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Doppler derived quantitative flow estimate in coronary artery bypass graft: A computational multiscale model for the evaluation of the current clinical procedure

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Abstract

In order to investigate the reliability of the so called *mean velocity/vessel area* formula adopted in clinical practice for the estimation of the flow rate using an intravascular Doppler guide wire instrumentation, a multiscale computational model was used to give detailed predictions on flow profiles within Y-shaped coronary artery bypass graft (CABG) models. At this purpose three CABG models were built from clinical patient's data and used to evaluate and compare, in each model, the computed flow rate and the flow rate estimated according to the assumption of parabolic velocity profile.

A consistent difference between the exact and the estimated value of the flow rate was found in every branch of all the graft models. In this study we showed that this discrepancy in the flow rate estimation is coherent to the theory of Womersley regarding spatial velocity profiles in unsteady flow conditions. In particular this work put in evidence that the error in flow rate estimation can be reduced by using the estimation formula recently proposed by Ponzini et al. [Ponzini R, Vergara C, Redaelli A, Veneziani A. Reliable CFD-based estimation of flow rate in haemodynamics measures. Ultrasound Med Biol 2006;32(10):1545–55], accounting for the unsteady nature of blood, applicable in the clinical practice without resorting to further measurements.

Keywords: Haemodynamics; Computational fluid dynamics; CFD; Doppler blood flow estimation; Bypass graft; Multiscale modeling; Doppler guide wire

1. Introduction

Recently, intravascular ultrasonic measurement systems have been used in coronary haemodynamic evaluation for clinical purposes [1,2]. In particular, intravascular Doppler guide wire (DGW) and biplane quantitative coronary angiography (QCA) have been used to evaluate flow in Y-shaped coronary artery bypass grafts [3,4] consisting of an in situ internal thoracic artery (ITA) and a radial artery (RA), which permit myocardial revascularization with excellent graft patency and improved clinical outcomes [2–5]. The current methodology is the so-called *mean velocity/vessel area* method in which the blood flow volume is defined as the product of the cross-sectional area (A) and the mean flow velocity (V_{mean}):

$$Q = V_{mean} A \tag{1}$$

Nevertheless, DGW instrumentation does not allow the direct measurement of the value of V_{mean}. Instead, the value of maximum flow velocity (V_{max}) can be recorded at each instant in the Y-graft (i.e., the main stem of the proximal left ITA (LITA), the distal LITA and the RA). In the same

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sections, QCA make it possible to obtain the values of the radius (R) of the cross-section. The mean velocity value is then linked to the maximum velocity value, on the a priori assumption:

$$V_{mean} = V_{max}0.5 \quad (2)$$

By combining Eqs. (2) and (1) we finally get the estimate actually applied in clinics:

$$Q_D = 0.5V_{max}A = 0.5V_{max}\pi R^2 \quad (3)$$

This formula, proposed in 1992 by Doucette et al. [1], emerged from in vitro experiments in a non-physiological setting (very long tubes, no branching) to validate DGW for intravascular coronary artery flow velocity measurements.

The main physical hypothesis involved in this estimate is that the spatial velocity profile remains constant and parabolic (the 0.5 constant coefficient in Eqs. (2) and (3)).

However, it is widely known from in vivo, in vitro and computational studies that the local fluid dynamics in vessels is complex [6–8], and velocity patterns are far from an axis-symmetric, vessel-centered parabola. The inaccuracy of the parabolic profile hypothesis has been clearly pointed out in several clinical studies [9–11] and has a consistent mathematical explanation in the Womersley theory [12] and in the extensive work by Nichols and O'Rourke [13]. Notwithstanding this limitation, Doucette's formula is widely applied in clinical practice to estimate blood flow rate in CABGs using DGW instrumentation [1,2,14].

Very recently, Ponzini et al. [15] have proposed a novel formulation for estimating the flow rate, accepting Eq. (1) as valid and introducing a modified linkage between V_{mean} and V_{max}.

The use of a CFD approach in order to perform reliable simulations and to obtain insights in realistic (with respect to boundary conditions and geometry) vessels models is not new and is becoming today more and more a valid partner to in vitro modelling and a possible substitute to animal modelling providing a privileged environment for cheap fast and reproducible data acquiring, as fully discussed in the review by Charles et al. [16] concerning the general topic of CFD approaches in haemodynamics and in the one by Migliavacca and Dubini [17] concerning the specific topic of vascular anastomosis study by means of CFD. Accordingly, in the first 6 months of this year alone about 30 papers have been published on this topic, and among the others we cite Botsianis et al. [18], Politis et al. [19], Morbiducci et al. [20], Morbiducci et al. [21] on the specific topic of bypass and coronary modelling.

In the present paper CFD is used to mime, in a controlled environment, a daily clinical procedure in order to test the reliability of a new blood flow rate estimated formula proposed by Ponzini et al. [15] for ultrasound Doppler clinical analysis. From this point of view the present work differs from all the other present in literature where more general fluid dynamics patterns are usually faced and discussed.

Table 1
Data used to build the computational models, as measured by clinicians: radii (R); minimum and maximum aortic pressure values (P); heart rate; Wommersley number in the three sections of the Y-graft (W); Reynolds number at the peak velocity time instant in the inlet section of the model (Re)

	Model a	Model b	Model c
$R_{LITA\text{-}proximal}$ (mm)	1.49	1.39	1.19
$R_{LITA\text{-}distal}$ (mm)	1.27	0.89	0.89
R_{RA} (mm)	1.26	1.49	1.39
$P_{min/max}$ (mmHg)	76/140	60/100	85/130
Heart rate (Hz)	1.72	1.81	1.49
$W_{LITA\text{-}proximal}$	3.40	3.26	2.54
$W_{LITA\text{-}distal}$	2.90	2.08	1.89
W_{RA}	2.87	3.49	2.95
Re_{peak}	781	625	311

Therefore, the purpose of the present study is to

- Reproduce the local haemodynamics inside three CABG multiscale models made of realistic image-based 3D Y-graft models, coupled with a lumped model of a part of the myocardial circulation.
- Mimic the DWG blood flow volume estimate based on the so-called *mean velocity/vessel area* method in a controlled environment and so in an objective manner.
- Compare the estimate given by Eq. (3) with the flow estimate proposed by Ponzini et al. [15].

2. Materials and methods

All the data used to build the three computational models of this study come from the clinical analysis performed on three subjects receiving a composite Y-graft at the Cardiac Surgery Unit of the L. Sacco Hospital in Milan (Italy) (see [2] for and exhaustive description of clinical procedure). DGW technique was used to record the blood flow maximum velocity V_{max} time course during postoperative cardiac catheterization; a 175-cm long, 0.014-in. diameter (Flow-Wire, Cardiometrics Inc., CA) and QCA were used to measure the diameters values at end diastole by means of angiographic images (see Fig. 1). Simultaneous electrocardiogram and arterial blood pressure signals were also continuously recorded in the aorta. Table 1 summarizes the values of radium, heart rate and maximum/minimum pressure used in the construction of the three computational models.

2.1. Three-dimensional computational models

The 3D models' geometries and meshes (approximately 200,000 hexahedral cells) were generated by using GAMBIT software (Ansys Inc.) (see Fig. 1). The grid is based on hexahedral elements. Fig. 1b shows that even if the core of the vessel geometry is fitted by hexahedral cell at the near-wall location locally refined boundary layers are present in order to obtain more fine and reliable computational results. Fig. 1