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Improved Education in Hemorheology and Fluid Dynamics is Necessary to Understand Recent Medical Insights

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ABSTRACT

Improved education in hemorheology and fluid dynamics is necessary for physicians to understand recent developments that affect cardiologists, cardiovascular surgeons, nephrologists, infectious disease specialists, internists, and general practitioners. Specifically, viscosity, non-Newtonian fluids, shear stress, shear rate, Reynolds number, the Dean number, laminar flow and turbulence should be taught.

Keywords: Hemorheology; Fluid Dynamics; Medical Education; Hematology; Blood Viscosity; Shear Stress; Shear Rate; Laminar Flow

Introduction

Recent research has shown the importance of hemorheology (the study of blood flow) in cardiovascular pathophysiology. In particular, the viscosity of blood has been shown to be involved in atherothrombosis, [1] the shortened lifespan of patients on hemodialysis, [2] the increased incidence of thrombosis in infectious disease,[3] especially coronavirus 2019 (COVID-19) [4], to name just a few clinical manifestations. Further, elaborate mechanisms to control blood viscosity have recently been elucidated [5]. For these reasons, our group has argued that blood viscosity should be considered part of the "milieu intérieur," the term used by the pioneering French physiologist Claude Bernard to describe the fundamental parameters which are necessary to maintain homeostasis, such as body temperature, pH, and serum osmolarity.

In order for physicians to understand these new developments in cardiovascular pathophysiology, they must have a sound foundation in fluid dynamics. An informal survey by one of the authors (GDS) has shown broad variation in exposure to fluid dynamics and hemorheology during their undergraduate education and medical school. We have included sections describing the fundamentals of fluid dynamics and hemorheology in many of our publications for this reason. All the authors are essentially self-taught hemorheologists. Most people are familiar with viscosity from everyday experience. Honey is more viscous than water. However, the concept of Newtonian and non-Newtonian fluids is much less familiar to physicians. Blood exhibits strong non-Newtonian properties, meaning that its viscosity varies with the shear rate. In low shear conditions, erythrocytes tend to aggregate which increases especially at higher hematocrits (Figure 1). This concept is vital to understanding the pathophysiology of thrombosis of all sorts, including atherothrombosis.

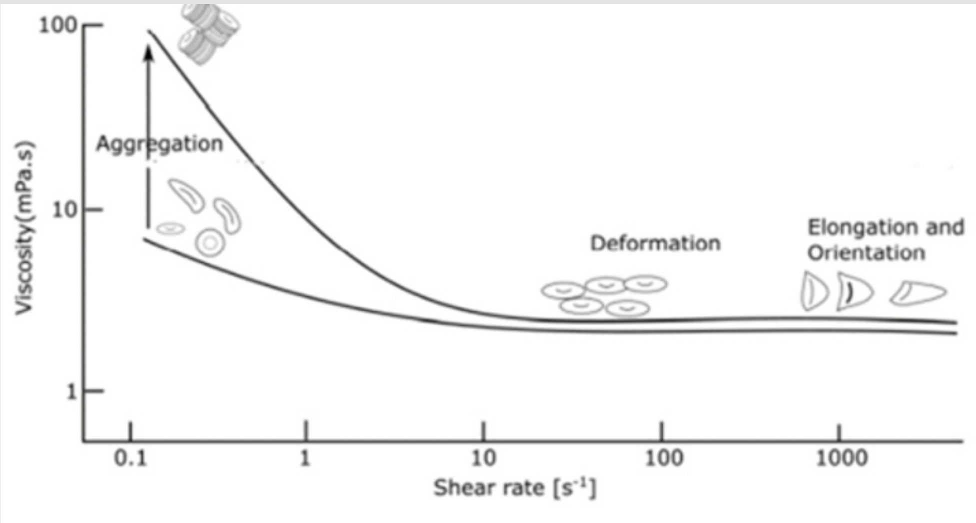

Figure 1: The lower line shows viscosity at a low hematocrit and the upper line is the viscosity at a higher hematocrit. This explains the appearance of anemia during infection, when the increased levels of acute phase proteins (especially fibrinogen) cause higher viscosity which subsequently is "normalized" by the human organism through decrease of the hematocrit (the anemia in chronic infectious diseases)

It is also vital in the understanding of the erythrocyte sedimentation rate, very common laboratory test. Blood viscosity decreases at high shear rates because erythrocyte deformability allows erythrocytes to entrain like racing cyclists, decreasing the resistance to flow. Conditions which decrease erythrocyte deformability, such as the "Western" or "Industrialized" diet make erythrocytes stiffer and increase blood viscosity [6] . The viscosity of a fluid is determined by the ratio of shear rate and shear stress. Most physicians are unaware of the meaning of these variables. This is unfortunate given that thrombosis occurs in areas of low shear. However, these variables are not difficult to understand. Shear rate is comparable to velocity and shear stress is the force causing flow. A fluid with low viscosity requires only a small shear stress to cause a high shear rate while a very viscous fluid requires a large force to produce a lesser degree of shear rate.

It has recently been described that shear stress is sensed in the carotid sinus [7]. This information is carried via the glossopharyngeal nerve to the brainstem and impacts the renin-angiotensin-aldosterone (RAAS) axis. Compared to viscosity, fewer physicians are familiar with the Reynolds and Dean numbers. Reynolds number describes the likelihood of losing laminar blood flow based on viscosity, vascular diameter, and blood velocity. It is important in understanding thrombosis in arteriovenous grafts placed for dialysis access. The Dean number describes the likelihood of losing laminar flow in vascular curves [8]. This is an important quantity given the convex surface of the heart and how common vascular curves are, especially because the number of curves increases due to loss of vascular elasticity with aging. It is sometimes difficult to find a straight section in the carotid arteries to properly examine the carotid arteries of older individuals by ultrasound. Nevertheless, it is more obscure than the Reynolds number. Vascular branches are created by cardiovascular surgeons in revascularization procedures. One author (GDS) has observed a coronary bypass graft which was placed at a particularly disadvantageous (obtuse) angle at autopsy shortly after a revascularization procedure. Computer simulations show that the more obtuse the angle of branching, the greater the disturbance of blood flow [9].

A PubMed search using the terms blood vessel Reynolds number yielded 497 results while a PubMed search using the terms blood vessel Dean number yielded only 73 results.

The concept of turbulence is probably familiar to most people who fly because of its impact on the enjoyment of the experience. Turbulence is very important in medicine because it causes heart murmurs, vascular bruits, vascular thrills associated with arteriovenous grafts for dialysis access, and high output cardiac failure. Turbulence wastes energy and thus cardiac power. Laminar flow is not as commonly understood although it is the optimal condition. Laminar flow allows transport of solutes to tissue using the least amount of energy. As befits part of the milieu intérieur, blood viscosity is tightly controlled. To date, three mechanisms have been described which impact blood viscosity. First is the RAAS. The impact of the RAAS on erythrocyte production blood viscosity is not widely appreciated. The most obvious example is post -transplant erythrocytosis [10]. Treatment is with angiotensin-converting enzyme inhibitors.

The second mechanism is the systemic vascular resistance response (SVRR) [11]. It is the physiologic antagonist of the RAAS. In the SVRR, in left ventricular cardiomyocyte mechanoreceptors sense systemic vascular resistance and response, elaborate B-type natriuretic hormone and reduce erythropoietin levels via a variety of mechanisms. It causes resistance to exogenous erythropoietin used to treat the anemia of renal failure. In the short term, splenic hemophagocytosis reduces blood viscosity. Finally, erythrocytes can sense shear rate and use this information to regulate their own deformability [12]. This allows erythrocytes to pass through capillaries which have a diameter smaller than their own.

To address these shortcomings, fluid dynamics should be taught in undergraduate physics classes. Two hours should be devoted to hemorheology in medical school physiology classes. At the very least, these concepts should be taught to cardiology fellows.

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