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Retraction

Retracted: Numerical Simulation of Particle Deposition in Arterial Bifurcation via Lattice Boltzmann Method

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This article has been retracted by Hindawi following an investigation undertaken by the publisher [1]. This investigation has uncovered evidence of one or more of the following indicators of systematic manipulation of the publication process:

(1) Discrepancies in scope

(2) Discrepancies in the description of the research reported

(3) Discrepancies between the availability of data and the research described

(4) Inappropriate citations

(5) Incoherent, meaningless and/or irrelevant content included in the article

(6) Peer-review manipulation

The presence of these indicators undermines our confidence in the integrity of the article's content and we cannot, therefore, vouch for its reliability. Please note that this notice is intended solely to alert readers that the content of this article is unreliable. We have not investigated whether authors were aware of or involved in the systematic manipulation of the publication process.

Wiley and Hindawi regrets that the usual quality checks did not identify these issues before publication and have since put additional measures in place to safeguard research integrity.

We wish to credit our own Research Integrity and Research Publishing teams and anonymous and named external researchers and research integrity experts for contributing to this investigation.

The corresponding author, as the representative of all authors, has been given the opportunity to register their agreement or disagreement to this retraction. We have kept a record of any response received.

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[1] H. Yi, "Numerical Simulation of Particle Deposition in Arterial Bifurcation via Lattice Boltzmann Method," *Journal of Function Spaces*, vol. 2022, Article ID 3873484, 6 pages, 2022.

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Research Article

Numerical Simulation of Particle Deposition in Arterial Bifurcation via Lattice Boltzmann Method

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Arterial bifurcation plays a key role in cardiovascular system, so studying the characteristic of the blood flows near bifurcated arteries is of great importance in hemodynamics. The lattice Boltzmann (LB) model is used to observe the behavior of the particle deposition near the bifurcated artery. The mechanical quantity, including particle trajectories, velocities, and angular velocities, is studied numerically by LB simulations. The particle is prone to stasis as it is close to the wall of bifurcated vessel for small flow Reynolds number. Larger branch angle leads to higher possibility of particle stagnation. The numerical results are consistent with the clinical observation. The study provides a basis for understanding the mechanism of hemodynamics near bifurcations and will provide a research basis for clinical diagnosis and treatment of patients with atherosclerosis.

1. Introduction

Arterial branching is a major feature in the cardiovascular system. The most common branching pattern is that one stream of blood divides into two independent streams. As a stream-dividing unit, arterial bifurcation plays a key role in cardiovascular system. Atherosclerosis refers to the deposition of lipids (cholesterol, cholesterol esters, and phospholipids) in the intima of the artery, accompanied by the proliferation of smooth muscle cells and fiber components, and gradually develops into localized plaques. Clinical and autopsy studies show that arterial disease such as atherosclerosis has high selectivity of the lesion in complex flow areas such as bifurcation, confluence, and bend in the coronary artery, abdominal aorta, femoral artery, and carotid artery. Investigating the characteristic of the blood flows near bifurcated arteries is of great importance in hemodynamics and may provide a better understanding of the relation between arterial disease and structure of arterial bifurcations. Due to the complexity and limitations of blood vessels and the human body, numerical simulation is considered to be an effective method to measure blood circulations.

As a branch of fluid mechanics, Computational Fluid Dynamic (CFD) is the use of numerical methods to solve hydrodynamic problems. It adopts numerical methods to solve the governing equations of fluid dynamics and predict the laws of fluid motion. Especially in complex situations, measurement is often difficult or even impossible, but CFD can easily provide detailed information about flow fields. In recent years, it has been widely used in chemical, metallurgy, architecture, environment, and other related fields.

Since the proposal of the lattice Boltzmann method (LBM) [1], it has been reckoned as an effective method in CFD. The LBM has the advantages of simple algorithm, easy processing of complex boundary, and suitable for parallel computing. Recently, the LBM has been extensively applied in theoretical research and engineering fields and has been successfully used to implement blood flow simulations. The research contents mainly include transient blood flow in arteries with an artificial heart valve [2], blood flow in cerebral aneurysms [3], multicomponent blood flows [4], leukocyte rolling in virtual blood vessel [5], vesicle shape changes [6], and blood membrane dynamics [7]. The lattice Boltzmann biviscosity model was also further proposed to study blood flow problems [8]. Recently, the LBM was developed

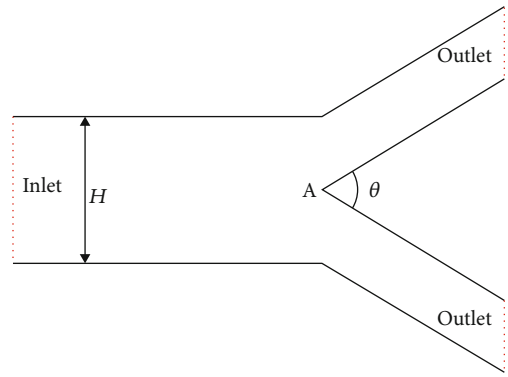

Figure 1: Schematic diagram of an arterial bifurcation in two dimensions.

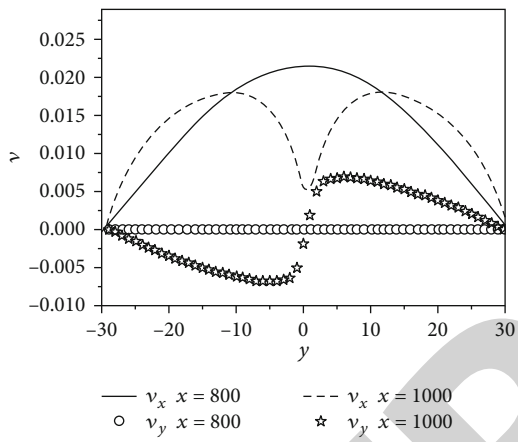

Figure 2: The velocities at position $x = 800$ (near straight vessel) and $x = 1000$ (near bifurcation vessel), respectively, in the case of without particle in the artery.

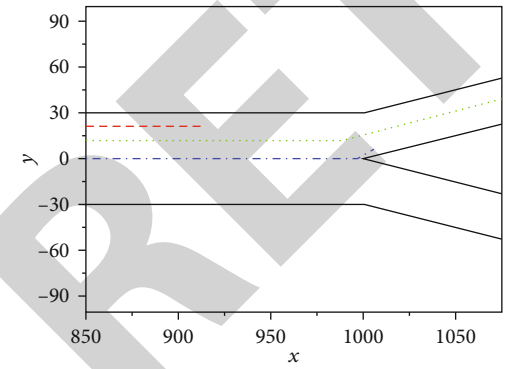

Figure 3: The trajectories of the particle settled at different positions for Re = 38.7. The angles between two branches is $\theta = 33.4^{\circ}$.

to study blood flow in arteries with aneurysm [9], advection-diffusion of chemicals and applications to blood flow [10], and deformable blockages in an elastic vessel [11].

The characteristics of blood flow near branches have been studied to understand the occurrence and development of diseases. The distribution of flow dynamic factors in two-dimensional symmetric bifurcation [12] and in an optimum bifurcation geometry [13] is studied numerically. The separation of red blood cells at microvascular bifurcations [14] and the effect of stenosis growth on blood flow at the bifurcation [15] were also studied by using the lattice Boltzmann method.

Most studies concentrate on the dynamic factors, such as flow velocity, shear stress, and pressure and shear rate, by assuming the blood is Newtonian fluid. But actually, the blood flow is composed of plasma, erythrocytes, leukocytes, platelets, and lipids (cholesterol, cholesterol esters, and phospholipids). The transportation of blood cells and lipids in blood vessels performs a very important duty in cardiovascular system. Here, the particles are used to substitute for blood cells or lipids. This paper focuses on the motion of the particles in the fluid flow near the bifurcated artery. The dynamic properties of the particle near symmetric arterial bifurcations for different positions, Reynolds numbers, and branch angles are studied numerically. The study provides a basis for understanding the mechanism of hemodynamics near bifurcations of the cardiovascular system and the deposition of lipids in the intima of the artery.

2. The Lattice Boltzmann Model

This paper uses a D2Q9 (two-dimensional square lattice with nine velocities) lattice Boltzmann model. $f_i(\mathrm{x}, t)$ is a nonnegative real number which describes the distribution function of fluid at site $\mathbf{x}$ at time t. The nine possible moving directions are $\mathbf{e}_0 = (0, 0)$; $\mathbf{e}_i = (\cos((\pi(i-1))/2), \sin((\pi(i-1))/2))$ for $i = 1, 2, 3, 4$; and $\mathbf{e}_i = \sqrt{2}(\cos((\pi(2i-1))/4), \sin((\pi(2i-1))/4))$, for $i = 5, 6, 7, 8$. The distribution functions satisfy the following equation according to the lattice Boltzmann model [1]:

$$f_i(\mathrm{x} + \mathbf{e}_i, t+1) + f_i(\mathrm{x}, t) = -\frac{1}{\tau}\left[f_i - f_i^{(\mathrm{eq})}\right]. \tag{1}$$

The fluid density and macroscopic velocity are denoted by ρ and $\mathbf{u}$ separately, which obey the following equations:

$$\begin{aligned} \rho &= \sum_i f_i = \sum_i f_i^{(\mathrm{eq})}, \\ \rho\mathbf{u} &= \sum_i f_i \mathbf{e}_i = \sum_i f_i^{(\mathrm{eq})} \mathbf{e}_i. \end{aligned} \tag{2}$$

Using Chapman-Enskog multiscale expansion, a suitable choice of the local equilibrium distribution function is

$$f_i^{\mathrm{eq}} = \alpha_i \rho \left[1 + 3\mathbf{e}_i \cdot \mathbf{u} + \frac{9}{2}(\mathbf{e}_i \cdot \mathbf{u})^2 - \frac{3}{2}u^2\right], \tag{3}$$

where $\alpha_0 = 4/9, \alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = 1/9,$, and $\alpha_5 = \alpha_6 = \alpha_7 = \alpha_8 = 1/36$. The pressure is defined as $p = (1/3)\rho$, and the kinematic viscosity is denoted by $\nu = (1/6)(2\tau - 1)$, respectively [1].

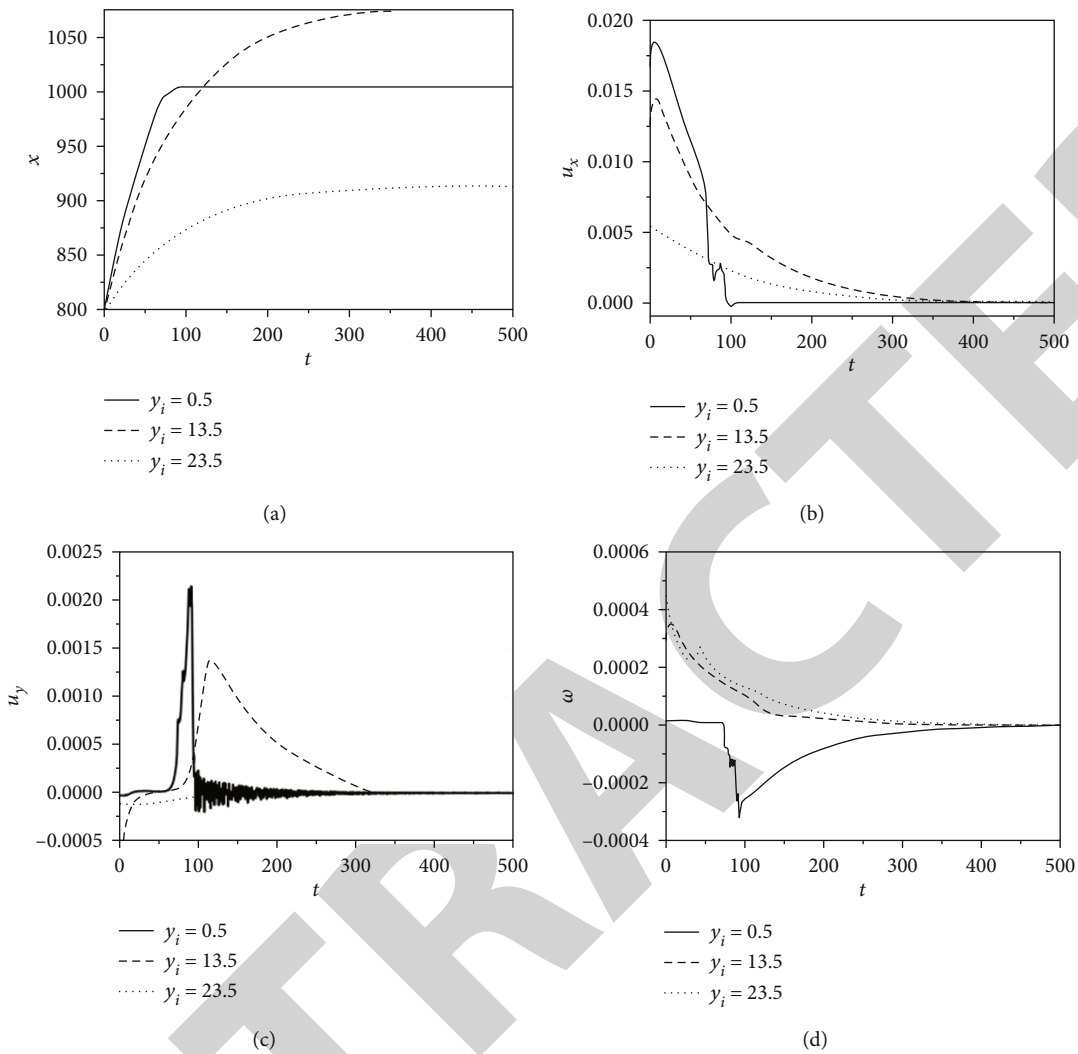

FIGURE 4: The particle x-directional position (a), x-directional velocity u_x (b), y-directional velocity u_y (c), and angular velocity ω (d) at different time steps t for the particle settled at $x_i = 800$, $y_i = 0.5$; $x_i = 800$, $y_i = 13.5$; and $x_i = 800$, $y_i = 23.5$, respectively. The angles between two branches is $\theta = 33.4^\circ$, and the flow Reynolds number is 38.7.

3. Results and Discussion

In this study, the two-dimensional configuration of the symmetric bifurcated artery is shown in Figure 1, which consists of a main vessel with diameter H of 60 lattice unit and two branches. The length of the main vessel is set to be 1000 lattice unit. The angles between two branches are denoted by θ. Here, the plasma is considered a Newtonian fluid and the particles are used to replace blood cells or lipids. In the study, the mass density of the plasma is 1 and the radius of the particle is 4.5 in lattice unit. $\tau = 0.55$ in each simulation. At the inlet of the main vessel, the velocity profile is supposed to be a parabolic distribution along the axial direction with the maximum center velocity v_0. The flow at outlets of two branches is considered to be fully developed. At the beginning, the distribution functions at all the fluid nodes are supposed to be zero velocity equilibrium distribution functions except for those at inlet of the main vessel. The curved boundary condition depicted in references [16, 17] is applied for the boundaries of the particle. The hydrodynamic force and moment on the particle boundary are calculated based on the method of stress-integration [18, 19].

A half-step "leapfrog" scheme is used to update the translational and rotational motion of particles at each Newtonian dynamic time step [20].

$$\mathbf{V}\left(t + \frac{1}{2}\delta t\right) = \mathbf{V}\left(t - \frac{1}{2}\delta t\right) + \frac{\delta t \mathbf{F}(t)}{M},$$
$$\mathbf{R}(t + \delta t) = \mathbf{R}(t) + \delta t \mathbf{V}\left(t - \frac{1}{2}\delta t\right) + \frac{\delta t^2 \mathbf{F}(t)}{M}, \quad (4)$$

where $\mathbf{V}$ and $\mathbf{R}$ are the velocity and displacement of particle centroid movement, respectively, and M are the mass of particle. At 10000 time steps, the flow field at the bifurcation of blood vessels reaches stability, at which time the particle is released. The flow Reynolds number at the inlet of the parent vessel is defined as $Hv_0/2\nu$.

3.1. The Velocity Field Near the Bifurcation. Figure 2 displays the velocity difference between the straight vessel and bifurcated vessel in the artery. The velocity v_x at $x = 800$ (near straight vessel) is a parabola while the velocity v_y is negligible compared with v_x. The existence of the bifurcation greatly hinders the x-directional flow v_x and leads to the sharp increase of outward velocity v_y near the bifurcation. The velocity is continuously distributed in the blood vessel without sudden change or eddy current, but a low velocity region is formed at the bifurcation and junction of the blood vessel. Clinical experiments also find the sudden increase of wall shear stress, and wall pressure happens on the wall near this position. Platelet particles and blood cell particles gather at this position, coupled with the synergistic effect of coagulase. The platelet and blood cell particles will grow continuously, so this position becomes the most suitable thrombus forming position.

3.2. Effect of Particle Initial Position on Its Deposition. If the blood vessel is straight, the fluid at these sites can be assumed as Poiseuille flow. When the particles flow into a straight pipe, the particles will stabilize in a position with a fixed distance from the center of the pipe after a certain distance of flow. This feature of motion is known as the Segŕe-Silberberg effect [21]. The phenomenon shows that the particles are separated by the driving force of the fluid along the mainstream direction and the lateral force perpendicular to the mainstream. This lateral force is the main cause of agglomeration movement of particles. The change of blood flow field near the bifurcation results in the change of the force on the particle, which leads to the particle's moving state. In order to compare the effect of vascular bifurcation for different particle positions, the particle is released at $y_i = 0.5, y_i = 13.5$, and $y_i = 23.5$ for $x_i = 800$, respectively. In the simulations, $\mathrm{Re} = 38.7$ and $\theta = 33.4^\circ$. Figure 3 (dot line) shows the trajectory of the particle which is released at $y_i = 13.5$. The particle settled at this place can move forward and pass through the whole vessel eventually. Unlike the behavior in straight tube, the particles released at $y_i = 0.5$ and $y_i = 23.5$ have large difference in the final positions. But they all stop in the end. The particle stagnates at the inner wall of the branch for $y_i = 0.5$ while the particle stops near the main vessel wall for $y_i = 23.5$. The stagnation of the particles can make the adhesion of particle to the vessel. This adhesive obstruction is one of the reasons of atherosclerosis or thrombus. It is observed experimentally that the atherosclerosis or thrombus has a higher possibility at the location near bifurcations than straight vessel [22, 23].

The particle x-directional position, u_x, u_y, and ω are also shown in Figure 4, respectively, in order to describe the process of particle changing with the time in detail. The particle released at $y_i = 0.5$ (center of the main vessel) moves the fastest and stops the earliest while the particle settled at $y_i = 23.5$ (boundary of the main vessel) is just the opposite. But they all stagnate at the junction between the straight vessel and the bifurcations. The particle released at $y_i = 13.5$ reaches at the junction at about 100 time steps. The bifurcation decreases the motion of the particle in the x-direction while it increases the particle motion in the y-direction. Although the particle velocity in the branch is much smaller than that of in the main vessel, the particle can move forward and pass through the whole vessel successfully.

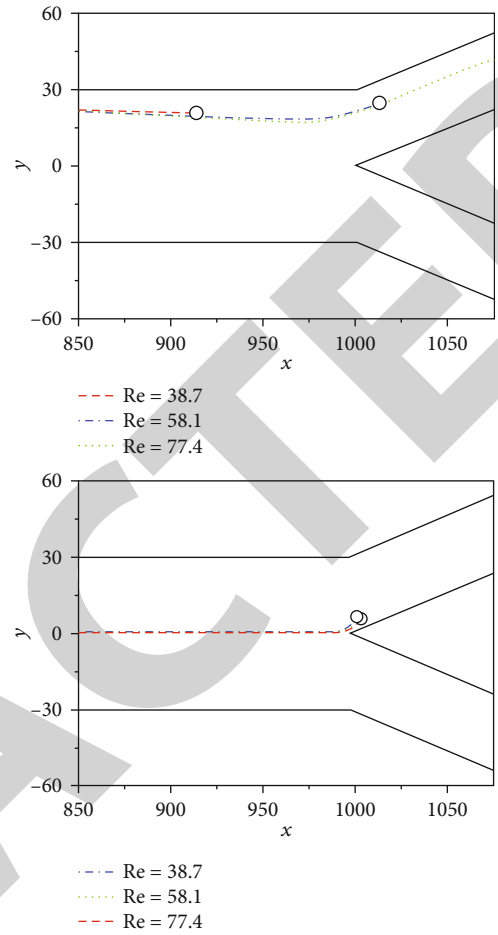

Figure 5: The trajectories of the particle for different flow Reynolds numbers for the particle are settled at $x_i = 800$, $y_i = 0.5$ and $x_i = 800$, $y_i = 23.5$ separately. The angles between two branches is $\theta = 33.4^\circ$.

3.3. Effect of Flow Reynolds Number on Particle Deposition. Figure 5 displays the behavior of particle near symmetric bifurcation for different Reynolds numbers. The circles denote the particle stagnation position. Smaller Reynolds number causes the particle stagnates in the main vessel while larger Reynolds number leads to the particle stop in the branch if the particle is settled near the upper boundary. The particle passes through the whole vessel for Reynolds number is even higher, for example, of $\mathrm{Re} = 77.4$. The increasing of fluid velocity can reduce particle deposition near the boundary of the artery. The particle released near the center of the main vessel deposits near the angle of the bifurcation when the Reynolds number is even higher. This result explains why this position is the most suitable thrombus forming position.

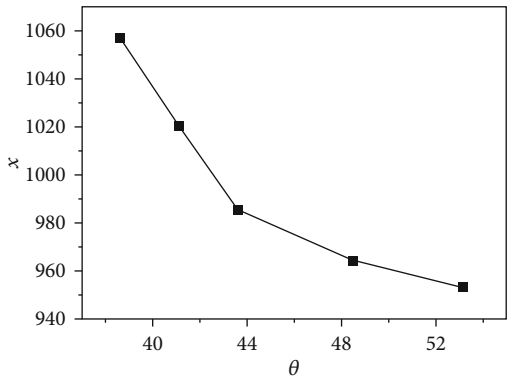

FIGURE 6: The particle final x-axis positions for different bifurcated angles θ for the particle is released at $x_i = 800$, $y_i = 13.5$at Re = 38.7.

3.4. Effect of Bifurcation Angle on Particle Deposition. Figure 6 displays the behavior of particle near symmetric bifurcation for different branch angles θ. The particle is released at$x_i = 800$,$y_i = 13.5$for flow Reynolds number which is 38.7. It is deduced from Figure 6 that the particle finally settles down at the junction of between the main vessel and the branches if θ is about 42°. Larger branch angle θ results in the particle stagnating in the main vessel. The particle can pass through the whole vessel if θ is smaller than 36°. The particle finally stops in the branches if θ is between 36° and 46°. Smaller flow Reynolds number and larger branch angle bring about higher possibility of particle stagnation near the bifurcations, which contributes to intimal thickening and atherosclerosis development. The artery with small flow Reynolds number and large branch angle is prone to develop atherosclerosis, which is consistent with the clinical observation [22, 23].

4. Conclusions

In summary, we used a lattice Boltzmann method to study the properties of particle moving near the arterial branches. The following conclusions are obtained by the simulation results.

(1) In the straight vessel, the fluid at these sites can be assumed as Poiseuille flow. The particles finally stabilize in a position with a fixed distance from the center of the pipe. Compared with the straight vessel, the change of blood flow field near the bifurcation results in the change of the force on the particle, which leads to the change of particle's moving state.

(2) The bifurcation has the function of hindering the particle motion. The particle is prone to stagnate near the wall of bifurcated vessels. Larger branch angle and smaller flow Reynolds number lead to larger possibility of the particle residence.

(3) The adhesive obstruction of the blood vessel has large reason of stasis of particles. Our study will contribute to the understanding of hemodynamic mechanisms around bifurcation and will contribute to the understanding of some cardiovascular diseases.

However, the current simulation is only a preliminary study of two-dimensional flow near arterial branches. Due to the complexity of blood flows and arterial structure, more studies combined with clinical observation are needed, and we are paying attention to this area.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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