Flow of human blood through capillary tubes and red cell concentration
by Ann Elizabeth Berg

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE in Chemical Engineering
Montana State University

Abstract:
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Various feed concentrations were used, along with various flow rates. These did not change the red cell concentration of the discharge with respect to the feed.

High molecular weight Dextrans were added to change the properties of the blood. These did not change the results either; the discharge red cell concentration was virtually the same as the feed concentration.

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Signature Ann Berg

Date September 4, 1973

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MONTANA STATE UNIVERSITY
Bozeman, Montana

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ABSTRACT

The flow of human blood through capillary tubes ranging from 15.1 to 36.9 microns in diameter was studied.

It has been previously noted (2) that at small tube diameters, the red cell concentration (hematocrit) at the exit of a capillary tube may be less than the concentration at the entrance. It was hoped to find exactly where this decrease occurs, if at all. The red cell concentrations of the feed and discharge blood were measured, and were found to be almost equal. Thus there is no screening effect causing a reduction in red cell concentration with flow through small tubes.

Various feed concentrations were used, along with various flow rates. These did not change the red cell concentration of the discharge with respect to the feed.

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BACKGROUND

Blood Characteristics

Understanding of the flow properties of blood has applications in many medical and pharmaceutical areas. By understanding both the macroscopic and microscopic behavior of blood, predictions may possibly be made about the flow in the circulatory system. Also, this information may be used in designing such medical equipment as heart-lung machines and artificial organs. Knowledge of the mechanisms of blood flow in glass capillary tubes is the first step in learning about flow in the small capillary networks of the body.

Blood is a suspension of cells in a solution called plasma. The plasma is an aqueous solution of organic and inorganic salts, other small organic molecules, such as urea and glucose, and proteins. The proteins, which make up about 7.0% of the plasma weight, are macromolecules of molecular weights ranging from 40,000 to over 1,000,000. These proteins consist of albumin, fibrinogen, and globulins. Albumin, with a molecular weight of 69,000, serves as a super transport molecule and helps regulate plasma volume. Fibrinogen is much larger, with a molecular weight of 170,000. It plays an important role in the clotting mechanism. Thrombin converts it to fibrin, which is the monomer used in building up a clot.

The cells consist of red blood cells (RBC's), white blood cells, and platelets. The red cells, also known as erythrocytes, make up about 97% of the cell volume. These cells have a biconcave disc shape,

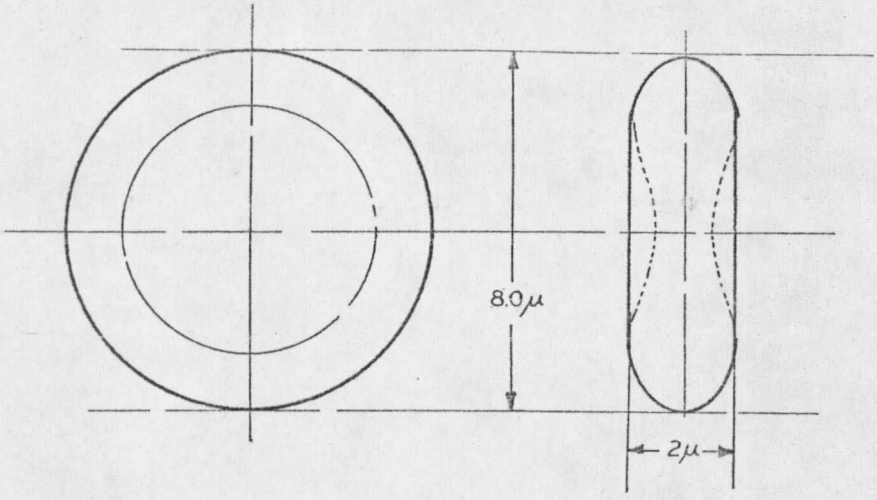

Fig. 1 Dimensions of a Red Blood Cell

averaging 8.0 microns in diameter and 2.0 microns in thickness. Various other values are also reported for the dimensions, however. A diagram of a red blood cell appears in Fig. 1.

The red cell is made up of a flexible membrane which is essentially unstretchable. The interior of this non-nucleated cell is a complex liquid, containing the hemoglobin. The membrane serves as a barrier to complex macromolecules, but allows small molecules to pass through rapidly. The membrane is the site of many chemical functions for the metabolism of the cell. The red cells serve to transport oxygen and carbon dioxide to and from the body.

The hematocrit is defined as the volume percent of the blood that is red blood cells. This is found by centrifuging a small volume of blood and comparing the relative volume of packed red cells to total volume. This gives accuracy to within 99%, as 1% of the packed cell

volume is trapped plasma.

The hematocrit can range from 37 to 54% in healthy humans. Changes in hematocrit for purposes of this study were made by centrifuging the sample and removing some of the plasma or red cell volume.

The white cells, also called leukocytes, are smaller in number and more varied in function than the red cells. There are five different kinds of white cells: basophils, eosinophils, segmented neutrophils, monocytes, and lymphocytes. Their sizes range from 8 to 22 microns in diameter. One of their main functions is fighting disease. These are nucleated cells and are more complicated in morphology than the red cells.

The platelets (thrombocytes) are small non-nucleated cells about 2-3 microns in diameter. Their main function is in blood coagulation, and thus they are closely involved in the clotting mechanism, or hemostasis. Hemostasis is activated <u>in vivo</u> by a complex chain reaction, initiated often by the rough edges of a cut in a vessel wall. This is of interest in the present study, as the rough ends of glass capillaries may also induce the clotting mechanism.

In studying the flow of blood, as well as in blood banking for medicinal transfusion or in clinical testing of blood, clotting presents a serious problem. Various anti-coagulants are used, including an acidified-citrate-dextrose (ACD) solution in the storage bags, and

heparin, a mucopolysaccharide obtained from dogs and cattle, used in hematocrit tubes to prevent coagulation. These compounds interfere with the clotting mechanism, usually by binding some protein in the reaction pathway, or by chelating calcium ions, which are essential for the clotting process.

When centrifuging the samples, the red cells are found in the bottom of the tube with a thin white layer on the surface of the red cell pack containing the white cells and platelets. It can be removed for investigations involving only red cells and plasma. This decreases the possibilities of clotting, due to the lack of platelets.

In normal, non-flowing blood, the red cells can aggregate face-to-face into a cluster known as a rouleau. At sufficiently high shear rates these rouleaux break up and the red cells exist individually. The addition of high molecular weight Dextrans increases the formation of the rouleaux.

Many of blood's properties vary greatly from donor to donor. Hematocrit and protein content are among the characteristics that have large normal ranges. But for the enzyme specificity of the body's metabolic functions, temperature, pH and ionic strength are virtually the same level in all humans. Thus, when working with blood, one has to consider both the similarities and the differences encountered from sample to sample.

Blood Rheology

Rheology is the study of the flow properties of a fluid, dealing especially with viscoelastic and non-Newtonian fluids. Blood rheology is concerned with understanding the effects various changes in the blood will have on its measurable properties.

Shear stress for unidirectional flow between two parallel plates is the force required per unit area to move a top layer of liquid over a lower layer. This can be expressed as

$$\tau = \frac{F}{A} \qquad (\text{dynes/cm}^2)$$

The strain rate is the velocity gradient and is given by

$$\dot{\gamma} = \frac{\Delta x}{\Delta t \; \Delta y} \qquad (\text{sec}^{-1})$$

for a layer of liquid Δy cm. thick moving a maximum relative distance Δx. The viscosity coefficient is the shear stress divided by the strain rate

$$\eta = \frac{\tau}{\dot{\gamma}} \qquad (\text{dynes/cm}^2, \text{ or poise})$$

and is a measure of the force required to move one layer of fluid over another at a given shear rate.

If one measured the viscosity of a sample of water at different shear rates, he would come out with a constant viscosity. But with blood, the viscosity varies over the range of shear rates, being higher at low shear rates, and lower at high shear rates.. The values obtained

are termed apparent viscosity, as they are the values the blood would exhibit at all points only if the blood were Newtonian. For some purposes, a more significant number is the relative viscosity, which is the ratio of the apparent viscosity of the blood to that of the suspending medium, in this case the plasma.

Poiseiulle was one of the first to study the flow of blood. His famous pressure drop-flow rate relationship for steady flow through a tube was originally developed for blood flow; however, it only applies to Newtonian fluids such as water, alcohol, and mercury--the fluids he worked with.

$$Q = \pi \frac{\Delta P}{L} \frac{R^4}{8\eta}$$

where Q = flow rate, ΔP = pressure drop, R = tube diameter, L = axial length of the tube, and η = viscosity coefficent. This applies to blood only when the flow has moderate to high shear stresses.

Non-Newtonian flow occurs for blood in a tube less than 300 microns in diameter when the flows are physiologically significant. This was investigated by Fahraeus and Lindqvist in 1929 (7). They used a capillary viscometer to study the relationship between tube diameter and viscosity at such high shear rates that the blood acted as a Newtonian fluid. They found that the relative viscosity, that is, the viscosity found by taking the ratio of the apparent viscosity of blood to the

viscosity of water, decreases with tube diameter. This lowering of the viscosity is of great significance to the body, as it allows the heart to pump a given volume of blood through the circulatory system with a smaller pressure drop than if the blood had a constant viscosity. The pressure drop across the human circulatory system has been found to be about 120 mm Hg.

Another factor affecting the viscosity of blood is the hematocrit. The results of an investigation by Chien, et. al. (6) are shown in Fig. 2. The viscosity of suspensions of cells hardened with glutaraldehyde or acetaldehyde and of normal cells was measured as a function of hematocrit. These cells were all suspended in Ringer's solution. The hardened cells show little shear dependence, but the normal cells show dependence on both hematocrit and shear rate.

This decrease in viscosity with increasing shear rate is further illustrated in Fig. 3. The deformability of the normal cells causes them to slip past one another much more easily, thus lowering the viscosity. This is not the case for hardened cells. The marked difference in viscosity, especially at high shear rates, is easily seen.

Addition of Dextran-40 further decreases the relative viscosity at high shear rates. This is due to an increased plasma viscosity, which acts to deform the red cells even more. This is shown in Fig. 4, where various concentrations of Dextran-40 were added to the suspending media,

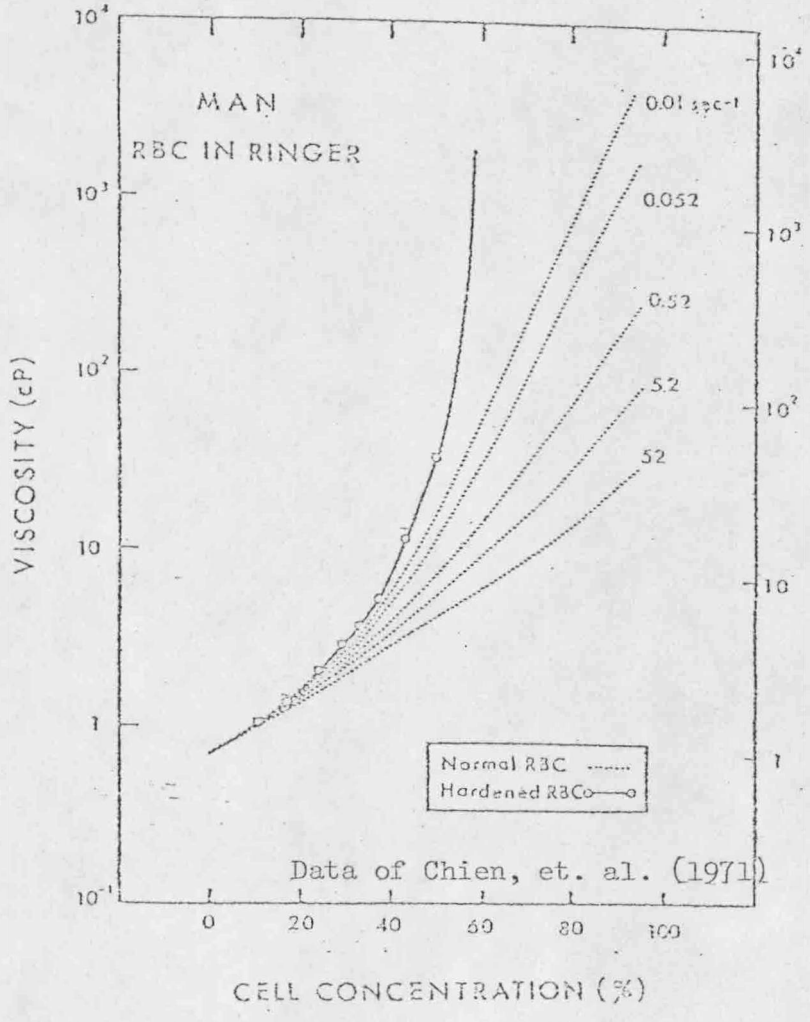

Fig. 2 Viscosity Dependence on Hematocrit

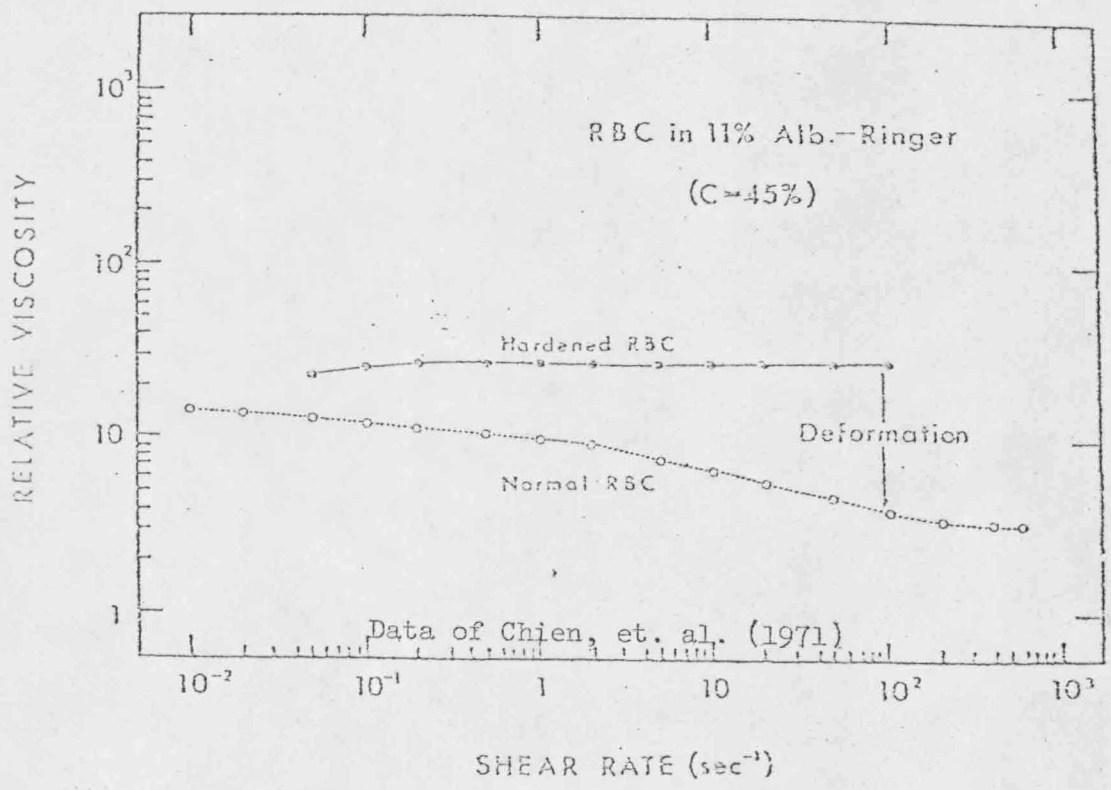

Fig. 3 Changes in Viscosity Due to RBC Deformation

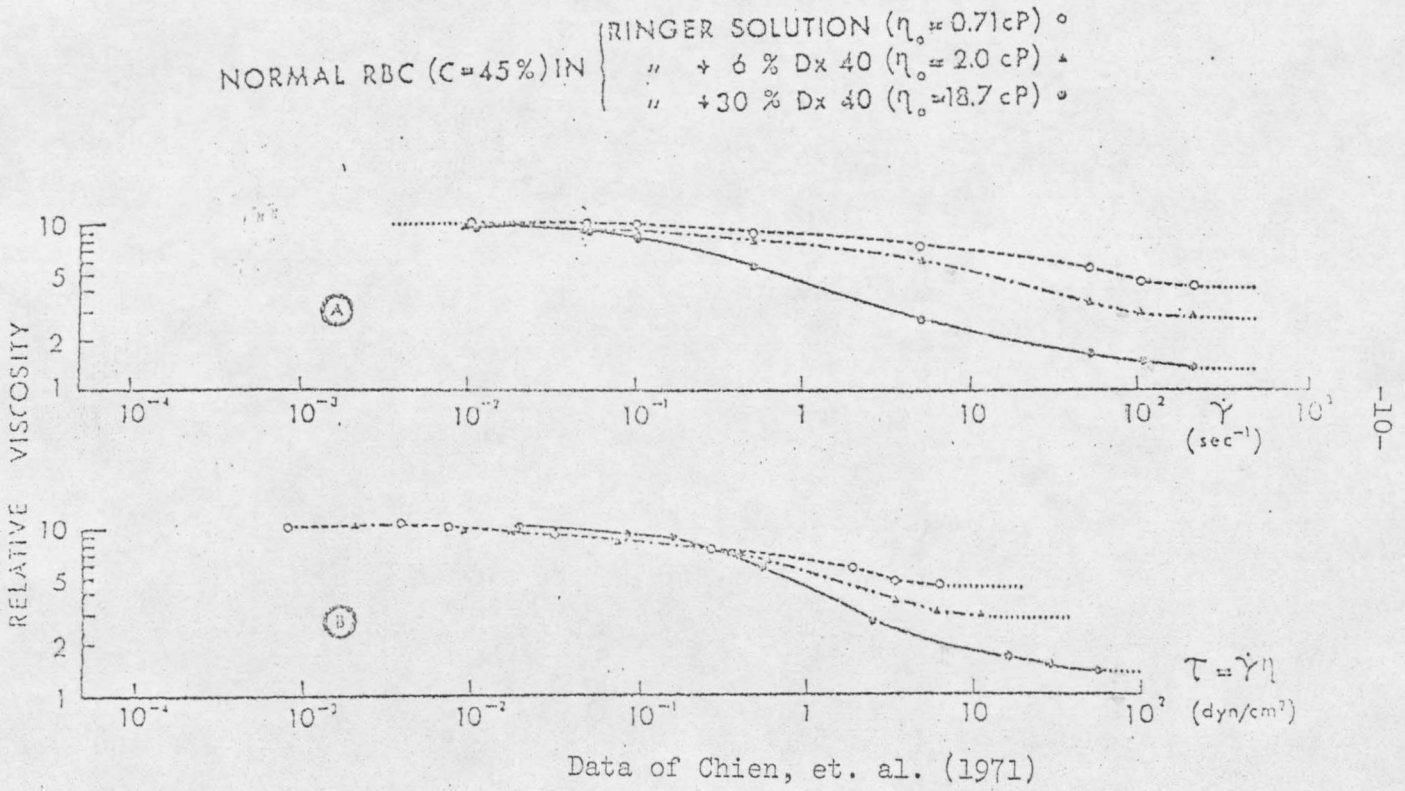

Fig. 4 Increase in Red Cell Deformability Due to Addition of Dextran-40 to Plasma

A) Shear Rate Vs. Relative Viscosity
B) Shear Stress Vs. Relative Viscosity

in this case Ringer solution. The abscissa is shear rate in A and shear stress in B.

The formation of rouleaux by red cells also has an effect on the viscosity. These rouleaux are broken up at high shear rates, but at low shears they serve to increase the viscosity. Fig. 5 shows the dependence of normal red cells suspended in plasma and in a Ringer solution containing 11% albumin. This latter solution does not allow the red cells to aggregate. Addition of high molecular weight Dextrans, such

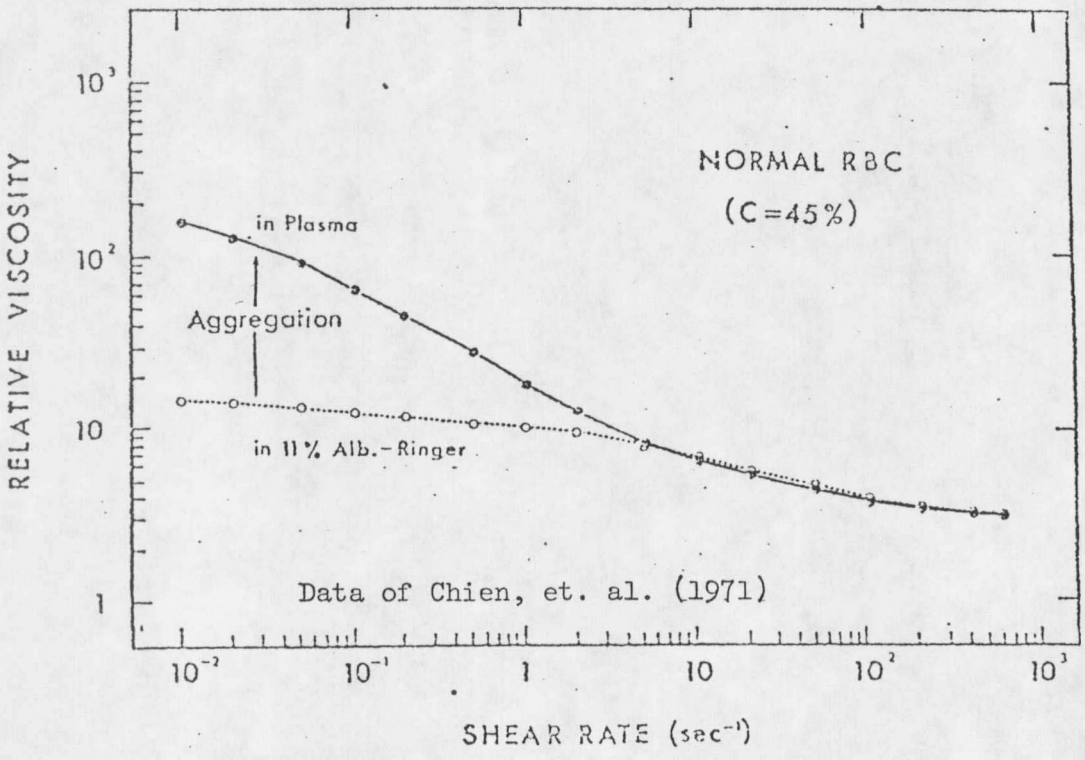

Fig. 5 Changes in Viscosity Due to Red Cel regation

as Dextran-250, increases the aggregation of the cells, however, and a reverse effect would occur. The Dextran-250 line would be above the line for normal cells in this case.

Further investigation into the relationship between viscosity and tube diameter has led to the discovery that for tubes less than 300 microns in diameter, the hematocrit is actually less in the tube than in the feed reservoir, and yet the hematocrit of the blood in a discharge reservoir was virtually the same as the feed. Mass balance considerations require, therefore, that the average red cell velocity must exceed that of the bulk velocity of the whole blood. A number of mechanisms have been proposed to account for this effect. The Vand effect allows for a layer of plasma next to the wall of the tube in which the local concentration of red cells is lower than in the center of the tube because the centers of the particles cannot possibly be AT the tube wall (11). This would give a higher concentration of red cells in the fast moving center portion, and a low concentration, in fact, almost zero concentration, in the slow portion next to the wall. Fig. 6 shows a schematic comparison of the velocity profile of the whole blood compared to that of red cells only.

The tube hematocrit was found, by Barbee and Cokelet (1), to decrease with decreasing tube diameter, as is shown in Fig. 7. However, the hematocrit in the discharge reservoir remained the same until tubes

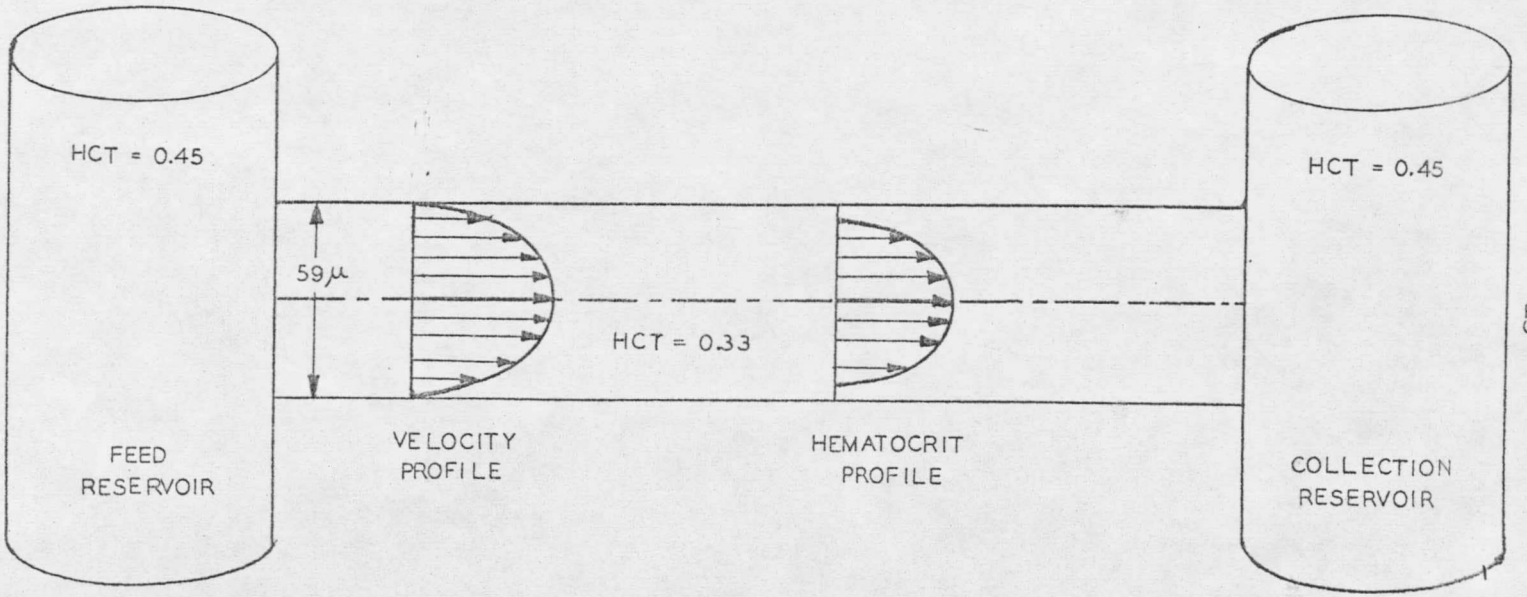

Fig. 6 Comparison of Hematocrit Profile and Velocity Profile in a Capillary Tube

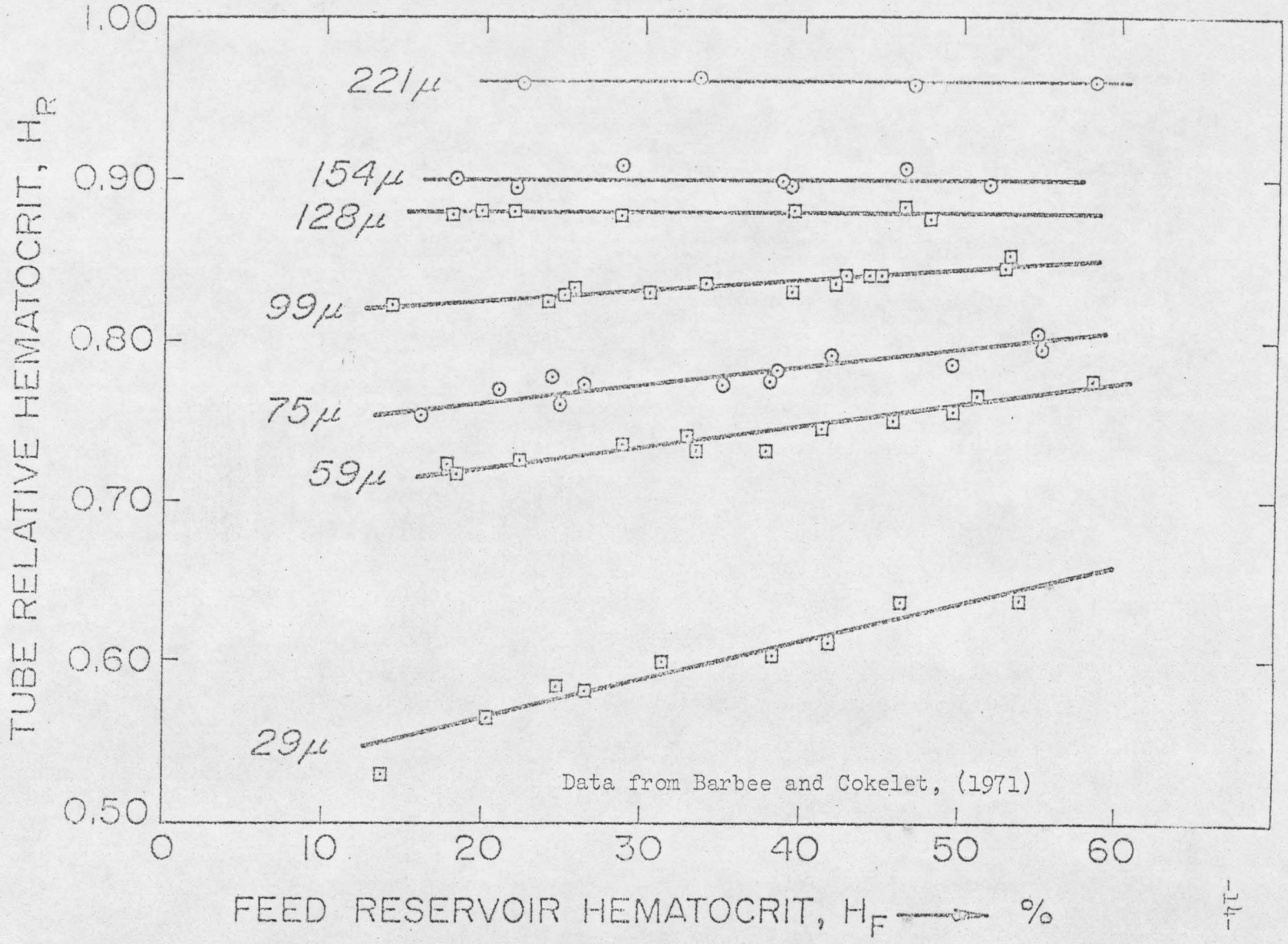

Fig. 7 Decrease in Tube Hematocrit with Decreasing Tube Diameter

of a 23 micron diameter were investigated. For smaller tubes it was found that some effect was causing screening of the cells at the tube entrance, because the exit hematocrits were less than the feed hematocrits.

The present investigation was undertaken to further study this decrease in exit hematocrit. Data from Barbee (2) are available for tubes with diameters of 8.1, 12.5, and 23 microns, as shown in Fig. 8. This graph assumes that no flow occurs for normal cells through diameters less than 2.8 microns, as reported by Gregersen, et. al. (9). The strange behavior between 8.1 microns and 12.5 microns was assumed to occur because of "crowding" at the entrance of the 12.5 micron tube--two cells struggling to enter the tube, and thus blocking it. This shouldn't occur at the 8.1 micron tube, as the cells can enter only one at a time, and must proceed in single file down the tube.

This study was done to obtain further data using five tube sizes: 15.1, 16.1, 19.4, 28.5, and 36.5 microns. The data obtained fills in some of the gaps on the graph in Fig. 8, and hopefully will show exactly where the drop-off in exit hematocrit occurs.

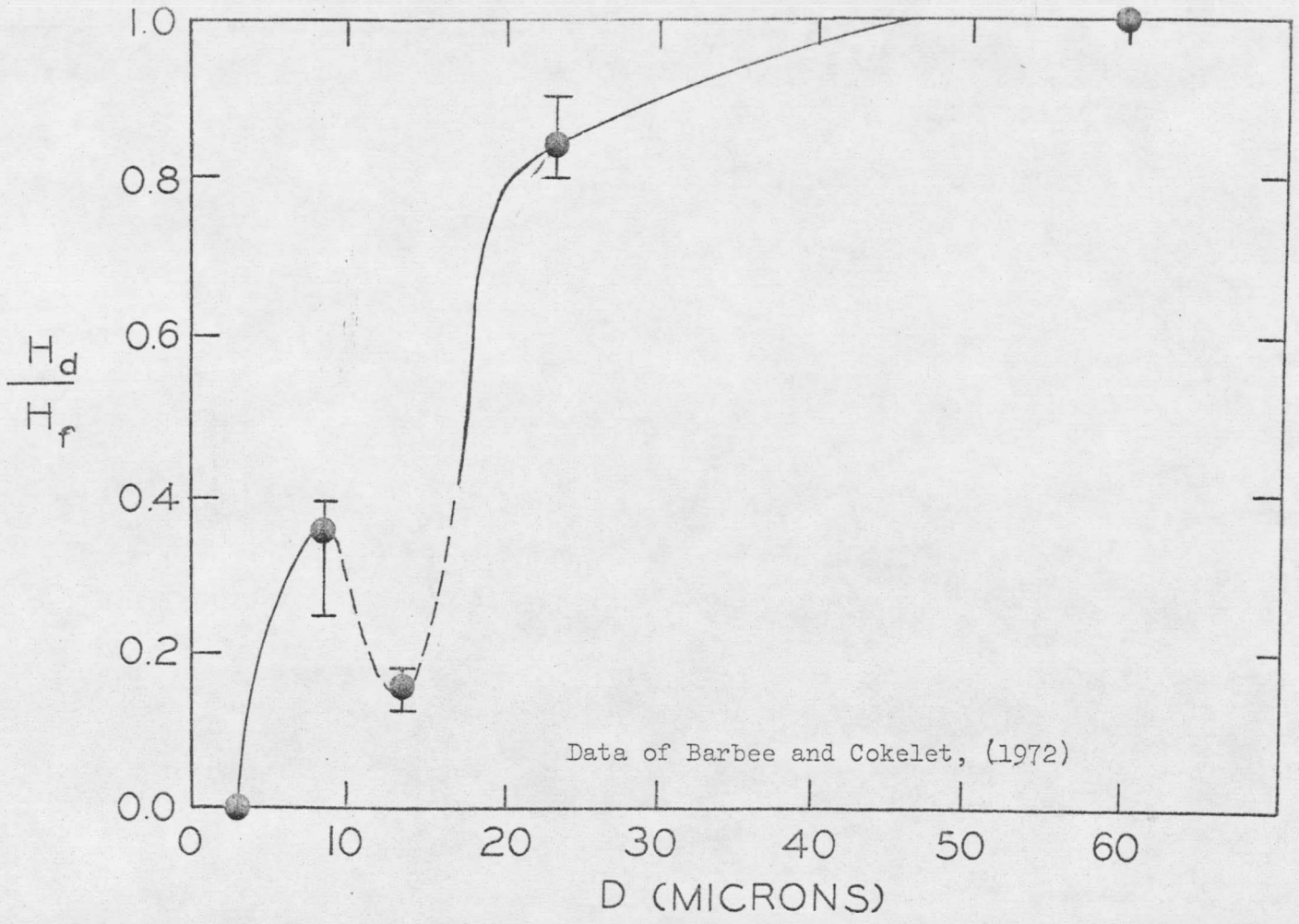

Fig. 8 Ratio of Discharge Hematocrit to Feed Hematocrit vs. Tube Diameter

RESEARCH OBJECTIVES

This research was undertaken to investigate the discrepancies found in the relationship between entrance and exit hematocrits. Five tube sizes were studied: 15.1, 16.1, 19.4, 28.5, and 36.5 microns. In previous studies, the drop-off effect was found to occur somewhere in the range between 23 and 59 microns. By using these tube sizes, it was hoped to pinpoint this range, and further study the region of tubes smaller than this range.

By adding high molecular weight Dextrans to the blood plasma, a relationship of the blood cells to various suspending media could be found. If the effect occurred at a given tube diameter, a change in the blood viscosity might either increase or decrease the effect.

Different flow rates and feed hematocrits were also investigated to see if this could have any influence on the effect.

APPARATUS

Blood Preparation

Blood was drawn from healthy donors by standard blood banking methods. Acidified-citrate-dextrose (ACD) solution was used as an anti-coagulant and the blood was stored at 4°C. until used.

Plugging of the capillary tubes was one of the major problems, and a number of steps were taken to avoid this effect. The samples of blood were filtered through Swank Blood Microemboli filters to remove any microemboli aggregates which may have formed during storage. These filters remove any debris down to 10 microns and allow the red cells to pass through with no hemolysis (bursting of cells) or damage to the cells.

Coagulation, presumably initiated by the platelets, was causing plugging, especially with units of blood one to two days old. So, the samples were centrifuged and the buffy coat removed. This contains the white cells, which may range up to 22 microns in diameter, and the platelets, which play an important role in coagulation. Plugging was most serious with the smallest tube sizes. It was found that storing the blood 4-5 days allowed most of the platelets to disintegrate, thereby reducing the plugging problems in these tubes.

For the whole blood runs, the cells were resuspended in the plasma after removing the buffy coat. When the two Dextran solutions were used, the viscosity of the plasma was measured in a Wells-Brookfield

viscometer at 37°C. The plasma was weighed, Dextran was added, and the viscosity of the plasma-Dextran solution was measured in the viscometer. Concentrations of the Dextran were 2.0% plasma weight Dextran-40, and 0.5% plasma weight Dextran-250. The plasma was then remixed with cells to give a hematocrit range between 35 and 45%.

Tube Preparation

Five sizes of capillary tubes were used. Measurement of the exact tube diameters was done in two ways. Initially, distilled water was run through the 29 and 37 micron tubes at steady state, and the pressure drop was measured. This was used with Poiseuille's equation to determine the tube diameter. A diagram of the apparatus used appears in Fig. 9. These tubes were measured to be 29.2 and 38.2 microns by this method.

Photographs of the ends of the tubes were also used to calibrate the tube diameters. Tube lengths approximately 1.0 cm. long were balanced on a microscope slide in clear nail polish. When the polish dried, the tubes were snapped off close to the surface of the hardened enamel. These were then photographed with a microscope and an oil immersion lens at 1000X magnification, along with a micrometer, which was used as a ruler to measure the inside diameter of the tubes. The measured tube sizes were 15.1, 16.1, 19.4, 28.5 & 36.9 microns.

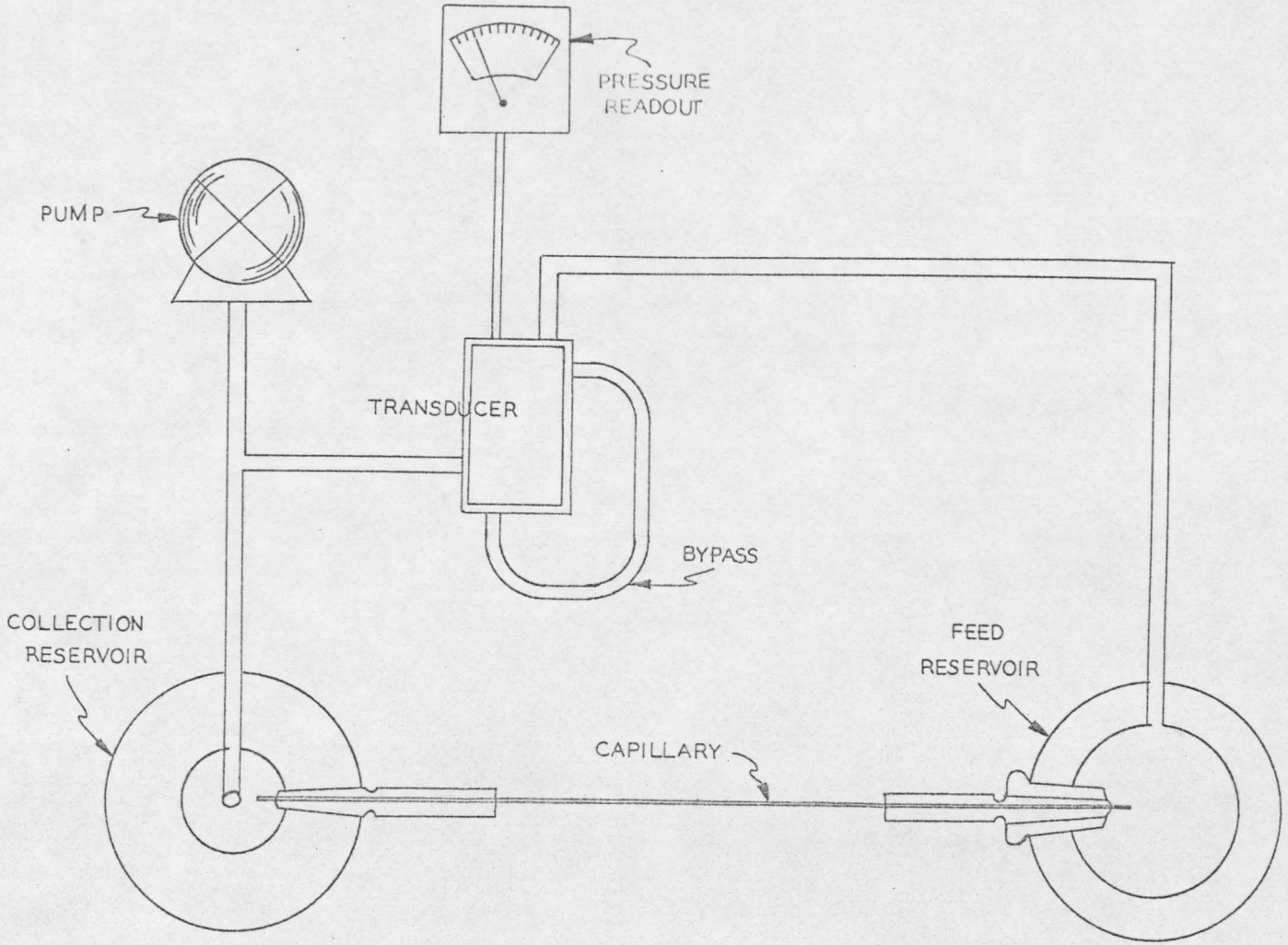

Fig. 9 Apparatus for Pressure Drop - Flow Rate Measurements

There was a difference of 2.40% for the 29 micron tube and 3.31% for the 37 micron tube by these two methods.

Photographs were also taken of the tubes at 100X magnification. These show that the tubes snap off perpendicular to the axial line of flow in most cases. Even a slight angle does not cause much change in the tube opening, as this is such a small area of the entire end of the tube. This precludes any possible variation in entrance effects due to cells entering the tube at an angle.

The tubes were cut into approximately 10.0 cm. lengths and glued into standard taper joints with epoxy glue. One tube was used for the 29 and 37 micron tube sizes. By gluing two tubes in parallel in a standard taper joint, two microhematocrit samples were obtained in the same time. This was done for the 15, 16, and 19 micron tube sizes. The fittings were re-enforced with brass wire, glued to the standard taper joint with epoxy, parallel to the capillary tubes.

Frequently the tube plugging seemed to occur at the entrance or exit of the tube. A possible reason for this is that the sharp edges of the capillary aggravated the platelets and induced the clotting action. In any case, snapping off a millimeter or two of the ends and forcing isotonic saline through the tube could sometimes restore it to utility.

Flow Apparatus

The flow equipment consists of a pump, a gas-tight syringe, a feed reservoir, the glued tubes, and a microhematocrit tube used as a collection reservoir. The pump forces liquid into or out of the syringe at various flow rates. Various syringe sizes may be used; this allows greater variation in flow rate.

The liquid from the syringe is forced into the feed reservoir, which in turn forces the blood out through the capillary into the microhematocrit tube. Three-way valves are located along the tubing between the syringe and the feed reservoir to allow refilling and cleaning the syringe or the reservoir without disassembling the entire apparatus.

The reservoir is a plexiglass cylinder positioned over a magnetic stirrer to insure uniform distribution of the red cells in the feed. It is fitted with a 5/20 standard taper joint and metal screws for holding the capillary tube in place.

The entire apparatus is surrounded by a plexiglass box, which allows for accurate temperature and humidity control. Water can be evaporated into the atmosphere of the box to keep it humid.

A diagram of the entire apparatus appears in Fig. 10.

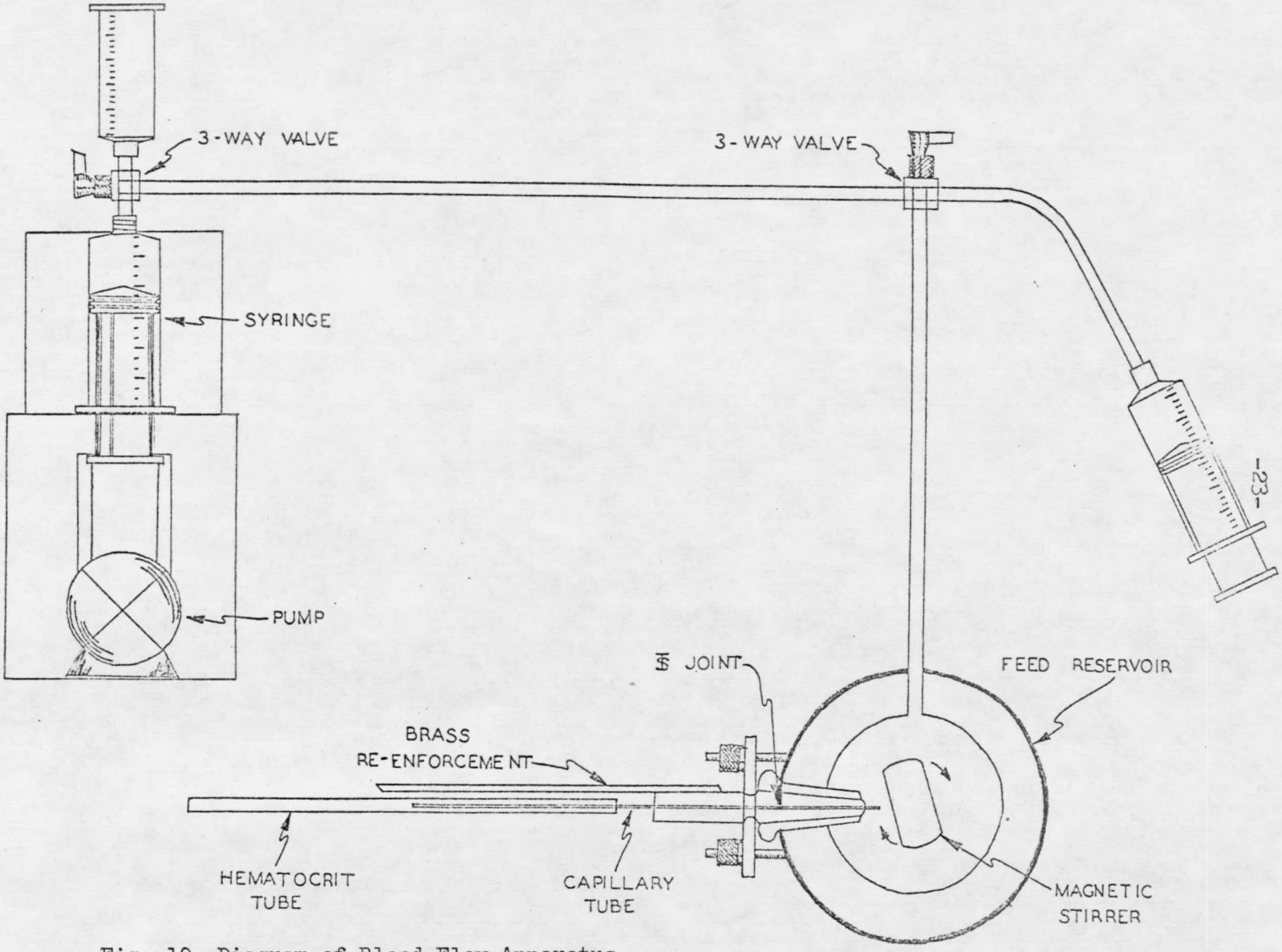

Fig. 10 Diagram of Blood Flow Apparatus

PROCEDURE

The entire system is filled with liquid except for the feed reservoir. The blood sample is poured into the reservoir and some is drawn up into the system towards the syringe. Originally, isotonic saline was used in the system; however, it was found that this was changing the feed hematocrit. A silicone fluid of a viscosity of about 5 cp. was used instead, as this is immiscible with the blood.

The hematocrit is taken of the sample in the feed reservoir, the system is sealed, and the pump is turned on. Hematocrit tubes are placed on the ends of the capillary tubes and sealed, either at the reservoir end with Vaseline, or at the other end with Critoseal, to prevent evaporation of plasma from the sample. When a large enough sample is obtained, the tubes are removed and centrifuged to obtain the discharge hematocrit.

Microhematocrit Method

Well-mixed anti-coagulated blood is drawn up into a microhematocrit tube (75 x 1.5 mm) to approximately three-fourths of its length. One end of the tube is sealed with Critoseal molding clay, and the tube is centrifuged in a microhematocrit centrifuge at 5500g for ten minutes. The hematocrit is calculated by measuring the length of the red cell volume (excluding the buffy coat, if any) and dividing this by the length of the entire sample. This fraction is reported as a percent. The normal range in healthy humans is 37 to 54%.

Either just before, or just after, a run is made, two microhematocrit tubes are filled to obtain the H_f value. These are averaged. Except where noted in the results, two tubes were filled from the capillaries to obtain the H_d values. If the sample obtained for the H_d was too small to be accurately measured with a machinist's rule, the distance was measured with a vernier scale on a microscope.

RESULTS AND DISCUSSION

Whole Blood Runs

The results of the whole blood runs are given in Table I. This table contains all the runs performed, including the runs at various flow rates and feed hematocrits. The values reported are the tube diameter in microns, the approximate flow rate in tube diameters per second calculated from the syringe pumping rate, the feed hematocrit H_f, the discharge hematocrit H_d, and the ratio of these last two, H_f/H_d. The values of this ratio were all very close to 1.0 for the range of tubes studied, indicating that little or no entrance effect occurs to cause a decrease in the discharge hematocrit.

Table II gives the averages of the hematocrit ratios for the various tube diameters. When a Student t test was done on this data, the differences between the averages were not significant. These data are plotted in Fig. 11. This graph shows the tube diameter plotted versus the ratio of the exit and entrance hematocrits, H_d/H_f. The curve does not drop at all before about 15 microns. The present data indicate that the curve may be beginning to drop off at this point. The results are entirely different from the results found earlier, as can be seen by comparing Fig. 11 with Fig. 8. It is thought, however, that the data for 8 microns on the earlier graph is correct, and therefore Fig. 11 is drawn using these data.

The differences in the two graphs can be explained by comparing the two methods used in obtaining the data. The earlier study (Fig. 8)

TABLE I

WHOLE BLOOD RUNS

TUBE SIZE (microns)	FLOW RATE (TD/sec.)*	H_f	H_d	$\frac{H_d}{H_f}$	COMMENTS
36.9	3644	41.25	41.50	1.006	
		27.95	27.65	0.989	blood dil. w/ saline
		36.65	36.10	0.985	
		29.80	29.10	0.976	hemolysis in bagged blood
		29.25	28.65	0.979	
28.5	7911	42.30	42.10	0.995	
		43.90	43.07	0.981	
		46.20	46.00	0.996	only one H_d tube
		29.37	28.45	0.968	
		41.30	41.20	0.997	
19.4	28,124	33.50	33.00	0.985	
		38.00	36.40	0.958	
		35.90	34.85	0.971	
	25,074	42.40	42.10	0.993	only one H_d tube
		37.50	36.50	0.973	very slight hemolysis
	14,062	44.67	44.50	0.996	
		38.00	37.75	0.993	

*calculated using pumping rate, see text for discussion

TABLE I (CONT)

WHOLE BLOOD RUNS

TUBE SIZE (microns)	FLOW RATE (TD/sec.)*	H_f	H_d	$\frac{H_d}{H_f}$	COMMENTS
19.4	14,062	35.90	35.60	0.992	
		38.75	39.23	1.012	humidified
	12,537	40.25	40.80	1.014	only one H_d tube
	7031	35.90	35.75	0.996	
16.1	49,213	27.70	27.30	0.986	only one H_d, hum.
	24,607	27.75	27.05	0.975	hum.
	12,303	38.75	37.00	0.955	only one H_d, hum.
		27.60	26.85	0.973	hum.
15.1	59,653	37.80	36.50	0.966	hum.
		38.10	36.85	0.967	hum.
		36.20	35.35	0.976	hum.
		42.65	41.25	0.967	hum., very slt. hemolysis
	28,828	38.75	38.25	0.987	hum.
		25.10	25.30	1.007	hum.
	14,414	25.05	24.25	0.968	hum.

*calculated using pumping rate, see text for discussion

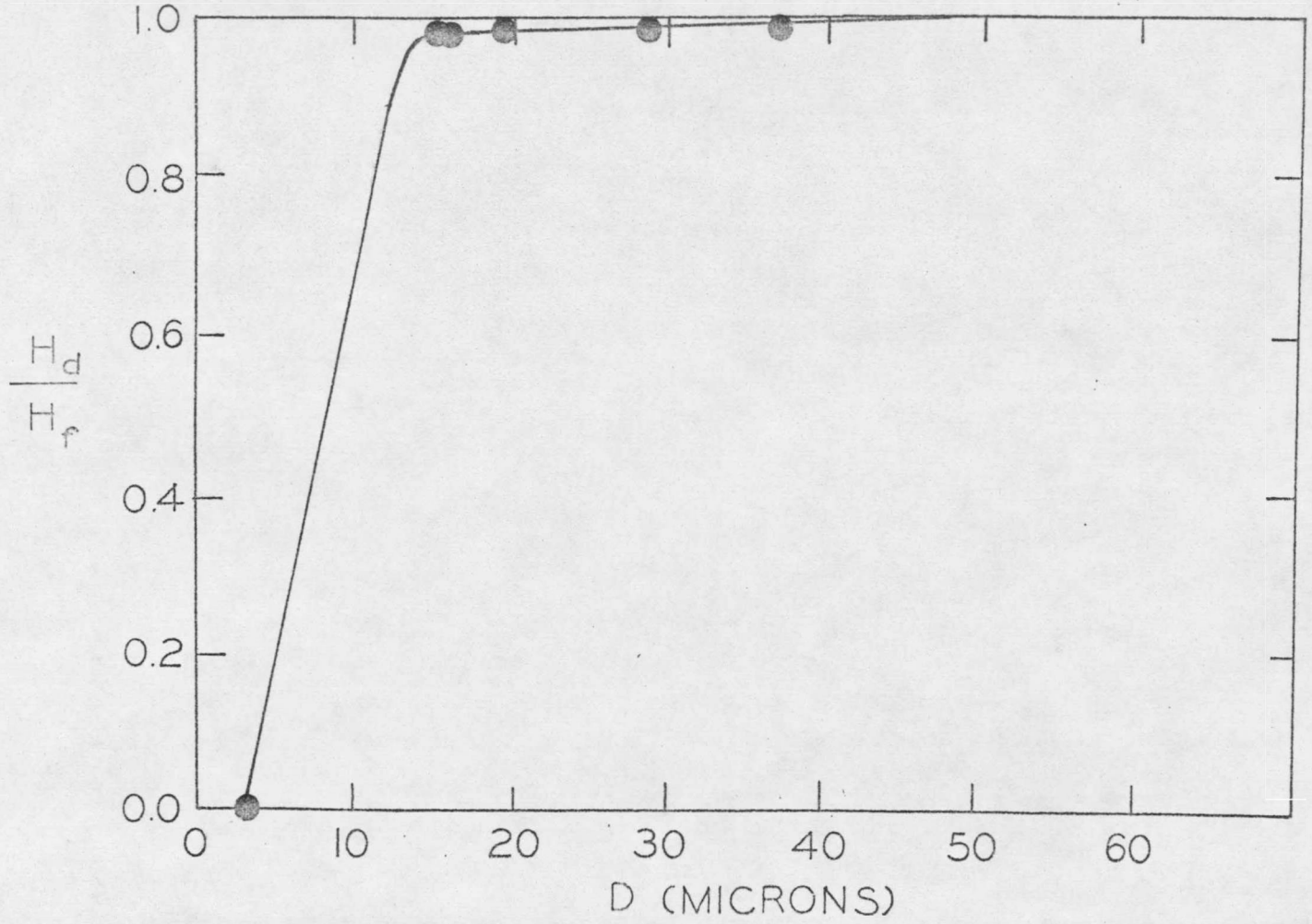

Fig. 11 Results of Whole Blood Runs

TABLE II

AVERAGES FOR WHOLE BLOOD RUNS

TUBE SIZE	NO. RUNS	AVERAGE $\frac{H_d}{H_f}$
36.9	5	0.987
28.5	5	0.987
19.4	11	0.989
16.1	4	0.972
15.1	7	0.976

used a cinemaphotography technique to count the number of cells flowing in the capillary tube. It can be shown that the ratio of the average velocity of the red cells to the average velocity of the blood is equal to the ratio of the discharge hematocrit to the hematocrit in the capillary tube, or

$$\frac{\overline{U}_c}{\overline{U}_B} = \frac{H_d}{H_t}$$

This is done by relating the particle velocity in the tube to the volume of liquid in the tube to get a measure of tube hematocrit, H_t. The discharge hematocrit is calculated by relating the blood velocity to the fluid flux across a given section of the tube. These two are compared and the relation between bulk velocity and particle velocity is found. This calculation is shown in the Appendix. Using this information, it should be possible to calculate the discharge hematocrit by

knowing both the cell velocity and the blood velocity.

However, in the calculations of the data shown in Fig. 8, the numbers used were average cell velocities rather than blood velocity. This gives discharge hematocrit values which in actuality are the same as the tube hematocrits. This does not completely explain the discrepancies between the two graphs, but it does explain the large difference, especially in the 15 micron range.

The rapid drop-off in Fig. 11 at the smaller tube diameter is more easily explained than the previous graph. Earlier, it was thought that at approximately two red cell diameters, or 14-16 microns, the red cells were crowding each other and allowing only plasma to get into the tube. But since cells are flexible, they can easily slip over one another to enter the various sized tubes. A crowding effect would merely deform them more and force them into the tube, with little or no change in the relation between the plasma and the red cells. As the tube sizes approach the cell diameter, that is, in the range of 8 microns, the actual size of the cell may impede entrance to the tube. At the range of tubes studied, however, there would not seem to be any actual blockage effect of the cells. Hardened cells may show this effect, and thus a reduction in the hematocrit ratio, at the entrance of a tube which is two particle diameters in diameter.

The range of H_d/H_f values obtained is very narrow; the variation could be due only to the error involved in the microhematocrit method.

When the tubes plugged up, it seemed to be an all or nothing situation, with neither plasma nor red cell flow. Apparently, cells aggregate into a clot that fills the whole tube diameter, not just one region which the cells may slip around. This is of physiological interest, as the body has to have a mechanism for removing any such emboli which might form in the circulatory system, or the flow of blood would be restricted. This is indeed the case; a system of enzymes breaks down any such clots that form in the system.

TABLE III

COMPARISON OF HEMATOCRIT RATIOS AT DIFFERENT FLOW RATES

TUBE SIZE (microns)	FLOW RATE* (TD/sec.)	NO. RUNS	AVERAGE $\frac{H_d}{H_f}$
19.4	28,124	3	0.971
	14,062	4	0.998
15.1	59,653	4	0.976
	28,828	2	0.997

*calculated using pumping rate, see text for discussion

Various different flow rates were studied for the smaller tube sizes. These are compared in Table III. The ratio seems to increase slightly as the flow rate is decreased, although this may be due to

the error involved in the microhematocrit method. A Student t test done on these data shows no significance in the differences between these averages.

One of the drawbacks of the apparatus used was that such a large pressure drop had to be maintained across the capillary to get any data within a reasonable length of time. This caused much leaking to occur--at the standard taper joint, at the various connections within the system, and around the gas-tight syringe. Thus the flows measured using the pumping rate were off by a large factor. The flows for the 16.1 micron tube were measured by calculating the rate which a volume is obtained in the hematocrit tube, and converting it to capillary tube diameters per second. The pumping rate, calculated flow rate and actual flow rate are compared in Table IV. This shows the

TABLE IV

COMPARISON OF CALCULATED AND MEASURED FLOW RATES FOR 16.1 MICRON TUBES

GEAR RATIO	CALCULATED FLOW RATE (TD/sec.)	MEASURED FLOW RATE (TD/sec.)
128/1	49,213	1990
256/1	24,607	991
512/1	12,203	528