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Computational modeling of local hemodynamics phenomena: Methods, tools and clinical applications

R. Ponzini(1), G. Rizzo(2), C. Vergara(3), A. Veneziani(4), U. Morbiducci(5), F. M. Montevecchi(5) and A. Redaelli(6)

(1) *CILEA, Sezione Applicazioni Scientifiche e Ingegneristiche - Milano, Italy*
(2) *Istituto di Bioimmagini e Fisiologia Molecolare del CNR - Milano, Italy*
(3) *Dipartimento di Ingegneria dell'Informazione e Metodi Matematici Università di Bergamo - Bergamo, Italy*
(4) *Department of Mathematics and Computer Science, Emory University Atlanta, GA, USA*
(5) *Dipartimento di Meccanica, Politecnico di Torino - Torino, Italy*
(6) *Dipartimento di Bioingegneria, Politecnico di Milano - Milano, Italy*

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Summary. — Local hemodynamics plays a key role in the onset of vessel wall pathophysiology, with peculiar blood flow structures (*i.e.* spatial velocity profiles, vortices, re-circulating zones, helical patterns and so on) characterizing the behavior of specific vascular districts. Thanks to the evolving technologies on computer sciences, mathematical modeling and hardware performances, the study of local hemodynamics can today afford also the use of a virtual environment to perform hypothesis testing, product development, protocol design and methods validation that just a couple of decades ago would have not been thinkable. Computational fluid dynamics (CFD) appears to be more than a complementary partner to *in vitro* modeling and a possible substitute to animal models, furnishing a privileged environment for cheap fast and reproducible data generation.

PACS 47.80.Jk – Flow visualization and imaging.
PACS 87.19.-j – Properties of higher organisms.

1. – Introduction

In the last decades the development of computational techniques in fluid dynamics, together with the increasing performances of hardware and software allowed engineers to routinely solve problems on a virtual environment, to understand the role of biomechanics factors in the healthy and diseased cardiovascular system and to reveal the interplay of biology and mechanics that would have been nearly intractable in the past. The choice for designing protocols, testing hypothesis and validating models on a virtual environment has several advantages with respect to more traditional approaches: i) the

full control on all the parameters involved in the experimentation; ii) the repeatability of the experiment; iii) the feasibility of particular (non standard) scenarios. Here the early *in vivo* application of previously developed computational tools and knowledge [1] is discussed. In particular among all the nowadays clinical and biological issues that need detailed local hemodynamics knowledge, the two aspects discussed here are: the correct estimate of blood flow volume, starting from velocity data, and the quantification, by means of a new synthetic index, of the interplay existing between characteristic flow patterns and related wall phenomena.

2. – Material and methods

2˙1. *CFD-based estimation of flow rate in hemodynamic measurements.* – The correct quantification of the blood flow rate is a critical issue when only a single centerline velocity value is known, V_M. A very common approach in clinics is to hypothesize an *a priori* knowledge on the shape of the velocity profile (usually a parabola or a flat one). If we denote by D the vessel diameter, ν the blood viscosity and f the frequency of blood impulse, the dimensionless index

$$W = \frac{D}{2}\sqrt{\frac{2\pi f}{\nu}}\,, \tag{1}$$

called Womersley number, can be defined. In Ponzini *et al.* [2] an improved blood flow rate estimate from maximum velocity have been devised by exploiting CFD results based on a novel computational approach for boundary condition setting [3]. The basic idea was to find a general equation by introducing an explicit dependence on the Womersley number of the mean velocity:

$$U = g(V_M, W). \tag{2}$$

In 2007 Ponzini *et al.* applied this new formulation to Y-shaped by-pass grafts models and found very good confirmation (see [4]).

2˙2. *Wall related and bulk indices: a CFD analisys.* – Research studies over the last years have established that hemodynamic interactions with the vascular inner wall as well as surgical injury incite mechanisms capable of eliciting distal wall vessel intimal thickening and hyperplasia. The attempt to quantify this interplay, the analysis of the correlation of a Lagrangian bulk fluid-dynamics index (the helical flow index (HFI) as defined in [5]), and a well-established wall index (oscillating shear index (OSI)), has been done in four aorto-coronary bypass models using CFD. The very high linear inverse relationship ($R = -0.97$) found between OSI and HFI for the models under investigation suggest that the direct study might of this synthetic bulk index can furnish a significant information concerning the mechano-transduction wall phenomena and thus that the index might constitutes an important flow signature in vessels (see [6] for all the details).

2˙3. *From CFD to in vivo: an image based approach.* – The herein presented CFD approaches in haemodynamics allowed to perform detailed local quantification and extract novel knowledge in the two topics faced. Nevertheless the *in silico* approach should be regarded as an elective experimental environment that necessarily need to be validated by further extensive *in vivo* and *in vitro* experiments. In order to apply and test the portability to *in vivo* data we designed a 3D Cine Phase Contrast MRI protocol (PCMRI).

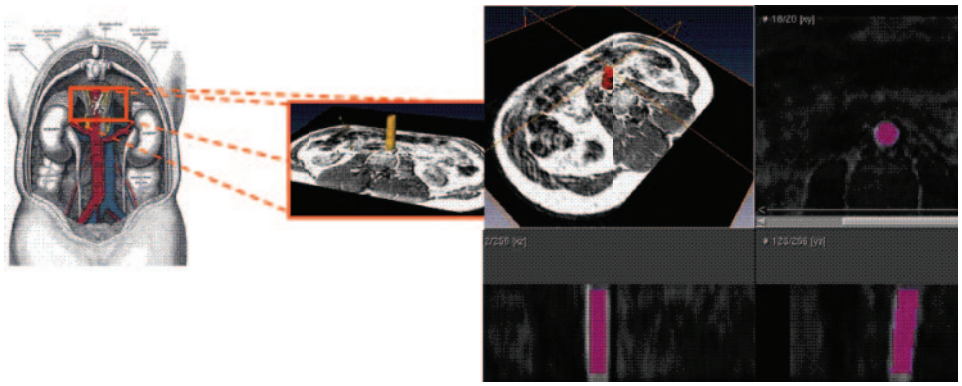

Fig. 1. – Anatomical site of interest.

This imaging technique is a suitable, accurate tool to acquire blood flow rate in human arteries. Moreover, within the same measurement procedure it is able to provide both geometrical and fluid dynamics data (the three directional velocity vector components along the heart cycle). In particular a straight section of 6 cm long of the abdominal aorta, proximal to the renal artery bifurcation (see fig. 1), of a healthy young man has been chosen as site of interest. The details on the parameters used in the acquisition of the PCMRI dataset, resulting in an acquisition time equal to ten minutes, are as follow: RM Philips Intera machine, 1.5T equipped with a 4 channel torse coil; TR equal to 16.1 ms; TE equal to 4.9 ms; voxel size of 1.37 mm × 1.37 mm × 3 mm; 22 time frames; 20 sections and a velocity encoding of 120 cm/s.

3. – Results

3˙1. *In vivo blood flow rate estimates.* – As expected by the high value of W (about 10), the 3D spatial velocity profiles are nor parabolic nor flat. In fig. 2 (left) they are shown in three time instant across the peak velocity instant in several slices. Keeping the blood flow rate value provided by the PCMRI data as gold-standard and using an *a priori* approach the estimate error on blood flow rate computation is about 30%; using the Womersely-based approach a percentage error value always below 5% is found.

3˙2. *In vivo HFI calculation.* – The full 4D (3D along time) nature of the blood as been captured thanks to the PCMRI dataset acquisition. By mimicking the Lagrangian approach used in CFD calculation the HFI value has been computed *in vivo*. In fig. 2 (right) a sample of particle traces injected at the end systole is shown. This is the first example of *in vivo* bulk index calculation in hemodynamics.

4. – Discussion and conclusion

A main remark can be made on the general methodological approach presented in [1] and discussed briefly here. A research approach based on CFD can be particulary rewarding in biomechanics. When based on robust computational tools and methods [3,6], CFD can furnish trustable data that can be used either to calibrate formulas either to validate clinical procedures either to describe biological complex phenomena. Starting

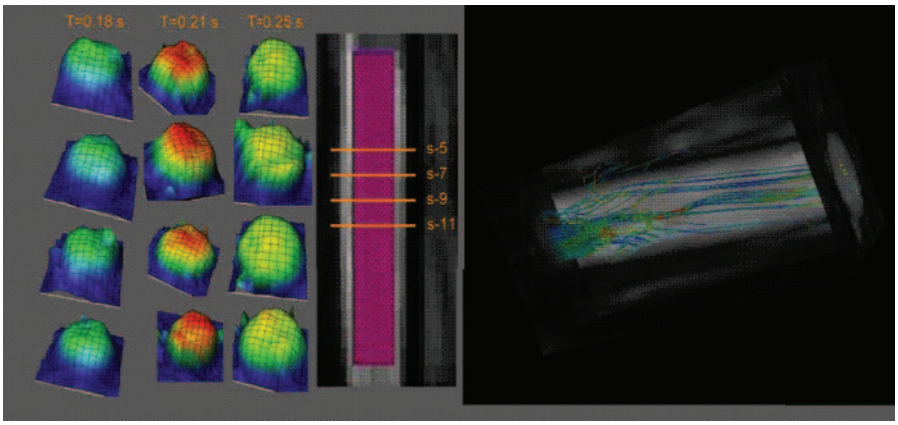

Fig. 2. – *In vivo* results: the spatial velocity profiles in three instant and across several section are shown (left). *In vivo* calculation and visualization of HFI index (right).

from the result provided *in silico* efficient and well-defined *in vivo* protocols can be then designed. At the moment the data acquisition on the two *in vivo* protocols described, with they very early results here, is still on-going but some concrete results has already been obtained in the analysis of the HFI in the human aortic arch (see [7]).

REFERENCES

[1] Ponzini R., "Computational modeling of local hemodynamics phenomena: methods, tools and clinical applications", PhD Thesis, Politecnico di Milano (2007).
[2] Ponzini R., Vergara C., Redaelli A. and Veneziani A., *Ultrasound Med. Biol.*, **32** (2006) 1545.
[3] Veneziani A. and Vergara C., *Int. J. Num. Methods Fluids*, **47** (2005) 803.
[4] Ponzini R., Lemma M., Morbiducci U., Montevecchi F. M. and Redaelli A., *Med. Eng. Phys.*, **30** (2008) 809.
[5] Grigioni M., Daniele C., Morbiducci U., Del Gaudio C., D'Avenio G., Balducci A. and Barbaro V., *J. Biomech.*, **38** (2005) 1375.
[6] Morbiducci U., Ponzini R., Grigioni M. and Redaelli A., *J. Biomech.*, **40** (2007) 519.
[7] Morbiducci U., Ponzini R., Rizzo G., Cadioli M., Esposito A., De Cobelli F., Del Maschio A., Montevecchi F. M. and Redaelli A., *Ann. Biomed. Eng.*, **37** (2009) 516.