Constituents of Blood

[This and the following section developed from the publication *A concentrated suspension model for the Couette rheology of blood, Can. J. Chem. Eng., 53, 126-133*, by C.E.Brennen.]

From a fluid-mechanical perspective blood is a *concentrated* suspension of red blood cells in plasma fluid. While other particle constituents are present (white blood cells, platelets, *etc.*, figure 1) they are not present in sufficients concentration to effect the rheological properties.

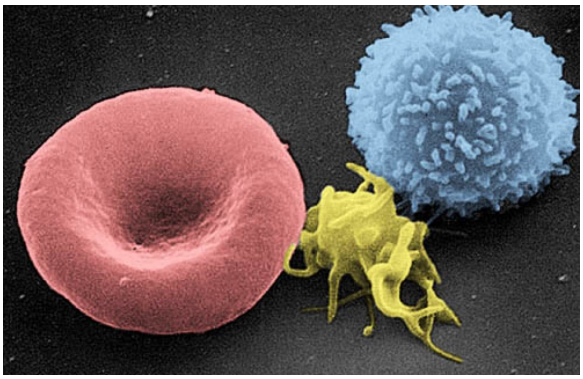

Figure 1: Particles present in blood, red cells, platelets and white cells.

One of the primary difficulties in understanding and modeling the flow of blood is that it is a *concentrated* suspension; that is to say the volumetric concentration, c (called the *hematocrit*), in terms of the ratio of volume of red cells to total volume is about 45% and therefore outside the range which can be handled by dilute suspensions theories. The comparative lack of hydrodynamic theory on concentrated as opposed to dilute suspensions can be ascribed to the difficulties in dealing with particle/particle interactions. The precise fluid mechanics of this situation is almost prohibitively complicated especially when the particles themselves change their shape in response to the fluid forces, as blood cells do.

The plasma or exterior fluid in which the red blood cells are suspended is, to all intents and purposes, Newtonian (see, for example, Cokelet (1972) and Brooks, Goodwin and Seaman (1970)). The red blood cell or *erythrocyte* consists of a membrane filled with a solution of hemoglobin and various salts. This interior fluid is also Newtonian and the viscosity as a function of hemoglobin concentration has been fairly well documented (Cokelet and Meisleman (1968), Chien, Usami and Bertles (1970), Wells and Schmid-Schonbein (1969) and Dintenfass (1964,68)). This viscosity is commonly some five or ten times that of the exterior fluid.

The nature of the red cell membrane and its deformation stress/strain relationship is less well established; a review article by Gitler (1972) on the plasticity of biological membranes indicates the complexity of this subject. He concludes that recent evidence suggests that biological membranes are quasi-fluid structures in which the constituent molecules are restricted only in an overall bilayer packing arrangement.

At rest the red blood cell is shaped like a bi-concave discoid which for human blood has a maximum thickness of about 2.4 microns and a diameter of about 8 microns. However in a flow situation this shape is rarely recognizable and the red blood cell is continuously deforming like a flimsy liquid-filled balloon. Such deformations clearly create motion of the interior fluid. Red blood cells in quiescent plasma

suspension tend to form aggregates known as *rouleaux* which may persist in flows at very low shear rates with consequent rheological effects. Aggregates do not form in suspensions of red blood cells in saline.

Brooks, Goodwin and Seaman (1970) estimate that the force required to disaggregate the red cells in rouleaux is less than the force required to initiate deformation of an erythrocyte and may be as little as one hundreth of that value. Thus when the shear rate and hematocrit in the plasma suspension are sufficiently large for red cell deformation to occur significant numbers of aggregates will not be present. The effect of rouleaux on the viscosity of blood at very low shear rates is not known.

Brooks Goodwin and Seaman (1970) also report that the height of a column of sedimented red cells in which deformation is first detected is .042 cm. At this height the force on the bottom layer of cells due to the weight of those above and in terms of an average pressure over the mean cross-sectional area of each cell is about 3.8 $dynes/cm^2$. If this is equated to a membrane yield stress of k $dynes/cm^2$ it follows that $2kt/a = 3.8$ $dynes/cm^2$ where a is the average radius of the cross-sectional area and t is the membrane thickness. The membrane yield stress, $k = 1.9a/t$ $dynes/cm^2$ will be employed in the membrane model of the section which follows.