 0.33 mm.

Table 1
Reconstructed coronary vessels and bypass grafts for each patient. LMCA = left main coronary artery; LCx = left circumflex artery; OM = obtuse marginal artery; diag = diagonal branch of LAD.

	Coronary arteries	Stenoses	Bypass grafts
P1	LMCA LAD LCx	LAD LCx	LIMA-to-LAD RA Y-graft on LIMA-LCx
P2	LMCA LAD LCx-OM	LAD OM	LIMA-to-LAD RA Y-graft on LIMA-OM
P3	LMCA LAD-diag LCx	LAD diag	LIMA-to-LAD SV Y-graft on LIMA-diag

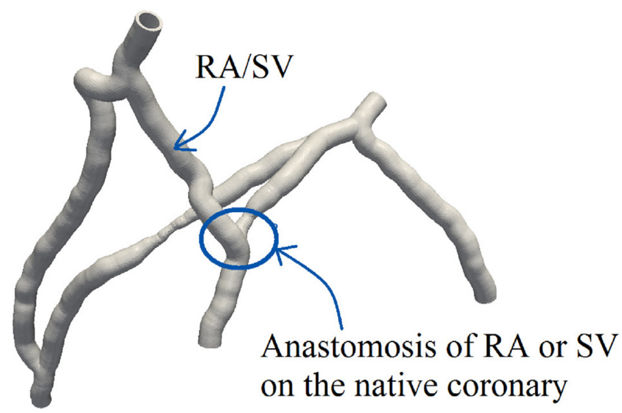

Fig. 1. Example of coronary Y-grafts. In the circle, we have highlighted the region of interest where hyperplasia may occur, i.e. the anastomosis of the radial artery or saphenous vein onto the native coronary.

2.2. Computational domains and mesh generation

The reconstruction of the 3D surface models representing the interface between blood and the vessel walls was performed with a level-set segmentation technique developed in the software VMTK (http://www.vmtk.org) starting from the CT images of the three patients. We report in Table 1 the details of the reconstructed coronary vessels and bypasses and in Fig. 2, top, the resulting reconstructed 3D geometries (in what follows, we refer to these as *original geometries*). In Fig. 1 we report a sketch of the region of interest, i.e. the anastomosis of the radial artery or saphenous vein onto the native coronary.

The main aim of this work is to compare the mechanical answers of two different Y-grafts commonly implanted to bypass the second stenosis. In particular, we consider the radial artery (RA) and the saphenous vein (SV), ideally implanted in the same patient in order to discard other possible sources of difference. To this aim, we characterized the two grafts as follows:

(1) by using different Y-grafts diameters (SV is bigger than RA);
(2) by using different values of Young's modulus (SV graft is stiffer than RA graft, see Section 4).

In view of the first point, for each patient we created a second *modified geometry* obtained by virtually changing the Y-graft diameter. In particular, both for P1 and P2, the SV Y-graft modified geometry was characterized by a diameter of 3.5 mm [26] (original RA bypass diameters of about 2.4 mm and 2.7 mm, respectively), whereas for P3 the RA Y-graft modified geometry was characterized by a diameter of 2.5 mm [26] (original SV bypass diameter of about 3.2 mm).