QUANTITATIVE MEASUREMENTS OF CEREBRAL BLOOD FLOW IN THE MACACQUE MONKEY[1]

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Received for publication September 8, 1942

After reviewing the evidence available in 1936, Wolff (12) made the following statement: "Unfortunately, the amount of blood going to the brain still remains an uncertain quantity." As far as we know nothing has happened subsequently to remedy this situation. In the present paper we report experiments in which cerebral blood flow has been measured quantitatively under conditions which, although not strictly normal, were considerably less abnormal than those existing in perfusions of excised brains—the only circumstances under which comparable measurements have hitherto been made.

The voluminous literature on the physiology and pharmacology of the cerebral circulation has been reviewed recently (1, 4, 12) and need not be discussed here. Reasons for our own interest in these problems, the various methods we have used to study them, and the results obtained, have been presented in a series of publications from this laboratory (4, 5, 6, 7, 8, 9). The latest of these (4) contained an elaboration of the theme of the first (6) in regard to the anatomical and instrumental difficulties involved in quantitative measurements of cerebral blood flow. At that time we hoped, by appropriate modifications, to adapt a thermostromuhr to the purpose. Our misgivings (4, p. 255) regarding the reliability of that instrument for quantitative purposes were proved by our subsequent experience to be well founded, and the recent careful studies of Gregg and his collaborators (2) have amply confirmed them.

In the present experiments we have measured cerebral arterial inflow directly by a method first employed to secure the *in vivo* calibrations of the thermostromuhr already referred to (4, pp. 255 and 263) and by so doing have finally obviated the instrumental difficulties. The anatomical difficulties (4, 6) have been circumvented partly by the use of the monkey (macacus rhesus), in which, as in man, there are only insignificant communications between the intracranial and extracranial parts of the cephalic circulation (1), partly by ligation of the basilar artery, a procedure which not only forces all of the blood entering the brain to pass through the measuring device, but also prevents escape of some of it into extracranial tissues through muscular branches of the vertebral arteries (4, pp. 237 and 254).

METHOD. The measuring device is a refinement of the "simple flowmeter" described by Soskin, Priest and Schutz (10). Several models have been tested but that shown in figure 1 has proved most satisfactory. It is provided with a

[1] This investigation was largely financed through the National Committee for Mental Hygiene from funds granted by the Committee on Research in Dementia Precox founded by the Supreme Council, 33° Scottish Rite, Northern Masonic Jurisdiction, U. S. A.

jacket through which water at a temperature of 38 to 40° is circulated from a thermostatically controlled bath. The blood, rendered incoagulable by heparin, passes through the meter on its way to the brain and the volume of flow is measured by timing the passage of an injected air bubble (about 0.2 cc. in our meters) over a space of known volume (about 6 cc. in most of these experiments). The air bubble is removed by a suitable trap before the blood reënters the arterial circulation and the measurements involve no interference with or alteration in the actual blood flow.

Male monkeys weighing 3 to 6 kilos were used. They were anesthetized with nembutal (about 0.04 gram per kilo intraperitoneally). A tracheal cannula was inserted, blood pressure was recorded by a mercury manometer from a femoral artery with heparin-saline as the anti-coagulant, respiration was registered by a conventional pneumograph-tambour system, and intravenous injections were made through a burette-cannula system connected with a femoral

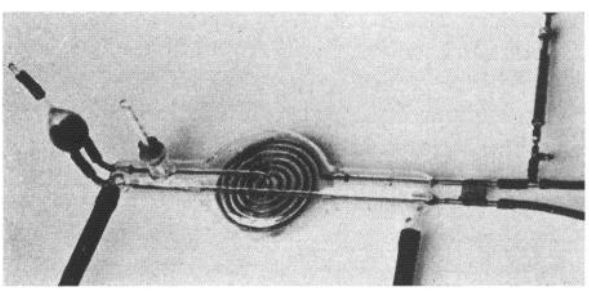

Fig. 1. Bubble flowmeter. A tuberculin syringe is connected through a small Bunsen valve system to a 22 gauge stainless steel tube so that bubbles, each of about 0.2 cc., can be injected into the inflowing stream. The space between the marks on the tube represents about 6.0 cc. The trap for collecting air bubbles is at the left. The large rubber tubes in the foreground connect the water jacket to a thermostatically controlled water bath.

vein. The operation for insertion of the flowmeter involved reflection upward of the larynx and esophagus, exposure of the anterior inferior aspect of the occipital bone, perforation of it by means of a dental burr, opening the dura, and passing a ligature around the basilar artery so that it could subsequently be tied. Silver clips, though easier to apply, turned out to be less dependable than actual ligation. Both common carotids were exposed to a point beyond the bifurcation and both external carotids were tied near their origins. Heparin was given intravenously as an initial 1000 unit (1 cc.) dose followed by 200 units every 15 minutes. A short glass cannula was inserted in each common carotid to collect blood coming from the heart, and these two were connected through a T-tube to the inflow side of the meter. The outflow tube was connected to a similar pair of cannulae inserted more peripherally in the common carotids with their tips pointing cephalad. The location of the needle for injecting the air bubbles is indicated in figure 1. In 6 experiments we attempted to connect a smaller (2 cc.) meter to the cephalic end of the basilar artery, so that flow could be measured in the carotid and basilar systems simultaneously. We succeeded in 3 of these

attempts but in the others the basilar artery was too small or too short for cannulization and we had to be satisfied with measurement of carotid flow with the basilar tied. At the end of each experiment a dye (usually india ink) was injected through the meter and its distribution ascertained by dissection. The only communications with tissues outside the brain were occasional small anastomoses around the basilar ligature, leading to spots of dye in the muscles of the neck, and occasional twigs in the orbits; these channels were so small as to be negligible, we believe. The brain was removed at the end of each experiment and its weight anterior to the basilar ligature was determined.

We have subjected this flowmeter to extensive calibration tests with a perfusion pump, and have also tried it in a number of pilot experiments on dogs and cats. As a result we are satisfied that it is dependable and accurate. There is a tendency toward overestimation of the actual flow, and the magnitude of this error increases both with the volume of the flow and with the viscosity of the fluid, but the deviation is almost imperceptible at flows smaller than 50 cc. per minute and even at the largest flow encountered in our *in vivo* measurements (103 cc. per minute) it would amount to less than 10 per cent. A correction could easily be applied for this but we have not thought it desirable to do so because of the implication of quantitative precision which the operative and other deviations from normal make illusory. The viscosity factor is much smaller than in the venturi meter (11) or rotameter (2). With these, even approximate estimations of flow call for accurate measurements of viscosity, not only for each experiment but for every supposed change in flow. With the bubble flowmeter even the change in viscosity from saline to whole blood has a barely measurable influence at flows lower than 50 cc. per minute; above that level the divergence increases progressively but it is only about 5 per cent at 100 cc. per minute. This independence of viscosity changes is the greatest advantage of the bubble flowmeter over the rotameter.

So far we have successfully employed this method to measure cerebral blood flow in 19 monkeys. The average weight of these animals was 4.2 kilos, the extremes being 3 and 6.2. The average weight of the brain above the level of the basilar ligature was 91 grams and the extremes were 85 and 105.

1. *The volume and range of cerebral blood flow.* The averages of our findings are shown in table 1. The "normal" values are those recorded at the start of each experiment. In many cases blood pressure fell considerably during the final stages of the preparation and in these pressure was restored, by intravenous injection of blood saved from an earlier experiment, approximately to its initial level before the "normal" readings were obtained. The "maximum" and "minimum" figures are derived from the highest and lowest flows recorded in each experiment, terminal states of progressive circulatory failure being excluded. The complete data are omitted in the interests of space conservation. A brief description of their distribution is therefore desirable.

In the 19 experiments in which flow was measured only through the internal carotids the "normal" flows ranged from 27 cc. (0.27 cc. per gram) to 78 cc. (0.81 cc. per gram); the corresponding blood pressure readings were 70 and 140

mm. Hg. The "maximum" flows in 7 instances were measured after intra-arterial injection (see below) of aminophylline or caffeine while blood pressure was lower than it was at the time of the "normal" reading; a similar coincidence was encountered in one experiment during a metrazol convulsion and in another during inhalation of oxygen. In the remaining cases the maximum flow was associated with a rise in blood pressure and was produced by intravenous injection of adrenalin in 4, by inhalation of oxygen in 2, and by inhalation of nitrogen in one, while in 3 it was encountered during the "normal" period. The highest flow (103 cc. total, 1.13 cc. per gram) was associated with a drop of blood pressure from a "normal" of 170 to 162 mm. during inhalation of oxygen; the "normal" flow was 75 cc. (0.77 cc. per gram). The "minimum" flow readings in 13 cases corresponded with a fall in blood pressure. Of the 6 in which at the time of the minimum flow pressure either was unchanged or elevated as compared with the "normal," 2 were obtained after intra-arterial injection of adrenalin and 2 after similar injection of benzedrine, one was found after intravenous injection of adrenalin, and one coincided with inhalation of nitrogen. The minimum readings ranged from 13 cc. (0.14 cc. per gram) at a blood pressure of 90 mm. following adrenalin intra-arterially, to 46 cc. (0.5 cc. per gram) with a blood pressure of 88 mm. after nitroglycerine intravenously. In the former experiment the "normal" and "maximum" values were 35 cc. (0.41 cc. per gram) at 104 mm. and 56 cc. (0.66 cc. per gram) at 100 mm.; in the latter the corresponding figures were 73 cc. (0.83 cc. per gram) at 150 mm. and 100 cc. (1.14 cc. per gram) at 152 mm.

TABLE 1

	CEREBRAL FLOW		B-P	
	cc./min.	*cc./g./min.*		
Average normal	55	0.60	125	19 expts.—carotid flow, basilar tied
Average maximum	69	0.76	131	
Average minimum	25	0.27	109	
Average normal	60	0.63	97	3 expts.—carotid plus basilar flow
Average maximum	77	0.81	131	
Average minimum	42	0.44	86	
Average normal	42	0.45	99	Same 3 expts.—carotid flow only

The 3 experiments in which flow was measured simultaneously in the carotids and basilar are treated separately because they show that the figures obtained by measuring only the internal carotid streams represent about 70 per cent of the total carried by both carotids and basilar when both are open. The individual figures were 81 per cent, 67 per cent and 63 per cent. The number of observations is small but the existence of this discrepancy as well as its approximate magnitude seem to us to be clearly indicated. If the 70 per cent factor is used to correct the findings in the 19 experiments in which only carotid flow was

measured the average "normal" cerebral blood flow in the monkey becomes 0.86 cc. per gram per minute. This figure we believe to be closer to the actual value than any that has previously been obtained.

The individual "normal," "maximum," and "minimum" figures show that while cerebral blood flow tends to vary directly with the blood pressure, it can also undergo independent variations of considerable size, particularly under the influence of drugs. Since this confirms in another animal and by another method the conclusions derived from previous experiments made in this laboratory (4, 5, 7, 8, 9) we attempted to parallel the earlier studies as far as possible.

2. *Effect of stimulation of the cervical sympathetic nerve.* Satisfactory tests were made 7 times on 4 animals and the results are summarized in table 2. A number of other trials in which mydriasis failed to occur (indicating ineffectiveness of stimulation) or measurements were unsatisfactory, are not included.

TABLE 2

Effects of cervical sympathetic stimulation

EXPT.	STIM.*		B-P		FLOW	
	On	For	From	To	From	To
					cc./min.	*cc./min.*
2-22	R	2′	108	100	39	38
	L	2½′	110	114	42	44
2-24	R	2′	142	142	46	57
	R	2′	140	142	44	46
	L	2′	146	138	50	34
2-26	L	2′	90	80	38	32
6-19	R	3½′	52	52	41	39

* Mydriasis occurred on the stimulated side in every case. In the experiment of 2-22 salivation also was observed.

The results give no indication of a direct effect of any importance, in which they confirm the outcome of our first attempt (6) at measuring total cerebral blood flow. They are very different from those obtained by a thermocouple in the parietal cortex of the cat (4, 9) where cervical sympathetic stimulation regularly gave rise to an indicated decrease in blood flow, but similar to those obtained by the same thermocouple in the medulla of the cat (5), where no such changes were seen. The possibility that reapportionment of the total stream may take place within the brain when the sympathetic nerve is stimulated receives some support from observations made in the last experiment shown in table 2, which is the only one in which we have as yet been able to study this question by separate measurement of the carotid and basilar blood flow. Of the total flow before stimulation (41 cc. per minute), 28 cc. was carried by the carotids, 13 cc. by the basilar. The carotid flow measurements during the stimulation were 27, 26, and 25 cc. The corresponding figures for basilar flow are

13.4, 13.7 and 14 cc. The blood pressure was constant throughout. The change, though slight, is in the direction demanded by the above hypothesis. That the cerebral blood vessels of these animals were capable of constricting is shown by the results obtained with adrenalin and other sympathomimetic agents (fig. 2).

3. *Effect of changes in the blood gases.* Anoxemia was induced by inhalation of 90 or 100 per cent nitrogen. Oxygen (100 per cent) and carbon dioxide (10

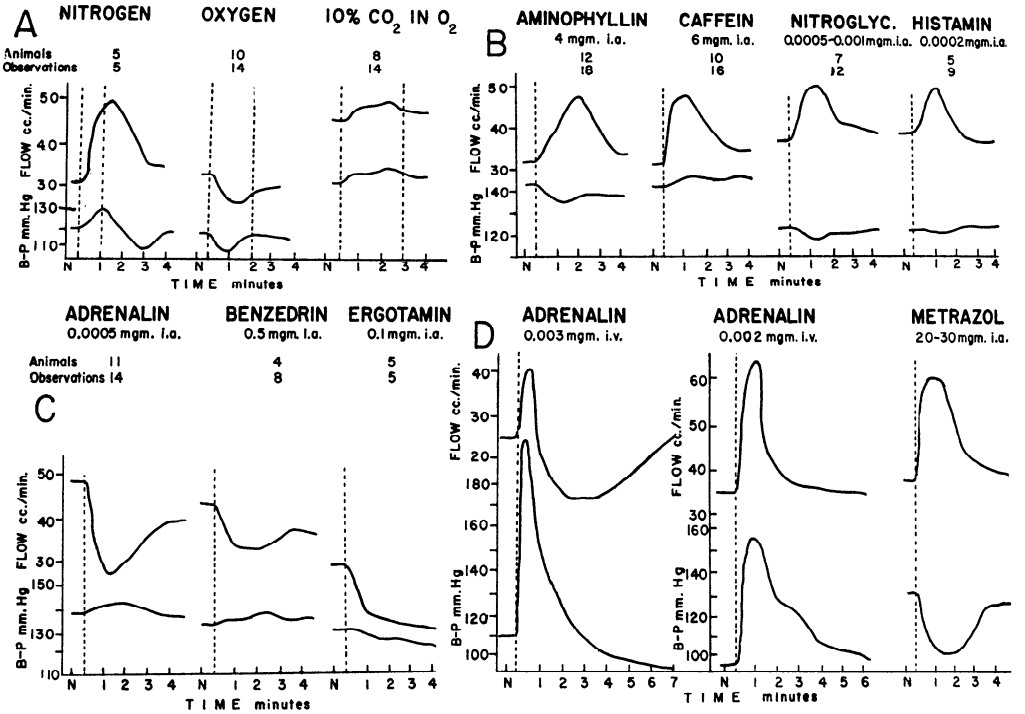

Fig. 2. Average effects on cerebral blood flow (upper) and blood pressure (lower); the numbers of animals and of observations on which curves are based are indicated. *N* signifies the "normal" value and the vertical broken line the time of injection; in A the two broken lines indicate inhalation of pure nitrogen, oxygen, or 10 per cent CO_2 in oxygen. In D the adrenalin curves represent single experiments but the metrazol record is based on the averages of the results of 8 injections in 6 animals. *i.a.* = intra-arterial injection (into the inflow tube of the meter). *i.v.* = intravenous injection.

per cent in O_2) were also tried. The average findings of these procedures are shown in figure 2 A. The individual results did not differ in any important respect from these.

The most important finding here, in our opinion, is the apparent superiority of anoxemia over hypercapnia as a dilator of cerebral vessels in the monkey. The increases in flow brought about by CO_2 were smaller than we had been led to expect by our experience with other animals, while those elicited by anoxemia were much greater. But attention must be called to the following experimental

circumstance, which may modify the deductions to be drawn from this comparison. None of these animals showed more than a slight hyperpnea during anoxemia, due, we believe, to damage to the carotid innervation during the dissection or insertion of the cannulae; that the chemoreceptor reflexes were normally active before these procedures were carried out was shown in a number of cases by vigorous responses to anoxemia or cyanide at the start of the experiment. As has been suggested elsewhere (3), the reflex hyperpnea of anoxemia may lead to sufficient reduction in arterial carbon dioxide tension to cause constriction of cerebral blood vessels. In that event the dilator effect of anoxemia would be antagonized and perhaps overcome, but in these animals no such antagonism was present. The increases in cerebral flow resulting from anoxemia may therefore have been considerably greater than under more nearly normal circumstances.

The effects of the other gases were qualitatively similar to those detected in other animals by other methods. There was a distinct hint of a constrictor action by oxygen, though this was never at all marked. The dilator action of CO_2 was consistent but not very great. In a few cases respiration ceased and asphyxia developed before oxygen could be given by tracheal catheter. In these, cerebral blood flow increased as long as blood pressure did not fall, and there was no sign of cerebral vasoconstriction associated with increased activity of the vasomotor center.

4. *Effects of drugs.* Since this preparation involved exteriorization of the arterial blood supply of the brain and therefore made intra-arterial injections very easy, we frequently availed ourselves of the advantages (see 4) of this method of studying the effects of drugs on the cerebral circulation. Data sufficient at least for tentative conclusions have been secured by intra-arterial injections of adrenalin, benzedrine, ergotamine, histamine, nitroglycerine, caffeine, theophylline, and metrazol. The results are illustrated in figure 2 B and C. They can be summarized by the statement that by intra-arterial injection of adrenalin or benzedrine the cerebral vessels can be constricted quite vigorously, and by similar injection of histamine, nitroglycerine, caffeine, and theophylline they can be dilated. Such changes can occur without any corresponding alteration in blood pressure. Ergotamine decreased cerebral blood flow, but since it also decreased blood pressure in that dosage, and smaller amounts were ineffective, the interpretation is as uncertain as was that of the results of comparable experiments on cats (4). Metrazol caused a pure and usually marked increase in cerebral flow (associated with convulsions, which came on instantly after these intra-arterial injections), while blood pressure fell sharply (fig. 2 D). Acetyl β-methylcholine (Mecholyl) was given intra-arterially 7 times in 3 animals, the dose being 0.0001 mgm. Cerebral blood flow was invariably increased while blood pressure fell slightly; recovery was complete within 3 minutes. The average figures were from 44 to 49 cc. per minute in flow, from 136 to 132 mm. Hg in pressure.

Observations on the effects of these drugs when given by channels other than the intracarotid have so far been infrequent. This is because most of the

drugs, when given in effective dosage, ordinarily have effects so prolonged that only one or two valid tests could be carried out in a single experiment. The experiments were so expensive and difficult that we tried to make as many different observations as possible in each, and intraarterial injections of minimum effective doses were preferred. However, enough intravenous injections were made of adrenalin (10 in 8 animals, excluding injections intended to restore a failing circulation) to show that the constriction of cerebral vessels which intracarotid injection of this drug produces is much less in evidence following intravenous administration (fig. 2 D). In all of these 10 instances there was an increase in flow as blood pressure rose. In 5 the flow descended faster than the pressure and reached a level lower than the starting point though pressure was at or above its control level. In the others the flow came back to a level either the same as or higher than the control. A representative example of each type of response is shown in figure 2 D.

Of the other drugs, only caffeine and theophylline have been given often enough intravenously to justify even tentative conclusions (5 times in 5 animals and 4 times in 3 animals, respectively). Caffeine, in dosage of 10 to 20 mgm., increased cerebral flow slightly in 3 cases, did not change it appreciably in the others; the most marked increase was from 24 to 29 cc. per minute; since blood pressure fell at the same time from 86 to 80 mm. this result appears to be significant. Theophylline (as the ethylene diamine derivative), when injected intravenously in dosage of 10 to 40 mgm., lowered blood pressure quite markedly; cerebral flow was decreased at the same time in 2 cases, increased in the other 2; the most marked increase in flow was from 25 to 30 cc. per minute, associated with a fall in pressure from 106 to 96 mm.—again a significant change.

We have also tried nitroglycerine and insulin by intravenous injection, each in 2 different animals. The former, in 0.5 mgm. dosage, only decreased cerebral flow as blood pressure fell and there was no sign of an effective vasodilator action in the brain. Insulin, in dosage of 5 and 10 units, was used because of the possibility that some of its convulsant effects might be due to violent constriction of cerebral vessels. No trace of any such action was evident (table 3). Blood pressure was lowered as hypoglycemia developed and cerebral flow followed this apparently quite passively. Recovery of the circulation began while the blood sugar was still falling. Convulsions did not appear, doubtless because of the anesthesia.

Posterior pituitary extract (Parke, Davis and Co. obstetrical pituitrin, 10 pressor units per cc.) was injected intra-arterially once in each of 3 experiments, the dose being 0.1 unit (0.1 cc. of a 1 to 10 dilution in saline). The result was an immediate, consistent, and considerable (though transitory) fall in blood pressure accompanied by a parallel decrease in cerebral flow. Thus in one case pressure fell from 116 to 82 mm. within 2 minutes and recovered to 120 by the end of 7 minutes. The corresponding figures for flow were 30, 12, and 28 cc. per minute. The changes in flow seemed to be the result of the fall in blood pressure, but we have not as yet investigated the latter rather surprising result any farther.

Nembutal (Abbott's veterinary solution, 6.5 per cent containing 20 per cent alcohol) was injected intra-arterially in 0.1 cc. dosage (6.5 mgm.) in 3 animals in which narcosis had become too light. The consistent result was a slight but distinct increase in cerebral flow (e.g., from 40 to 46 cc. per minute) associated with a slight fall in blood pressure (from 116 to 110 mm.), with recovery of both within 5 minutes. Other narcotics have not been tried, nor have we as yet attempted to dissociate the effect of the alcohol of this solution from that of the barbiturate.

5. *The basilar-carotid anastomosis.* In the 3 experiments (see table 1) in which we were able to measure flow through the basilar and the internal carotid systems separately, we had an opportunity to determine not only the portion of the total flow carried by each of these, but also the extent to which read-

TABLE 3

	ANIMAL 1			ANIMAL 2			COMMENT
	Cereb. flow	B-P	Blood sugar	Cereb. flow	B-P	Blood sugar	
	cc./min.	*mm. Hg*	*mgm. %*	*cc./min.*	*mm. Hg*	*mgm. %*	
Control	51	118	109	42	108	89	
15 min. after insulin*	33	76	71	23	54	55	Hyperpnea in both animals at this time
30 min. after insulin*	28	60	61	39	100		Hyperpnea ended in both at this time
45 min. after insulin*	36	90		35	94	46	
60 min. after insulin*	39	102	43	31	115	42	Glucose in animal 2 at 65 min.**
75 min. after insulin*	43	108		29	114		Glucose in animal 1 at 80 min.**
100 min. after insulin*	35	100	54	27	112	70	

* Insulin was injected intravenously in dosage of 5 units in animal 1, 10 units in animal 2. Weight of animal 1, 5.5 kilos; of animal 2, 6.2 kilos.

** Glucose was injected intraperitoneally, 25 cc. of 5 per cent solution being given to each animal.

justments can occur under different circumstances. One of these findings, indicating that the carotid component amounts only to about 70 per cent of the actual total when the basilar is closed, has already been mentioned (p. 424). Other observations bearing on this subject are shown in table 4.

These data indicate several points of some importance. One is the variability of the basilar:carotid ratio. In the last experiment cited the basilar was larger than in the other two and it is probable that the ratio here (80 per cent) is quite exceptional. Furthermore, the basilar arteries in all three of these animals were larger than they were in three others in which the vessel was too small for cannulization. For these reasons we do not think it advisable to venture, from the data now available, any deduction other than that the basilar contributes a highly variable portion of the total cerebral flow. More definite conclusions can however be derived on another point, viz., the extent to which the flow

through each system is increased when the other is closed. The increase in basilar flow resulting from carotid occlusion was much greater, in two of the three experiments, than the increase in carotid flow resulting from basilar occlusion. This is to be expected in view of the relative sizes of the two sets of vessels and the volumes carried by them. It is noteworthy in this connection, however, that even the greatest percentile increase in basilar flow (90 per cent) meant that when the carotids were closed the total cerebral flow was 21 cc. per minute, which was only 40 per cent of the amount previously carried by both systems (53 cc.). In the same animal the carotids carried 43 cc. when the basilar was closed, and this, although it was an increase only of 10 per cent in carotid flow, nevertheless amounted to 81 per cent of the previous total.

TABLE 4

EXPT.	FLOWS—BOTH OPEN				CAROTID FLOW ON BASILAR OCCLUSION				BASILAR FLOW ON CAROTID OCCLUSION				CONDITIONS
	Car.	Bas.	B-P	Bas./Car.	From	To	Incr.	B-P	From	To	Incr.	B-P	
	cc./min.	*cc./min.*		*per cent*	*cc./min.*	*cc./min.*	*per cent*		*cc./min.*	*cc./min.*	*per cent*		
6-19	42	11	96	26	39	43	10	84	11	21	90	98	Control—O_2 by tracheal catheter
	37	11	80	30	39	43	10	82	11	18	64	82	Same
	28	13	48	46	28	33	18	52	13	17	30	52	After caffeine, theophylline, and nitroglycerine i.v.
6-23	54	23	140	43	26	33	27	100	23	35	52	152	Control (basilar occlusion later than others)
6-24	24	19	70	80	24	27	13	71	19	22	16	72	Control—O_2 by tracheal catheter
	22	18	72	82	24	29	21	73	18	22	22	74	After adrenalin and caffeine i.v.
	27	17	69	63	23	27	17	67					Later—follows caffeine i.a.

At the other extreme, the smallest percentile increase in basilar flow on carotid occlusion (16 per cent) brought the total flow to 22 as compared with 43 cc. or 51 per cent, and the corresponding increase in carotid flow on basilar occlusion (to 27 cc.) amounted to 65 per cent of the original total. These figures serve to show the order of magnitude of the readjustments brought about through the circle of Willis in these particular animals. The individual variations were so great as to suggest that the consequences of occlusion of these vessels in any given subject can scarcely be predicted.

SUMMARY AND CONCLUSIONS

The volume of blood flowing into the brain through the internal carotids has been measured in 19 monkeys anesthetized with nembutal. The average figure is 0.60 cc. per gram per minute at an average blood pressure of 125 mm. Hg.

Direct measurements of flow through the internal carotids and the basilar indicate that this figure probably represents only about 70 per cent of the total normal flow. The corrected value therefore is 0.86 cc. per gram per minute.

Stimulation of the cervical sympathetic nerve produced no significant alterations in cerebral flow, though in one experiment results suggesting a redistribution of blood were obtained.

Anoxemia and hypercapnia both increased cerebral flow and increased oxygen tended to decrease it. The effects of anoxemia were more striking than those of CO_2 and much more marked than was expected from comparable experiments on other animals.

Given by intracarotid injection and in minimum effective dosage, adrenalin and benzedrine produced consistent and rather striking decreases in cerebral flow and caffeine, theophylline, histamine, and mecholyl produced comparable increases. Ergotamine and pituitary extract caused a decrease in both flow and blood pressure when similarly given.

When given intravenously adrenalin increased cerebral flow as blood pressure rose; when pressure fell flow fell at the same rate in half the cases, at a faster rate (leading to a definitely subnormal flow) in the others. Caffeine and theophylline, similarly administered, sometimes increased flow distinctly, although blood pressure fell, but nitroglycerine had no such effect.

In 3 experiments in which flow through the basilar and internal carotid systems was measured simultaneously, the part contributed by each to the total flow varied widely (basilar: carotid ratio 26, 43 and 80 per cent). Flow through each system increased when the other was closed but the magnitude of the readjustments thus brought about was subject to such great individual variations as to suggest that the quantitative consequences of occlusion of any of these vessels cannot be predicted.

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