# O Método MPS de Simulação Computacional: aplicações ao estudo do escoamento sanguíneo

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## RESUMO

A necessidade de analisar, em termos microscópicos, o comportamento mecânico do escoamento sanguíneo foi uma das principais motivações para investigar as potencialidades do método MPS ("moving-particle semi-implicit") no estudo dos biofluidos. Este novo método, de geração automática de malhas, utiliza as equações de "Navier-Stokes" para simular diversos fenómenos em fluidos incompressíveis. Em termos gerais, o escoamento sanguíneo é discretizado por partículas que se deslocam por intermédio de coordenadas "Lagrangianas", onde o plasma e as plaquetas são modelados por partículas do fluido, os glóbulos vermelhos por partículas elásticas e as paredes dos vasos sanguíneos por partículas rígidas. Neste âmbito, o principal objectivo deste artigo é fazer uma breve descrição de várias aplicações do método MPS no estudo do escoamento sanguíneo. Estudos preliminares sugerem que o método permite analisar a deformação dos glóbulos vermelhos sob a acção do plasma bem como a formação, desenvolvimento e destruição do trombo.

# A Particle Method Computer Simulation: applications to the study of blood flow

## ABSTRACT

The need to analyse the microscopic mechanical behaviour of blood flow was one of the main reasons to develop a new computer simulation using a particle method. This new mesh free method is based on a moving-particle semi-implicit (MPS) method, which has been developed to simulate incompressible fluids based on the Navier-Stokes equations. The simulation region was discretized by particles that moves in Lagrangian coordinates, where the plasma and platelets were modelled as fluid particles, red blood cells (RBC) as elastic particles and vessel wall as rigid particles. In this paper, some applications of the MPS method to study the blood flow are briefly analysed, such as the motion and deformation of red blood cells (RBC) in plasma flow and the platelet aggregation process in blood flow. Some preliminary studies suggest that there is evidence that the proposed method enables the analysis of the RBC motion and deformation in the plasma flow and also the initial thrombogenesis, growth and destruction of thrombus.

## INTRODUCTION

Presently, cardiovascular disease is one of the most frequent causes of death in the industrialized world [1]. There is considerable indication that complex hemodynamics (blood fluid mechanics) play an important role in the development of artherosclerosis and other kinds of vascular diseases [2, 3]. Although, the high amount of experimental, numerical and theoretical studies conducted in this area, according to our knowledge, there is not any study that reveals a direct evidence of the role of the blood fluid dynamics in the atherogenic process [3]. In this way some unresolved questions need to be clarified, specially mechanisms at a microscopic level, such as the interaction between blood cells and the plasma and the aggregation process of platelets in blood flow.

Although the human blood can be regarded as a homogenous fluid from a macroscopic point of view, at a microscopic scale blood can be treated as a fluid mainly composed of plasma and

cells such as red blood cells (RBCs), white blood cells (WBCs) and platelets. Consequently an excellent approach to investigate the microscopic mechanical behaviour of blood flow is to consider the human blood as a set of suspended discrete particles. As a result the particle methods are a natural choice to simulate blood flow at a microscopic viewpoint.

Over the years, classical numerical techniques, such as finite element method (FEM) or finite volume method (FVM), have been considering blood as a homogeneous fluid in order to model vascular flow. However, recently some computational approaches using discrete particle have been proposed to investigate the dynamic behaviour of blood cells in the blood flow, such as formation and destruction of thrombi by platelet interaction [4], interaction between monocytes and platelets and a vascular surface [5]. More recently, Tsubota and his colleagues [6] have been developing a computer simulation method for microscopic blood flow using a particle method in order to analyse the RBC motion and deformation, plasma flow and their interactions. This new computer simulation method is based on the Moving-Particle Semi-Implicit (MPS) method.

The first purpose of this paper is to give some essential background about the mesh free particle methods. A second purpose is to investigate the potentialities of the MPS method to model blood flow from a microscopic viewpoint.

## MESH FREE PARTICLE METHODS

Since the invention of the FEM (1950), this very powerful method has become the most popular and widely used to solve engineering problems. In general, the FEM divides a continuum domain into discrete elements, which are connected together in a predefined manner (mesh or grid). In this way, the key of FEM is that a mesh must be predefined in order to provide a particular relationship between the nodes. Despite the great success of the grid-based numerical methods, such as FEM, these methods have several limitations in analysing very complex geometries and physical problems, which consequently limit their applications to solve many kinds of complex problems in biomechanics [7, 8].

The limitations of grid-based method have promoted (from 1977) the development of several mesh less or mesh free (MFree) methods in order to eliminate a mesh with predefined relationship between the nodes. MFree methods use not only a set of distributed nodes (or particles) within the problem domain but also a set of nodes (or particles) distributed on the boundary of the domain in order to represent the problem domain and its boundaries [7, 8].

The mesh free particle methods (MfreePM) are the earliest class of MFree methods and some examples are SPH, Molecular dynamics (MD), Lattice Bolztmann equation (LBE), Discrete element method (DEM) and MPS. Generally, this kind of MFree methods uses a set of finite number of discrete particles to express the system in a discretized form and to analize its mechanical behaviour, as shown in Fig.1. Every particle can represents one discrete physical object (ex. platelets) or can be generated as a set of particles to represent a part of the continuum domain (ex. RBCs, or plasma) [8].

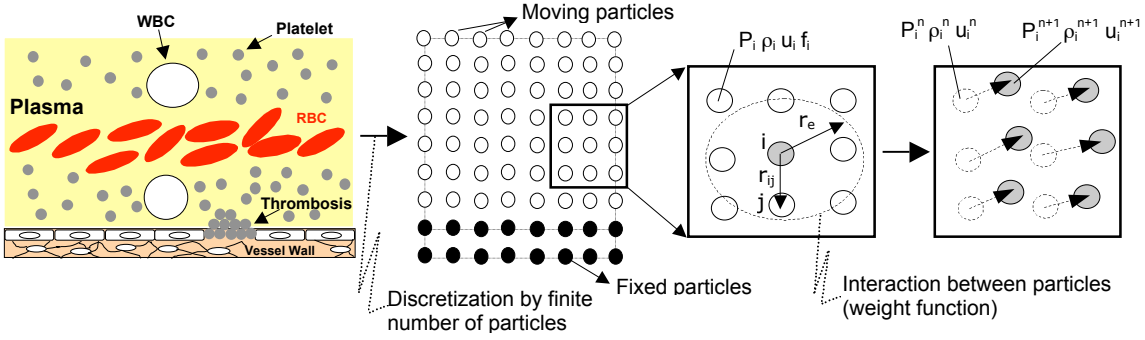


Figure 1 – General concept of the particle method in the blood flow.

The distinct advantages of the MfreePMs,such SPH over traditional grid-based numerical methods have motivated some researchers to implement the SPH into a wide range of

problems in either computational fluid or solid mechanics. Despite the wide applications of this method, there have been relatively few studies on modelling blood flow.

Several improvements have been developed through the years to improve stability, accuracy and computation speed of the SPH method [7, 8]. A good example is the MPS method developed by Koshizuka and his colleagues [9]. This method due to the modification of the Kernel function and incompressibility model the numerical stability and computation speed was remarkably improved. In brief, the MPS method is a deterministic particle method that uses a fully Lagrangian technique to simulate incompressible viscous flow. The method uses a modified kernel function in the particle interaction models and a semi-implicit algorithm is employed for the incompressible model. The algorithm consists in a penalty-like formulation to adjust the pressure whenever density variations occur [9].

## METHODS

### Governing Equations

Navier-Stokes equations were solved for blood plasma flow using a particle method in which continuum body was discretized by moving particles. In both studies, a moving particle semi-implicit (MPS) method was used as a particle method, where the particle number density was kept to be its reference value in order to express the incompressibility condition. Spatial differentiation such as gradient and Laplacian of physical quantity was expressed by the sum of the interaction between two particles with a weighing function of the particle distance. More detailed explanation about the MPS model and algorithm can been seen in the references [6, 9].

## APPLICATIONS TO STUDY THE BLOOD FLOW

### Motion and Deformation of blood cells

RBC Deformation

A two-dimensional circular model of RBC membrane was constructed from 60 line elements. Elastic energy of the membrane was considered for changes in the length of the element and the angle between the neighbor elements [10]. Based on minimum energy principle, shape change of a swollen RBC was obtained by decreasing the area by $70\,\%$. More detail description can been seen in the References [6,10,11].

Particle Model of Blood Flow

A two-dimensional particle model was constructed for the blood flow between parallel rigid plates placed as vessel walls. The model consisted of fluid particles for the blood plasma, elastic particles for the RBC membrane, and rigid particles for the vessel wall. The physical property of the plasma was assumed to be the same as that of water. The total number of the particles was 4737, and the mean distance between two particles was $0.5\,\mu\mathrm{m}$. As a boundary condition, constant and uniform velocity in the axial direction was applied to the virtual fluid particles placed at the inlet. Reynolds number to the distance between the plates $D$ was 0.008. Zero pressure was applied at the outlet, and non-slip condition at the inner vessel wall [11].

Results

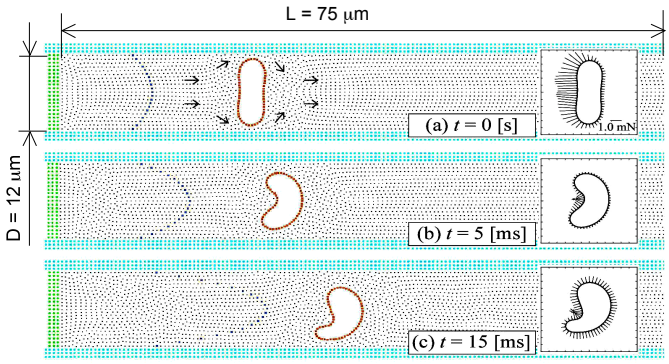


Figure 2 – RBC motion and deformation in plasma flow.

A simulation result revealed change in RBC shape and position in flowing plasma. At the initial state, the plasma flow with the fixed RBC was steady as shown in Fig.2(a). Poiseuille flow of the blood plasma was obtained in the upstream side of the RBC. The plasma flowed between the fixed RBC and the vessel wall, as indicated by the arrows in Fig.2(a), with decreasing its pressure. The fluid force due to pressure was higher at the upstream side than the downstream. The RBC was subjected to the pressure force near the wall, leading to compression of the RBC in the direction perpendicular to the vessel walls. These forces drove the RBC to move toward the downstream side, and caused deformation of the RBC in parachute-like shape, as shown in Figs.2(b) and (c)[11].

## Platelet Aggregation Process

Model of platelets aggregation

In this study, we propose the mathematical model of the aggregation and adhesion of platelets to the injured vessel [12]. Since the size of each platelet is considered to be very small compared to the characteristic size of blood vessel, platelets are assumed to move along with blood plasma flow when they are far from the injured part of blood vessel. In the near region of the injured part, aggregation of the platelets is assumed to be stochastic and its probability to be higher for the platelets closer to the injured part. This probability is expressed by introducing an attractive force acting between platelets and the injured wall (Eq. 1). When the platelets are very close to injured part, the platelets are assumed to adhere with injured part and neighbour platelets, and to behave as solid. The deformation of adhered platelets as a solid is expressed by introducing spring force acting between platelet and injured wall, and between platelet and platelet (Eqs. 2 & 3) [12].

$$f^{I}_{ij} = -\frac{\partial \Phi}{\partial r}\frac{\boldsymbol{r}_{ij}}{|\boldsymbol{r}_{ij}|} = -A\frac{1}{\delta}\left(2-\frac{|\boldsymbol{r}_{ij}|}{\delta}\right)\exp\left\{-\left(\frac{|\boldsymbol{r}_{ij}|}{\delta}-1\right)\right\}\frac{\boldsymbol{r}_{ij}}{|\boldsymbol{r}_{ij}|} \qquad (r_{ij} < d_{ag}) \quad (1)$$

$$\boldsymbol{f}^{S}_{ij} = \begin{cases} \int k_S(\boldsymbol{v}^{j}_{s} - \boldsymbol{v}^{i}_{s})dt & (r_{ij} \le d_{ad}) \\ 0 & (r_{ij} > d_{ad}) \end{cases} \quad (2)$$

$$\boldsymbol{f}^{A}_{ij} = \begin{cases} k_A(r_{ij} - r_0) & (r_{ij} \le d_{ad}) \\ 0 & (r_{ij} > d_{ad}) \end{cases} \quad (3)$$

Here the parameter "$r_{ij}$"denotes the distance between the particles "i" and "j". The parameters "$d_{ag}$" and "$d_{ad}$" ($d_{ad} < d_{ag}$) are used to determine the platelets condition, where "$d_{ag}$" is for aggregation of the platelets and "$d_{ad}$" for adhesion. Thus, for $d_{ag} < r_{ij}$ the platelet moves along with plasma flow; $d_{ad} < r_{ij} < d_{ag}$ the platelet approaches to the injured part (due to the attractive force) and when $r_{ij} < d_{ad}$ the platelet behaves as solid (with a spring force) [12].

A two-dimensional model of blood flow between parallel plates was constructed using fluid particles for plasma and platelets, and rigid particles for the parallel plates as blood vessel walls.

Results

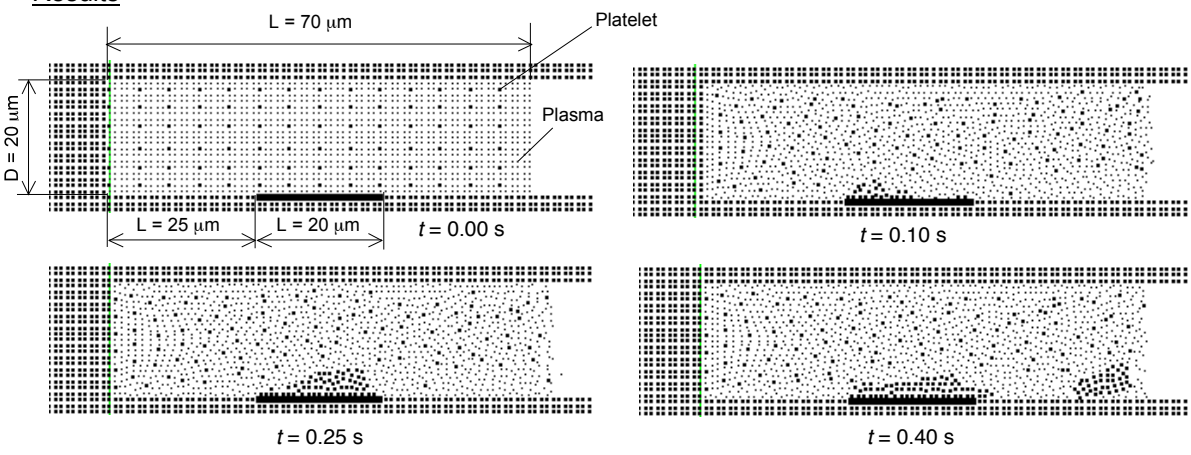


Figure 3 – Thrombogenesis due to platelets aggregation.

At t = 0.1s the platelets start to aggregate to the injured wall due to an attractive force acting between platelets and the injured wall. After the first aggregation the number of platelets

attached to the injured wall increases with time and the shape of the aggregated platelets grows until t = 0.4s. Thereafter, the platelets detach due to the fluid force of the plasma flow. These results suggest that the proposed particle method can simulate initial thrombogenesis, growth and destruction of thrombus [12].

## FUTURE RESEARCH DIRECTIONS

Although the proposed method seems to be very useful in evaluating the microscopic mechanical behaviour of blood flow, the results obtain by numerical simulation need to be validated by comparing with experimental data. In this way, we are currently developing a parallel plate flow chamber by means of a confocal micro particle image velocimeter (μPIV). In addition, another very important ongoing work is to perform larger-scale calculation using a parallel computer system. The large-scale calculation will increase significantly the number of particles used in the propsed particle method, which enables us to perform a three dimensional analysis for a larger domain.

## CONCLUSIONS

Two applications of the MPS method to study the blood flow were briefly analysed. Some preliminary studies suggest that there is evidence that the proposed method enables the analysis of the RBC motion and deformation in the plasma flow and also the initial thrombogenesis, growth and destruction of thrombus. As a result, the proposed particle method suggest that this method is potentially an important and useful approach to investigate the mechanical behaviour of the blood cells under blood flow at a microscopic level.

## ACKNOWLEDGMENTS

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