Numerical Simulation of Thrombus Aspiration Catheter: Preliminary Results

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Abstract— **Thrombus aspiration is one of the available therapies for the treatment of thrombosis diseases. It is an effective option especially in the case of early stage clot formation. Nowadays there is a major research effort to improve catheter design in term of ease of use, less drawback and higher efficiency. The main aim of this study is to consider the performance of a standard catheter and predict the behavior of clot during the aspiration phase using computational fluid dynamics (CFD) techniques. Three cases are modeled and compared one another to assess catheter performance and efficiency according to different rheological models for the clot. In the first case the clot is considered to be Newtonian with early stage coagulation and no surface tension, in the second case the clot exhibits higher viscosity due to the longer time passed after coagulation, but it has not surface tension, in the third case the clot is assumed to be Newtonian which is formed in early stages of coagulation but has surface tension. In all cases clot is assumed to behave like a viscous fluid.**

Keywords— **Catheter, Clot, Viscosity, surface tension, CFD.**

I. INTRODUCTION

As a biological pump, heart needs nourishment and oxygen that are supplied through the coronary system. The coronary system can face different diseases like blockage by thrombosis. Vascular injury can lead to platelet aggregation and coagulation which per se lead to thrombin. In this process aggregation is the result of physical process while coagulation is the result of biochemical enzyme reactions [1]. Thrombosis is one of the main causes of mortality. There are different locations for thrombus formation: venous, deep vein, portal vein, renal vein. The thrombus formation process is complex and relates to a number of mechanical, physiological and pathological parameters. Among theses many factors, rheological parameters [2] are the most important and, in turn, mainly relate to the ratio of thrombin to fibrinogen [3] and the time elapsed after clot initiation.

Balloon angioplasty and stenting, fibrinolysis and mechanical thrombectomy are three approaches which can be used for the treatment. In any approach the efficacy of clot removal, procedure-related embolization rate and mortality are main parameters [4].

Angioplasty and stenting include:

Exciter laser coronary angioplasty, Cutting balloon angioplasty, Bare-metal stents, Drug-eluting stents.

Thrombectomy consists of: Simple Aspiration Devices, Hydrodynamic devices, Fragmentation Devices (Directional atherectomy, Rotational atherectomy, Extraction Athrectomy), Ultrasound devices. [4-5]

However cutting balloon and laser angioplasty did not show any improvement in restenosis. The most common used device is Angiojet Rheolytic Thrombectomy System (Possis Medical, Minneapolis,MN, USA) and the Export XT Aspiration Catheter (Medtronic Vascular, Santa Rosa, CA) [5].

However, generally speaking the comparison of the approaches is sometimes hard to judge because of lack of consistent data. There are many different aspiration catheters especially regarding to the tip shape like TVAC (duck-bill tip shape) (Nipro,Osaka, Japan), Thrombuster (Kaneka Medix Corporation, Osaka, Japan), Percusurge Export catheter (Medtronics, Minneapolis, MN), Rescue (oblique straight tip shape) (Boston Scientific, Natic, MA) and Diver CE Catheter (Invatec, Roncadelle, BS, Italy). For example TVAC showed high performance for intramural aspiration due to its special tip shape [6-7]. The aim of this work is to describe and better understand the clot behavior during absorption through catheter under different assumptions on clot rheology.

II. MATERIAL AND METHODS

For absorption of clot, the catheter is deployed and guided along the coronary vessel to proximally reach the clot. From case to case the absorption can be even done from the distance of 2 cm. In the normal procedure it is sometimes needed to apply aspiration more than one time to absorb the entire clot.

Usually the catheter for coronary purpose has 2-2.6 mm (6F-7F) diameter, almost half of the size of the coronary. (Figure 1) [7]. The catheter is formed of two lumens which are inside each other: the smaller tube is for guidance while the larger one is for clot absorption. However in this study the catheter assumed to have 0.85 mm diameter.

In reality the applied suction pressure follows a diagram in such a way that it is almost flat in its starting phase, then decreasing to zero with steep slope [8], however in this work a constant negative pressure is applied through the catheter.

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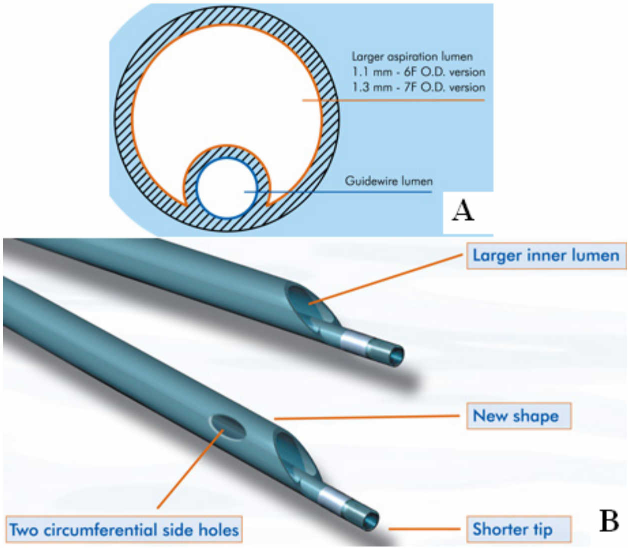

Fig. 1 Schematic view of Diver CE Catheter , A) tip shape and B) body shape for the catheter with and without lateral holes, [7]

A. *Viscosity Models*

The mechanical properties of blood and clot are very important in predicting and modeling their behavior during suction. In this work the blood behavior is considered to be Newtonian. This is mainly true when the velocity is high enough, say the shear rate is higher than 100 s^{-1} [9]. The clot mechanical properties varies radically due to different parameters like blood hematocrit [10], time passed after coagulation, clot type and forming procedure [2]. The properties of blood are given in Table 1 according to Gay et al. [11].

Balossino et al. [8] considered the clot in its early time after coagulation when its viscosity is 0.035 Pa·s, ten times larger than normal blood viscosity and the surface tension is 0.05 N/m.

In this work it is assumed that clot absorption in blood field can be described as a two-phase flow and the Volume-of-Fluid (VOF) technique is used to trace the interface of two phases [8].

Table 1 Mechanical properties of blood and clot

Parameters	Value
Blood density	1060 kg/m^3
Blood viscosity	0.0035 Pa·s
Early clot viscosity	0.035 Pa·s
Late clot viscosity	0.6 Pa·s

B. *Modeling*

In this work the clot behavior is studied in the period after suction start, monitoring how much clot is absorbed and how its shape changes. To the purpose three different cases are applied and considered. In case 1, the clot has just formed and is almost soft enough to be considered with a ten-time viscosity of blood (0.035 Pa·s) [8]. In this case surface tension is not considered between clot and blood, the vessel nor catheter. Furthermore blood density is set to 1060 kg/m^3. In case 2, the clot has a much higher viscosity (0.6 Pa·s) which corresponds to a longer time elapsed since coagulation initiation. In Case 3, the surface tension with amount of 0.1 N/m is considered to play a role while the clot viscosity is Newtonian (viscosity equal to 0.035 Pa·s). The geometry is meshed using ANSYS ICEM CFD 12.1 (ANSYS Inc., Canonsburg, PA, USA) with tetrahedral elements.

C. *Mathematics Background*

The adopted numerical procedure is based on the finite volume commercial package ANSYS/Fluent 12.1. First the domain is discretized to apply the finite volume form of equation of mass, momentum and volume of fluid interface.

The formula of mass and momentum conservation for an incompressible fluid are as follow:

$$\nabla u = 0 \tag{1}$$

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla\left(\rho \vec{u} \vec{u}\right) = -\nabla p + \nabla \tau + \rho g \tag{2}$$

where u is the fluid velocity, ρ is the fluid density, p is the pressure and τ is the stress tensor. The interface locations between the two fluids (blood and clot) are traced through Volume of Fluid (VOF) approach. In VOF methodology [12], the volume of each fluid is defined in the cell through the formula $F_{vol}=\gamma \cdot V_{cell}$, where V_{cell} is the computational cell volume and γ is the liquid fraction in this cell. When the cell is totally filled by one fluid, γ is equal to 1; if it is filled by the other, γ is equal to 0; if the cell is partially filled by either volume, γ should satisfy the following equation:

$$\frac{\partial \gamma}{\partial t} + \nabla\left(\gamma u\right) + \nabla\left[\gamma\left(1-\gamma\right)u_r\right] = 0 \tag{3}$$

where u_r is the velocity field at interface [13]. A single momentum equation is solved for the entire domain and the velocity filed is shared between the fluid phases [12].

The generic properties in each cell (θ) are computed according to following equation [13]:

$$\theta = \gamma \cdot \theta_{fluid\,1} + \left(1-\gamma\right)\theta_{fluid\,2} \tag{4}$$

In this study the adopted solution methods include: PRESTO for pressure, second order upwind for momentum, PISO for pressure-velocity coupling and Geo-reconstruct for volume fraction.

The vessel diameter is 4.2 mm while the inside diameter of catheter is 0.85 mm in this study. A schematic view of the catheter tip in the artery is shown in Figure 2. The applied pressure through catheter is 100.000 Pa.

III. RESULTS

Figures 3 shows snap shots of fluid (blood and clot movement) as time progresses from start of applying negative pressure. Clot is visible as black part in the figure. At early stage of clot absorption (0.005 s after suction start) the amount of absorbed early clot is higher than late clot. This trend will be same until all clot is absorbed, which means that it needs a little bit more time to absorbing late clot comparing to early clot. However this extra time is not significant. Anyhow the shape of clot during absorption is almost the same for theses two cases. Regarding to Figure 3-c the shape of clot during absorption is completely different when the surface tension is considered by the amount of 0.1 N/m. Furthermore it seems that the absorbed clot in this case is almost the least at the same time comparing the two other cases (with no surface tension). However it is clear that the entire clot is absorbed via catheter in all the three cases.

The velocity contours and vectors at the time 0.005 s after suction start for the first case are presented in Figure 4. The velocity differs radically from inside to outside the catheter. Furthermore there is a relatively large area of vortex flow right at the tip, in upper region of the catheter. Inside the catheter the velocity shows a higher amount in the superior aspect of the catheter rather than in its inferior part.

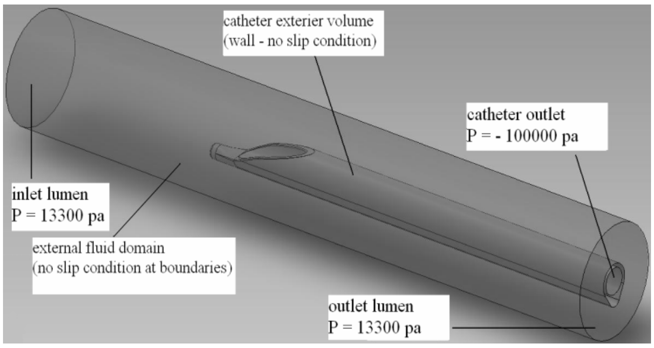

Fig. 2 Schematic view of the vessel, the catheter inside and the imposed boundary conditions

Fig. 3 Snap shots of clot absorption when time progresses, for the three cases of A) early clot, Newtonian, viscosity 0.035 Pa•s, no surface tension; B) late clot, Newtonian, viscosity 0.6 Pa•s, no surface tension; C) Newtonian, viscosity 0.035 Pa•s, surface tension 0.1 N/m

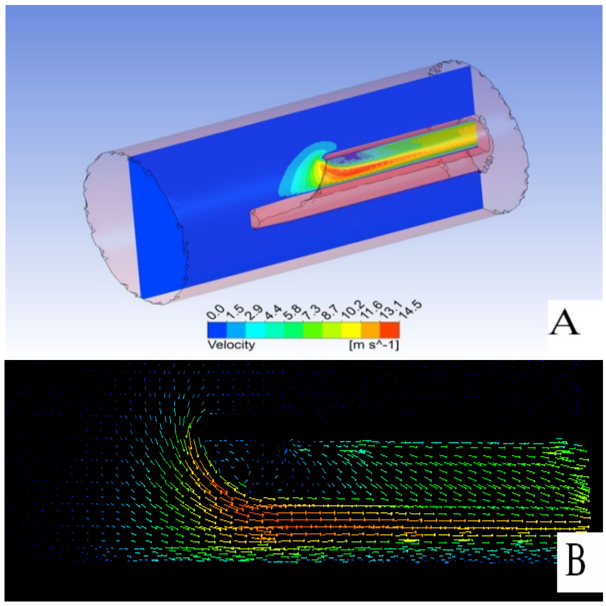

Fig. 4 The A) contour and B) vector maps of fluid velocity in the area around the catheter tip at time 0.005 s after suction start for the case of clot with viscosity 0.035 Pa•s and no surface tension

IV. Conclusions

In this work the behavior of a blood clot is investigated. The preliminary results from modeling show that during the clot absorption procedure, the shape of clot and the absorbed amount vary according to the rheological properties of clot. So far clot properties have been changed in terms of viscosity, whether they are in an early and late phases of maturation. The case with surface tension has also been studied to assess whether it may cause a difference in the absorption rate. In the case of late clot type the amount of clot absorption slightly varies, but the clot shape is more importantly affected when surface tension is modeled.

Numerical simulations clearly indicated that mechanical properties can play role in clot movement, which is different in the three cases. According to the model results in all cases, clot will be completely absorbed in a short time after suction start. It means that the applied pressure is large enough for aspiring all clot inside the vessel in all cases. When the surface tension is taken into account, simulation results indicate that it has a main effect on the clot shape during absorption.

One may consider that manipulating the entrance geometry at the tip of catheter can lead to higher performance in term of less blood, but higher fraction of clot absorption. In future development, the effect of different designs of the catheter tip on clot aspiration will also be investigated. Since there is a limitation for the aspiration pressure mainly due the collapse of the arterial wall, the pressure parameter will also be studied to understand the whole system behavior in terms of the ratio of clot to blood absorption. Furthermore the applied negative pressure curve exhibits an extended plateau at the beginning and then a decrease while the adopted boundary conditions at the vessel wall are steady in the present study. Future work could include the systolic-diastolic change, too.

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References

1. Leiderman K, Ferguson AL (2010) Grow with the flow: a spatial–temporal model of platelet deposition and blood coagulation under flow. Math Med Biol 28:47-84
2. Anand M, Rajagopal K, Rajagopal K R (2006) A viscoelastic fluid model for describing the mechanics of a coarse ligated plasma clot. Theor Comput Fluid Dyn 20: 239–250
3. Collet JP, Woodhead JL, Soria J et al. (1996) Fibrinogen Dusart: Electron Microscopy of Molecules, Fibers and Clots, and Viscoelastic Properties of Clots. Biophys J 70: 500-510
4. Muller-Hulsbeck S and Jahnke T (2003) Peripheral Arterial Applications of Percutaneous Mechanical Thrombectomy. Techniques in Vascular and Interventional Radiology 6: 22-34
5. Hudson PA, Kim MS, Carroll JD (2010) Coronary ischemia and percutaneous intervention. Cardiovascular Pathology 19:12–21
6. Sakurada M, Ikari Y and Isshiki T (2004) Improved Performance of a New Thrombus Aspiration Catheter: Outcomes From In Vitro Experiments and a Case Presentation. Catheterization and Cardiovascular Interventions 63:299–306
7. INVATEC at http://www.invatec.com/tool/home
8. Balossino R, Dubini G, Migliavacca F et al. (2010) Numerical simulation of thrombus aspiration in two realistic models of catheter tips. Artificial Organs 34:301–310
9. Johnston BM, Johnston PR, Corney S, Kilpatrick D (2006) Non-Newtonian blood flow in human right coronary arteries. Transient simulations Journal of Biomechanics 39: 1116–1128
10. Schmitt C, Henni AH and Cloutier G (2007) Characterization of Time-Varying Mechanical Viscoelastic Parameters of Mimicking Deep Vein Thrombi with 2D Dynamic Elastography. IEEE International Ultrasonics Symposium Proc, New York, USA, 2007, pp 1009-1012
11. Gay M and Zhang LT (2009) Numerical studies of blood flow in healthy, stenosed, and stented carotid. Int. J. Numer. Meth. Fluids 61:453–472
12. Hirt CW and Nicols BD (1981) Volume of Fluid (VOF) method for the dynamics of free boundaries. J Comp Phys 39: 201-225
13. Favero JL, Cardozo NS, Secchi AR, Jasakc H (2010) Simulation of Free Surface Viscoelastic Fluid Flow Using the viscoelastic InterFoam Solver. 20th European Symposium on Computer Aided Process Engineering – ESCAPE20 Proc, Ischia, Naples, Italy, 2010, pp 31-36