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Turbulent Flow in Agent-based Blood Vessel Model

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Abstract- The aim of this study is to model the flow in blood vessel at the simulation environment, in accordance with hemodynamic principles. The circumstances that may cause turbulent flow in the blood vessel model, developed in the agent based simulation environment, have been discussed in this study. Whether or not the flow in the blood vessel is turbulent is determined by the Reynolds' number. The Reynolds' number is calculated based on the diameter of blood vessel, flow velocity in the blood vessel, blood density and viscosity. The circumstances of turbulent flow that may occur based on the radius and viscosity in a narrowed region of blood vessel are shown graphically through experimental studies. It is thought that this study can be used for the educational purposes in medical education and engineering applications.

Keywords Agent, agent-based modelling and simulation, blood vessel, turbulent flow.

1. Introduction

Human life continues directly or indirectly depending on many systems (biological, social, economic, etc.). System dynamics vary according to ambient conditions, leading to the formation of different behaviors throughout the system. This is the reason why it is difficult to understand and model the behavior of a dynamic system as a whole in the virtual environment. In order to model real system components, it is necessary to analyze the factors that make up the system and the relations in between well. Agent-based modelling and simulation (ABMS) is one of the most flexible and robust methods of abstraction of complex systems. ABMS is a rule-based, computational modeling approach that focuses on rules and interaction among the individuals (agents) or components of the real system. The goal is to generate a large set of interacting agents of the system components of interest and simulate their interactions and behaviors in a virtual world [1]. Each individual on the system is represented by an agent that operates in the environment in order to mimic its real-world behavior. The expected global behavior of the model emerges from the local agent interactions. In this study, the movement of blood flow in a cross-sectional blood vessel model has been examined. The blood vessel model was developed with ABMS technique. Hemodynamics behaviors, which enable the blood flow, were observed in the blood vessel model based on cardiovascular system parameters. Hemodynamics is a part of cardiovascular physiology dealing with the physical factors that govern blood circulation [2].

In this paper, we present our model for turbulent flow of blood in detail. The principal way in which our study is distinguished from other research in this area is that the system we propose is relatively simple: we identify simple rules for interactions between agents without complex mathematical calculations. Our goal in this regard is to offer a system that is as simple as possible through a bottom-up modeling approach [3].

This paper is organized as follows: Section 2 offers a detailed account of agent-based blood vessel model. Section 3 provides a brief account of the fundamentals blood flow based on cardiovascular parameters. Experimental results are illustrated in Section 4. Evaluated of the results of this study and suggestions are given in the conclusions section.

2. Agent-based Blood Vessel Model

In this study, the blood vessel is assumed to be in the form of a straight rigid pipe. The blood vessel model consists of 50 blood vessel agents representing the arterial system. We have divided the blood vessels into segments which represented by agents (Figure 1).

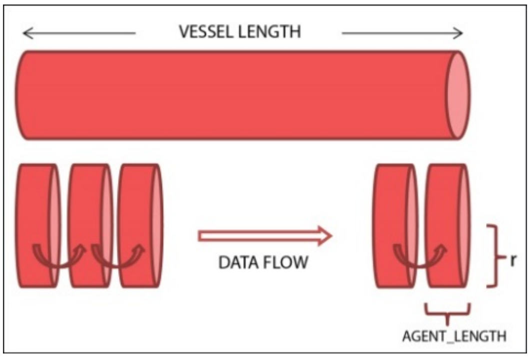


Fig. 1. Vessel agents.

Each agent has its own identity knowledge (id), location knowledge (x, y, z), and radius knowledge (r). Incoming information is transmitted from the first agent to the next agent and from that agent to the next until the last agent is reached. The vessel agents are all the same type and same length. We implement a publish-subscribe interact package in order to provide interaction between agents. All agents subscribe itself to the corresponding agent and publish messages in order to propagate messages to their listeners. When an agent receives a message, adapts itself if required and regulates its behavior according to the current environment situation. Each vessel agent evaluates its current situation according to its local knowledge and performs its behavior [4].

3. Blood Flow Model

In physiology, the blood movement is evaluated with two different parameters.

- Blood flow (Q): Blood flow is the volume of blood carried in the unit time. The blood flow in a blood vessel is dependent on two factors: pressure difference between the two ends of the vessel (ΔP) and resistance (R). The flow through the vessel is calculated by the following formula, as in Eq. (1), which is called Ohm's law [5]:

$$Q = \Delta P/R \tag{1}$$

ΔP refers to the pressure difference between the two ends of the vessel. R refers to the vessel's resistance to the blood flow [5-6]. R is calculated by Eq. (2).

$$R = \frac{8 * Viscosity}{PI * r^4} * AGENT\_LENGTH \tag{2}$$

AGENT_LENGTH is the ratio of the length of vessel to the number of agents. The length of the vessel and the number of agents are given as parameters VESSEL_LENGTH and AGENT_COUNT respectively in Figure 3 [4]. Viscostiy is an inherent fluid property of liquid. Blood viscosity is also given as a parameter in Figure 3. r is radius of blood vessel.

- Blood flow velocity (V): Blood flow velocity is the amount of displacement per unit time. Velocity of blood is measured in cm/sec. It is a value equal to the total volume of blood (Q) divided by the cross-sectional area (A) of vascular bed , as in Eq. (3):

$$V = Q/A \tag{3}$$

The cross-sectional area (A) of each agent is calculated by Eq. (4) in accord with the exponential function of distance, as in Eq. (5) [7]. The tapering factor (k_0) per length is given in the table in Figure 3.

$$A(n) = PI * r_n^2 \tag{4}$$

$$A(d) = A(n) * e^{-k_0 d} \tag{5}$$

r_n is the radius value of the agents.

$$r_{n_t} = r_{n_{t-1}} \pm \Delta r \tag{6}$$

$$\Delta r = \left(perturbation_t - perturbation_{(t-1)}\right) * r_{max} \tag{7}$$

Δr is represented changes in diameter in response to a perturbation. Δr refers to the change in the diameter of a vessel agent at the t^{th} tick and is directly proportional to the difference between the perturbations at the t^{th} tick and at the $(t-1)^{th}$ tick, as in Eq. (6, 7).

Having examined the flow in a vessel, it has been observed that the flow movement is smooth at low speeds but turbulence is observed when the speed is over a certain speed. The flow in the fluid mechanics turns into streamline flow at lower speed, into transition flow as speed increases and then into turbulent flow (Figure 2).

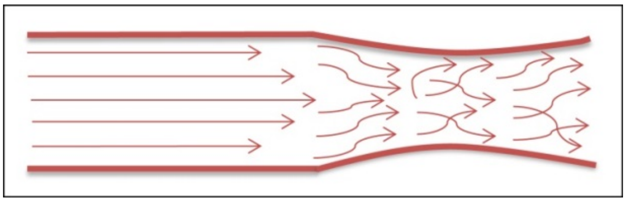


Fig. 2. Flow from laminar flow to turbulent flow.

Generally in the vessels, blood flow is laminar. Laminar flow is the flow of blood at a constant velocity in a long straight vessel. However, when the flow velocity drastically increases or blood passes through a stenosis region or rough region in blood vessels, laminar flow can be disrupted and become turbulent [8].

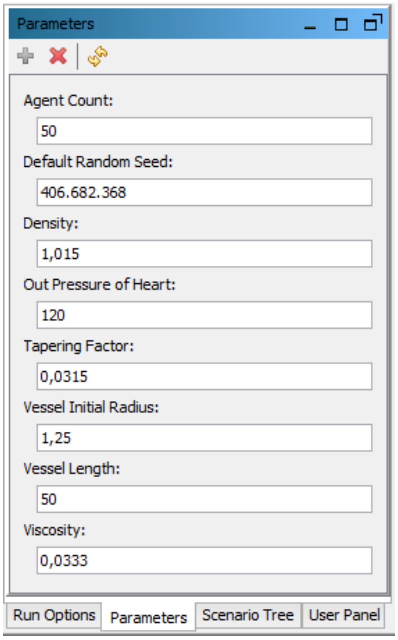
Turbulence occurs when a critical Reynolds number (Re) is exceeded. Re is a way to predict under ideal conditions when turbulence will occur. The British scientist Osborne Reynolds (1842-1912) showed in the conducted experiments that the flow behavior is dependent on the critical flow rate, the fluid density, the viscosity of the fluid and the pipe diameter [8]. Re is the ratio of intertial forces to viscous forces. It is calculated by closed pipe fluid flow mean velocity (V), internal pipe diameter (D), fluid density (ρ), internal pipe diameter (D) and fluid viscosity (η), as in Eq. (8).

$$Re = \frac{intertia\ forces}{viscous\ forces} = \frac{\rho V D}{\eta} \tag{8}$$

If Re is lower than critical (Re < 2000), the flow is laminar. If Re is higher than critical (Re > 2300), the turbulent flow will occur [9].

4. Experimental Study

We developed our model using the Java language with the Repast Simphony 2.2 tool. Our main parameters for agent-based blood vessel model developed in the simulation environment are vessel length, cycle duration, agent count, tapering factor, viscosity, and blood density. Each model parameter has a predefined value, as shown in Figure 3. The user can edit these values in order to observe the effects of and changes in the behaviors/outputs of the simulation.



Agent Count: 50

Default Random Seed: 406.682.368

Density: 1,015

Out Pressure of Heart: 120

Tapering Factor: 0,0315

Vessel Initial Radius: 1,25

Vessel Length: 50

Viscosity: 0,0333

Fig. 3. Model parameters.

We performed two experiments in order to observe the turbulent flow of blood in a narrowed vessel and in the presence of low viscosity. In these experiments, we ignored the compliance of the vessels which is the ability of a blood vessel wall to expand and contract passively with changes in pressure. We assumed that the mean pressure of the vessel and the radius of the vessel were kept constant.

4.1. Experiment 1: A narrowed vessel

In order to observe the turbulent flow, we narrowed a part of blood vessel in the simulation. Initial radius of first blood vessel agent is a parameter of the simulation shown in Figure 3 and its value is given as 1,25. The 20th agent represents the vessel segment at which the vessel starts to narrow gradually until the 50th agent is encountered, so that the structure of the vessel changes in the graph as shown in Figure 4. This leads to decrease the radius of agents as much as Δr.

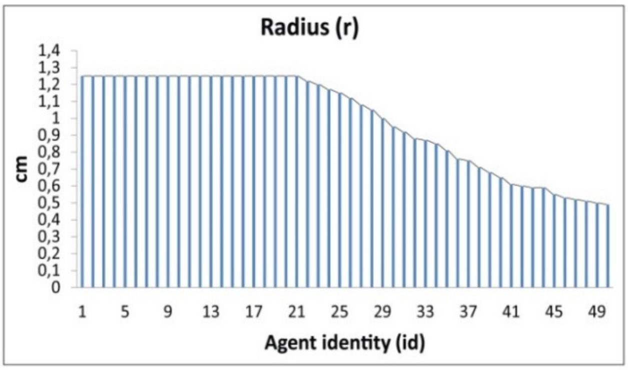


Fig. 4. Radius of blood vessel agents.

In the narrowed region (stenosis), the velocity increases as the diameter decreases (Figure 5). The region of the stenosis, with increased flow velocity causes turbulence.

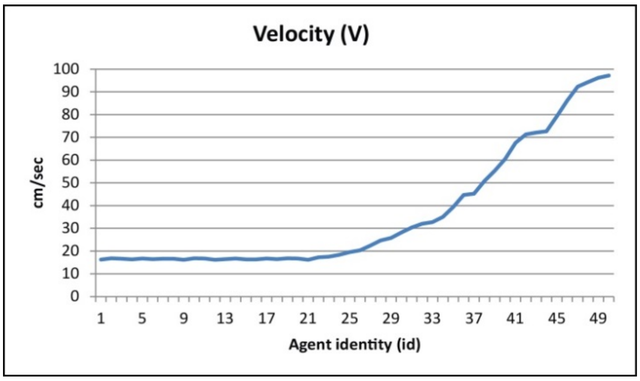


Fig. 5. Velocity of blood vessel agents.

Turbulence in blood flow starts at the 38th vessel segment representing by the 38th agent when the Re reaches 2300. Re reaches it maximum value at the 49th vessel segment for this simulation environment. When the Re numbers are higher than 2300, the turbulent flow will occur.

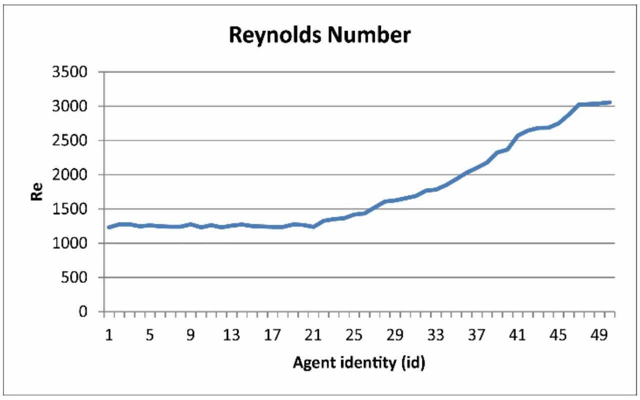


Fig. 6. Reynolds' number.

The turbulent flow of blood is harmful in blood vessels. Therefore, it is critical for vessels to diagnosis the turbulent flow. Since we ignore the compliance of the vessel in this experiment, we only observed the turbulent blood flow in a narrowed vessel. Indeed, healthy vessels are flexible and elastic; however, over time, the walls in vessels harden and become thick and stiff. This condition is commonly called hardening of vessels (arterioseleoris) [5]. We will perform the experiment in case of hardening of vessels for future work.

4.2. Experiment 2: The effect of Viscosity

Another of the important factors in Poiseuille's equation is the viscosity of the blood. Viscosity is the resistance against fluidity. Viscosity is a feature that slows down the flow of a substance. As the viscosity increases, the fluidity decreases. Viscosity has the SI units Pascal seconds (Pa s) which is called the Poiseuille. More commonly used is the dyne sec/cm^2 which is called Poise. The viscosity of blood at body temperature is about 0.03 Poise [5]. The viscosity of blood depends on the level of hematocrit. Hematocrit is the percentage of the blood that is cells. Hematocrit in a healthy person is about 38-42 per cent of the blood volume. There is an exponential relation between the value of Hct and the viscosity of blood [10].

In the simulation, hematocrit is decreased in the 30th tick count. Until this tick count, Hct is normal range. When Hct starts to decrease, the viscosity of the blood gradually decreases, as shown in Figure 7 and 8.

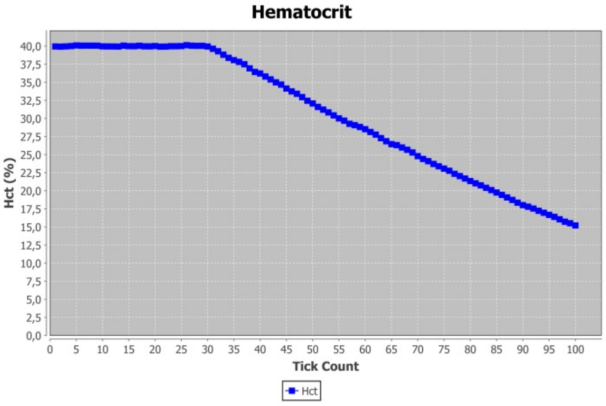


Fig. 7. Decrease in hematocrit value.

This decrease in hematocrit value causes the disease known clinically as anemia [5]. The viscosity values depending on the hematocrit levels are given in Fig. 8 Viscosity value is normally 4 cP. This value drops to 2 cP.

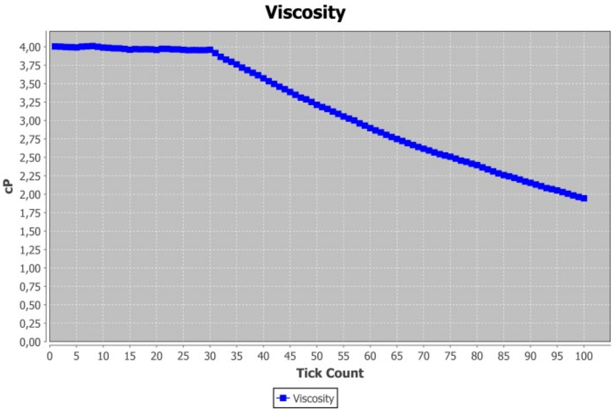


Fig. 8. The viscosity value depending on hematocrits.

After the 30th tick, the blood viscosity starts to decrease. Until the 90th tick, the turbulent flow cannot be observed since the Reynolds' number does not reach its critical value. After the 90th tick, the turbulent flow occurs.

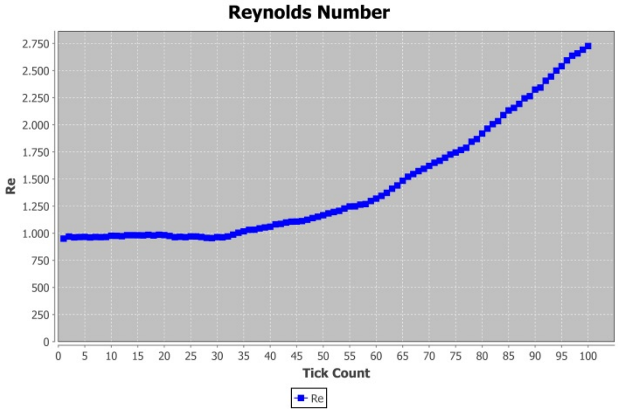


Fig. 9. Reynolds' number.

5. Conclusions

In this paper, we presented the turbulent flow in agent-based blood vessel model and model details. We observed the tendency for turbulent flow increased in direct proportion to the velocity of blood flow, the diameter of blood vessel, and the density of the blood, and was inversely proportional to the viscosity of the blood. According to the simulation results, we observed the points at which the turbulent flows began in our agent-based blood vessel model. In this study, we offer an abstraction approach using the ABMS technique to be comparable to the numerical methods.

In further steps of our simulation study, we will improve graphical user interface and generate visual outputs/results. The purpose of this long term project is to develop a tool for clinical applications, research and education in order to estimate accurate physiological responses against a plethora of internal and external environmental factors.

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