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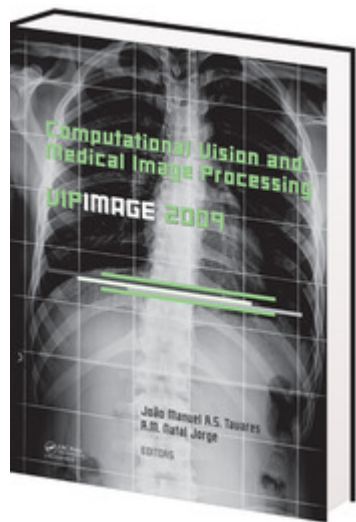
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Computational Vision and Medical Image Processing: VipIMAGE 2009

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[Description](#) | [Table of Contents](#)

Table of Contents

- Preface
- Acknowledgements
- Invited lectures
- Thematic sessions

On building photographic portraits using statistical techniques, R. Roque, A. Puga, E. Carrapatoso & F. Barbosa
 Geometric analysis of female pelvic floor muscles by using manual segmentation, T.H. Da Roza, R.M. Natal Jorge, M. Parente, João Manuel R.S. Tavares, C. Saleme, M.P. Barbosa, A.L.S. Filho, T. Mascarenhas & J. Loureiro
 Analysis of the fibers direction in the tympanic membrane, C. Garbe, F. Gentil, M.P.L. Parente, P. Martins, R.M. Natal Jorge & S. Santos
 Construction of a 3D model for the female pelvic organs, A.J.C. Arteiro, M.P.L. Parente, R.M. Natal Jorge, A.A. Fernandes & T. Mascarenhas
 A versatile matching algorithm based on dynamic programming with circular order preserving, Francisco P.M. Oliveira, João Manuel R.S. Tavares & Todd C. Pataky
 Construction of a 3D model from medical images: Application to knee joint, H. Mata, R.M. Natal Jorge, S. Santos, A. Sousa & F. Raposo
 A novel method to segment the levator ani muscles in MR images, Zhen Ma, João Manuel R.S. Tavares & R.M. Natal Jorge
 3D reconstruction of human temporomandibular structure, V.L. Trindade, R.M. Natal Jorge & S. Santos
 Spectral imaging of retinal tissue oxygenation, E. Ohel, S. Rotman, D.G. Blumberg & N. Belfair
 Automatic segmentation of the optic radiation using DTI in glaucoma patients, A. El-Rafei, J. Hornegger, T. Engelhorn, A. Dörfler, S. Wärtges & G. Michelson

Comparison between Kalman and unscented Kalman filters in tracking applications of computational vision, Raquel R. Pinho & João Manuel R.S. Tavares

Thematic session on computer vision in robotics

Model based localization for a mobile robot in an indoor environment, F. Valente & M. Ramalho
 Obtaining the distance map for perspective vision systems, A.J.R. Neves, D.A. Martins & A.J. Pinho
 Real-time vision in the RoboCup—Robotic Soccer international competitions, L.P. Reis, A.J.R. Neves & A. Sousa

Thematic session on imaging of biological flows trends and challenges

Diffusion in concentrated suspensions of biological cells, T. Ishikawa
 X-ray micro-imaging of various bio-fluid flows, S.J. Lee
 Patient-specific blood flow analysis of pulmonary artery affected by severe deformations of the lung 335
 J.-J. Christophe, N. Matsuki, T. Yamaguchi, T. Ishikawa, Y. Imai, M. Thiriet & K. Takase
 Motions of particles and red blood cells in a bifurcation: Comparison between experiments and numerical simulations, M. Lagoela, B. Oliveira, D. Cidre, C. Fernandes, C. Balsa, R. Lima, R. Dias, T. Ishikawa, Y. Imai & T. Yamaguchi
 In silico multiscale study of the hemodynamics in a human carotid bifurcation model, D. Gallo, D. Massai, F. Consolo, A. Satriano, F.M. Montevicchi, U. Morbiducci, R. Ponzini, L. Antiga & A. Redaelli
 Influence of blood rheology on bulk flow in carotid bifurcation: A numerical study, D. Massai, D. Gallo, A. Satriano,

Motions of particles and red blood cells in a bifurcation: comparison between experiments and numerical simulations

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The blood flow dynamics in microcirculation depends strongly on the microvascular networks composed with short irregular vessel segments which are linked by numerous bifurcations. This paper presents the application of a confocal micro-PTV system to track RBCs through a rectangular polydimethylsiloxane (PDMS) microchannel with a bifurcation. By using a confocal micro-PTV system, we have measured the effect of bifurcation on the flow behaviour of both fluorescent particles diluted in pure water and RBCs in concentrated suspensions. After performing simulations with the commercial finite element software package POLYFLOW[®], some experimental results were compared with the numerical results. Our preliminary qualitative results suggest that the *in vitro* blood flowing ($Re = 0.007$) through a bifurcation seems to have a tendency to behave more closely as a Power law model than as a Carreau or Newtonian model.

1 INTRODUCTION

Several studies have revealed that the information obtained on the rheological properties of blood in straight glass microtubes differs from the *in vivo* situation (Pries et al. 1994, Suzuki et al. 1996). The main potential causes for these discrepancies may be due to the endothelial surface layer and microvascular networks composed with short irregular vessel segments which are linked by numerous bifurcations (Maeda 1996, Pries and Secomb 2003).

The main purpose of this paper is to analyse the non-Newtonian flow characteristics of blood flowing in microvascular network models. To accomplish it experimental flow studies performed with a micro-PIV/PTV system will be complemented by hemodynamics computational models (commercial finite element software package POLYFLOW[®]). By using this combination we expect to gain understanding about several important parameters that affect the blood flow through a diverging microvessel bifurcation.

2 MATERIALS AND METHODS

2.1. Working fluids and microchannel

Two working fluids were used in this study: pure water and dextran 40 (Dx40) containing about 14% (14Hct) of human red blood cells (RBCs). The blood was collected from a healthy adult volunteer, where ethylenediaminetetraacetic acid (EDTA) was added to prevent coagulation. The RBCs were separated from the bulk

blood by centrifugation and aspiration and then washed twice with physiological saline (PS). The washed RBCs were labeled with a fluorescent cell tracker (CM-DiI, C-7000, Molecular Probes) and then diluted with Dx40 to make up the required RBCs concentration by volume. All blood samples were stored hermetical at 4°C until the experiment was performed at controlled temperature of about 37°C (Lima et al. 2009).

The microchannel used in this study was a symmetric PDMS bifurcation (150 μm wide, 50 μm deep for parent vessel; 75 μm wide, 50 μm deep for daughter vessel) fabricated by a soft lithography technique (Lima et al. 2008).

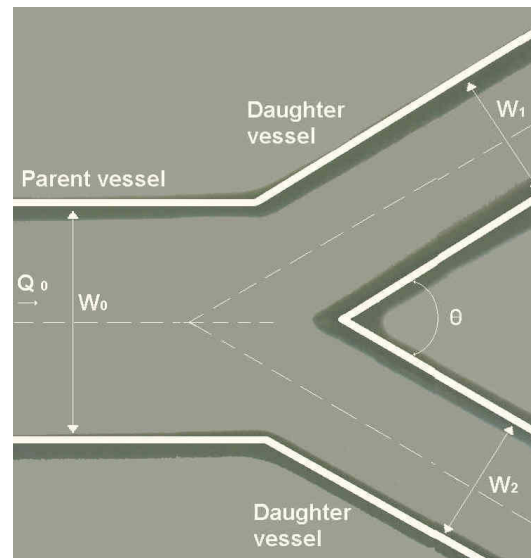


Fig. 1 Symmetrical bifurcation geometry used in this study: $Q_0 = 0.18 \mu\text{l}/\text{min}$, $W_0 = 150 \mu\text{m}$, $W_1 = 75 \mu\text{m}$, $W_2 = 75 \mu\text{m}$, $\theta = 60^\circ$, depth = 50 μm .

2.2. Confocal micro-PTV experimental set-up

The confocal micro-PTV system used in our experiment consists of an inverted microscope (IX71, Olympus, Japan) combined with a confocal scanning unit (CSU22, Yokogawa) and a diode-pumped solid state (DPSS) laser (Laser Quantum Ltd) with an excitation wavelength of 532 nm. Moreover, a high-speed camera (Phantom v7.1) was connected into the outlet port of the CSU22. The microchannel was placed on the stage of the inverted microscope where the flow rate of the working fluids was kept constant ($Re = 0.007$) by means of a syringe pump (KD Scientific Inc.). The Reynolds number (Re) and associated experimental parameters are summarized in Table 1. A thermo plate controller (Tokai Hit) was set to $37^{\circ}C$. All the confocal images were captured in the middle of the microchannels with a resolution of 640×480 pixels, at a rate of 100 frames/s with an exposure time of 9.4 ms. The recorded images were transferred to the computer and then evaluated in the Image J (NIH) (Abramoff et al. 2004) by using the manual tracking MtrackJ (Meijering et al. 2006) plugin. As a result it was possible to track single RBCs through the middle plane of the microchannel.

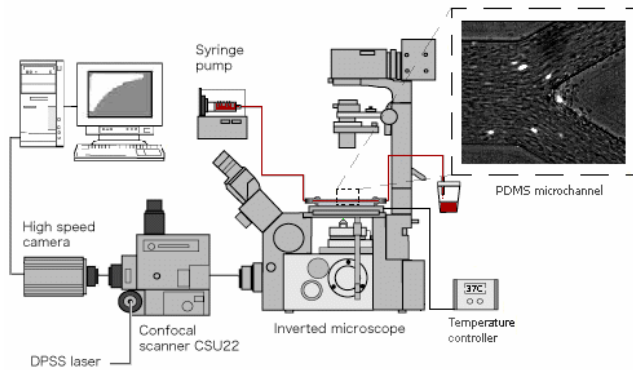


Fig. 2 Experimental set-up.

Table 1 - Experimental parameters used to calculate the Re .

Density (kg/m^3)	1046
Mean velocity (m/s)	3.8×10^{-4}
Hydraulic diameter (m)	7.5×10^{-5}
Viscosity of Dx-40 (Ns/m^2)	4.5×10^{-3}
Re	0.007

2.3. Simulation method

The numerical calculations for the laminar isothermal flow of pure water were performed using the finite-element computational fluid dynamics (CFD) program POLYFLOW[®]. The simulations were carried out in a 3D geometry representing the microchannel. The mesh used in the simulations was mainly constituted by quadrilateral elements, the discretization of the walls of the channel. The size of

the elements was fixed after a grid independence test. The grids were successively refined and the velocity obtained with the different meshes were compared, the results being considered independent of the mesh when a difference below 1 % was achieved (Fernandes et al. 2007, 2008).

The equations solved were the conservation of mass and momentum equations for laminar incompressible flow of water. The problem is a non-linear problem, so it was necessary to use an iterative method to solve the referred equations. In order to evaluate the convergence of this process, a test based on the relative error in the velocity field was performed and the convergence test value was set to 10^{-4} (Fernandes et al. 2007, 2008).

The boundary conditions were established in order to reproduce the experimental conditions. The flow rate at the inlet of the microchannel was $0.18 \mu l/min$ and slip at the walls of the channel was assumed to be non-existent.

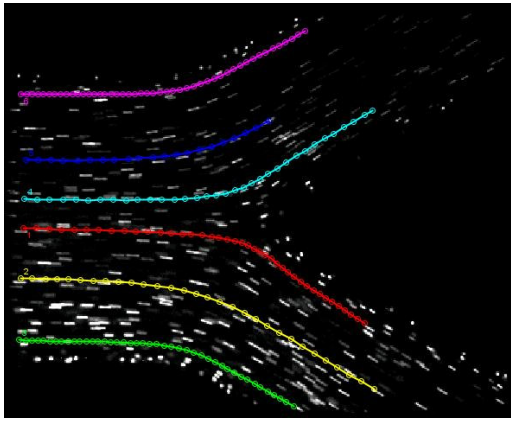
3 RESULTS AND DISCUSSION

The confocal micro-PIV system was first evaluated by comparing the experimental results not only with a well established analytical solution for steady flow in a rectangular microchannel (Lima et al. 2006) but also with a reliable numerical method that was used in past investigations to study the flow behaviour of Newtonian or non-Newtonian fluids at low Reynolds numbers (Fernandes et al. 2007, 2008).

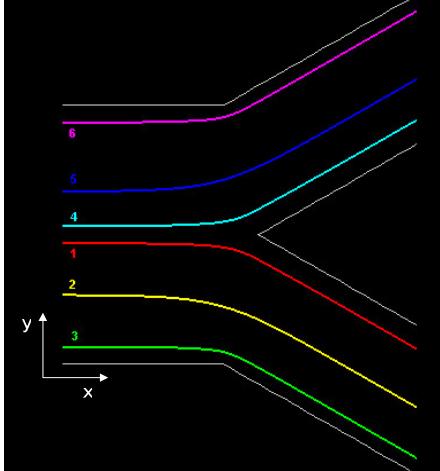
The numerical, experimental and analytical results of the present work were obtained for the middle plane ($25 \mu m$ height) of the rectangular microchannel. The averaged velocity data obtained from the confocal micro-PTV measurements, analytical solution and numerical simulation were in close agreement. A more detail description of these results can be found elsewhere (Oliveira et al. 2009).

By using a confocal micro-PTV system it was possible to obtain series of successive images at the middle of the bifurcation. Figures 3a and 4 show images with both fluorescent particles and labeled RBCs (laser-emitted light) flowing through a symmetric bifurcation, together with the correspondent time position tracking of both particles and individual RBCs.

By comparing the experimental data from pure water (see Fig. 3a) with the results of the numerical simulation (see Fig. 3b), it is possible to observe that in both cases the trajectories do not exhibit any appreciable deviations in the transversal (yy axis) direction.



a)



b)

Fig. 3 a) Paths displacement of fluorescent particles flowing in pure water; b) Numerical trajectories using pure water.

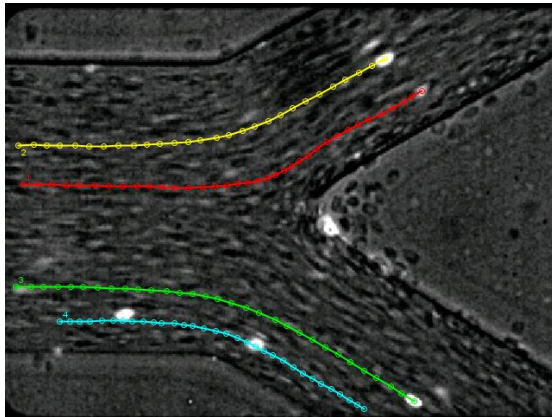


Fig. 4 Paths displacement of labeled RBCs (bright spots) flowing in physiological fluid with 14% Hct (32x).

In addition by comparing qualitatively the experimental data from both pure water and in vitro blood (14% Hct) it is possible to observe that some RBC paths seems to suffer small deviations from the streamlines of the plasma flow probably due to flow perturbations caused by cell interactions in the neighbourhood of the apex of bifurcation.

Moreover numerical simulations of non-Newtonian models were performed around the bifurcation and compared with the experimental results at the regions 1 to 7 (see Fig.5)

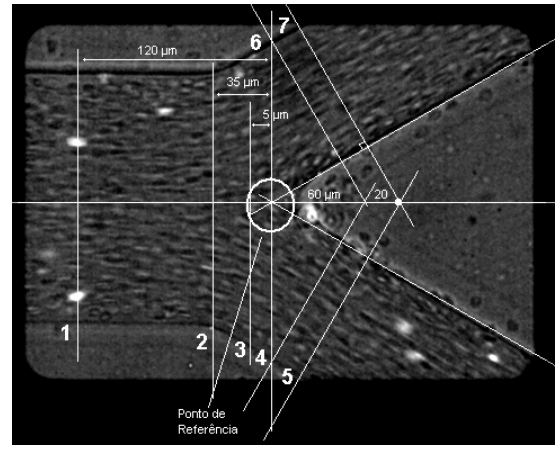
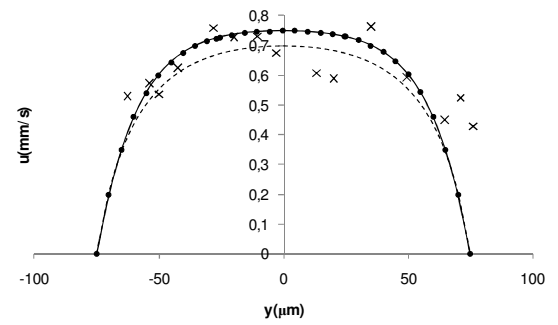
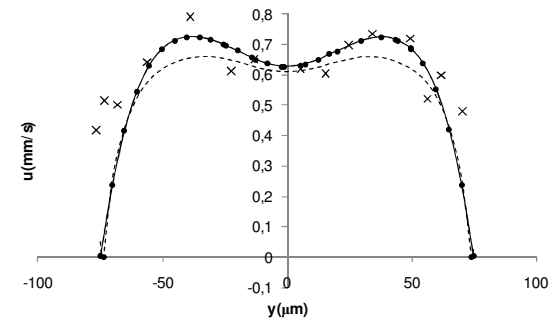


Fig. 5 Regions where the velocity profiles of the numerical and experimental results were compared.

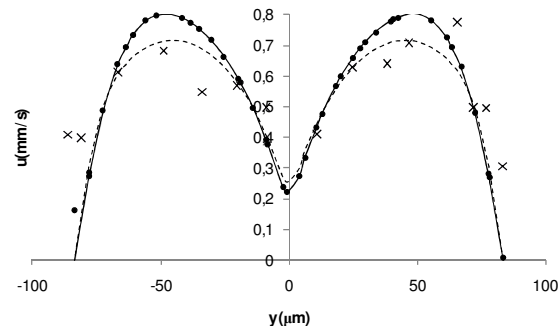
Figures 6 and 7 show the velocity profiles for both computational and experimental results before and after the bifurcation, respectively.



a)



b)



c)

Fig. 6 Velocity profiles for both computational and experimental results before the bifurcation: a) region 1; b) region 2; c) region 3. (—) Newtonian; (- - -) Power Law; (●) Carreau Model; (×) Confocal micro-PIV.

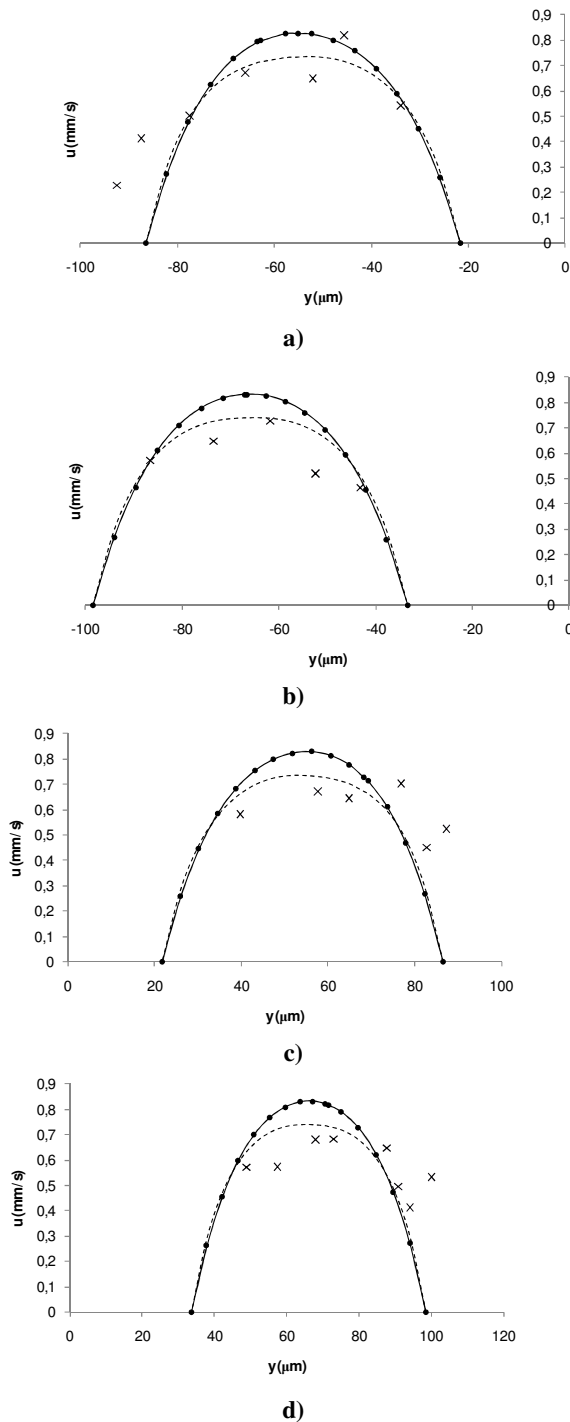


Fig. 7 Velocity profiles for both computational and experimental results after the bifurcation: a) region 4; b) region 5; c) region 6; d) region 7. (—) Newtonian; (- - -) Power Law; (●) Carreau Model; (×) Confocal micro-PIV.

A qualitative examination of Figures 6a) and 6b) does not show a clear correspondence of the experimental results with the numerical models used in this study. However Figure 6c) reveals a tendency of the *in vitro* blood to behave more closely as a Power law model. This is further confirmed by the results obtained in Figure 7, in particular Figures 7 a) and b). An on going study to obtain more detailed quan-

titative measurements of the blood flow behavior through a bifurcation is currently under way.

ACKNOWLEDGMENTS

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