

The Rheology of Blood

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Introduction

The best measure of circulatory adequacy is the quantity of blood flow to the tissues. Major investigative emphasis has been placed on the development of supportive techniques during periods of inadequate tissue perfusion that have generally improved cardiac or vascular function. Considerable basic work has clearly defined the rheological behavior of blood; yet, little has been done to apply this information in situations involving circulatory insufficiency in man.

density = specific gravity?

Rheological Terms and Concepts

Before we can discuss the clinical aspects of *flow*, a basic understanding of its principles and a definition of its terminology must be imparted. These basic definitions are summarized by Table 1 and discussed below.

Rheology is the study of the flow of liquids and semi-solids. The word is derived from the Greek "rheo," meaning to flow and "ology," meaning a science.

Liquid is any physical body that is readily deformed by a tangential or shearing stress which remains deformed after the stress is removed; a solid tends to regain its shape.

Fluid is flow of a liquid and the movement of that liquid between two points. For flow to begin and continue, there must be a pressure difference. Flow will stop when the pressure difference is abolished; as in death. With death, there is the abolition of flow and peripheral resistance, and for physical reasons alone, the mean pressure within the vascular system extrapolates to 7 mm Hg.

The flow between two vessels at different pressures can be shown to increase when the pressure difference is increased. An increased "perfusion pressure" may thus produce better perfusion to an organ or limb. This improvement in circulation, for physical and biological reasons, is limited; and it is of no avail to raise pressure indefinitely in the hope of achieving a parallel increase in flow. A fluid may flow in one of two manners: laminar flow or turbulent flow.

Laminar Flow

When the flow is *laminar*, the fluid moves in layers of infinitesimal thickness that slide over one another.

In the flow of this type, when it takes place in an enclosed space such as a pipe, the movement of the fluid can be conceived as the sum of the forward motion of the concentric cylindrical layers, much like the movement of the parts of a collapsible telescope. The central lamina moves fastest, and the lamina in contact with the wall of the vessel is almost stationary.

Certain factors influence flow. Among these are: 1) the pressure differential between two points of a pipe or vessel; 2) the length of the pipe or vessel; 3) the calibre of the vessel or pipe; and 4) as far as the blood flow is concerned, the viscosity of the fluid in flow.

Poiseuille, over 100 years ago, described by formula the relationship of the factors that influence flow. Poiseuille, the father of hemodynamics, experimented with the flow of pure liquids through capillary tubes. Poiseuille's¹ law states that the volume of flow is directly proportional to the pressure drop across a given length of the tube and to the 4th power of the radius of the tube, and inversely to the length of the tube and to the internal friction of the fluid.

Described mathematically, the formula is represented by the following formula: $Q = \frac{\Delta P r^4}{8 \eta l}$

Q = flow in ml's per minute

η = viscosity in poisons

ΔP = pressure difference

r = radius

l = length of the tube in cm.

This formula describes an ideal form which is *not* applicable to blood for the following reasons:

1. Blood flow is pulsatile, not steady.
2. The vessel walls are elastic, not rigid, and not of a constant diameter.
3. And most important of all from the chemical standpoint, blood is not a pure fluid, it is a *non-Newtonian* fluid.

To clarify, a Newtonian fluid is one in which the viscosity, or internal friction of the fluid, is constant at all velocities. Water is a classical example of a Newtonian fluid and blood, in the large vessels, can be considered to be Newtonian.

Laminar flow relationships and hence Poiseuille law, applies only to Newtonian fluids. Laminar flow is the most efficient manner in which fluid moves since all the energy not dissipated in surface friction or viscosity is expended for propelling the fluid forward.

Turbulent Flow

In the second type of flow, *turbulent flow*, the fluid particles, instead of moving in paths parallel with the direction of flow, follow irregular paths at various angles to the flow direction, thus creating eddies and dissipating part of the available energy as heat.

The factors responsible for turbulence are not nearly as accurately known as those responsible for laminar flow.

Reynolds, towards the end of the last century, felt that turbulence largely depended on: 1) flow velocity; 2) vessel diameter; 3) fluid density; and 4) fluid viscosity. He expressed this mathematically in the formula $Re = VDd$.

Where Re = Reynolds Number

D = Vessel Diameter

V = Flow Velocity

d = Fluid Density

η = Viscosity

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The Reynolds number represents the minimum number for a given fluid below which it will not be turbulent. What the minimal Reynolds number will be depends upon the geometrical configuration of the local vessel as well as on the fluid and on the acceleration with which a given velocity is approached or lost.

Turbulence can be *local*, against a small part of the vessel circumference, it may be *temporary*, particularly with pulsatile flow, and it may *return* to laminar flow quite spontaneously.

Turbulence is essential for adequate mixing. Experimental data indicates that turbulence will occur at anatomical stenosis, anatomical dilatations, with intravascular foreign bodies, such as prosthetic valves, intracatheters, etc., and physiological dilatations and constrictions as in heart chambers. Turbulence will not occur until the Reynolds number is exceeded.

Turbulent flow can be regarded as any deviation from laminar flow. Extra pressure will be required to maintain a flow which has become turbulent because, in addition to forward flow, particles of fluid will follow projectories at any angle up to a right angle to the axis of flow. Energy is used up in excess to supply that needed for these haphazard movements.

The Poiseuille formula applies to volume flow. It is possible to express flow in term of velocity, but practically difficult to do and, on the whole, people involved in flow studies tend to express their data in terms of volume flow.

Viscosity

Viscosity is characteristic of all fluids moving in relation to a stationary surface. The greater the surface contact, the more important viscosity becomes. No viscous forces come into play if a fluid is stationary.

Viscosity depends upon inter-molecular adherence of adjacent lamina moving parallel to one another. The unit of measurement of viscosity is the poise, after Poiseuille. The more viscous a fluid, the higher the poise value.

There are many different kinds of viscosity: absolute viscosity, apparent viscosity, anomalous viscosity and relative viscosity. Our concern here is only with relative viscosity.

Relative viscosity, like specific gravity, expresses the value of a particular fluid by comparing it with water. The relative viscosity of blood at 37°C is approximately 4.

*WHAT ABOUT BLOOD
IN 1/2" OR 3/8" TUBING*

Viscosity is measured in various ways. One method is the capillary method. Under standard conditions of temperature and pressure, the volumetric flow of a liquid is timed as it passes through a standard size capillary tube. Under the same conditions, the experiment is repeated with an equal amount of distilled water. *The rate of flow of the fluid divided by the rate of flow of distilled water times the density of the fluid to be measured is the relative viscosity of that fluid.*

Another form of measuring viscosity is by the rotating cylinder method. If two concentric cylinders are suspended one within the other so that a fine gap between them can be filled with the fluid to be tested, and if one cylinder is set in motion, the viscosity of the fluid measured is related to the speed of passive rotation of the other cylinder.

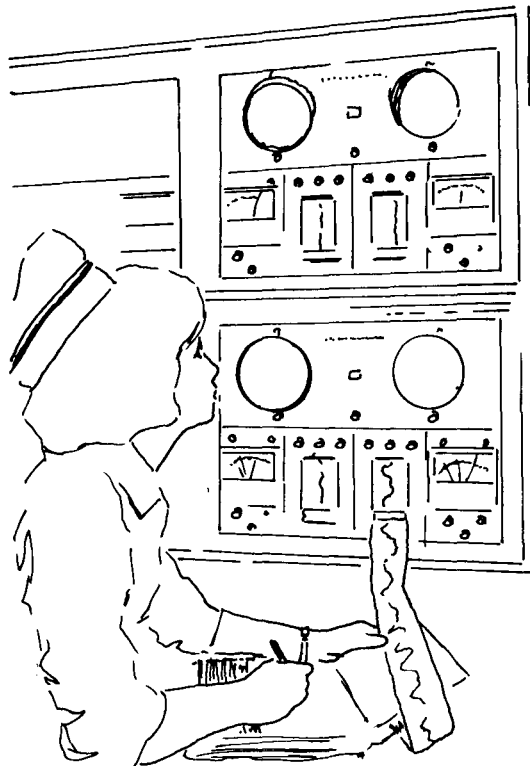
Viscosity measurements, in general, are difficult and vary according to the method and apparatus used. Average values for human blood given by different workers vary from 2.5 to 5.4 centipoises.

Shear Forces

The viscosity of a fluid is actually determined by the ratio of shear stress to shear rate. To be more explicit, shear stress is the tangential force applied to a theoretical fluid plane or lamina, causing that plane to slide over its neighbor, divided by the area of that plane and is measured in Dynes/cm². Shear rate, also called the velocity gradient, measures how fast that plane or lamina moves with respect to its neighbor and is measured in cm per sec.⁻¹

For example, if one supposes that the fluid is like a deck of playing cards lying on a table and if one pushes horizontally on the top card, the cards will progressively slip over each other and each card experiencing a slipping friction with the card immediately above and below. The less friction, the more cards will slip horizontally within a given instance under a given horizontal push.

Continuing this analogy of the cards, we define shear stress then as the horizontal pushing force divided by the



area of the card, i.e., force/area. Shear rate, then, is the horizontal distance of displacement per second of a given card beyond its neighbor, divided by the thickness of the card. Thus, viscosity, the analogue of friction, is expressed as the shear stress divided by the shear rate.

The method of measuring viscosity with double or coaxial cylinders as described above is a cylindrical approximation of the planar "flow" of the deck of playing cards, and it is particularly useful because shear stress and shear rate can be separately and clearly determined.

Blood Behavior

Blood, in the larger of vessels, behaves like and, for all practical purposes, is a Newtonian fluid and follows both Poiseuille's and Newton's principles. Blood, as it flows in the smaller vessels and microcirculation, becomes a non-Newtonian fluid and does not follow Poiseuille's or Newton's laws.

Thus, a Newtonian fluid can be defined as a fluid in which the ratio shear stress to shear rate is constant at all velocities. A non-Newtonian or Thixotropic fluid is one in which the viscosity varies at different velocities; that is, the ratio of shear stress to shear rate depends upon the velocity. Different velocities will produce different shear rates. Blood behaves as a non-Newtonian, or Thixotropic, fluid in the smaller blood vessels.

A Bingham body is the term used to describe the character of blood in the smallest of vessels. The term describes a plastic, semifluid substance. Whereas both Newtonian and Thixotropic fluids flow as soon as a pressure differential is applied, a Bingham body will not flow until a certain minimum pressure has been exceeded. The pressure at which flow begins is the yield pressure and the friction between the lamella of a Bingham body is called the yield shear stress.

Colloidal suspensions, like blood, do not obey either Poiseuille's or Newton's principles and have anomalous rheological behavior; blood viscosity varies with the shear rate at which it is measured, if one considers the microcirculation.

It is very important to understand the relationship of viscosity to shear rate. At low shear rates, such as those found in the microcirculation, the viscosity is quite high and at high shear rates where flow is fast, the viscosity, in comparison, is markedly less.

Example: blood at a shear rate of 0.01 cm/Sec.⁻¹ has a viscosity of 800 centipoises while blood flowing more rapidly at a shear rate of 1 cm/sec.⁻¹ has a viscosity of 20 centipoises. Blood viscosities measured at shear rates above 100 cm/sec.⁻¹ have Newtonian characteristics.

Example: keeping shear stress at an arbitrary constant of 10, Newtonian viscosity = 10/100 cm/sec/sec = 0.1 centipoises while 10/0.01 cm/sec/sec = 1000 centipoises. Thus, it can readily be seen that impressive changes in viscosity occur with only small changes in shear rates. These changes occur in the smaller vessels and microcirculation.

Blood Viscosity

Thus, viscosity of a non-Newtonian fluid depends upon the relationship of shear stress to shear rate. What is the intrinsic property of a fluid, specifically blood, that allows its viscosity to be altered? The intrinsic property of blood that does this is the relationship of fibrinogen to the red cells.

If whole blood is defibrinated, or if washed, RBC (red blood cells) are suspended in saline or Ringer's solution, at a hematocrit below 30%, almost Newtonian behavior of the suspension is observed. When fibrinogen is added to these suspensions, they again demonstrate non-Newtonian characteristics.

It is apparent then, that it is fibrinogen and its effect on red cells that is largely responsible for the anomalous rheological behavior of whole blood. Fibrinogen may act as an intercellular bridge, bonding red cells together, causing groups of them to clump in multicellular aggregates. The propensity for red cells to clump is greater when they have little dynamic force; that is, aggregation is at a maximum when the cells are not moving.

Photomicrographic studies show complete cessation of blood flow for short periods in the smallest blood vessels and it is here that red cell aggregation most frequently occurs. Aggregation, or sludging, has been described in the smaller blood vessels of the bulbar conjunctiva and nail bed and considerable speculation has arisen about the effect of this phenomenon on blood flow in the microcirculation.

Resversible Aggregation

Red cell aggregation is reversible and as the velocity of blood flow increases, the aggregates are stirred up and break apart. The extent of disaggregation is directly proportional to the velocity of blood flow. During intervals of low flow, a considerable portion of the shear stress applied to the blood must be expended to break up the red cell aggregates, which are constantly forming and breaking up. This means that only part of the applied shear stress is used to produce flow velocity. As the flow velocity increases, the red cell aggregates quickly break up and it becomes necessary for proportionately less of the shear stress to be utilized to separate the clumps of cells.

➤ At high shear rates, the fraction of the total shear stress needed to disrupt the aggregates is very small and blood at viscosities measured at shear rates above 100 sec per cm⁻¹ has Newtonian characteristics.

Despite the abundant literature describing red cell aggregation in the microcirculation as a disease or a symptom of a disease, it seems that the extent of blood sludging is a function of red cell-fibrinogen interaction and the extent of this interaction is dependent on the concentration of each.

As the concentration of red cells increases, the contribution by direct red cell-red cell interaction becomes increasingly important. A combination of polycythemia and hyperfibrinogenemia is the worst possible rheological combination. It has been calculated that the maximum hematocrit that may exist in a closed vessel before all the red cells are in contact is 58%. Above this value, the red cells must be in direct contact and it seems likely that the contribution of fibrinogen red cell interaction to sludging above this hematocrit level must be relatively unimportant.



Blood flowing at very low shear rates closely follows the Casson equation. The Casson equation predicts a linear relationship of shear stress to shear rate. By plotting the square root of shear stress against the square root of shear rate, the value for shear stress at a zero shear rate (when blood is motionless) can be calculated and this value is called the *yield shear stress*. Yield shear stress is a result of the reversible formation of red cell aggregates by fibrinogen red cell interaction. In the absence of fibrinogen, there is no yield stress.

Yield shear stress, then, represents the force necessary to disrupt red cell clumps or aggregates formed in standing blood. It is increased, as mentioned, by the same factors that promote the tendency for red cells to aggregate, that is, the fibrinogen and red cell concentration of the suspension. Yield stress appears to be the ultimate expression of the non-Newtonian characteristics of blood, since it represents the shear stress that must be applied to overcome the greatest degree of red cell aggregation, that is, static blood. As the shear rate increases, the fraction of shear stress represented by yield shear stress becomes less and less until very high shear stress then becomes relatively small, i.e., when the red cell aggregates are all broken up.

Since approximately 90% of total blood flow resistance between the aortic valve and the right atrium occurs in the microcirculation, any factor tending to alter viscosity should cause a marked effect in flow. *anticoagulate*

Thus, at low shear rates as found in the microcirculation, it seems likely that the yield stress may represent in itself a significant portion of the peripheral resistance to blood flow. Yield stress is *not* affected by anticoagulants. This may be an important consideration clinically, since thrombotic tendencies are believed to be associated with an increased Hct, high blood viscosity and low flow states.

Although yield stress increases non-linearly with the plasma fibrinogen concentration at normal hematocrit levels, it has been demonstrated by *in vivo* studies that at least 140 mgm% of fibrinogen must be present in a red cell suspension before any significant shear stress is observed. Since apparently 60% mgm of plasma fibrinogen is sufficient for a satisfactory clotting mechanism, this fortunate differential makes the modification of yield stress theoretically applicable to a clinical situation.

An elevated blood viscosity has been associated in a variety of clinical entities; among these are polycythemia, hyperlipemia, hyperfibrinogenemia, hypertensive vascular diseases, mitral insufficiency, Raynards Disease, Waldenstrums Microglobulinemia, and various types of trauma.

Definitions

Viscosity-internal friction of a fluid.

Absolute viscosity-a physical standard.

Relative viscosity-expresses the value of a particular fluid by comparing it with water.

Newtonian Fluid-viscosity is constant at all velocities.

Thixotropic (non-Newtonian) Fluid-Viscosity varies at different velocities.

Bingham body-plastic semi-fluid substance. It will not flow until a certain minimum pressure differential has been exceeded. Blood behaves as a Bingham body in the smallest vessels.

Yield pressure-The pressure at which flow begins.

Yield shear stress-Force needed to put in motion static blood.

Shear Stress-horizontal pushing force divided by the area of lamella.

Shear Rate-horizontal displacement of a lamella from its immediate lower neighbor divided by the thickness of the lamella and measured in second.⁻¹

Viscosity (the analog of friction) = shear stress/shear rate.

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BOOK REVIEW

A MANUAL OF RESPIRATORY FAILURE

By Eli Rush Crews, M.D. and Leopoldo Lapuerta, M.D.
Charles C. Thomas, Publisher, \$11.75

This book provides in a very clear and easily understood manner the basic current knowledge for anyone interested in this rapidly growing new field of medicine.

There are few, if any, books of this scope presenting so succinctly such practical basic information for physicians who have little understanding of respiratory failure, interpretation of blood gases, and their application to treatment. This is also an excellent book with specific chapters for nurses and inhalational therapists who are or will be caring for patients with respiratory failure.

There are chapters devoted to the history of respiratory failure, physiopathology, laboratory and clinical diagnosis, treatment guidelines, mechanical ventilation and discussion of respirators. There are special chapters on the management of pediatric respiratory diseases, care of the surgical patient with respiratory diseases, airway obstruction problems, tracheostomy and intubation techniques and complications.

Reading this book will provide one with an excellent grasp of worthwhile current concepts regarding the understanding of respiratory failure.

ELEMENTS OF PEDIATRIC ANESTHESIA

By C. R. Stephen, M.D., E. Warner Ahlgran, M.D. and
Edward J. Bennett, M.D.
Charles C. Thomas, Publisher

Since the last edition 15 years ago, many radical changes have occurred in pediatric anesthesia especially in pharmacology, techniques, and general knowledge. There is an excellent discussion of the physiological background of pediatric variations including specific reference to the premature and neonate regarding preoperative preparation, anesthetic management, fluids, and post operative care. The newer pharmacologic agents for premedication are discussed along with a detailed consideration of the newer parenteral agents for anesthesia. New concepts of relaxant drugs in the severely ill and cardiac infant are mentioned. There is a good unique basic discussion on newer concepts in fluid balance and replacement and temperature regulation. Also presented are techniques for anesthesia with special reference on monitoring and a detailed chapter on anesthesia for special procedures peculiar to infants including most anomalies and their inherent problems. An eloquent chapter on respiratory therapy and current concepts in pediatrics has been added.

This book is a valuable addition for anyone dealing with pediatric anesthesia and pediatric intensive care.

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