THE VISCOSITY OF THE BLOOD IN NARROW CAPILLARY TUBES

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Nearly one hundred years have passed since the French physician Poiseuille (1) took up for consideration the important problem of the resistance of the bloodstream in the narrow parts of the vascular system. As experimental difficulties arose with blood, his fundamental investigations were confined to experiments with water and different fluids in glass capillaries. He found, as is well known, that the time of efflux of a given volume of fluid is directly as the length of the tube, inversely as the difference of pressure at the two ends and inversely as the fourth power of the diameter.

During the following time the law of Poiseuille seems to have been generally accepted with regard to the blood also and the results of the first experimental studies by Ewald (2) and Benno Lewy (3) were, like those of many re-examinations, in accordance with the law in question. The now prevailing opinion is that the blood behaves as a real fluid in the vascular system with regard to its viscosity (see the survey by Neuschlosz, 4).

Against this opinion, however, objections have been made from a theoretical point of view. Von Kries (5) and Hürthle (6) have pointed out that the results of investigations of the viscosity of the blood in comparatively wide capillary tubes probably do not apply to the conditions in the narrower parts of the vascular system, whereby these authors especially seem to have had the true capillaries in view.

As far as we know, the only statement in the literature regarding the viscosity of the blood being altered in narrow capillary tubes is found in the paper of Denning and Watson (7). In the narrowest capillary employed in their researches, namely, one of a diameter of 0.3 mm., they observed *increased* values. This result is, however, certainly erroneous, for reasons that will be given below.

It is true that the viscosity of the blood has been earlier investigated in capillary tubes, where a divergence from the law of Poiseuille—corresponding to our own results—ought to appear. Thus Hess (8) has examined the viscosity of the same blood in capillaries of a diameter of 0.239 and 0.126 mm. respectively under the same conditions. A calculation on the basis of the values, he found, gives a relative viscosity in the narrower one, which is only 89 per cent of that in the wider one—a fact which the author himself seems to have overlooked.

The present investigation deals with the problem of the influence of the diameter of the capillary tube upon the viscosity of the blood and pays special attention to the conditions in capillary tubes which are as narrow as possible.

The blood was obtained from one of us through venepunction. To prevent coagulation 10 cc. of blood were mixed (in the syringe) with 0.5 cc. of a concentrated sodium citrate solution, an addition which may have some influence upon the viscosity of the blood, but which is of no importance in our experiments which were only intended to make a comparison between the values obtained in capillary tubes of different diameter.

Many investigators have used viscosimeters of Ostwald's type, where the blood from a reservoir is pressed by its own weight through a vertical capillary. This apparatus has, however, a great source of error. The red corpuscles have time to settle in the reservoir, during the experiment. The consequence of this will be that the concentration of the corpuscle suspension entering the capillary will change during different phases of the streaming. This complication will have a great influence in the direction of increased time of efflux, especially when sinking speed of the red cells is large as is the case in human blood under many pathological conditions, and also in horse blood. This fact certainly explains the above mentioned result of Denning and Watson, who found the viscosity of horse blood increased in narrow tubes.

Also in viscosimeters constructed after the principle of the apparatus of Hess even normal human blood will lose its homogeneous condition through the sedimentation of the red cells, when the time of the determination is prolonged, as will be the case when using such narrow capillary tubes as in our experiments.

The researches here in question have been performed with an apparatus arranged in the following way.

Glass capillary tubes[1] of length and diameter as given below, were at both ends put together with wider cylindrical glass tubes, one of which served as reservoir for the fluid to be determined, the other being used as receptacle of the fluid which had passed the capillary. With its receptacle end this "viscosimeter" was connected by a short rubber tube with the movable part of an airtight hollow glass bearing. With a longer rubber tube the fixed part of the glass bearing was joined with a manometer of Hg and further with a big glass bottle, protected against changes of temperature and evacuated so as to obtain the desired pressure. As will be seen from

[1] The capillaries were prepared from machine-worked glass tubes specially ordered from Glasfabrik Sophienhütte, Ilmenau, Thüringen, Germany.

the figure 1, the viscosimeter was brought into a somewhat wider glass tube, put through the side walls of a thermostate (38 °C.) quite close to its anterior glass wall. To prevent the sedimentation of the red corpuscles, the viscosimeter was kept in a rotary motion within the glass tube of the thermostate. The speed of the rotation was about one turn per second. The displacement of the meniscus of the fluid in the receptacle glass tube for a certain number of millimeters, was determined by a Zeiss measuring microscope placed before the glass wall of the thermostate and the time was measured with a stop watch.

Regarding the pressure used in our experiments, the following may be remarked. More than twenty years ago, Hess (9) found that the product of the time of efflux and the difference of pressure at the two ends of the capillary tube is increased, when too low pressures are used. This result, confirmed by Rothmann (10) and Rothlin (11) and, as a matter of fact forming a divergence from the law of Poiseuille, was not considered to have any influence upon the streaming resistance of the blood in the vascular

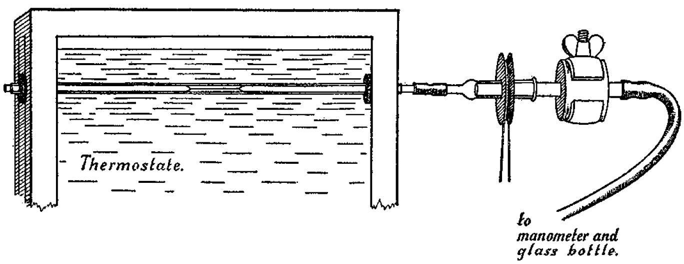

Fig. 1

system, but to be of great importance for the technics of measurement of blood viscosity. In this connection, it may be remarked that the authors mentioned apparently overlooked the fact that the length of the capillary tube has as great an influence as the difference of pressure at the two ends but in the opposite direction; in other words, it is the fall of pressure per unit of length of the capillary tube which is decisive with regard to the point where the divergence in question occurs. As we were anxious to investigate the influence of the diameter of the capillary tube upon the viscosity of the blood above the critical fall of pressure per unit of length of the same, certain preparatory investigations were necessary, the result of which may here be omitted. We state only that the pressure of 100 mm. Hg, which has been used in these researches with regard to all capillaries employed, renders the experiments we made far above the critical point in question.

The relative viscosity of the blood was as usual obtained by dividing the figure representing the time of efflux in seconds for a given volume of blood with the analogous figure for water.

It is important to remark the values obtained with water in the different capillary tubes with regard to the relation between length of the tube, difference of pressure at the two ends, diameter of the same and time of efflux for a given volume agreed very well with the law of Poiseuille.

Results. Four representative series of experiments are shown in the following tables. The corresponding curves are given in diagram figure 2.

LENGTH OF THE TUBE	DIAMETER	RELATIVE VISCOSITY
Series 1. Blood from T. L. Relative viscosity of the plasma 1.63		
mm.	*mm.*	
126.5	0.505	4.60
121.0	0.311	4.54
45.6	0.175	4.22
50.0	0.120	3.98
32.6	0.081	3.65
11.8	0.065	3.38
11.8	0.047	2.95
12.6	0.040	2.79
Series 2. Blood from T. L. Relative viscosity of the plasma 1.65		
122.5	0.277	4.96
45.6	0.175	4.72
50.0	0.120	4.30
11.8	0.047	3.15
Series 3. Blood from R. F. Relative viscosity of the plasma 1.60		
—	0.460	5.21
100.0	0.277	5.10
85.0	0.105	4.28
—	0.052	3.52
Series 4. Blood from T. L. Relative viscosity of the plasma 1.72. In order to investigate a blood specimen of higher viscosity, the blood was centrifuged and a part of the plasma taken away.		
122.5	0.277	6.80
45.6	0.175	6.28
50.0	0.120	5.59
27.9	0.081	5.08
7.0	0.065	4.71
11.8	0.047	4.28

Discussion. As will be seen from the diagram, the viscosity of human blood is far from being a constant quantity, but changes with the diameter of the capillary tube. These growing narrower, the viscosity begins to decrease in capillaries slightly wider than about 0.3 mm. and is subsequently more and more reduced, the lowest values being found in the narrowest capillaries used, namely, those of a diameter of about 0.04 mm. It was impossible to press the blood through still narrower tubes and therefore we could not continue the examination in this direction. But from the curves obtained, the viscosity seems to be further strongly reduced with reduced diameter of the tubes. Very likely in a capillary tube of a diameter, for instance, of 0.03 mm., the values are only about 50 per cent of those obtained in a capillary tube of a diameter of 0.3 mm. There seems to be no reason why the viscosity of the blood in still narrower tubes may not

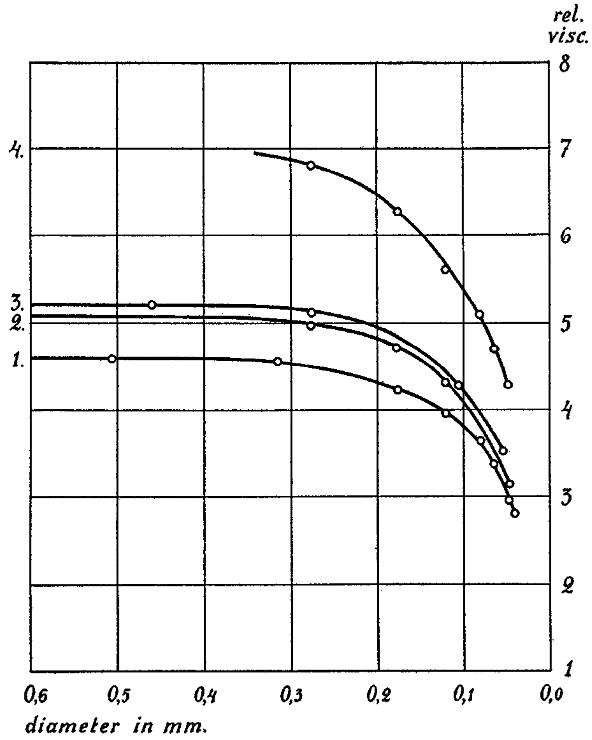

Fig. 2

come very close to or perhaps coincide with the viscosity of the plasma. *The law of Poiseuille does not apply to the flow of blood in capillary tubes of a diameter below about 0.3 mm.*

This fact has an important bearing upon the technics of measurement of blood viscosity. Contrary to the common practice in researches of this kind it is necessary to state the diameter of the capillary tubes, with which a certain value has been obtained. Our experiments show, for instance, that two different blood specimens (curves 3 and 4 in the diagram) give the same relative viscosity of 4.28 in capillary tubes of 0.105 and 0.047 mm.

diameter, though these blood specimens examined in capillary tubes of 0.3 mm. diameter or wider ones, i.e., within the range where the law of Poiseuille is still valid, show very different viscosity values.

But the result of these researches might be of interest also from an hemodynamic point of view. Our knowledge of the blood pressure at different parts of the vascular circuit points very distinctly to the chief resistance in the vasular system as being situated in the arterioles (Starling, 12). May be that what is called arterioles includes somewhat larger vessels, but certainly the greatest part of the resistance to the flow of blood is to be found in those parts of the arterial system that have a diameter from about 0.3 mm. down to the smallest arteries, from which the capillaries themselves ramify. If the viscosity of the blood like that of a fluid were a constant quantity independent of the diameter of the tube, the resistance ought, ceteris paribus, to increase with the fourth power of the diameter of the vessel. The result of our experiment in glass capillary tubes indicates, however, that that part of the resistance in the narrow vessels of the arterial system, which is due to the viscosity of the blood, is far less than has hitherto been expected. Thus the peculiar viscosity of the blood allows the heart to drive a given volume of blood through the arterioles at a much lower pressure than would be the case if the blood behaved as a fluid.

It is not necessary to point out that analogous conditions occur in vessels of corresponding width belonging to the venous sytem. The result of this investigation is not able to elucidate the state of affairs in the capillaries themselves, where the diameter of the corpuscles and the vessel coincide.

As to the physical explanation of the anomalous viscosity of the blood, here pointed out, it is certainly dependent on its being a suspension. The comparatively great viscosity of the blood is to a very high degree due to the suspended red corpuscles. The relative viscosity of the plasma of normal human blood is about 1.6. With addition of red corpuscles, the viscosity increases and reaches with the relative amount of red cells, characteristic for normal human blood, a value of about 4.5 to 5 (the viscosity determined in capillary tubes of a diameter above 0.3 mm.).

One of us (Fåhræus, 13) has recently stated that the blood streaming through a capillary tube of small diameter undergoes a change with regard to its composition. As is well known, the red corpuscles are transported in the fast axial stream, the slow marginal stream consisting only of plasma. The fact that the average speed of the red cells is thus greater than that of the plasma particles has the consequence that the amount of corpuscles in relation to the amount of plasma will be diminished; in other words, the corpuscle suspension will be diluted while streaming through a narrow capillary tube. The following table shows the average velocity of the plasma and the corpuscles and the composition of the blood, while streaming through capillary tubes of different diameter.

DIAMETER OF THE TUBES	COMPOSITION OF THE BLOOD		AVERAGE VELOCITY OF THE ERYTHROCYTES, THAT OF THE PLASMA = 100
	Erythrocytes	Plasma	
mm.	*per cent*	*per cent*	
1.100	40.5	59.5	100
0.750	40.1	59.9	101
0.450	39.8	60.2	103
0.250	39.2	60.8	106
0.095	33.6	66.4	135
0.050	28.0	72.0	175

As will be seen the relative velocity of the corpuscles and the accompanying dilution of the corpuscle suspension begin to appear in tubes of a diameter of about 0.3 mm. and rapidly increase in narrower tubes. It seems very probable that it is this dilution of the corpuscle suspension which causes the anomaly of the blood viscosity, shown by these experiments.

SUMMARY

The viscosity of the blood is not a constant quantity, but dependent on the diameter of the tube. Below a critical point at a diameter of about 0.3 mm. the viscosity decreases strongly with reduced diameter of the tube. As a consequence the resistance to the flow of blood in the arterioles (and in the small veins) is considerably less than would be the case if the streaming of the blood followed the law of Poiseuille, *i.e.*, behaved as a fluid with regard to its viscosity.

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