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A Solution That Simulates Whole Blood in a Model of the Cerebral Circulation

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An accurate elastic model of the human craniocervical arteries has been developed to study flow characteristics in normal and abnormal states (Kerber et al., paper presented at the annual meeting of the American Society of Neuroradiology, Orlando, March 1989). Flow perturbations at various Reynolds numbers can be created easily and the effects evaluated by observing the flow streamlines directly. However, perfusing whole blood, albumin preparations, or pure water in the model has been unsatisfactory. Whole blood, except in small arteries, is not transparent and carries the risk of infection to the experimenter. Albumin is costly, decomposes rapidly, and is an excellent culture medium. Water, though transparent and inexpensive, is newtonian. Therefore, we have endeavored to find a liquid that has nonnewtonian viscocity characteristics approximating those of whole blood while avoiding its disadvantages.

Materials and Methods

Stock solutions of polyvinyl alcohol (PVA) (Eastman Kodak, Rochester, NY) in water were made in several concentrations ranging from 0.5% to 2.0% PVA. A stock solution of 4.0% sodium borate (Fisher Scientific, Pittsburgh, PA) was also prepared. To 25-ml aliquots of the PVA stock solutions were added 3, 6, and 9 ml of the sodium borate stock solution (Table 1). Each PVA-borate solution was then examined on a Wells-Brookfield Cone/Plate Viscometer (Brookfield Engineering Laboratories, Inc., Stoughton, MA) using a cone spindle of 0.8° (model LVT, cone #cp-40). Eight rotational speeds were available, translating into the following shear rates:

rev/min	shear rate (sec^{-1})
60	450.0
30	225.0
12	90.0
6	45.0
3	22.5
1.5	11.25
0.6	4.50
0.3	2.25

A dial reading that reflected the tension on the internal spring was recorded. Viscocity in centipoise (cp) was calculated by multiplying the dial reading by a range factor that was a constant for each shear rate. Sample size was 0.5 ml, which was pipetted onto the center of the viscometer cup. Each measurement was made three times and the average used for the viscocity calculation. All measurements were made at 22°C.

Results

Our data are presented in Table 2. PVA concentrations of 2% and greater create solutions that are too viscous grossly for our purposes and were not measurable with our equipment. At low shear rates the dial readings were usually so low as to be considered off scale and inaccurate, and therefore they have been excluded. A variation of plus or minus 1 in the measurements (dial readings) for the middle and high shear rates was typical (recall that 3 measurements were made for each sample).

The pertinent data are displayed in graph form in Figure 1 along with the values for whole blood determined by other investigators as a comparison. The range brackets indicate the margin of error for our experimentally derived values.

Discussion

While many methods have been developed that are able to measure regional and/or total blood flow to the brain [1–3], the local streamline effects on the vessel walls and on the intima of the craniocervical arteries have rarely been observed or measured. Notable exceptions are the work of Ku (unpublished data) in evaluating the carotid bifurcation, and the work of Karino et al. [4] in demonstrating streamlines in vascular models. Results of endovascular manipulations (interventional neuroradiologic procedures) have been equally difficult to observe. To that end, an in vitro model that permits the study

TABLE 1: Polyvinyl Alcohol–Borate Solutions

Concentration of Polyvinyl Alcohol (%)	Amount of Borate[a] (ml) Added to 25 ml of Polyvinyl Alcohol	Final Concentration of Borate (%)	Solution Code
0.5	3	0.43	A
	6	0.77	B
	9	1.1	C
1.0	3	0.43	D
	6	0.77	E
1.5	3	0.43	F
	6	0.77	G
2.0	3	0.43	H[b]

[a] 4.0% sodium borate in water.
[b] This solution was too viscous grossly to evaluate further.

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TABLE 2: Viscocity (cp) vs Shear Rate

Solution[a]	Shear Rate (sec^{-1})							
	2.25	4.50	11.25	22.5	45.0	90.0	225.0	450.0
0.5% polyvinyl alcohol								
A. 3 ml borate	na[b]	na	1.64	1.03	1.10	1.38	1.37	1.41
B. 6 ml borate	na	na	na	5.89	2.69	2.38	1.96	1.60
C. 9 ml borate	24.0	7.71	1.85	1.40	1.17	1.40	1.41	1.43
1.0% polyvinyl alcohol								
D. 3 ml borate	na	na	2.88	2.60	2.38	2.42	2.65	2.56
E. 6 ml borate	na	na	na	3.84	3.00	2.42	2.62	2.50
1.5% polyvinyl alcohol								
F. 3 ml borate	na	na	6.51	8.05	8.76	9.09	9.27	na
G. 6 ml borate	na	na	4.87	6.13	6.96	6.93	6.61	na
2.0% polyvinyl alcohol								
H. 3 ml borate	na	na	na	na	na	na	na	na

[a] From Table 1. 25 ml polyvinyl alcohol/(ml 4.0% borate).
[b] na = not available. Value off scale or solution too viscous grossly.

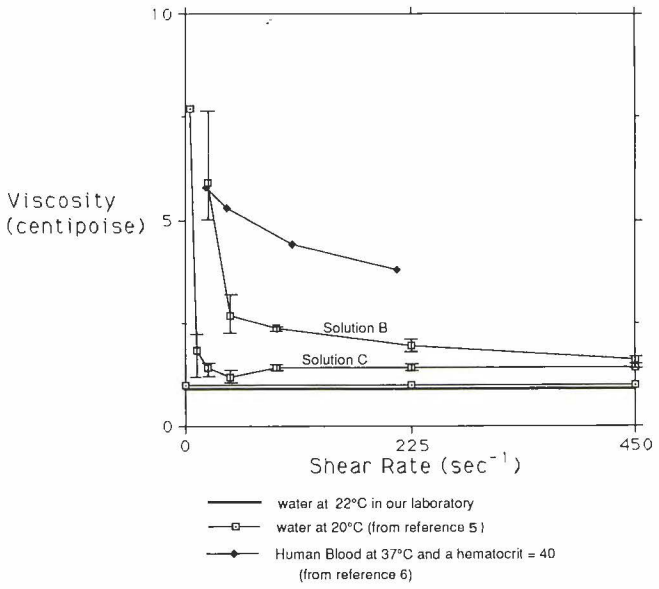

Fig. 1.—Viscosity versus shear rate.

of flows and their effects in the cerebral vasculature has been under development (Kerber et al., paper presented at ASNR, 1989).

However, before the model can be of practical use or yield valid physiologic data one requires a fluid to perfuse the system that has physical properties similar to those of whole blood at 37°C. Specifically, blood is nonnewtonian in character. That is, the viscocity of blood is not constant but varies inversely with the shear rate [6]. Stated differently, since the viscocity of blood is not constant, its reaction to variations in the rate of flow and the size and shape of the vessel will not be constant. Traditional descriptions of fluid dynamics will not be applicable, since they assume newtonian fluids, and the flow dynamics within vessels, therefore, will be hard to predict or to simulate on a computer model.

The PVA-borate solution that has viscocities most closely approximating those of whole blood is solution B (25 ml of 0.5% PVA plus 6 ml of 4.0% sodium borate). These values are slightly less throughout the range of shear rates than the values of whole blood as determined by other investigators [6]. Nevertheless, in the model we should be able to compensate for these small differences by making minor alterations in factors such as stroke volume and stroke rate. Reynolds numbers in the model that are similar to the Reynolds numbers derived experimentally in the carotid artery have been attained in our laboratory. The 0.5% PVA plus 9 ml 4.0% borate solution (solution C) also exhibits nonnewtonian viscocities but the values are further from the values of whole blood than solution B.

Other requirements for a fluid to be useful in our context are that the fluid be transparent, stable, a poor culture medium (unlike whole blood or serum albumin preparations), and relatively inexpensive. The PVA-borate solution satisfies these requirements.

There is a significant difference between our solution and whole blood; namely, that blood is particulate and the PVA-borate solution is not. Some differences are to be expected as a result. Also, our measurements were obtained at a nonphysiologic temperature (22°C). The temperature should not be a significant factor, however, because the PVA-borate solution was measured at the same temperature that will be maintained when the solution is used in the model. In fact, this is a distinct advantage, since laboratory work can be performed at room temperature rather than at body temperature.

To summarize, a PVA-borate solution exhibits nonnewtonian viscocity characteristics approximating those of whole blood. Study of fluid mechanics in the arteries of the head and neck should now be facilitated.

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