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# Inflow boundary conditions for image-based computational hemodynamics: Impact of idealized versus measured velocity profiles in the human aorta

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ABSTRACT

Here we analyse the influence of assumptions made on boundary conditions (BCs) extracted from phase-contrast magnetic resonance imaging (PC-MRI) in vivo measured flow data, applied on hemodynamic models of human aorta. This study aims at investigating if the imposition of BCs based on defective information, even when measured and specific-to-the-subject, might lead to misleading numerical representations of the aortic hemodynamics. In detail, we focus on the influence of assumptions regarding velocity profiles at the inlet section of the ascending aorta, incorporating phase flow data within the computational model. The obtained results are compared in terms of disturbed shear and helical bulk flow structures, when the same measured flow rate is prescribed as inlet BC in terms of 3D or 1D (axial) measured or idealized velocity profiles. Our findings clearly indicate that: (1) the imposition of PC-MRI measured axial velocity profiles as inflow BC may capture disturbed shear with sufficient accuracy, without the need to prescribe (and measure) realistic fully 3D velocity profiles; (2) attention should be put in setting idealized or PC-MRI measured axial velocity profiles at the inlet boundaries of aortic computational models when bulk flow features are investigated, because helical flow structures are markedly affected by the BC prescribed at the inflow.

We conclude that the plausibility of the assumption of idealized velocity profiles as inlet BCs in personalized computational models can lead to misleading representations of the aortic hemodynamics both in terms of disturbed shear and bulk flow structures.



## 1. Introduction

The complex hemodynamics observed in the human aorta make this district a site of election for an in depth investigation of the relationship between fluid structures, transport and pathophysiology (Kilner et al., 1993; Stonebridge et al., 1996; Markl et al., 2004; Morbiducci et al., 2011a; Frydrychowicz et al., 2012).

In recent years coupling medical imaging and computational fluid dynamics (CFD) has been more and more extensively developed and applied to study the aortic hemodynamics, because of the possibility to obtain highly resolved blood flow patterns in anatomically realistic arterial models. In the context of a subject-specific oriented approach, PC-MRI has emerged as able to provide the anatomical and hemodynamic inputs to even more realistic, fully personalized flow simulations (Taylor and Steinman, 2010). However, the computation of hemodynamic quantities enabled by the combination of in vivo imaging and in silico methods requires some assumptions. In particular, the way BCs are imposed to design personalized studies might influence the predicted hemodynamic scenario (Long et al., 2000; Moyle et al., 2006; Grinberg and Karniadakis, 2008; Wake et al., 2009; Kim et al., 2009a, 2009b; Spilker and Taylor, 2010; Gallo et al., 2012a).

In particular, inlet BCs are usually derived from patient-specific measured volumetric flow rate waveforms. However, in general the knowledge of the flow rate waveform at the inlet section of the fluid domain of interest is not sufficient to guarantee the existence and uniqueness of the solution, in computational hemodynamics. This is a limiting factor in a scenario where subject-specific simulations represent a powerful instrument to complement the information given by clinical images. For this reason, the prescription of additional constraints is required at boundaries for the well-posedness of the computational problem. A common approach applied to overcome this problem is based on *a-priori* selection of the velocity profile fitting the measured flow rate, turning the defective boundary data problem into a classical Dirichlet problem. In general, a practical workaround is to resort to idealized BCs prescribed at inlet

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sections either (1) in terms of velocity profiles obtained as analytical solutions, or (2) imposing flat velocity profiles, i.e., the so-called plug flow, which does not depend upon the radial distance in the vessel cross section.

Several authors have studied the effect of inlet BCs on CFD predictions of aortic flow resorting to idealized geometric models or to simplifications in the description of the physics of the problem (Shipkowitz et al., 2000; Glor et al., 2002; Nakamura et al., 2006; Tan et al., 2012). Among them, Nakamura et al. (2006) proposed an integrated model of the left ventricle and aorta, demonstrating the nonuniformity of the aortic inflow velocity profiles. Alternative strategies, based on an augmented formulation of the problem, were also proposed, where the conditions on the flow rate at not physical inlet section(s) are prescribed in a weak sense by means of Lagrangian multipliers (Formaggia et al., 2002; Veneziani and Vergara, 2005). For example, a multidomain method was proposed to couple a lumped parameter heart model and a 3D aorta model, where the shape of the velocity profiles of the inlet boundary were constrained (Kim et al., 2009b). However, the assumption done on the shape of the velocity profile at the inlet section(s) of the fluid domain can influence the entire numerical solution.

To partially drop out some of the limitations arising from the imposition of defective BCs, recently PC-MRI flow maps acquired above the aortic root were used to obtain pixel-based time-varying axial velocities (neglecting the in-plane velocity) to be prescribed as inlet BCs (Tan et al., 2012). Alternative to making assumptions on the shape of the inflow velocity profile, Jin and coworkers developed a computational model to examine the effect of wall motion and distensibility on aortic hemodynamics, where all the three components of the measured PC-MRI velocity data were used as BCs at the inlet section (Jin et al., 2003).

Here we report a numerical experiment in which different possible strategies of applying PC-MRI measured flow data as BCs in an image-based hemodynamic model of human aorta are implemented. In detail, we present our findings about the influence of assumed velocity profiles shape imposed as inflow BC. Technically, different inflow conditions were generated, by imposing at the inlet of the ascending aorta: PC-MRI measured 3D and axial (1D) velocity profiles, plug flow and fully developed profiles derived from the PC-MRI measured flow rate waveform. The impact that the applied inflow BC strategy has on the modelled aortic hemodynamics was evaluated both in terms of wall shear stress (WSS) distribution at the luminal surface (which is related to arterial disease) and of bulk flow structures (we focused on helical flow, because the natural blood flow in aorta has been demonstrated to be helical (Kilner et al., 1993)).

## 2. Materials and methods

4D PC-MRI images of an ostensibly healthy human aorta were acquired using a 1.5 T scanner (Achieva, Philips Healthcare, The Netherlands). Blood velocity vector fields and anatomical data were acquired in 22 oblique sagittal slices (field of view $=280\times280$ mm$^2$) aligned with the aortic arch and the entire aorta was covered with an isotropic spatial sampling (measured voxel size $=2\times2$ mm$^2$; slice thickness $=4$ mm, 2 mm slice spacing). A gradient echo spin sequence was used with velocity encoding (VENC $=150$ cm s$^{-1}$) in all three directions. The scan parameters were: TR/TE $=5.4/3$ ms; VENC $=150$ cm/s. A navigator echo technique was used to reduce motion artifacts. The phase-contrast pulse sequence was arranged to allow synchronization of the data to the cardiac cycle. This allowed to reconstruct a cine series of 3D data sets from multiple phases of the cardiac cycle. The resulting cine pulse sequence was retrospectively gated to the electrocardiographic cycle (cardiac rate of 54 bpm) to obtain 22 cardiac phases (Morbiducci et al., 2011a). An example of the acquired three-directional velocity map frames is displayed in Fig. S1 of Supplementary Materials.

PC-MRI images were used to generate the model of aorta (Fig. 1) into the Vascular Modeling Toolkit (VMTK) environment (http://www.vmtk.org/) (Antiga et al., 2008), as described in a recent study (Gallo et al., 2012a). Briefly, a multiple step procedure was applied for the extraction of the surface mesh of the thoracic aorta from PC-MRI data. The first step consisted in obtaining an additional image representing the velocity modulus from the three gray-scale images (containing the three velocity vector components). This new image was segmented into a level set representation, using an implicit deformable model algorithm which was initialized by providing a rough representation of the vessel geometry, consisting in the binarization of the gray-scale images of the velocity magnitude. In addition, five seed points were placed downstream at specific locations to define the vascular segments of interest. A more accurate vessel volume was then created using the geodetic active contour algorithm. Finally, (1) a marching cubes

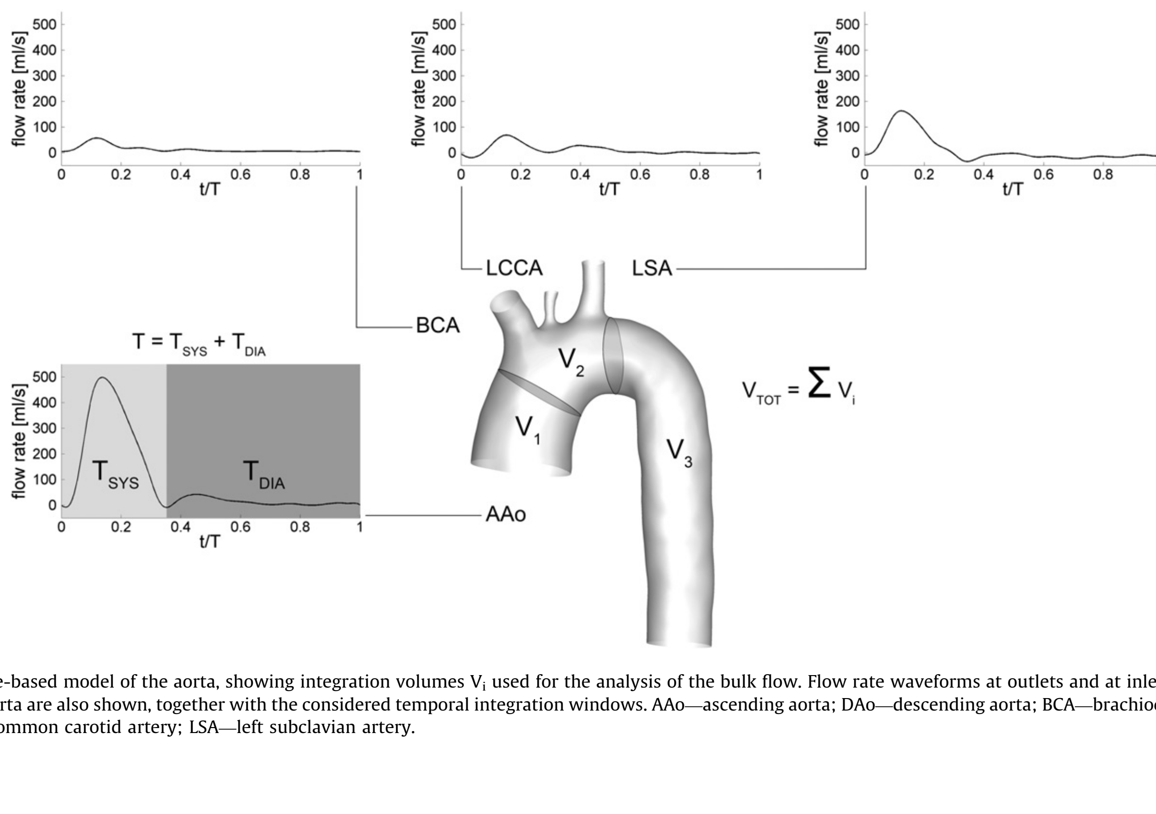


**Fig. 1.** Image-based model of the aorta, showing integration volumes $V_i$ used for the analysis of the bulk flow. Flow rate waveforms at outlets and at inlet section of the ascending aorta are also shown, together with the considered temporal integration windows. AAo—ascending aorta; DAo—descending aorta; BCA—brachiocephalic artery; LCCA—left common carotid artery; LSA—left subclavian artery.