Flow-based molecular communication system for the detection of hyperviscosity syndrome

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***Abstract*—Hyperviscosity syndrome can play an important role in the occurrence of cardiovascular diseases. For this reason, in this work we propose a monitoring system based on molecular communication to provide a real time estimation of the blood viscosity level without the need of invasive blood tests. The main idea is to leverage the particle dispersion in blood as a function of blood viscosity, and measure the time needed to cover a suitable distance to carry out a viscosity estimation.**

***Index Terms*—Flow-based molecular communications, blood vessel, hyperviscosity, simulation**

I. Introduction

In recent years, flow-based molecular communication inside blood vessels has been investigated on various biological contexts, bringing some relevant results on both monitoring of specific biological parameters and on the activation of biological processes [1]. Indeed, an early detection of altered conditions on patients could increase the effectiveness of treatments increasing both the life quality and expectancy.

An independent risk of factor to future cardiovascular disease is the hyperviscosity syndrome, which is an altered condition that prevents blood from flowing freely. Plasma hyperviscosity is a rare complication of both monoclonal and polyclonal disorders associated with elevation of immunoglobulins whereas, whole-blood hyperviscosity is due to abnormal red blood cells shape (sickle cell anemia) or even to a high concentration of both blood cells and proteins in the bloodstream [2]. This syndrome affects both children and adults, reducing blood flow to vital organs (e.g. heart, intestines, kidneys and brain), but It may occurs also with autoimmune diseases, such as rheumatoid arthritis or systemic lupus, or It may also develop with blood cancers, such as lymphoma and leukemia.

In this work a molecular communication system is proposed for the fast detection of high viscosity conditions through the release of small molecules inside the blood stream. The measured parameters allow to infer about the viscosity condition without the need of slower and invasive blood tests.

II. System model

The blood which flows inside venules (i.e. small blood vessels) is considered in this work. Blood flows along laminar components without any relevant turbulent component, acting like a Newtonian fluid. In fact, in general this is not true, because even if the plasma component has the Newtonian fluid properties, the small particles and blood cells immersed in the plasma make it non-Newtonian [3]. A very important factor for the normal operation of the circulatory system is the viscosity of the blood, since it affects the pressure drop and the wall shear stress in the blood vessels. High viscosity values means high resistance to flow along blood vessel due to high friction among molecules, cells and lumen [4]. When this condition occurs, a multitude of symptoms may appear, spanning from neurological disorders, visual defects and thromboembolic events [2]. In adults, hyperviscosity syndrome typically causes symptoms when blood viscosity is about 4 times or more higher than normal values. An increase in the viscosity corresponds a decrease in the flow velocity, as stated by the well known Poiseuille's equation:

$$v(r) = \frac{1}{4\eta}\frac{\Delta P}{L}(R^2 - r^2) \tag{1}$$

where η is the blood viscosity, ΔP is the pressure drop along a vessel section of length L, R is the vessel radius and r is the distance from the longitudinal axis of the vessel. This equation show that the flow velocity assumes a parabolic profile, reaching its maximum on the longitudinal axis decreasing to zero close to the vessel walls. Moreover, at every increase of viscosity, the flow rate Q decrease accordingly, leading to tissue ischemia:

$$Q = \frac{\pi R^4}{8\eta}\frac{\Delta P}{L} \tag{2}$$

To preserve the equilibrium of the equation constants in the circulatory system, blood pressure should increase when also viscosity increases or, alternatively, an equivalent vasodilation is expected [5]. However, the absorption of food, drugs or even pathologic conditions (e.g. atherosclerosis, hypertension and ischemia) may hinder these compensation mechanisms. Indeed, in these cases atherosclerotic vessels cannot dilate enough as well as the risk for ischemia may increase in hypertensive patients that have no reserve capacity to increase the blood pressure to compensate the circulatory load. This means that the only possible treatment is to give those patients specific drugs able to reduce the blood viscosity.

This work is focused on the latter case, where the compensation is not possible and blood flows under critical conditions. This means that both the flow velocity $v(r)$ and the flow rate Q are affected by a variation of the blood viscosity value η, as modeled in eq.(1), (2) respectively.

The proposed idea is to release and monitor the propagation pattern of a burst of molecules that flow across a short section

TABLE I
SIMULATION PARAMETERS

Symbols	Description	Value
m_r	Molecule radius	1.75, 3.5 nm
T	Plasma temperature	310 °K
η	Plasma viscosity	0.001, 0.01 cP
v_m	Blood flow velocity (mean)	0.5, 0.05 mm/s
L	Blood vessel length	5 mm
R	Blood vessel radius	30 µm
d_r	Release point (distance from the central axis)	0, 30 µm
B	Size of the burst of molecules	1000

of a blood vessel. The analysis was performed by means of BiNS2 simulator [6], [7], where the burst of molecules has been released in two relevant positions, along the central axis of the vessel and close to the vessel walls. For each initial position, different simulation cases that differ for molecules sizes, plasma viscosity and blood flow velocity were considered, as reported on Table I. The blood vessel section was filled by proper concentration of blood cells [6].

III. SIMULATION RESULTS

The simulation results are compared for both normal and high viscosity conditions, for each molecule sizes and each release position. The monitored sections are those close to the vessel walls, where the endothelium is able to absorb the released molecules. The collected results show that the initial release point does not affect the steady state molecules distribution for positions close to the vessel walls (Fig.1). Moreover, the distribution of molecules follows a sort of circular symmetry along the transverse section of vessel (not shown here for space constrains). This means that a high precision of the release point is not required for the overall performance of the monitoring system, for each simulated configuration (both normal and high viscosity conditions), because after a short time from the release instant, the overall amount of molecules is nearly the same over time.

Fig.2 shows the average positions of the cloud of molecules around the vessel walls (i.e. its barycentre). The solid lines are relevant to the high viscosity cases, whereas the dashed lines are relevant to the normal viscosity. The results show that after just 1 second since the molecules release, in the normal case the barycentre of molecules have covered a greater distance than the hyperviscosity case, which shows a propagation delay greater than 3.5 times than the normal case for large molecules and greater than 2 times for small molecules. These results allowing an easy viscosity estimation based on the time required to detect a relevant portion of these molecules on a fixed distance from the release point.

From the collected results, an external smart sensor should be able to provide a real time estimation of the patient blood viscosity level without the need of blood tests in lab. Moreover, based on these measures, it is possible to manage a targeted drug delivery in order to reduce the overall blood viscosity lowering the workload on the cardiovascular system.

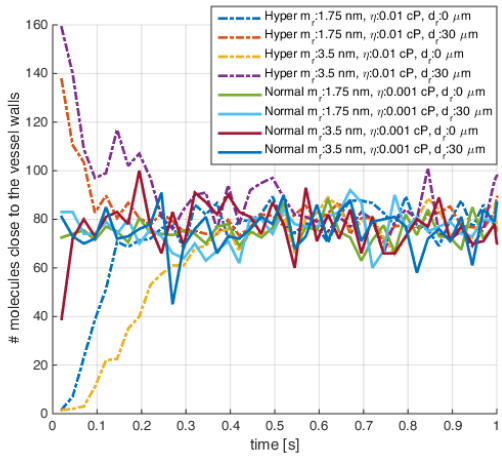

Fig. 1. Total amount of molecules on position close to the vessel walls.

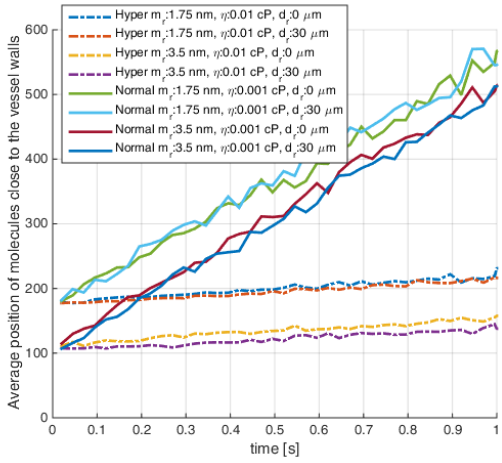

Fig. 2. Barycentre of molecules close to the vessel walls.

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