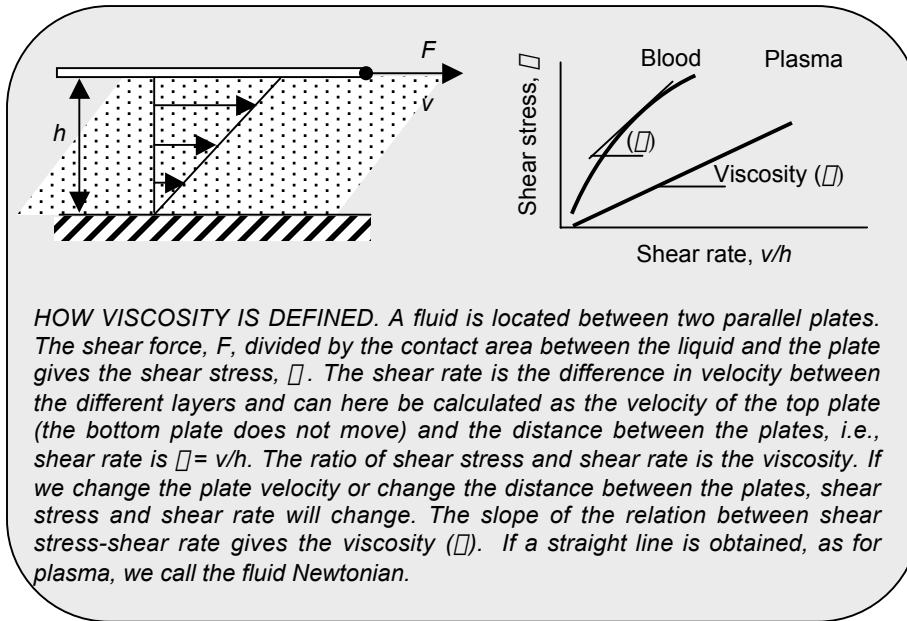


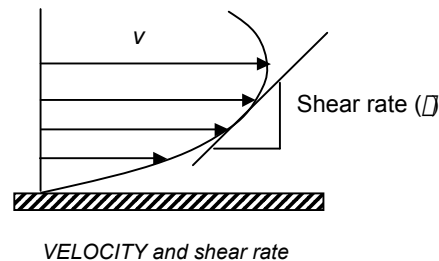
VISCOSITY



Description

Consider the experiment shown in the figure above. The top plate is moved with constant velocity (v) by the action of a shearing force F , and the bottom plate is kept in place (velocity is zero). The result is that the different layers of the blood move with different velocities. The difference in velocity in the different blood layers causes a shearing action (friction) between them. The rate of shear ($\dot{\gamma}$) is the relative displacement of one fluid layer with respect to the next. In general, the shear rate is the slope of the velocity profile as shown in the figure on the right. In our particular example where the velocity profile is linear, going from zero at the bottom to v at the top plate. Therefore, the slope of the velocity profile, and thus the rate of shear, is equal to v/h , h being the distance between the plates. The units of shear rate are $1/s$. The force needed to obtain a certain velocity depends on the contact area (A) between fluid and plates. Instead of force, the term shear stress is used, defined as the force per area $\tau = F/A$ with units Pa or Newton/m^2 (N/m^2).

We may think of the following experiment: we pull the top plate at different velocities v and we measure the shear force F . When we plot the shear stress, τ against the shear rate, $\dot{\gamma}$ We obtain a relation, the slope of which is the viscosity (figure in box):



$$\eta = \text{shear stress/shear rate} = \tau / \dot{\gamma}$$

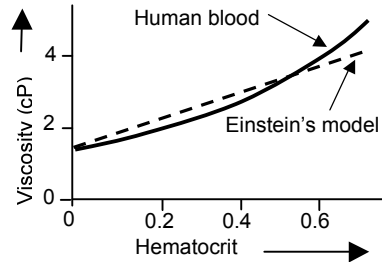
The units of viscosity are $\text{Pa}\cdot\text{s} = \text{Ns}/\text{m}^2$, or Poise ($\text{dynes}\cdot\text{s}/\text{cm}^2$). Fluids with a straight relationship between shear stress and shear rate are called Newtonian fluids, i.e., viscosity does not depend on shear stress or shear rate. Viscosity is sometimes called dynamic viscosity in contrast to the kinematic viscosity, which is defined as viscosity divided by density η/ρ .

Viscosity of blood

Blood consists of plasma and particles, such as the red blood cells. The viscosity of blood thus depends on the viscosity of the plasma, in combination with the hematocrit (Ht). Higher hematocrit implies higher viscosity. The relation between hematocrit and viscosity is complex and many formulas exist. One of the simplest is the one by Einstein:

$$\eta = \eta_{\text{plasma}} (1 + 2.5 Ht)$$

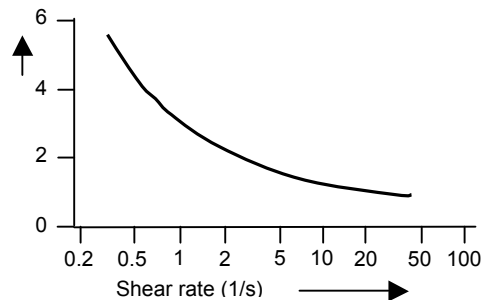
The viscosity of plasma is about 0.015 Poise (1.5 cP) and the viscosity of whole blood at a physiological hematocrit of 45 is about 3.2 centipoise (cP), or $3.2 \cdot 10^{-3} \text{ Pa}\cdot\text{s}$.



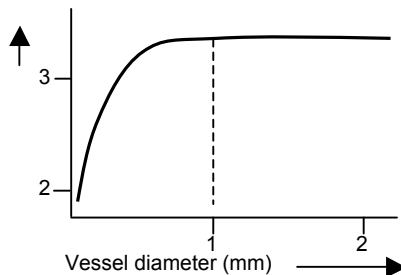
VISCOSITY as function of hematocrit

Anomalous viscosity or non-Newtonian behavior of blood

The viscosity of blood depends on its velocity of the blood. More exactly formulated, when velocity (shear rate) increases viscosity decreases. At higher velocity the disc-shaped Red Blood cells (RBC's, erythrocytes) orient in the direction of the flow and viscosity is lower. For extremely low shear rates formation of RBC aggregates may occur, thereby increasing viscosity to very high values. It has even been suggested that a certain minimum shear stress is required before the blood will start to



VISCOSITY as function of shear rate for hematocrit of 48



VISCOSITY as function of vessel size

flow, the so-called yield stress. In large and medium size arteries shear rates are higher than 100 $1/\text{s}$, so viscosity is practically constant. The physiological range of wall shear stress is 10 to 20 dynes/cm^2 .

The viscosity depends on the size of blood vessel (Fahraeus-Lindqvist effect). In small blood vessels, and at higher velocities, blood viscosity apparently decreases with decreasing vessel size. This effect begins to

play a role in vessels smaller than 1 mm in diameter.

The anomalous character of blood viscosity results from the red blood cells, and the effects are mainly found in the microcirculation at low shear and small diameters. The effects are of little importance for the hemodynamics of the larger arteries. Thus in hemodynamics it may be assumed that viscosity is independent of vessel size and shear rate.

Viscosity is strongly dependent on temperature. A decrease of 1°C in temperature yields a 2% increase in viscosity. Thus in a cold foot blood viscosity is much higher than in the brain.

How to measure viscosity

Blood viscosity is measured using viscometers. Essentially they consist of two rotating surfaces, as a model of the two plates shown in the box figure. Blood is usually prevented from air contact and temperature is controlled. When comparing of viscosity data one should always keep in mind the measurement technique, as results are often device dependent. (See also chapter Law of Poiseuille)

Physiological and Clinical relevance

Determination of blood viscosity *in vivo* is almost impossible. In principle pressure drop over a blood vessel and the flow through it, together with vessel size, can be used to derive viscosity on the basis of Poiseuille's law. Since in Poiseuille's law the vessel diameter appears as the fourth power, the determination of the vessel diameter often is not sufficiently accurate. Also, since the mean pressure drop over a short length of uniform vessel is only a few mmHg, viscosity estimation requires unobtainable accurate pressure measurements techniques. Moreover, hematocrit is not the same in all vessels. Finally, Poiseuille's law may only be applied when there are no effects of inlet length (see Poiseuille's law).

The main purpose of the circulation is to supply tissues with oxygen. Oxygen supply is the product of flow and oxygen content. The hematocrit determines the (maximum) oxygen carrying capacity of blood. It also determines viscosity and therefore resistance to blood flow. Low hematocrit, as in anemia, decreases oxygen content and viscosity of blood. The former lowers oxygen supply and the latter increases blood flow thus increases supply. Inversely, polycythemia increases oxygen content but lowers blood flow. At sea level, under normal barometric pressures in the healthy human the optimum hematocrit is about 45, with small difference between females and males. At high altitude a large hematocrit is advantageous. In endurance sports higher hematocrit is more efficacious during increased oxygen demand.