FLOW RATE ESTIMATION IN Y-SHAPED CORONARY ARTERY BY-PASS GRAFT BY MEANS OF INTRAVASCULAR DOPPLER AND COMPUTATIONAL FLUID DYNAMICS

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INTRODUCTION

This work is aimed at the study of the hemodynamics of coronary by-pass done with a "Y graft" surgery technique. The Y-graft, is realized through anastomosis between the mammary artery (AMI) and the radial artery (AR). The study consisted of an experimental part and a numerical one.

The experimental protocol regarded the angiographic study and flow-meter analysis of the by-pass through the tubing of the femoral artery with a 6F catheter in which a Doppler guide wire (DGW) had been inserted. The average peak velocity (*APV*) was measured in the by-pass and the flow rate was calculated by using the equation indicated in the paper written by Doucette [1] as

$$Q_d = 0.5\, APV\, \pi R^2$$

where R is the vessel radius.

To investigate the reliability of the Doucette formula, a benchmark model has been developed using computational fluid dynamics. Four Y-graft models have been constructed on the basis of the angiographic projections of four patients. Realistic haemodynamics conditions have been simulated and the actual flow rates have been calculated in the three branches of the Y-graft models. Consequently, the flow rates have been estimated with the Doucette formula with reference to sample planes and their values have been compared with the actual ones.

MATERIAL AND METHODS

Acquisition system

The DGW is constructed of a 175 cm long and 0.22 diameter flexible and steerable guide Wire with a 12-MHz piezoelectric ultrasound trasducer integrated onto its tip. The forward directed ultrasound beam diverges 20^0 from its axis as measured to the –6 dB (round-trip) points of the ultrasonic beam pattern. A repetition frequency of 40KHz whit a pulse duration of 0.83µs and a sampling delay of 6.5µs has been used. The choice of this parameters determined that the sample volume was 0.65 mm thick by 1.7 mm in diameter and was located 5mm beyond the DGW.

Experimental protocol

23 patients underwent the acquisition protocol which consists in one acquisition at rest and one acquisition at 85% of the maximum heart rate. The DGW was placed in the left AMI before and after the Y anastomosis and in the AR. The position of the DGW inside of the graft was checked through two perpendicular angiographic projections, and the average peak velocity (*APV*) was measured in the three branches of the by-pass. After having measured the *APV*, the area of the coronary sections were measured by means of angiography.

Model geometry

Figure 1 reports the four 3-D Y-graft models used in the present study. Each 3-D model has been reconstructed on the basis of two perpendicular angiographic images; for each branch of the Y-graft, five cross sections have been selected, approximately every 4 millimeters, and the vessel diameter, centroid and orientation have been measured in the two angiographic projections. This information has been used to build three cylindrical bent conduits representing the proximal and distal mammary arteries and the radial artery, respectively. Consequently, the overall Y-graft model has been obtained by merging the three conduits.

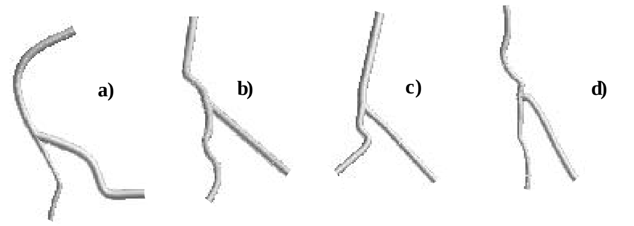

Fig.1 - 3-D Y-graft models attained from angiographic images. Data have been extracted from 4 patients (a to d).

Boundary conditions

The simulations have been performed in transitory; the blood maximum velocity time course in the proximal mammary artery has been recorded with the Doppler guide wire for each patient and processed with a Fast Fourier Transform algorithm in order to attain its analytical formulation. This information has been used to calculate, as a first approximation, the inlet flow rate under the hypothesis of a parabolic velocity profile. The attained flow rate time course has been applied to a straight conduit (length equal to 20 times the diameter value) connected to the proximal mammary artery of each model in order to simulate the correct developed velocity profile in the mammary artery [2]. To calculate the pressure time course at the distal mammary artery and radial artery outlets two lumped parameters models have been used, one for each branch. During the simulation the lumped parameters models receive as input the flow rate from the Y-graft 3-D model and give as output the pressure acting at the outlet. They simulate the compliance and the resistance features of the vascular net downstream the two branches. The lumped parameter models have been derived from the work by Mantero [3] describing the overall coronary tree; the model parameters have been scaled in order to attain the blood partition observed in the specific patient and a coronary pressure in the proximal artery inlet ranging between 80 and 120 mmHg. Finally, concerning the 3-D model walls, they have been assumed rigid and the no slip condition has been imposed at the walls.

Simulation set up

The fluid dynamics simulations have been performed by using a control-volume-based technique, implemented in the CFD code FLUENT (Fluent Inc., Lebanon, NH). 4-node tetrahedral elements have been used in the discretization for a total number of about 200,000 elements per model. The lumped parameters model simulating the model outlet boundary conditions have been implemented within the overall model by means of a C-compiled user subroutine. A segregated solver has been employed for the solution method. The velocities have been calculated according to the second order upwinding scheme. The pressure-velocity coupling is the Pressure-Implicit with Splitting of Operators (PISO) scheme. The time integration technique adopted is the second order trapezoidal, with a fixed time step of 3 ms. The fluid has been considered Newtonian with a density of 1060 Kg/m^3 and a viscosity of 0.0022 Pa s. Three cardiac cycles have been performed for each simulation in order to attain stable solutions. The flow rates have been recorded in the three branches throughout the third cycle. Contemporary, the maximum velocity has been also recorded with reference to three sample planes, one for each branch, normal to the flow direction; they have been chosen according to the surgeon experience in order to avoid artefacts due to conduit bendings or closeness to the anastomosis. The computations have been carried out on a cluster of 3 PC dual processor (AMD Athlon 1.33 GHz, 2.1 MB of RAM). The CPU time was approximately 36 hours for each simulation.

RESULTS AND DISCUSSION

Figure 2 refers to the fluid dynamics within the 3-D model of one of the patients examined and shows the pressure contour at the flow rate peak and the path lines. Figure 3 shows the velocity profiles in four instants of the cardiac cycle; for each branch a sample plane is selected; for each plane a diameter is chosen and the profile drawn. Despite the profiles look to be parabolic, indeed under pulsatile flow conditions the profile tends to be flatter [4].

By calculating the error (ε) as the ratio between the difference of the actual and the Doucette flow rates and the actual flow rate, its value varies between 2 and 15% and it is always positive. This means that the Doucette formula always underestimates the actual value of the flow rate. Again this is due to the flatness of the pulsatile profile. This phenomenon has been firstly investigated by Hale, McDonald and Womersley [5]. In this study it was demonstrated that the pulsatile developed profile differs progressively from the parabolic one as the so-called number of Womersley α increases:

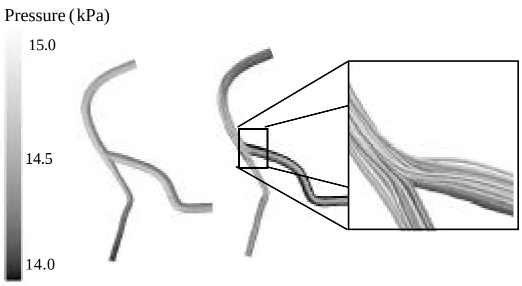

Figure 2 - 3-D Y-graft model results. Pressure contours (left panel) at the flow rate peak and path lines (right panel)

Accordingly we propose that a more reliable estimation of the flow rate can be achieved by including the number of Womersley in the flow rate calculation as follows:

$$Q = 0.5\pi R^2 v_{max} \alpha^k$$

where v_{max} is the Doppler estimated maximum velocity, R is the radius and k is a constant. Through best fitting analysis we have calculated a value of the constant k equal to 0.26. In this case the approximation is more satisfactory and, the estimated error is about 2% $\pm$ 3%. By using this formula with respect to the data collected in the experimental protocol, the error in estimating the actual peak flow rate varies between 2-and 22%.

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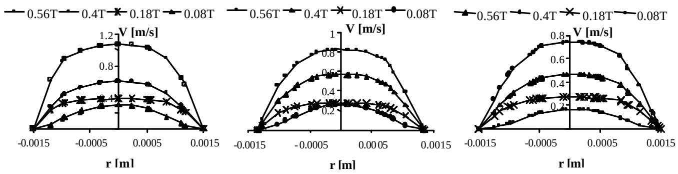

Figure 6 - Velocity profiles in four instants of the cardiac cycle (model a). Panels refer to the proximal and distal mammary artery and to the radial artery, respectively.