Blood Flow Analysis in Portal Vein System – Unsteady-State Case Study

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Abstract— **Anatomical features and a complex vascular system characterize the liver. The blood flow results as a complex interaction between fluid, vascular system complex geometry and liver functional and structural features. The disease presence produces pathological changes that may induce hemodynamic perturbations not only due to geometry modification but especially due to liver perfusion alteration. The analysis of the blood flow dependence on the geometry variability in physiological condition could emerge in its parameterization and quantification. This may eliminate the confusion between blood flow modification due to geometry variability in physiological conditions and flow alteration due to pathological conditions or congenital anomalies presence.**

In this paper the analysis focuses on portal vein system and consists in blood flow analysis under unsteady-state conditions. The study involves the investigation of 12 patients by MRI techniques followed by 3-D portal vein system geometry acquisition, blood flow simulations based on mathematical models that include constitutive equations describing the hemodymanics and its relations with the deformable vessels wall. The computational technique applied to model the blood flow approaches both the velocity field and the pressure field. The vessels wall was considered elastic, coupling in this way the vessel/wall deformability problem.

The blood flow analysis in physiological conditions enables the improvement of understanding of the complex blood flow behavior in the portal vein system; enables to identify critical information and to parameterize the domain of normal portal vein circulation.

Keywords— **blood flow, CFD, MRI, mathematical modeling, hemodynamics.**

I. Introduction

During the recent years, especially in the field of medicine [1], visualization techniques gain an increased role in the scientific and/or engineering work. In parallel with the increase in computer power the techniques of image acquisition and processing became important investigation tools and data sources for modeling and simulation [2]. The research field employing flow visualization in anatomical features was the first beneficiary of the development of these techniques [3].

Coupling image acquisition and processing techniques with large computational grids originating from computational fluid dynamic (CFD) simulation the quality of feature representation and process analysis is improved.

Through the visualization and preprocessing techniques the real-world models and their associated data (i.e. velocity) are transposed in a virtual one, able to numerically simulate the flow and the fluid/structure interaction, by solving complex mathematical models based on Navier-Stokes equations and gaining scientific data and comprehensive graphical representations.

There are several authors that used this approach for studying the blood flow in the human body [4-6]. The velocity components being acquired either from MRI sequences or form ultrasound Doppler measurements and the data compared qualitatively with the predictions of CFD calculations.

In the present analysis the MRI sequences were used for 3D reconstruction of the portal vein system and the ultrasound Doppler measurements to provide the boundary condition for CFD model implementation.

The accuracy of such approach and the validity of the mathematical model used for blood flow simulation in 3D complex geometries were demonstrated in a previous work of Botar et al. [7]. Based on that, the purpose of this research was tracking physiological features of the blood flow in the portal vein system.

II. Problem Statement

The essentials in the present analysis relay on differentiation of physiological characteristics of the portal vein blood flow, its parameterization and quantification. For this reason, after obtaining the approval from the Ethics Committee of the University of Medicine and Farmacy "Iuliu-Hatieganu" and informed consent of patients, there were included in the study a series of 12 patients with physiological liver aspect. The clinical investigation consisted of Magnetic Resonance Imaging (MRI) and Ultrasound Doppler (UD).

The MR images were processed with MatLab software - Image Acquisition and Image Processing Toolboxes

S. Vlad and R.V. Ciupa (Eds.): MEDITECH 2011, IFMBE Proceedings 36, pp. 332–337, 2011.
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creating a binary version of the image by using the thresholding approach. The 3D portal vein system geometry reconstruction was performed using the SolidEdge V20 software. Further on, the computational fluid dynamics (CFD) technique was applied to describe the blood flow in the portal vein system.

The elastic wall conditions have been introduced based on mathematical models that include constitutive equations describing the hemodynamic and its relations with the deformable vessels wall. The constitutive model for the vessel wall is considered the hyperelastic one, as this model may cover non-linear stress-strain behaviour at modest strains, or elastic one up to huge strains.

The portal vein hemodynamic analysis considers the contribution of the confluent abdominal veins.

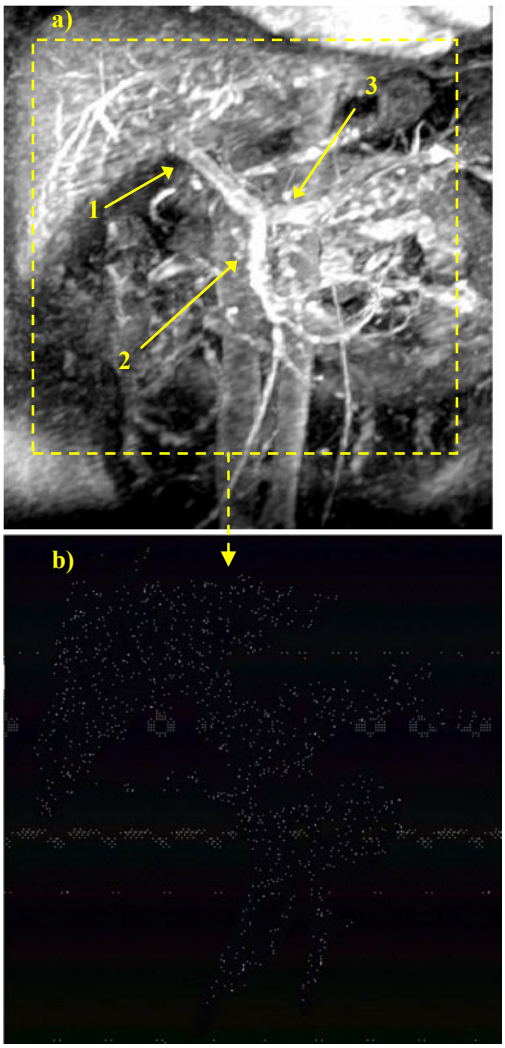


Fig. 1 Portal vein system: a) MRI and b) 3D SolidEdge V20 reconstruction, 1 - portal vein, 2 - Superior mesenteric vein, 3 – Splenic vein

III. Representation of the 3D Portal Vein Geometry

The objective of the 3D reconstruction of the portal vein system was to obtain a 3D realistic volume that reproduces as intimate as possible the complexity of the portal and of the associated veins system.

For each patient the same type of 3D reconstruction has been done in order to incorporate in the simulation the high diversity of the portal vein geometries.

The portal vein geometry acquisition has been done using a 1 T MRI system (Sigma LX, GE Medical Systems) with a 9.1.0723d software, 1270 MHz IP30 processor, main memory size 512 Mbytes, and a phase array TORSOPA receiver. The geometrical information have been extracted from a 3D TOF SPGR vascular sequence acquisition, using the SmartPrep option based on bolus detection (gadolinium). The apparatus settings consisted in: Angio TOF SPGR – 3D acquisition; maximum monitor period 12 s; image acquisition delay 4 sec; imaging options: Fatsat; SmartPrep; TE Min; Prep Time 21; FA 35; Bandwidth 41,67; FOV 40; Sl Th 2.2; Locs per slab 34; Freq/Phase 256/192; NEX 0.50; PhaseFOV 0.90; scanning time 0:23, breath hold.

The flow related data were acquired using in vivo Eco-Doppler technique. The medical investigations have been conducted using an Ultrasound Logiq 7 BT 06 machine, a Convex probe 4C, with the following B mode settings (Freq 4.0 MHz, AO=100%, Gn 78, DR 111), Doppler color settings (Freq 3,3 MHz, PRF 1.2 KHz, Gn 29, WF 175 KHz) and Pulse Doppler settings (SVL 4 mm, GN 23, PRF 3,5 KHz, DR 40, WF 69 Hz).

The 3D geometry reconstruction was done using the SolidEdge V20 software capabilities. An approximation has been made in what it concerns the shape of the geometric section in the distal branches of the geometry; the section shape has been considered circular.

The volume geometry has been imported in GAMBIT. The surfaces mesh was generated, using the face surface Quand/Pave algorithm and smoothed using the length-weighted Laplacian algorithm. The volume mesh was generated using the Tet/Hybrid/Tgrid algoritm. The spacing used was 1. The simulations were carried out by means of the CFD software Fluent. The geometric parameters (Table 1) used in simulations were determined by medical investigations.

The domains of the portal vein system investigated were the main branch and its left and right branches.

An un-steady state model has been used; considering the fluctuations of the blood flow between inspiration and expiration periods. In this way dependency of the blood flow in portal vein system has been considered. The tixotropic properties of the blood have been taken into account. The differential equations have been discretized in a manner of

finite element method. Mass flow boundary conditions have been specified at the geometry inlet. The inferior and superior values are provided by Doppler Ultrasound measurements to supply the user defined profile functions. The vessel walls have been treated as elastic. The no-slip condition was imposed to the vessels wall. It is necessary to mention that the geometric variability of the portal vein system from one patient to the other is very high.

Table 1 Values of experimental (clinical) parameters used in simulation

Pacient		1	2	3	4	5	6	7	8	9	10	11	12
Hepatic dimensions	LD [mm]	204	178	167	179	170	180	183	198	175	169	181	171
	LS [mm]	88	80	60	57	75	87	85	86	78	71	59	73
	LC [mm]	48	42	30	38	45	47.9	39.7	44	45	36	40.1	48
Portal vein dimensions	Inspiration [mm]	15	15.5	12.5	11.4	14.3	14.8	13.9	14.7	15.7	13.9	12.3	14.1
	Expiration [mm]	13.9	14.5	11.6	11	13.4	13.7	11.7	13.3	14.1	12.1	11.5	12.9
	length [cm]	6.7	5.4	6	5	7	6.8	6.3	6.5	5.5	6.2	5.2	6.8
Portal vein stream velocity	max. [cm/s]	29	27.2	25	28	26.1	30	29.8	28.2	26.9	25.7	27.1	26.7
	min. [cm/s]	22.9	23.5	19.7	20.1	19.2	25.3	23.6	21.8	21.3	18.9	20.9	19.3
Flow type		L	L	L	L	L	L	L	L	L	L	L	L
Splenic vein	max. velocity [cm/s]	21.8	21.6	22.1	27.2	22.3	26.3	24.1	21.7	21.5	20.1	20.9	26.7
	flow [ml/min]	192	210	177	185	168.5	188.3	181.7	189	206	197	179	147.1
Superior mesenteric vein	max. velocity [cm/s]	15.9	18.2	18	19.4	16.2	17.8	17.3	15.4	17.9	19.2	18.7	17.3

* flow type L = laminar, LD – right lobe, LS – left lobe, LC – caudate lobe.

IV. Modeling approach

The flow model considers the tixotropic characteristics of the blood. The blood is considered as a non-Newtonian fluid, the relation between the shear stress and the strain rate is nonlinear and time-dependent. The blood viscosity was defined according to the non-Newtonian power law:

Table 2 Values of experimental parameters used in simulation [8]

Power law index (n)	0.4851
Consistency index k (kg-s^n-2/m)	0.2073
Reference temperature (K)	310
Minimum viscosity limit ηmin (kg/m-s)	0.001
Maximum viscosity limit ηmax(kg/m-s)	0.003

The hemodynamic was described by the Reynolds stress model (RSM) instead of laminar model as the past experience showed that it gives accurate prediction of the blood flow in complex geometries [4]. The RSM is abandoning the isotropic eddy-viscosity hypothesis, and closes the Reynolds-averaged Navier-Stokes equations by solving transport equations for Reynolds stresses together with an equation for the dissipation rate. Since the RSM accounts for effects of streamline curvature, swirl, rotation, and rapid changes in strain rate, in a more rigorous manner than the one-equation and the two-equation flow models, it has been used in simulation due to its greater potential to give accurate predictions for complex flows [FLUENT 6.3 user guide]. More than that, using the Quadratic Pressure-Strain Model it is possible to obtain superior performance in a range of basic shear flows, including plane strain, rotating plane shear, and axisymmetric expansion/contraction. The non-equilibrium wall functions have been also considered to extend the applicability of the wall function approach by including the effects of pressure gradient and strong non-equilibrium (Fluent 6.3 User Guide, Chapter 12.7.4).

More than that, for low Reynolds numbers past experience showed that RSM model

The model equations are the following ones:

- the Reynolds stresses:

$$\rho\overline{u_i'u_j'} \tag{1}$$

- the transport equations:

$$\underbrace{\frac{\partial}{\partial t}\left(\rho\overline{u_i'u_j'}\right)}_{Local\ time\ derivative} + \underbrace{\frac{\partial}{\partial x_k}\left(\rho u_k\overline{u_i'u_j'}\right)}_{C_{ij}\equiv Convection} = \underbrace{-\frac{\partial}{\partial x_k}\left[\rho\overline{u_i'u_j'u_k'} + \overline{p\left(\delta_{kj}u_j' + \delta_{ik}u_j'\right)}\right]}_{D_{T,ij}\equiv Turbulent\ \ diffusion} + \underbrace{\frac{\partial}{\partial x_k}\left[\mu\frac{\partial}{\partial x_k}\left(\overline{u_i'u_j'}\right)\right]}_{D_{L,ij}\equiv Molecular\ \ diffusion} - \underbrace{\rho\left(\overline{u_i'u_k'}\frac{\partial u_j}{\partial x_k} + \overline{u_j'u_k'}\frac{\partial u_i}{\partial x_k}\right)}_{P_{ij}\equiv Stress\ production} - \underbrace{\rho\beta\left(g_i\overline{u_j'\theta} + g_j\overline{u_i'\theta}\right)}_{G_{ij}\equiv Buoyancy\ \ production} + \overline{p\left(\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i}\right)} - \overline{2\mu\left(\frac{\partial u_i'}{\partial x_k}\frac{\partial u_j'}{\partial x_k}\right)} - \underbrace{2\rho\Omega_k\left(\overline{u_j'u_m'}\epsilon_{ikm} + \overline{u_i'u_m'}\epsilon_{jkm}\right)}_{F_{ij}\equiv Production\ \ by\ system\ \ rotation} + \underbrace{S_{user}}_{\text{User-defined source term}} \tag{2}$$

Unsteady state conditions have been used. The differential equations have been discretized in a manner of finite element method. The operation and the boundary conditions have been specified. The vessel was treated as elastic. A dynamic mesh model was used in order to address the movement of the mesh in the unsteady state solver. The no-slip condition has been imposed.

V. Simulation results

The hemodynamic simulations in the portal vein system have been initialized considering the contributions of the

splenic and superior mesenteric veins. The resulted data, provided by the computer simulation, supply the values of the blood velocity along the entire portal vein geometry.

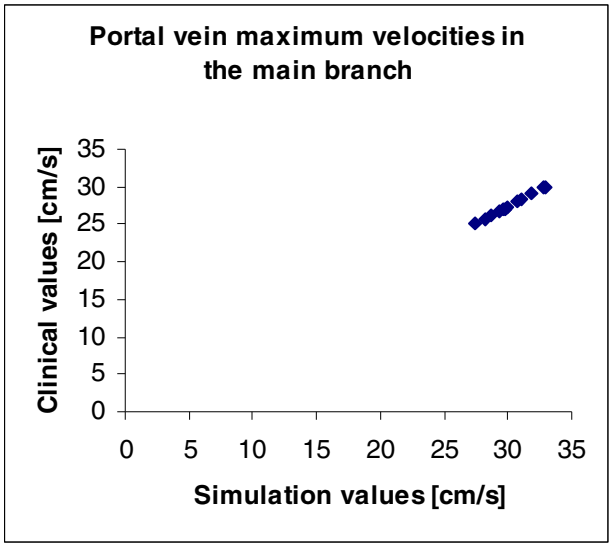


Fig. 2 Correlation between clinical and mathematical modeling data of blood velocity in the portal vein main branches during the inspiration period

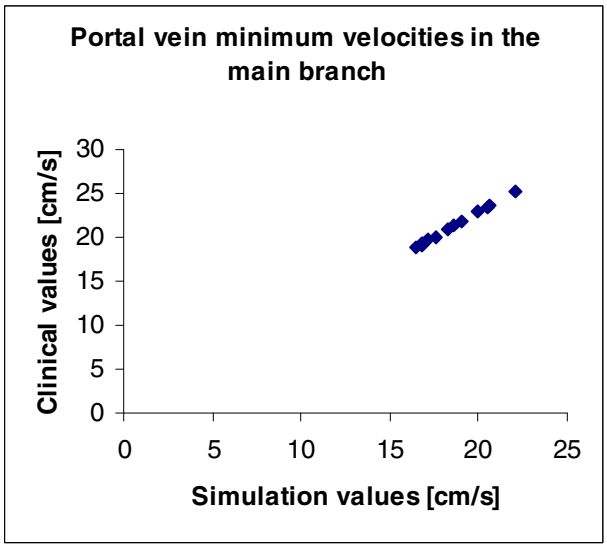


Fig. 3 Correlation between clinical and mathematical modeling data of blood velocity in the portal vein main branches during the expiration period

The analysis of the simulation results has been done according to the clinical investigations (Doppler Ultrasound). In the clinical experiments the velocity was measured in the portal vein main branch at 1 cm ahead from the branches bifurcation. A user profile user defined function was usedin simulations in order to cover the inspiration expiration cycle. The simulation results show a good agreement between clinical and mathematical modeling and simulation data (figures 2 and 3); both in case of inspiration and expiration periods.

To illustrate and to parameterize the behavior of the portal vein blood flow in its main branch, the distribution of the Reynolds number has been computed for all the geometries analyzed. The simulation results (figure 4) demonstrate that there exists a certain laminar domain in which the physiological blood flow takes place.

The range of Reynolds number extends between the values 2600 and 1020 in the region situated at 1 cm ahead the main portal vein bifurcation.

Extending the analysis to the left and to the right branches of the portal vein, the Reynolds number distribution is consistent with the data obtained in the portal vein main branch; even if the domain of Reynolds number differ significantly in the region situated this time at 2 cm after the main portal vein bifurcation.

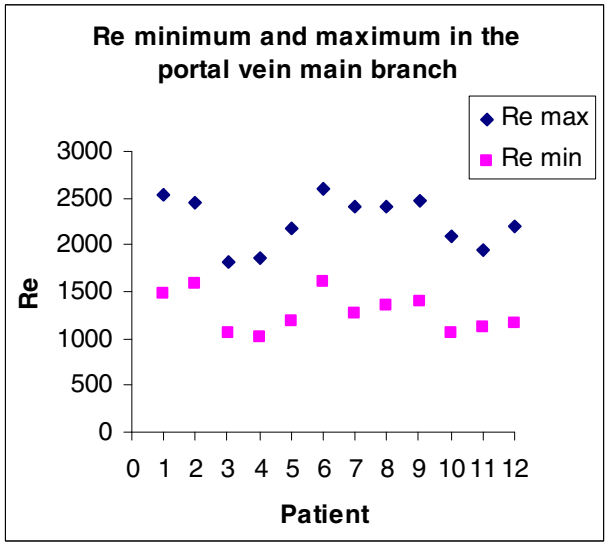


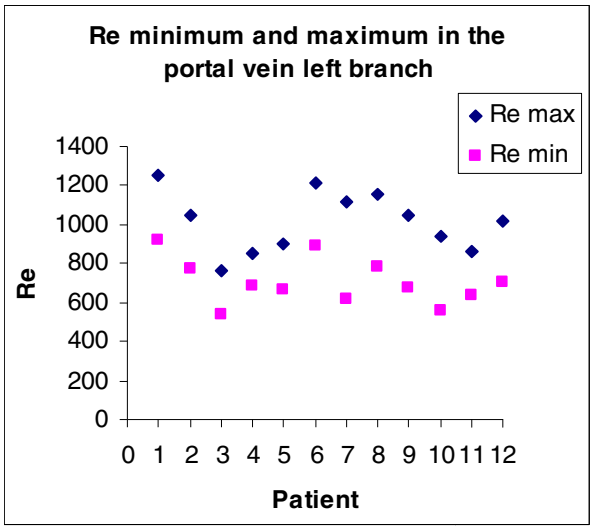
Fig. 4 Flow parameterization in the main branch of the portal vein

For the portal vein left branch the domain of Reynolds number extends between 1255 and 540 (Figure 5a), and for the portal vein right branch the values are comprised between 790 and 460 (Figure 5b).

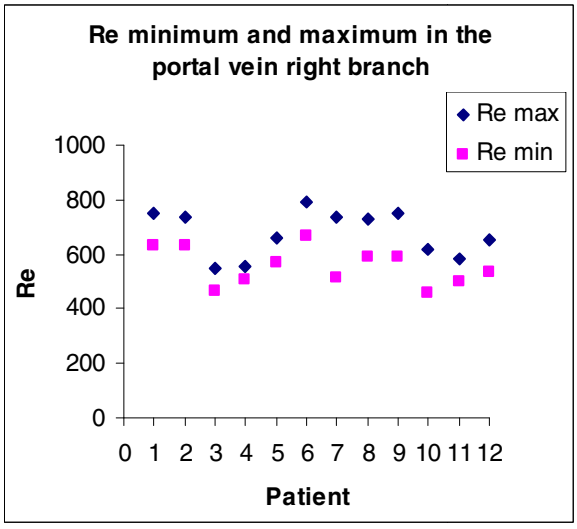
The flow homogeneity observed in the three regions of the portal vein system, for such a high geometric variety, enables the prediction of the blood flow behavior.

Turbulent blood flow, as anticipated by the clinical investigations, is uncommon in normal circulation, but it could occur when pathological signs are established.

In pathological conditions disturbed flow may result from reflux, outflow obstruction, and/or stasis which leads to venous inflammation and thrombosis, and as a consequence the development of chronic venous diseases.



(a)



(b)

Fig. 5 Flow parameterization in the left and right portal vein branches

The ability to predict blood flow along the portal vein system can lead to a better understanding of the liver blood perfusion in physiological conditions and to eliminate the confusion between blood flow modification due to geometry variability and flow alteration due to pathological or congenital anomalies presence.

Understanding of the physiological flow may also provide mechanistic insights into the role of complex flow patterns in pathogenesis of vascular diseases.

VI. Conclusions

In this paper a comprehensive framework for exploiting the 3D geometric variability of the portal vein system has been presented.

Specifically, the research was focused on detecting the geometric-dependent parameters capable to predict the behavior of the blood perfusion of the liver. The Reynolds number distribution has been found to be comprised in compact values ranges according to the topology of the investigated domain. This conclusion suggests the possibility of blood flow parameterization in liver physiological conditions. The proposed approach and the results obtain enables a straightforward analytical evaluation of the portal vein flow parameters especially for quick diagnosis purposes.

Acknowledgment

The authors are thankful for the financial support provided by the national project PNCDI2-12131, title “Expert system for the non-invasive prognosis of chronic hepatic pathology evolution through the analysis of the biological and portal hemodynamic parameters.”

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