A Numerical Approach to Investigate the Influence of Deformable Blockages on Blood Flow in an Elastic Vessel
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Abstract

In this work, we presented a new numerical approach to study the deformation of blockages and fluid properties in an elastic blood vessel. In computational hemodynamics, only a few of the current numerical models considered the elasticity of the vessels, and those models were difficult to extend to other topics like the deformation of blockages in elastic blood vessels. In addition, the approach that we employed is especially effective on visualization. A validation for the present method is carried out by comparing the simulation results with a theoretical prediction of the deformation of the pulmonary blood vessel in a steady flow. Subsequently, the method is applied to study the relationship between the fluid properties and the deformation of blockages.

Introduction

Last decade, cardiovascular diseases were the major cause of death for both males and females in the world [1]. Recent experimental studies are relatively difficult, computational fluid dynamics (CFD) for modeling cardiovascular system has become an innovative and popular field [2]. A lattice Boltzmann method (LBM) is a modern approach in CFD and two reasons have explained its high efficiency. First, the LBM solved the Boltzmann equation to obtain fluid behaviors. In other words, it avoided solving the nonlinear Navier-Stokes equations directly [3]. Secondly, the architecture of the LBM is particularly suitable for GPU parallel computing. However, most researchers still use the traditional finite element method or finite difference computing. Therefore, the results point represents a solid model for the incompressible fluid point (LSM) is reported to the other deformable objects such as carotid plaques because the vessel walls are only difficult to extend to other topics like the deformation of blockages in elastic blood vessels. In addition, the approach that we employed is especially effective on visualization. A validation for the present method is carried out by comparing the simulation results with a theoretical prediction of the deformation of the pulmonary blood vessel in a steady flow. Subsequently, the method is applied to study the relationship between the fluid properties and the deformation of blockages.

Methods

In this method, the lattice Boltzmann method is used to capture fluid behavior, and the lattice spring model is employed to mimic the deformation of the blood vessel and blockages while the immersed-boundary method is applied to deal with the fluid-solid interaction. The lattice Boltzmann method (LBM): Lattice Boltzmann method is a relatively new computational fluid dynamics method. In this method, fluid domain is represented by a series of regularly arranged nodes and each node has several particle distribution functions (see Figure 1). All macroscopic fluid properties such as fluid densities, velocities, and pressures can be derived from the distribution functions. Moreover, the architecture of the LBM is particularly suitable for GPU parallel computing which is a promising technology in the future decades.

The lattice spring model uses plenty of particles to represent a solid body like a vessel. Harmonic spring and angular bonding potential energies exist between the two neighboring particles and the two adjacent springs, respectively. Once both potential energies have been calculated on a solid particle, the elastic force can be evaluated to update the position and velocity of the solid particle. Since every solid particle has different positions and velocities, the movement and deformation of the entire solid body can be expressed.

Results

Validation:

To validate the present method, a fluid flow in an elastic pulmonary blood vessel is simulated. The flow is driven by a pressure gradient, and the width D (see Figure 4) of the elastic vessel is reduced in the downstream due to a pressure drop and deformation of the vessel walls. The comparison between the simulation and the theory results is given in Figure 4, where the red line and blue circles represent the analytical and simulation results respectively.

Elastic vessel with blockages:

Both of the deformation of blockages (see Figures 6 and 7) and the influence of blockages in an elastic blood vessel on fluid properties (see Figures 8 and 9) are investigated by using the validated method. In the simulations, the stenosis of the blockages is varied in three different degrees: 18.2% (case 1), 36.4% (case 2), and 54.6% (case 3).

Conclusion

In this work, the lattice-Boltzmann lattice-spring method (LBSLM) is reported to simulate the deformation of blockages in an elastic blood vessel. The method is validated by comparing the simulation results with the theory of radiuses of a pulmonary blood vessel. Subsequently, the method is applied to model the fluid properties when the thickness of blockages is varied at three different levels. It is found that the top and bottom blockages are rotated in two opposite directions and expanded to the vessel central area. In conclusion, as the thickness increases, the left gap between the top and bottom blockages, fluid velocity, and flow rate decrease, and the inclined angles of blockages increase. Therefore, the results indicated that the deformation of blockages enhances the resistant of fluid flowing.

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