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Red Blood Cells and Turbulence

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ABSTRACT

Measurements were made of the turbulence intensity of blood of various hematocrits (volume percentage of red cells in blood) flowing through an orifice. The maximum relative turbulence intensity was found to occur in the hematocrit range of 20% - 30%.

INTRODUCTION

It is well known that some materials (i.e. long chain polymers) when added to liquids may diminish the turbulence while other materials may increase the turbulence. Up until this present research, little was known about the effects of red blood cells (erythrocytes) on turbulence in blood.

The effects that red blood cells have upon the turbulence of flow may be of practical significance. We have found highly disturbed, probably turbulent flow occurs in the thoracic aorta of normal patients, and definitely turbulent flow occurs downstream to stenotic aortic valves of patients, Stein and Sabbah (1975). A variety of pathophysiological conditions appear to be affected by turbulent flow. The present authors have previously shown that turbulent flow, under laboratory conditions, contributes to thrombus formation, Stein and Sabbah (1975) and Smith, Blick, Coalson, and Stein (1972). Others have produced evidence that hydraulic factors, Murphy, et. al. (1962) and turbulence, Sako (1962), may contribute to atherosclerosis. Disturbances of flow also have been shown to produce intimal damage of blood vessels, Fry (1968). Turbulent blood flow in vitro appears to augment the sickling process of blood taken from patients with sickle-cell disease, Stein and Sabbah (1974).

In the present study a determination was made of the contribution to the intensity of turbulence of the volume percentage of red blood cells in blood. It was hoped that this study may add information concerning the relationship between turbulence and diseases of the circulatory system.

METHODS

The investigative methods can be briefly summarized as follows: Blood of various hematocrits, and plasma of comparable viscosity and density was caused to flow in a turbulent fashion through an in vitro flow system (Fig. 1). The viscosity of the plasma was made equal to that of blood by the addition of dextrose. The density of the mixture of plasma and dextrose was within 0.5% of the blood. The intensity of turbulence of the blood was compared to that of the plasma at equal Reynolds numbers. The contribution to turbulent flow produced by red blood cells that was independent of viscosity and density was therby determined.

The in vitro flow system consisted of a plexiglas reservoir attached to a smooth tube of 0.6 cm internal diameter and 180 cm in length (Fig. 1). Since the first pressure port was over 100 diameters from the inlet, a fully developed velocity profile should be present at this point for conditions of flow with Reynolds numbers below 2,000, Langhaar (1942). A turbulence producing orifice 0.2 cm diameter was inserted at the downstream end of the tube. Turbulent flow occurred downstream from the orifice. Thus, at appropriate Reynolds numbers, there was laminar flow upstream from the orifice, and turbulent flow downstream from the orifice. The random fluctuating velocities associated with the turbulent flow were measured with a hot-film anemometer. The sensing element of the hot-film transducer was 4.0 cm downstream from the turbulence producing orifice, and along the midline of the axial stream of flow. The blood or equally viscous plasma flowed past the hot-film transducer through a cannulating electromagnetic flow transducer and into a collecting chamber.

Constant flow through the test device was produced by a high pressure oxygen and valve system. Pressures were adjusted to cause flows within the upstream portion of the tube to be laminar (below a Reynolds number of 2,000). Flow downstream from the orifice was found to be turbulent at Reynolds numbers as low as 250. The Reynolds number at the orifice was calculated on the basis of the diameter of the tube and the mean cross sectional velocity.

The apparent viscosity of the flowing blood or plasma was calculated by the Poiseuille equation (viscosity = $\Delta P \pi r^4 / 8LF$ where P=pressure, r=tube radius, L = tube length and F=flow rate).

A minature wedge type probe (1232-NACL) with a quartz coating was used with a TSI Inc. 1050 constant temperature anemometer and a linearizer to analyze the turbulent fluctuating velocities. The probe was dipped in a silicone solution, washed with water, and allowed to dry overnight. This minimized adhesion of red blood cells. No signal drift was experienced. The base of the probe occupied 6 percent of the cross sectional area of the tube. The sensor of the hot-film probe was placed at a distance of twenty diameters from the orifice and on the axis of flow in order to measure fluctuating velocities within the region of fully developed turbulence. The existence of turbulence was documented by measurement of the longitudinal components of the random fluctuating velocities within the turbulent jet. The instantaneous velocity along the centerline of the axial stream of flow was defined as $\overline{U} + u$ where $\overline{U}$ represents the time-mean velocity at the point of measurement and u represents the fluctuating component. The violence of the random fluctuations, u', was measured as the root-mean-square value of the fluctuating component of velocity, Hinze (1959), and thus defined the absolute intensity of turbulence. The relative intensity of turbulence (dimensionless) was defined as $u'/\overline{U}$, the ratio of turbulence intensity to time-averaged mean velocity Hinze, (1959). The hot-film probe was calibrated at only the lowest blood hemotocrit.

Flow within the system was measured by attaching the flow tube to a cannulating electromagnetic transducer. The transducer was calibrated with each of the various liquids by utilization of a stopwatch and a graduated cylinder. Average velocity along the cross section of the tube was calculated as the ratio of flow to the cross sectional area.

All studies were performed on heparinized human blood. Blood of hematocrits 10, 20, 30, and 40 percent was prepared by combining the red cells and plasma at appropriate concentrations. The red cells were centrifuged out of whole blood taken from a blood bank. The viscosity of the test samples of plasma was made equal to the viscosity of the corresponding samples of blood by the addition of a solution of dextrose in saline. A cone-in-plate viscometer was utilized for the preparation of these samples. However, the viscosity as calculated from the Poiseuille equation under the conditions of the study, was utilized for the calculation of the Reynolds number. The densities of both the blood and plasma were measured with a hydrometer. The density of plasma differed from the blood by less than 0.5 percent.

RESULTS

The random longitudinal fluctuations of velocity along the centerline of the axial stream of flow are illustrated for a blood with a 30% hematocrit (30% red cells by volume) (Fig. 2). The magnitude of the fluctuations, which correspond to the absolute intensity of turbulence is noticeably greater with the sample of blood than with the plasma at a comparable Reynolds number.

The absolute intensity of turbulence, shown as a function of the Reynolds number, is shown for 30% hematocrit blood and plasma (Fig. 3). As shown, at a hematocrit of 30 percent, the intensity of turbulence of the blood was about twice as great as that of plasma. The addition of more cells, (hematocrit 40%) caused a reduction of the difference of the intensity of turbulence between blood and plasma.

The relative intensity of turbulence ($u'/\overline{U}$) reached a maximum for all Reynolds numbers tested at a hematocrit of about 20% (Fig. 4). With further increments or reductions of the hematocrit the relative intensity of turbulence diminished.

DISCUSSION

The viscosity of blood at the condition of flow within the test system was calculated by utilization of the Poiseuille equation. This permitted a more accurate estimation of viscosity than could be obtained by utilization of a viscometer because the shear rate in the region of the orifice was not readily calculable. Since plasma is a Newtonian fluid, viscosity measured at any shear rate would be constant. Utilization of a viscometer for measurement of the viscosity of the plasma served as a check of the accuracy of the viscosity as calculated by the Poiseuille equation. The difference of viscosity, as measured by the two techniques, was less than one percent.

The characteristics of flow in the region of an orifice have been studied in detail, Pai (1954), Hinze (1959) For this reason, an orifice was utilized in this system in order to produce turbulence. In the region of turbulence, the local minimum velocity along the centerline of the axis of flow does not disappear before an axial distance of about 20 diameters of the jet, Pai (1954). Although a similarity of mean velocity profiles is effectively reached at 2 or 10 diameters, real kinematic similarity is not reached until about 20 diameters, Pai (1954). In this study, the longitudinal velocity components of the random fluctuations indicative of turbulence

were measured. Measurements were made at a distance of 20 orifice diameters along the centerline of the axis of flow, which was in the region of fully developed turbulence.

Density variations affect the characteristics of jets only slightly, Hinze (1959). The density of blood was within 0.5% of the samples of plasma utilized in this study.

Although the literature is sparce, we are aware of two studies of turbulence intensity in fluids containing particles, Michael (1964) and Pfeffer and Kane (1974). Glass beads of 36μ diameter were shown to increase the relative intensity of turbulence in a gaseous stream flowing at high Reynolds numbers, Pfeffer and Kane (1974). The effects however appear to be dependent upon the size of the particles Michael (1964).

The mechanism of the peak effect of turbulence followed by a suppression of turbulence at higher hematocrits, as observed in this study, may be explained by the obervations of Soo (1967). With relatively few particles, there are large fluctuations of velocity in the wakes of the particles, which result in a high intensity of turbulence. For a larger concentration of particles, the dense cloud of particles starts to behave more as a continuum or filter which dampens the motion of the fluid. Hence, it would seem reasonable that as the hematocrit was increased beyond a certain value, the intensity of turbulence would probably start to decrease.

In summary the concentration of red blood cells appears to affect the intensity of turbulence of blood. Blood of hematocrits 10% to 40% shows more turbulence than does plasma of virtually equal viscosity and density flowing at equal Reynolds numbers. The presence of cells in suspension tends to increase the turbulence. A maximum relative turbulence intensity was found to occur with blood containing approximately 20% red cells.

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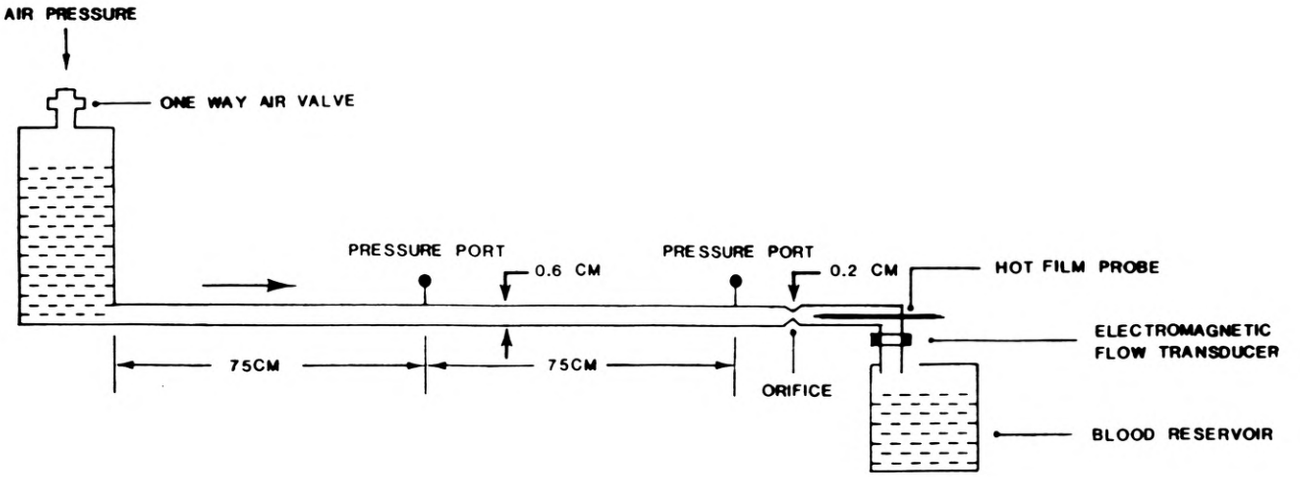

Figure 1 Diagram of Flow System

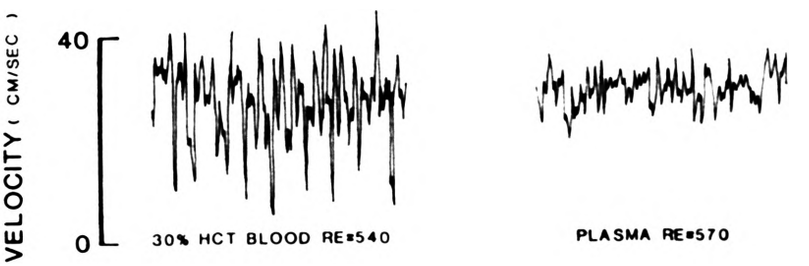

Figure 2 Velocity Fluctuations of 30% Hematocrit Blood and Plasma

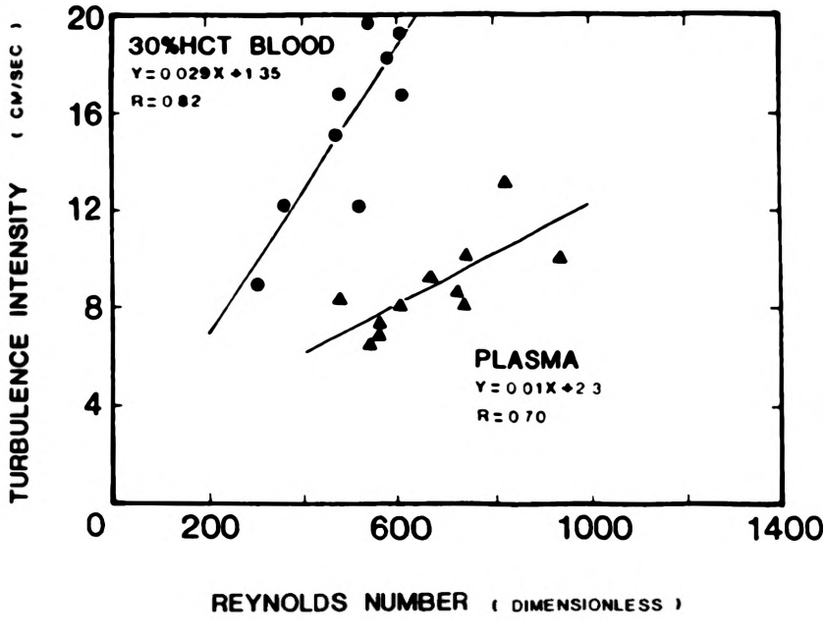

Figure 3 Absolute Turbulence Intensity of 30% Hematocrit Blood and Plasma

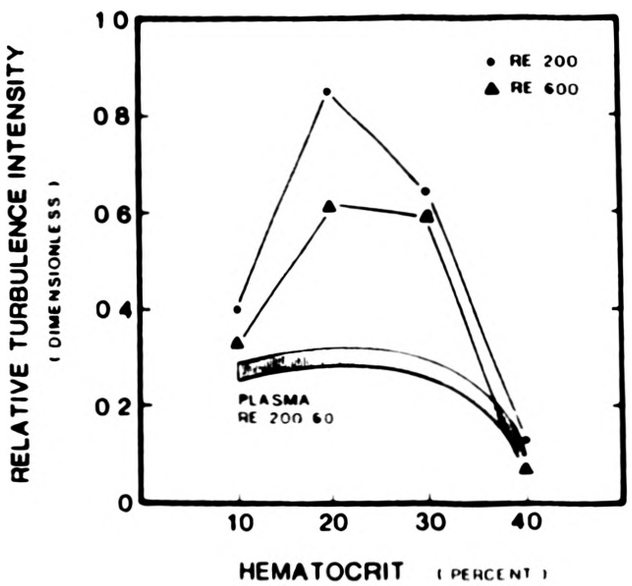

Figure 4 Relative Turbulence Intensity of Blood as a Function of Hematocrit

DISCUSSION

E. M. Moffat, United Aircraft Corp.: What sort of probe were you using?

Blick: The probe was a hot-film wedge 1232 NACL with a quartz coating and we used a TSI 1050 constant temperature anemometer.

Moffat: Did you examine the probe and see whether or not this varying increase in intensity might be due to some fouling on the probe?

Blick: Yes they were examined and no evidence of fouling was seen.

Moffat: The reason it came to mind is that the shape of the curve you showed here is the same as the shape of the curve that Tom Morrow produced in his study of fouling on wires. I don't recall what Tom did on wedge probes, but he found the first incidence of fouling is to increase the sensitivity and cause faulty high readings, and then as the layer of sediment and stuff on the wire built up, it would decrease the sensitivity again and finally would fall below the clean calibrations.

G. K. Patterson, UMR: In response to Dr. Moffat's comments, it seems as if he may be confusing an unsteady state effect (flapping lint causing high intensity, for instance) with a steady-state fouling effect. That leads me to ask whether equilibrium was really established on these probes. When turbulence intensity was being measured, was that constant for a good length of time?

Blick: Yes the signal remained constant for a long period of time. We had some experience in using the probes in live dogs and had the electric signal fade-out due to material collecting on the probe tip. We later injected heparin in the dog's blood and no tip fouling nor signal fade-out was experienced. In this present study the blood had been heparinized. Heparin is an anti-coagulant additive.

Patterson: It seems to me that what Dr. Moffatt was talking about is really something that should change with time rather than with concentration of particles of the red blood cells. The other thing is that in everything that I have seen for the fouling of wedge probes, and we've used them a lot, the turbulence intensity has always gone down but I think that might have a little bit to do with size of particles that are coating out on it, and whether secondary turbulence is generated on the sensor surface itself or not. Another thing different between wedge probes and cylindrical probes is that for the wedge, sensing takes place primarily in a stagnation region whereas in cylindrical probes sensing is also influenced by the heat transfer that's occurring all around the cylinder. This can cause their behavior to be quite different under fouling conditions.

Lindon Thomas, Univ. of Akron: We have made measurements in vitro and in vivo blood with conical and flush-mounted probes and found that, first of all, periodicity is increased with the addition of polymer. You're talking about an effect that is similar to the drag reducing effect that you find with the addition of polymer. Also, you made comments about the potential helpfulness of the use of increased hematocrit in connection with the decrease of atherosclerosis, perhaps the relationship between turbulence and the generation of that disease. I want to mention briefly that we have run an experiment where we fed rabbits high cholesterol diets. One of the groups was injected with drag reducing additives and there were enormous differences in the fatty deposits in the arterial system. I believe that these findings of ours supplement what you're reporting here.

Ronald Humphrey, Disa Electronics: What overheat ratio did you use?

Blick: The overheat ratio was 1.2.

Humphrey: You would get this fouling or coating if you tried to get too hot, like using it in plain water above 1.05 or 1.08.

R. V. Edwards, Case Western Reserve: Have you tried the same measurements with rigid red blood cells? There may be a difference in the results compared with those for flexible red blood cells.

Blick: These were red blood cells taken from the blood bank and added to the plasma and as far as I understand they are still flexible. It might be interesting to run the tests with rigid cells. We may do this.