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Bypass Blood Flow during Carotid Endarterectomy

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The relationship of bypass shunt blood flow to arterial pressure and stump pressure was studied in 12 informed patients undergoing carotid endarterectomy. These patients were anesthetized with halothane plus nitrous oxide. Systemic arterial blood pressure was measured with a radial artery catheter, and stump pressure as well as distal shunt pressure (carotid pressure distal to the shunt) were measured with a 25-gauge needle inserted cephalad to the bypass shunt. From the pressure drop across the bypass shunt, blood viscosity, geometry of the bypass tubing and the use of Poiseullie's law, the shunt blood flow can be calculated. The calculated shunt flow shows a close correlation with the difference between arterial pressure and stump pressure ($r = 0.91$) as well as with the slope of arterial pressure increase following carotid occlusion ($r = 0.82$); but it is poorly correlated with the stump pressure. Administration of 100 ml low molecular weight dextran solution does not improve the shunt blood flow, whereas 500 ml low molecular weight dextran significantly decreases blood viscosity. The patency of the carotid artery as assessed by angiogram does not give a proper indication of the need for a bypass shunt. The shunt flow as well as the need of such a shunt might be predicted by the use of the difference of arterial pressure and stump pressure. If the slope of arterial pressure increases rapidly following carotid occlusion, it can also be used to determine the necessity of such a shunt. **(Key words: Blood: hemodilution; plasma protein; viscosity. Blood pressure: stump pressure. Brain: blood flow. Measurement techniques: blood flow; blood pressure. Surgery: carotid endarterectomy.)**

THE CRITICAL LOWER LIMIT of blood flow of ipsilateral brain during carotid endarterectomy has been reported to range from 18 to 24 $\text{ml} \cdot 100\ \text{g}^{-1} \cdot \text{min}^{-1}$ by the simultaneous measurements of regional cerebral blood flow and electroencephalogram.[1] To ensure the adequacy of blood flow to the brain following carotid occlusion, a bypass shunt is frequently inserted.[2,3] The insertion of a flow bypass tubing (shunt) during carotid endarterectomy, however, has been controversial. The undesirable effects of the insertion of the shunt are the added risk of embolism, which is a major problem in carotid endarterectomy,[4] and the technical inconvenience caused by the presence of the shunt. On the other hand, the fear of cerebral ischemia following complete carotid artery occlusion often indicates the need for a shunt. In the absence of an easily applied procedure to measure blood flow through the shunt, the appropriate size of the shunt that can convey an adequate amount of blood flow cannot be determined readily.

The stump pressure, the back flow carotid arterial pressure measured cephalad to the occlusion, has been used frequently as an indicator for the state of cerebral perfusion during carotid occlusion,[5–7] but it has been proven recently to be an inaccurate variable for this purpose.[1,8] The stump pressure is presumably controlled by two factors: the state of collateral circulation and the systemic arterial pressure.[9] An increase of either factor can raise the stump pressure. A variable that can incorporate both the systemic arterial pressure and stump pressure should therefore be a better indicator for the state of cerebral perfusion. The present investigation was designed to assess the bypass shunt flow, and to arrive at an easily obtainable variable to determine the state of collateral circulation.

Because low molecular weight dextran solution can decrease blood viscosity, it is frequently infused into patients with intracranial aneurysm[10] and acute cerebral thrombosis[11] to improve circulation to the ischemic area. We therefore administered ten per cent dextran solution during carotid endarterectomy in this study to determine its effect in enhancing cerebral circulation following carotid artery occlusion.

Methods

Twelve patients, 40–73 years of age and scheduled for carotid endarterectomy, were anesthetized with 0.3–1 per cent halothane plus nitrous oxide following induction with thiopental (3–5 mg/kg). Informed consent regarding the nature and risks of the study, which had been approved by the Institutional Review Board, was obtained from each patient. Respiration was controlled with a ventilator following intubation to maintain the arterial CO_2 tension (Pa_{CO_2}) between 28 and 33 torr. Muscle relaxation was maintained with the use of metocurine (0.3 mg/kg). Arterial O_2 tension (Pa_{O_2}) was kept between 100 and 150 torr by controlling the inspired oxygen concentration. Systemic arterial blood pressure (AP) was measured with a radial artery catheter connected to a Statham® transducer and a Hewlett-Packard® 8-

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channel recorder. Heparin (2000 units) was injected intravenously to prevent blood clotting following the insertion of a bypass shunt. A 25-gauge needle was then inserted into the internal carotid artery cephalad to the bypass shunt to measure pressures, and care was taken to avoid insertion of the needle in areas of atheromatous changes based on angiographic studies. This needle was connected to a second Statham® transducer to record the stump pressure (SP) and also the distal shunt pressure (DSP) after flow through the bypass shunt had been established. A period of more than one minute was allowed for the SP and DSP measurements to stabilize. At the time the pressure measurements were made, a blood sample was taken for the determination of blood viscosity and related parameters. After the inital measurements had been completed, 100 ml of 10 per cent low molecular weight dextran solution was infused intravenously over a period of 20 min. During the period of dextran infusion, no other intravenous fluid was given. Another set of pressure measurements and blood sampling was taken after the infusion. A third sample was taken for the measurements of blood viscosity and related parameters after another 400 ml dextran solution had been given at a rate of 50 ml/h. Since the surgery normally ended within an hour, a third set of pressure measurements could not be obtained following the additional dextran. Carotid angiography was done on all the patients prior to the operation, and the result was correlated with the hemodynamic data in each patient.

In vitro studies were conducted to compare shunt flow measured directly with electromagnetic flow probe with that obtained by calculation using Poiseuille's law. Such comparisons were made with perfusates of normal saline and blood at two hematocrit levels (28 and 41 per cent).

DETERMINATION OF BLOOD VISCOSITY AND RELATED PARAMETERS

Viscosities of arterial blood and plasma were measured in an airbearing coaxial cylinder viscometer, originally designed by Gilinson *et al.*§ and modified in our laboratory. The viscosity measurements were performed at 37°C and covered shear rates ranging from 200 to 0.5 s^{-1}. Arterial blood gases were determined by the use of an IL-813 blood-gas analyzer. The hematocrit value of each sample was determined after centrifugation for seven min at 15,000 × *g*. No correction was made for the 1 per cent plasma trapping in packed cell volume. Red blood cell counts were determined in an electronic particle counter, and hemoglobin determinations were made by the cyanmethemoglobin method. The total plasma protein concentration of each sample was measured by refractometry. Plasma fibrinogen concentration was determined by the method of Ratnoff and Menzie,[12] and the plasma protein fractions were analyzed by means of electrophoresis on cellulose-acetate strips.

CALCULATIONS OF SHUNT BLOOD FLOW

Blood flow across the shunt (Q_s) was calculated by the use of Poiseuille's law.

$$Q_s = \frac{(AP - DSP)\pi r^4}{8\eta L}$$

where AP and DSP are mean systemic arterial and distal shunt pressures, respectively, r is the radius of the shunt tube and L is its length, and η is blood viscosity determined at a shear rate 200 s^{-1}. The DSP was measured distal to the bypass shunt when it was kept patent. The blood flow across the shunt was calculated both in the control state and after 100 ml of 10 per cent low molecular weight dextran solution (LMD) had been infused.

The slope of the increase of systemic arterial pressure with time ($S_A = dAP/dt$) following the occlusion of carotid artery was recorded over a period of 10 min following the occlusion. S_A was determined only in the control state because it was considered undesirable to expose patients to another 10 min of carotid occlusion.

For statistical analysis, the difference between control and LMD treatment groups was analyzed by Student's paired *t* test, and the relationship between different parameters and shunt blood flows was compared by the use of regression and correlation analysis.

Results

With the use of whole blood with hematocrit values of 28 and 41 per cent and normal saline as perfusate, the *in vitro* shunt flows measured with electromagnetic flowmeter were in good agreement with those calculated from the use of Poiseulle's law. ($r = 0.96, P < 0.05$) (fig. 1).

All patients were operated upon successfully, and no blood transfusion was necessary in any patient. The results of the angiographic study on the per cent patency of the internal (fig. 2), external and contralateral carotid arteries showed no consistent relationship with the bypass shunt flow (table 1). *In situ*, the calculated bypass shunt blood flows ranged from 12

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§ Gilinson PJ, Dauwalter CR, Merrill EM: A rotational viscometer using an AC torque to balance and air bearing. Transactions Society in Rheology 7:319–332, 1963.

ml/min to 200 ml/min (table 1) in various patients, and these blood flows showed no significant changes following the infusion of 100 ml dextran. The stump pressure correlated poorly with the distal shunt pressure (fig. 3) or the simultaneously calculated shunt blood flow both before and after the administration of 100 ml dextran solution (fig. 4). Several patients with low stump pressure (less than 50 torr) following carotid artery occlusion had relatively low shunt blood flows (approximately 60 ml/min), whereas others with low stump pressure showed higher shunt blood flows (ranging from 100 to 200 ml/min). When the shunt blood flow was compared with the difference of arterial pressure and stump pressure, an excellent correlation existed between these two parameters ($r = 0.91$) (fig. 5). In patient 4, the large difference between arterial and stump pressure was associated with the highest shunt blood flow, whereas in patient 6 the small pressure difference was accompanied by the lowest shunt blood flow (table 1).

Upon occlusion of the carotid artery, arterial pressure increased with time, and the slope of the rise of arterial pressure also correlated well with the shunt blood flow (fig. 6) ($r = 0.82$).

Infusion of 100 ml dextran solution did not significantly alter the mean arterial pressure, mean stump pressure or shunt blood flow (table 1), and the hematocrit, total plasma protein, and blood and plasma viscosities also remained unchanged. However, the infusion of 500 ml dextran solution significantly decreased the hematocrit from a control of 37 to 33 per cent (table 2); the whole blood viscosity was also significantly decreased from a control of 4.14 to 3.19 cp (centipoises) at a shear rate of 200 s^{-1}, while the plasma viscosity remained unchanged. The total plasma protein concentration decreased from 6.61 to 5.60 g/dl, and the plasma α_2- and γ-globulins and fibrinogen also decreased significantly. The stump pressure and shunt blood flow were not determined after the administration of 500 ml dextran solution.

Discussion

A bypass shunt is frequently inserted during carotid endarterectomy in some institutions to provide adequate blood flow to the ipsilateral brain during carotid artery occlusion. Others have argued against such a shunt for its liability in causing embolism and inconvenience for operation.[2,3] Since there is no easy way to measure blood flow through the bypass shunt, the need for a shunt under different conditions cannot be easily determined. It is well known that, with the measurements of blood viscosity, tube geometry, and pressure drop, one can calculate the blood flow through the tubing using Poiseulle's law. The shunt flow calculated in this manner correlates very well with that measured directly by the use of electromagnetic flowmeter in an *in vitro* study utilizing blood samples at different hematocrits (fig. 1). In our *in vivo* investigation, when the difference between arterial pressure and stump pressure is small, the shunt provides minimal blood flow (as low as 12 ml/min) (table 1, fig. 5), and hence its insertion would seem unnecessary and less desirable. On

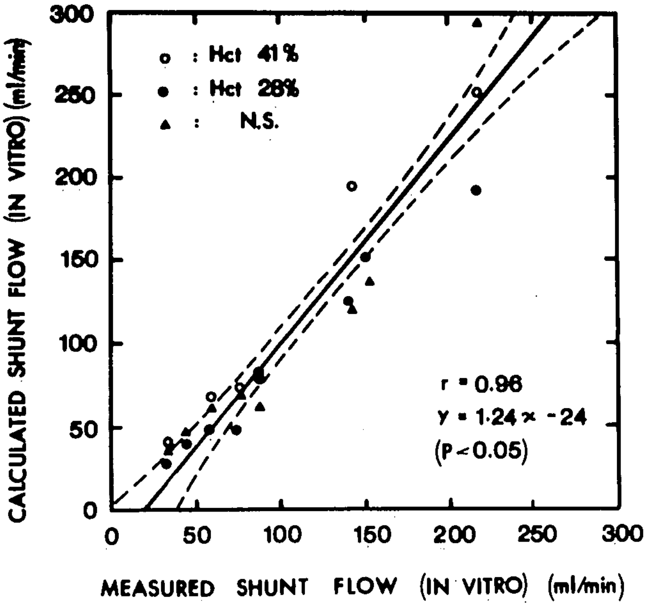

FIG. 1. Comparison between shunt flows calculated by the use of Poiseuille's law and that measured with electromagnetic flowmeter. Solid line represents line of regression and dotted lines show 95 per cent confidence limits. N.S.: normal saline.

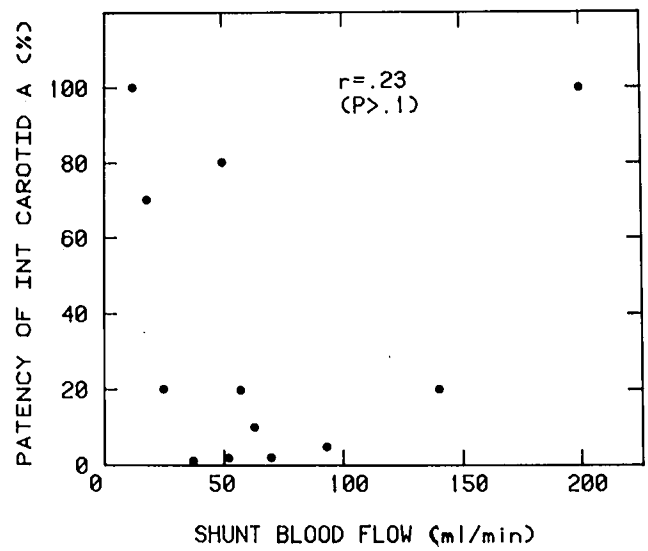

FIG. 2. Comparison between calculated shunt blood flow and the patency of internal carotid artery by angiographic study.

TABLE 1. Results on Carotid Angiographic Studies and Hemodynamic Measurements of Patients before and after Infusion of 100 ml LMD*

Patient Number	Carotid Angiogram (Per cent of Patency)			Control			100 ml LMD Infusion		
	Internal	External	Contra-lateral	MAP† (torr)	MSP† (torr)	Shunt Flow (ml/min)	MAP (torr)	MSP (torr)	Shunt Flow (ml/min)
1	80	100	100	115	59	50	116	52	51
2	2	5	0	100	51	70	88	49	49
3	70	100	100	85	67	18	99	72	38
4	100	70	100	150	42	200	117	43	150
5	5	100	60	127	74	93	107	72	73
6	100	20	100	98	85	12	80	66	24
7	20	40	40	94	45	57	109	59	103
8	10	60	100	107	61	63	116	56	60
9	2	100	100	97	53	52	92	52	45
10	20	40	0	128	32	140	120	38	119
11	0	100	100	93	69	37	114	80	52
12	20	50	75	92	67	25	93	63	28
MEAN ± SE				107 ± 6	59 ± 4	61 ± 11	104 ± 4	58 ± 4	63 ± 9

* LMD means low molecular weight dextran. MAP = mean arterial pressure; MSP = mean stump pressure.

the other hand, in the presence of large arterial-to-stump pressure differences, the bypass shunt provides very high flow (as high as 200 ml/min) (table 1, fig. 5), and the insertion of a bypass shunt is indicated under this condition. A high value of bypass shunt flow indicates the importance of such a shunt in alleviating possible cerebral ischemia following carotid occlusion. Therefore, it may be advisable to use a bypass shunt with a large lumen. Since no direct correlation has been established between the shunt blood flow and cerebral blood flow, the significance of using this bypass shunt flow to represent the state of cerebral circulation requires further validation.

The increase of arterial pressure following carotid occlusion is probably a response to cerebral ischemia or a result of baroreceptor reflex, or a combination of the two.[13] In five of the patients studied, the clamp was placed distal to the carotid bifurcation. Since the arterial pressure still increased in these patients, cerebral ischemia appears to have been the main cause for the response. The result that the slope of arterial pressure increase showed a good correlation with the shunt blood flow (fig. 6) also points more to the cerebral ischemia component. This current investigation, however, is far from conclusive in resolving the question as to what is the cause for the pressure increase after carotid occlusion, the possible role of baroreceptor reflex in the arterial pressure increase following carotid occlusion has not been ruled out in these studies. Regardless of the cause of this pressure increase, the good correlation between the slope of pressure increase and shunt blood flow illustrates that the slope may help to determine whether a

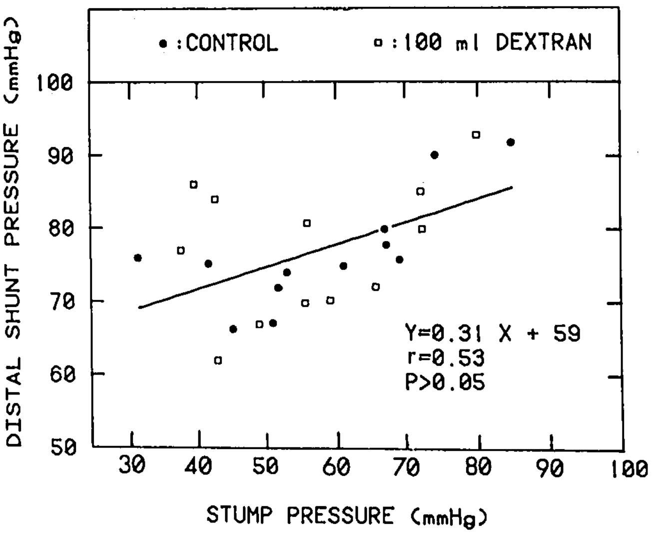

FIG. 3. Relationship between distal shunt pressure and stump pressure. Solid line represents line of regression.

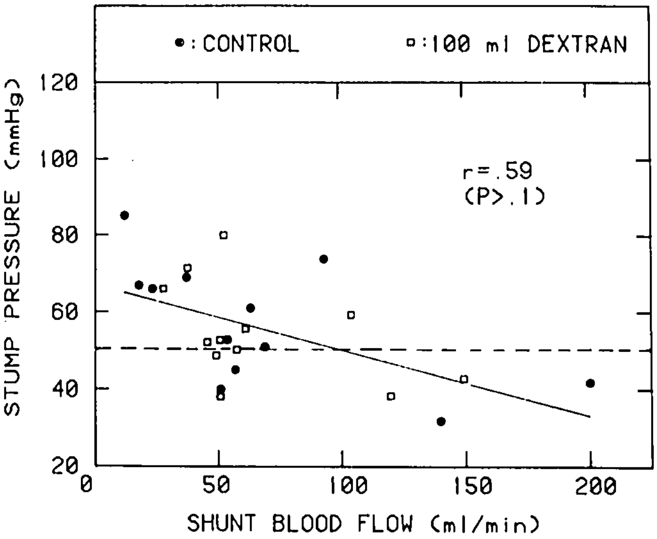

FIG. 4. Relationship between stump pressure and calculated shunt blood flow. Solid line is the line of regression. Dotted line represents stump pressure at 50 torr.

shunt is needed, if this information can be gathered before the decision making.

Recently, controversy has arisen over the use of stump pressure as an indicator for the adequacy of cerebral collateral perfusion.[1,8] By simultaneous measurements of regional cerebral blood flow (rCBF), EEG, and stump pressure during carotid occlusion, McKay *et al.*[1] demonstrated a critical rCBF of 18–24 ml·100 g^{-1}·min^{-1} for adequate cerebral perfusion. Once the cerebral blood flow was lower than this critical limit, the EEG started to show abnormal patterns. If stump pressure can reliably reflect cerebral perfusion, it should show a positive correlation with rCBF. McKay *et al.*, however, found results contrary to this expectation. Thus, in 8 per cent of their patients, the rCBF was lower than 18 ml·100 g^{-1}·min^{-1} while the stump pressure was higher than 50 torr; in 28 per cent of their patients the rCBF was higher than 24 mg·100 g^{-1}·min^{-1} while the stump pressure was lower than 50 torr. In the present investigation, the relationship between stump pressure and the shunt blood flow is also scattered (fig. 4); at a stump pressure of approximately 50 torr, the shunt blood flow was quite variable. It is, therefore, difficult to predict the shunt blood flow with the use of stump pressure. These results, as well as those obtained by McKay *et al.*,[1] clearly indicate that the stump pressure is not a reliable index for determining the state of cerebral perfusion and the necessity of a bypass shunt. The difference of systemic arterial pressure and stump pressure is a better parameter than stump pressure in assessing the state of cerebral perfusion.

Decisions on the need for a bypass shunt during carotid endarterectomy have also been based on the findings of angiography. Frequently, it is believed that a shunt is not needed if the carotid artery to be operated is completely obstructed. In the present study, we cannot establish a consistent correlation between the bypass shunt blood flow and the carotid angiographic findings (table 1, fig. 2). In patients 2 and 10, the operated sites were 2 and 20 per cent patent with the contralateral artery completely obstructed, and the shunt blood flows were found to be 70 and 140 ml/min, respectively. Whereas in patient 11, with the operated site 100 per cent obstructed and the contralateral artery completely patent, the shunt blood flow was relatively low. Therefore, the state of collateral circulation to the area supplied by the diseased artery is not only determined by the degree of obstruction of the operated artery but also by the contralateral artery. When both arteries are obstructed, the shunt might provide a high flow and is needed; when the operated artery is obstructed and the contralateral carotid artery is patent, the shunt will provide a lesser blood flow and is not as essential. Thus, these results clearly indicate the value of bilateral arteriogram in the evaluation of cerebral circulation.

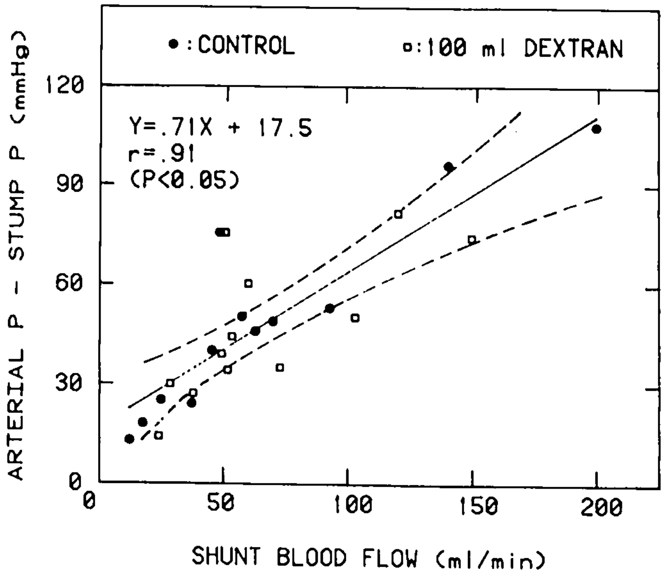

FIG. 5. Comparison between difference of arterial pressure and stump pressure and calculated shunt blood flow. Solid line represents line of regression. Dotted lines indicate 95 per cent confidence limits.

Low molecular weight dextran (LMD) solution has been frequently administered to improve circulation in patients following craniotomy for cerebral aneurysms,[14] and in patients with acute cerebral thrombosis.[11] The rationale of using LMD solution is to

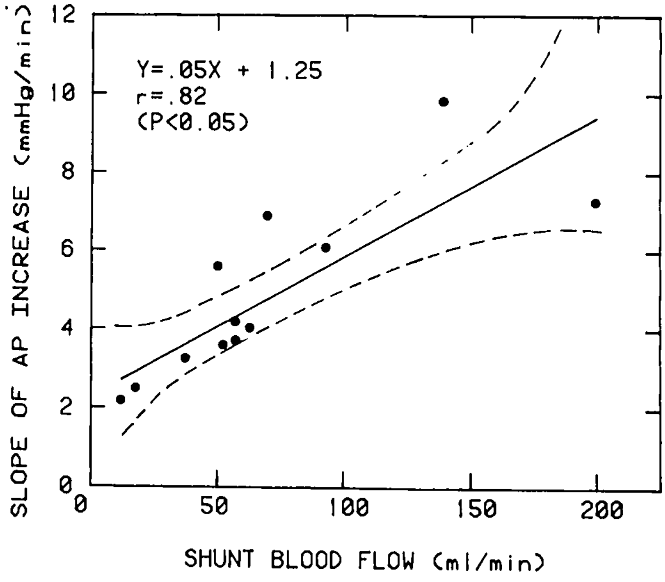

FIG. 6. Correlation between the slope of arterial pressure increase following carotid artery occlusion and the calculated bypass shunt blood flow. Solid line represents line of regression. Dotted lines indicate 95 per cent confidence limits.

TABLE 2. Effects of 10 Per Cent Low Molecular Weight Dextran (LMD) on the Blood Viscosity, Hematocrit and Protein Components

	Blood Viscosity ($\gamma = 200$ sec^{-1})	Plasma Viscosity ($\gamma = 200$ sec^{-1})	HCT Per Cent	Total Protein (g/dl)	Albumin (g/dl)	α_1-Globulin (g/dl)	α_2-Globulin (g/dl)	β-Globulin (g/dl)	Fibrinogen (g/dl)	γ-Globulin (g/dl)
Control	4.14 ± 0.24	1.26 ± 0.04	37 ± 1	6.61 ± 0.18	3.57 ± 0.15	0.26 ± 0.03	0.68 ± 0.05	0.88 ± 0.04	0.38 ± 0.03	0.79 ± 0.06
100 ml LMD	3.65 ± 0.20	1.26 ± 0.05	36 ± 1	6.61 ± 0.28	3.71 ± 0.13	0.24 ± 0.03	0.60 ± 0.07	0.91 ± 0.06	0.35 ± 0.03	0.78 ± 0.06
500 ml LMD	3.19 ± 0.15*	1.23 ± 0.12	33 ± 1*	5.60 ± 0.39*	3.21 ± 0.38	0.27 ± 0.03	0.47 ± 0.04*	0.79 ± 0.08	0.29 ± 0.04*	0.62 ± 0.08*

Values are means ± SE, n = 12.
γ = shear rate.

* Significantly different from control, $P < 0.05$.

decrease blood viscosity and in turn to improve regional circulation.¶ At a given temperature, the blood viscosity is controlled by four major factors, *viz.*, plasma viscosity, red blood cell (RBC) concentration, RBC deformation and RBC aggregation. Variations of hematocrit cause the most obvious changes in blood viscosity.[15,16] In the present study, with the infusion of 100 ml LMD solution, arterial pressure, stump pressure, and calculated shunt blood flow were not changed (table 1). With this small dose of dextran, the blood viscosity remained unchanged because hematocrit, plasma fibrinogen and globin concentrations were not significantly altered. The larger dose of LMD (500 ml), however, caused a significant decrease in hematocrit, total protein concentration and blood viscosity (table 2). Therefore, if LMD is given for the purpose of lowering blood viscosity in order to improve regional microcirculation following carotid arterial clamping, a larger dose (up to 500 ml) should be given. This large dose of LMD can be safely administered over a long period (90 min) prior to the arterial clamping.

In conclusion, the difference between arterial pressure and stump pressure, which represent the upstream and downstream pressures of the collateral circulation to the ischemic brain, respectively, is a better parameter than the stump pressure alone for the assessment of the adequacy of cerebral perfusion. This pressure difference might be used to determine the need for a bypass shunt during carotid endarterectomy. Furthermore, the slope of arterial pressure rise following carotid artery occlusion, which also correlates well with the shunt blood flow, might be used as another indicator for the need to place a bypass shunt.

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