THE DISTRIBUTION OF BLOOD TO THE BRAIN

By D. A. McDONALD and J. M. POTTER

From the Department of Physiology, St Bartholomew's Hospital Medical College, London

Willis (1664) gave the first anatomical description of the arterial circle at the base of the brain. He also performed injection experiments on cadavers, but some of his physiological concepts of the circulation appear confused even by standards that were modern in his day; for Harvey's *De Motu Cordis* had been published 36 years previously.

No physiological study of the circle was made until the present century. Kramer (1912) was the first to study the distribution of blood to the brain in the living animal. He injected methylene blue directly into the carotid or vertebral arteries of fifty dogs and three monkeys, and studied the post-mortem distribution of the dye shortly afterwards. He showed that both carotid and vertebral arteries have distinct territories of supply, and concluded that the circle was an antero-posterior anastomosis which, 'under physiological conditions does not permit the mingling of the blood streams'. He also made a model of the circle of Willis, and noted that after 'carotid' injection the dye stopped in the 'posterior communicating artery'—there being here a 'dead-point' where carotid and vertebral blood streams meet. He made no comment on the relation of one side to the other.

With this work the subject lapsed until interest revived with the introduction of cerebral arteriography by Moniz (1927) but, although this was a great diagnostic advance, it has added relatively little to the knowledge gleaned by Kramer. 'Rapid serial angiography' (Curtis, 1949) is a technical improvement that may add to the knowledge of this aspect of the cerebral circulation in man.

Rogers (1947), like Kramer, constructed a model of the circle of Willis, which, together with clinical and arteriographic evidence, helped him to draw conclusions similar to those of Kramer regarding its function as an anastomosis.

The object of the present work was to determine in what manner the blood is distributed to the brain when conditions of flow are as near normal as possible, and to study the factors which govern or cause an alteration in this distribution. We have not therefore been directly concerned with the quanti-

tative aspects of the blood flow to the brain as a whole, a subject which has received so much attention from such workers as Schmidt (1950).

METHODS

Two series of experiments have been performed. In one, dye was introduced into the bloodstream with a powerful coagulating agent, and the distribution of dye studied after death. In the other series, parts of the brain were exposed and the flow of dye observed with a binocular dissecting microscope.

Rabbits were used as experimental animals. They were anaesthetized by intravenous pentobarbitone (Nembutal), 30 mg./kg., and inhaled ether.

Method of introducing dyes

In nearly all cases the dye was introduced by retrograde injection into the arterial stream through a branch artery some distance from the artery destined for the brain. Thus the internal carotid artery was filled from a cannula (made from a gauge 14 hollow needle) placed in the external carotid, and the vertebral from a cannula in the axillary artery. In either case, the dye was introduced towards the heart. This was the only method which produced constant results, for the lumen of the artery to be studied was in no way occluded and the pressure within it remained essentially unchanged. The contralateral artery corresponding to that holding the cannula was also ligated to render conditions similar on the two sides.

In certain early experiments a distally pointing cannula, connected to a mercury manometer, was placed in one common carotid with the external carotid artery tied. This provided some measure of the intracranial arterial pressure. Systemic blood pressure was not recorded.

The rate of injection varied in the coagulation experiments between the extremes of 0·1 and 1·3 ml./min. Constant results were obtained with an injection of 2 ml. lasting 3–4 min. (0·5–0·7 ml./min.). The same rate was found optimal for the injection of dye alone. An excess of circulating dye made the plasma too blue; this factor alone limited the volume of dye injected. During retrograde injection, occasional much faster rates were seen not to alter the blood-streams in the basilar artery. On this observation and on the internal carotid artery pressure measurement we base the conclusion that retrograde injection is satisfactory.

The dye-coagulation method

The method of using an intravascular blood-coagulant has already been described in detail (McDonald & Potter, 1950). The animal is killed and the brain fixed in formalin. Dissection then demonstrates the vessels where dyed blood was coagulated during life.

Direct observation

The second method was to study with a dissecting microscope thin-walled arteries either on the dorso-lateral surface of the cerebral hemispheres and cerebellar vermis, or on the ventral aspect of the medulla oblongata during life while dye was flowing. Evans's blue dye in concentration varying between 0·2 and 5·0% (usually 1·0%), or methylene blue 1·0% were used. The latter diffuses from the vessels and temporarily stains the nervous tissue, which was advantageous for making colour photographs.

The cortical arteries were exposed by nibbling away the convexity of the skull so that the sagittal sinus was exposed. The membranes were reflected dorsally on either side as a flap based on the sinus in the midline and extending caudally to the lateral sinuses and the torcular, so that some of the posterior cerebral artery territory was visible. The cerebellar vermis was similarly exposed more caudally, and, if necessary, bone was left to cover the region of the torcular and lateral sinuses which intervened between the two fields of study.

The basilar artery was exposed by reflecting the pharynx and pre-vertebral muscles and removing the basal part of the occipital bone (McDonald & Potter, 1949b). This preparation usually

took 3½–4 hr. because of the problems of haemostasis. With such care, however, the animals were still in good condition after 6 or even 8 hr., 5½ hr. being the average duration of an experiment.

The walls of all arteries studied were sufficiently thin to allow detailed study of the flow of dye within them.

The occurrence of anatomical anomalies was verified or excluded by dissection (especially at the root of the neck to demonstrate the origins of the common carotid and vertebral arteries) or by histological examination (to exclude a median septum in the basilar artery) in suspected cases.

In occlusion experiments the vertebral arteries were obstructed close to the subclavian artery and the internal carotid arteries distal to the carotid sinus.

ANATOMICAL DATA

Anatomy of the cerebral vessels of the rabbit

The disposition of the cerebral arteries is similar to that seen in man. Fig. 1 shows the ventral aspect of the rabbit's brain. The two internal carotid and
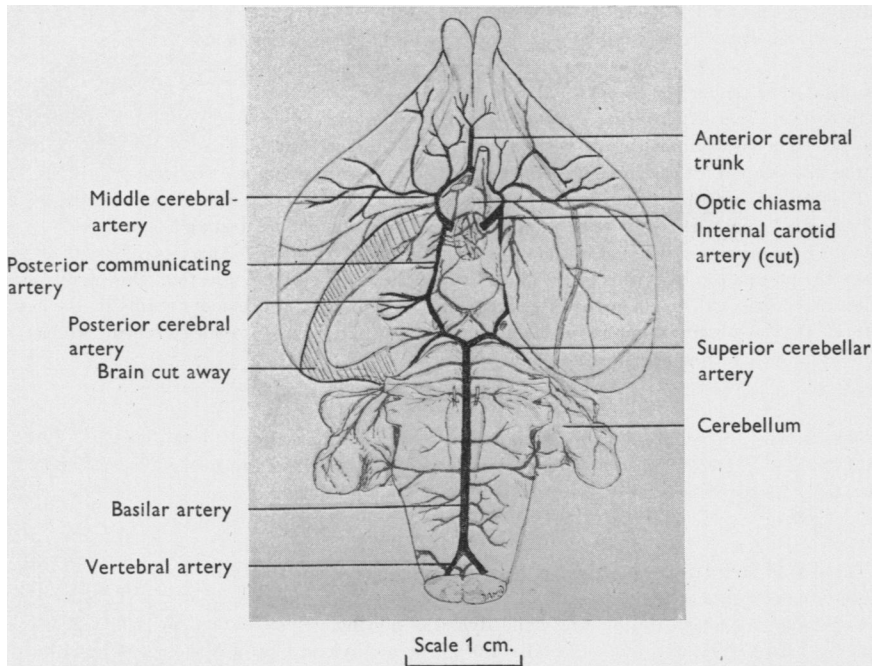

Fig. 1. Arteries of rabbit's brain seen from ventral aspect.

two vertebral arteries supply virtually all the blood that goes to the brain. There is no *rete mirabile* between external and internal carotid systems. The principal features to be noted are that there is a single anterior cerebral trunk formed by the fusion of two branches of the internal carotids, and that the basilar artery is relatively long compared with that found in primates.

The relative sizes of the vessels

Measurements of the external diameters of the main cerebral vessels were made (with an eyepiece micrometer) in a series of rabbits killed by an intravenous injection of Russell's viper venom. The technique was used as described (McDonald & Potter, 1950); it was hoped that the intravascular clotting would reduce post-mortem constriction of the arteries, but it is doubtful if it does lessen it at all. If we presume that the contraction at death is of the same order for all these arteries then their relative sizes are of interest (Table 1).

TABLE 1. External diameters of arteries after death (μ.)

Artery	Representative animals (mean of right and left arteries)							Range of all cases	No. of arteries measured
	1	2	3	4	5	6	7		
Vertebral	470	450	—	—	550	—	450	380–600	10
Basilar	600	600	440	450	620	390	540	390–650	15
Superior cerebellar	410	280	300	300	260	320	340	260–410	24
Posterior cerebral	500	250	430	310	410	380	340	240–540	22
Posterior communicating	—	230	340	340	280	250	240	200–340	18
Interior carotid	—	470	430	516	600	600	580	430–600	18
Middle cerebral	310	300	260	300	400	430	340	260–430	20
Anterior cerebral	340	260	300	260	300	260	260	260–340	7

The general observations to be made are first, that the diameters of the internal carotid and vertebral arteries are approximately the same in this species, and, secondly, that the *circulus arteriosus* is of much the same calibre throughout. In particular, it should be noted that the posterior communicating artery is a major vessel.

Some measurements have also been made during life. The basilar artery (ten cases) ranged between 680 and 1170μ. in external diameter at its proximal end, and between 660 and 1050μ. near its mid-point. The anastomoses between cerebral arteries on the hemisphere were about 50μ. in life, but between 15 and 25μ. in animals killed with venom. It will be seen that after death and fixation the vessels shrink to approximately one-half their vital calibres.

It is possible that exposure of these arteries during life causes some dilatation, for the normal cerebrospinal fluid pressure has been released and unbuffered irrigating solutions (0·9% NaCl and Ringer's) have been used. Such solutions have been shown to cause marked dilatation of the pial vessels (Elliott & Jasper, 1949). Our exposures have, however, always been bilateral, so such changes are unlikely to invalidate our qualitative findings.

EXPERIMENTAL RESULTS

(1) *The distribution of blood between internal carotid and vertebral systems*

This was first studied in four animals by injecting dye and venom indirectly into one internal carotid while all other vessels were open. The middle cerebral

artery and territory anterior to it was filled with dye and clot; this extended about half-way along the *posterior communicating artery* of the same side. Posterior to this point there was undyed blood. In two of these cases this was still unclotted, indicating that there was so little mixing at the carotid-vertebral blood interface that the venom had not passed across. In addition, the hemisphere vessels in the posterior cerebral artery distribution contained no blue dye (Fig. 2).

Posterior communicating artery showing interface. between carotid and vertebral blood

Anterior cerebral trunk

Right internal carotid artery (injected)

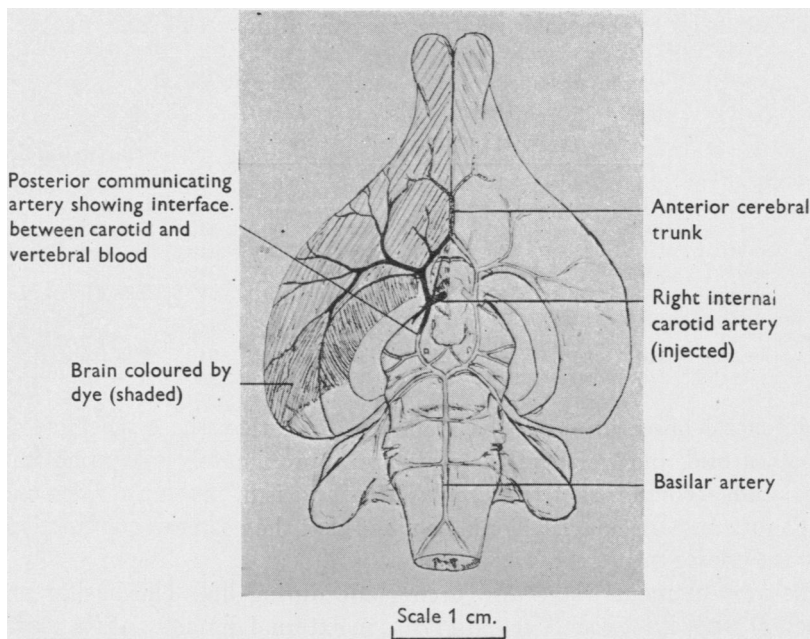Brain coloured by dye (shaded)

Basilar artery

Scale 1 cm.

Fig. 2. Distribution of right internal carotid artery. (Note incompletely bilateral distribution of common anterior cerebral trunk.)

In a further two cases a distally pointing cannula was placed in the opposite carotid to register any pressure changes that might occur in the circle during injection. No pressure fluctuations were noted, thus supporting the opinion that the indirect injection method was preserving the normal pressure relations. In these cases an interface between carotid and vertebral territories was seen in both posterior communicating arteries.

In three cases of vertebral artery injection the reverse effect—of dye passing only into the posterior portion of the communicating artery—was noted.

It is not feasible to study directly the posterior communicating arteries during life. The distribution of the arteries arising from either end of it (the middle and posterior cerebral arteries) can, however, be studied in the living animal. In three cases the injection of the vertebral artery caused a distribution of dye in the posterior cerebral territory alone (Fig. 3). The surface of the

hemisphere was studied with a binocular microscope and in the anastomoses between the branches of the middle and posterior cerebral arterial systems the demarcation points between blue dye and red blood could be seen. These moved slightly at each pulse, presumably because the pulse wave did not arrive coincidentally on either side of the interface. The dye would gradually disappear into the brain-substances through branches.
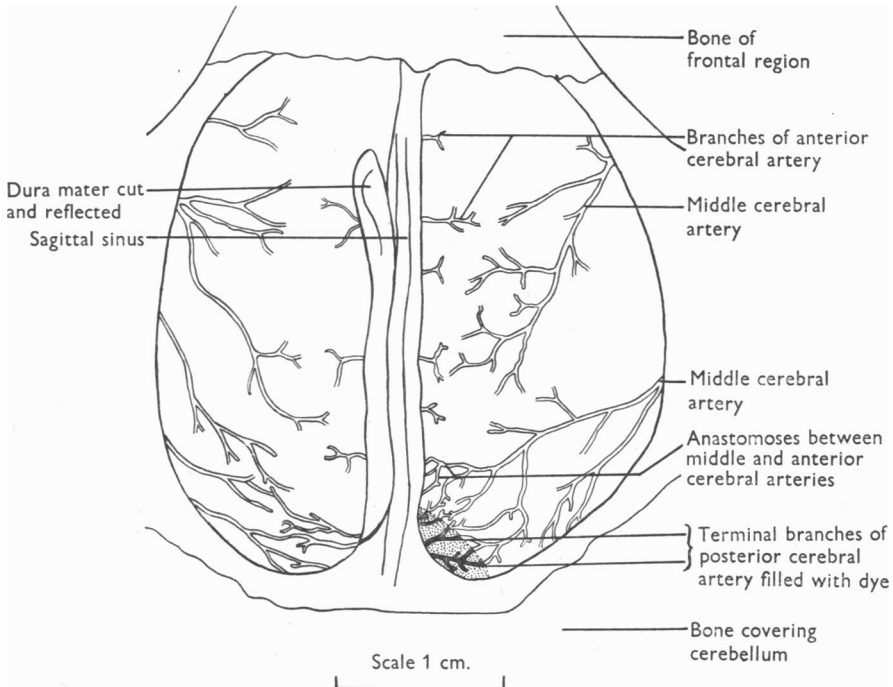

Fig. 3. Dorsal surface of cerebrum showing main arteries only. Distribution of right posterior cerebral artery shown stippled. (Outline drawing from Kodachrome transparency.)

If the pressure balance is upset the posterior communicating artery functions as an anastomosis. If the internal carotid arteries are occluded the blood from the vertebrals supplies the whole brain; this has been observed both with the coagulation technique and in the living preparation with the hemisphere exposed. Even temporary overloading, as in some early experiments in which the cannula was inserted directly into the carotid artery (before the more refined technique of indirect cannulation was developed), may cause a flow from the carotid into territory normally supplied by the vertebral.

Conversely, both vertebral arteries may be acutely occluded and the flow of blood from the carotid will supply the hind-brain with blood. In two experiments this was performed in the preparation with the basilar artery exposed, and dye injected into a carotid was seen to flow from before backwards along

the basilar towards the occluded vertebral arteries. The flow appeared to be confined to a unilateral stream as is the normal flow from the vertebral arteries (see § 2c below). The satisfactory injection of the carotid in this preparation, however, is difficult and was not repeated.

In one experiment with the basilar artery exposed the vertebral artery was injected, and a McDowall vertebral clamp applied immediately afterwards. The vertebral occlusion immediately reversed the direction of flow, and dye which had flowed anteriorly came back into view. A partial occlusion of the vertebral arteries was then achieved such that a balance between dye (now flowing with blood from the carotids) and blood (from the partially obstructed vertebrals) was formed in the portion of the basilar artery in view. It pulsated with each heart-beat and moved with respiration but otherwise remained constant until the dye had all dispersed into various branches. This presumably is the same type of 'dead point' that normally occurs in the posterior communicating artery but which moves when the pressure in one or other arterial system is changed.

(2) *The distribution of blood between the right and left sides of the brain*

This will be considered at both the anterior end of the circle of Willis (the anterior cerebral artery) and posteriorly with regard to the two vertebral and the basilar arteries.

(*a*) *The anterior cerebral artery.* In the rabbit this is a single, long trunk which is not easily accessible. In this series of experiments observations on it have merely been incidental to the study of the more posterior regions. We have not observed the artery itself directly during life, only parts of its territory.

Dye from one internal carotid stained the anterior cerebral territory on both sides of the brain, although rather more markedly on the side of the injection. This has been observed after coagulation experiments and in the living animal (see Fig. 2).

Ligation of one internal carotid caused the blood from the other to fill the whole of the anterior portion of the circle of Willis. Demarcation from the vertebral blood still occurred in both posterior communicating arteries.

In some early experiments, where the common carotid artery was injected, a marked staining of the olfactory bulb of that side was seen. This did not occur when the external carotid was ligated, suggesting that this structure in the rabbit is normally supplied by the external carotid. This was the only evidence we observed of branches of this artery supplying blood to the brain.

(*b*) *The vertebral arteries.* Proximal to the point where they fuse to form the basilar artery, the vertebrals supply little blood to the brain proper.

Dye introduced into the vertebral artery by retrograde injection of the axillary artery stained the ipsilateral half of the spinal cord from the first thoracic segment to the junction of the medulla oblongata and first cervical

segment. The blood was supplied to the cord by the anterior spinal artery and segmental branches at each space between the arches of the vertebrae.

Injection of one vertebral artery when the other was occluded at its origin caused dye to be distributed to both sides of the spinal cord.

The passage of blood into the territory of the occluded vertebral was not primarily due to the functioning of the numerous but fine anastomoses of the spinal branches of either side. It was mainly the result of blood flowing from the free vertebral artery into the basilar artery and then back down the occluded artery. This was seen on many occasions and has been recorded cinematographically.

Release of the occlusion up to 5 sec. after this retrograde flow had occurred caused dye to be carried up into the basilar artery once more. This indicates that the vertebral artery distal to the point of occlusion is something of a cul-de-sac. Therefore the branches given off along its length, although numerous, must in aggregate be so small that they drain only a small proportion of the total flow through the artery.

(c) *The basilar artery.* Experiments using the coagulation technique provided evidence in five animals that blood from one vertebral artery was distributed to the branches of the basilar artery on its own side only (McDonald & Potter, 1949 a).

Direct observation of the basilar artery was made in twenty-five living animals during the indirect introduction of dye into one vertebral artery. The flow from that artery remained rigorously on its own side of the basilar artery (Fig. 4). Analysis of a cinematograph film taken at 24 frames/sec. showed no evidence of eddying or mixing even at the point where the two streams meet. Normally the line between dye and blood appeared as if it had been drawn with a straight edge down the centre of the artery from the angle made by the fusing walls of the vertebral arteries. The two streams were seen to supply the blood flowing into the branches arising from the respective sides of the basilar.

If there was inequality between the diameters of the two vertebral arteries then the streams they formed in the basilar artery showed a corresponding disparity. In one animal one vertebral was so small that its cranial end was a branch rather than a tributary of the basilar, and dye always flowed into it, as well as into the basilar, from its fellow vertebral. The stretch of the basilar artery thus under direct observation was about 7·5 mm., or about half its total length. That the two streams continue unmixed along the whole extent of the artery is confirmed by two other observations. First, dye appeared in a vein running alongside the basilar artery, between 1 and 2 sec. after the passage of the dye. Only the vein on the same side as the injected vertebral artery contained dye. As this vein drains territory supplied by the superior cerebellar artery (one of the two major terminal branches of the basilar artery) this indicates that the distribution remains unilateral.

Secondly, the direct observation of the dorsal surface of both cerebral hemispheres and the cerebellum (also reported in § 1 above) showed that the dye only appeared in the terminal branches of the posterior cerebral (Fig. 3) and superior cerebellar arteries of the same side as the injection. This was seen in three animals.

In only one case where injection was successful was there failure to see streams as described. In this early case no ligature had been placed on the non-injected axillary artery. Dye flowed up the vertebral artery, filled the
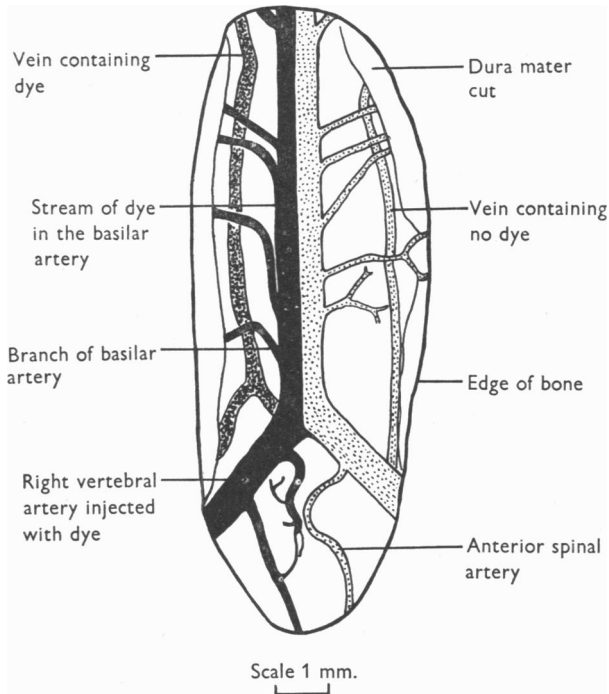

Fig. 4. Unilateral distribution of dye in the basilar artery and its branches following vertebral injection. (Tracing of a photograph.)

basilar artery and passed into the distal 1 mm. of the other vertebral artery. Here an interface between dye and blood was formed which pulsated (like those described in § 1 above). Ligating the axillary artery to make the preparation symmetrical restored the normal streamline pattern.

As the ligation of the axillary artery must temporarily raise the pressure proximal to it, this effect was attributed to a slight imbalance of pressure between the two vertebral arteries. In subsequent experiments both axillary arteries were occluded at corresponding points.

If one vertebral artery is occluded, blood from the other artery fills the

basilar artery and supplies the branches to both sides, including both posterior cerebral arteries. In addition, as already described (§ 2*b*), blood flows back into the distal end of the occluded vertebral artery.

<div align="center">

DISCUSSION

Previous work
</div>

The function of the *circulus arteriosus* has been the subject of much interest and speculation. It is therefore curious that there is relatively little experimental study of this function in the living animal to be considered. Deductions made from anatomical considerations and injection of dead specimens will not concern us further, but we must acknowledge that they may be of some value, together with models, in interpreting experimental findings, provided their limitations are clearly understood. Batson (1944) has stressed some anatomical pitfalls which beset the experimental study of the circulation in animals. Failure to appreciate species variations, for example, may render much work valueless. Wolff (1938) has given a useful review of the comparative anatomy of the cranial circulation.

Studies in the living animal by Kramer (1912) and angiography in man have given information about the territories supplied by the main cerebral arteries. From this information deductions have been made concerning the flow in the circle of Willis, but direct observations have not apparently been made before the present study.

Kramer (1912) used methylene blue injection in fifty dogs and three monkeys and studied the areas of brain stained. Comparing his findings with ours, we note that, in both, blood from one carotid is distributed to the middle and anterior cerebral arteries of the same side and to the anterior cerebral territory of the other side. If the contralateral carotid was occluded, Kramer found little difference in the distribution, whereas we found both middle cerebral arteries and all territory anterior to them supplied by the patent internal carotid. Kramer's result implies that *vertebral* blood moved forward to supply the territory of the occluded carotid. Another possibility is that external carotid blood performed this function, but it seems probable that Kramer, referring merely to 'carotid', used always the common carotid, whereas we have been at pains to introduce dye into the internal carotid with both external carotids occluded. The difference in species used must also be considered in any explanation of these different results.

Considering vertebral injections, we find the discrepancy in results to be greater. Kramer reported that injection of one vertebral artery, with the other patent, caused staining on *both* sides of the spinal cord, hind-brain, cerebellum· and posterior cerebral artery territory. Our experimental results of dye distribution and, above all, the long series of observations of flow in the

basilar artery make it clear that, owing to the streamline (laminar) blood flow in these arteries, the stream from one vertebral artery remains on the same side of the basilar artery and is distributed to the branches of that side alone.

The difference here must be attributed to injection technique. We have exercised great care to introduce dye so that the normal flow of blood along the artery is neither obstructed by a needle nor the pressure appreciably increased by the force of the injection. We have also noted how the small imbalance of pressure due to failure to ligate the axillary arteries symmetrically may vitiate the result.

Kramer injected directly into the vertebral artery with a syringe and needle. However gently this rather difficult procedure be carried out, it is likely, from our observations, to cause a false distribution. Further, the relatively large anterior spinal artery in the dog (the animal most used by Kramer) may be an additional factor in facilitating the crossing of the mid-line and producing the picture of bilateral distribution.

Kramer's finding that the staining from vertebral injection tends to become ipsilateral if the other vertebral is occluded is directly contrary to our own; for under this circumstance the very free anastomosis provided by the basilar artery distributes blood to both sides. From his data we can advance no explanation of this result.

With his views on the function of the posterior communicating artery as an antero-posterior anastomotic channel we are in complete agreement. He pointed out, by inference from his experiments and the behaviour of his model, that this artery was where opposing streams from the carotid and vertebral arteries meet to form a 'dead point' but not to mix. Therefore a given cerebral artery will be supplied by one or other of the systems but not by both at the same time—unless the 'dead point' happened to occur exactly athwart its origin.

The only other experimental findings to be considered are those obtained from angiographic studies in man, using radiopaque substances. The method is primarily diagnostic of pathological conditions and a review of the literature would be out of place here. The circle itself is rarely visualized, although the basilar artery may be. The general criticism of injection methods made when considering Kramer's results is particularly apposite here. In order to obtain the maximum contrast the radiopaque substance is usually injected fast directly into the artery. Commonly, 5–10 ml. will be injected into the carotid within 2–3 sec. This must cause a great local increase in the volume in this arterial system for a short while with a consequent surge of pressure. Thus Curtis (1949), using 'rapid serial angiography', finds that injection into the internal carotid overflows into the posterior cerebral artery in the first 2 sec. but that this clears before the middle and anterior cerebral arteries. This finding is to be expected if the carotid supply, normally stopping in the posterior communicating artery, were, during the surge of pressure consequent on the injection, momen-

tarily to overwhelm the vertebral system and prevent its normal contribution to the posterior cerebral artery.

It has been suggested (Lima, 1950) that this filling of the posterior cerebral artery by carotid injection may be due to its being fed naturally this way through an abnormally large posterior communicating artery rather than from the basilar artery. Such an anomaly occurred in only 3% of human brains in Stopford's (1916) series, while posterior cerebral filling occurred in 25% of Moniz's angiographies (Moniz, Pinto & Alves, 1933). It is perhaps pertinent that Elvidge (1938), who partially occluded the common carotid proximal to the injection site, obtained filling in only 14%. This filling may, however, be missed unless the film is exposed early (Curtis, 1949).

Similar considerations presumably apply to the filling of the contralateral anterior cerebral artery.

Vertebral artery injection is much less commonly done because of its greater technical difficulty. We can find no published case which showed unilateral filling of the basilar artery and its branches, even though Schmidt (1950) says that it occurs frequently. Indeed, our experiments suggest that, with the usual techniques, this would be unlikely to occur. Retrograde injection of the subclavian artery has been used in man, and, if the contralateral subclavian were also to be occluded, then the physiological picture might be seen. This is not a purely academic consideration because bilateral filling of the basilar artery indicates an overloading of the local circulation. Such overloading is gross where the middle cerebral artery is filled from vertebral injection. Although it is realized that the purpose of angiography is to obtain the anatomical filling of as many vessels as possible, these factors should be appreciated.

The role of arterial anastomoses in the supply of blood to the brain

Kramer (1912) drew attention to the fact that since the time of Willis (1664) it had been believed that the function of the circle was to equalize the blood supply to all parts of the brain and to act as a kind of reservoir. Rogers (1947), mentioning the continued prevalence of this concept, also quotes the English translation of Willis (1684) as authority for it. Comparison of this work with the original (1664) reveals in places a certain embroidery during translation, so that it is probably as fruitless to try to guess Willis's original meaning as it is to define precisely, in the language of physics, the meaning of the terms 'distributor' or 'equalizing station'. These expressions should therefore be dropped; for the satisfactory application of a law of the Poiseuille type to a complicated haemodynamic system of varying velocity, in a branching ring of non-rigid tubes of variable calibre, is not yet practicable.

The recognition by Kramer and Rogers of the circle of Willis as an anastomosis between carotid and vertebral systems is the theme we wish to elaborate.

Our conclusion is that any such concept must extend beyond the strictly anatomical limits of the *circulus arteriosus* and include the vertebral and basilar arteries. Four large anastomotic channels can then be considered; two antero-posterior—the posterior communicating arteries; and two median, side-to-side channels—the *basilar artery itself* posteriorly and the common anterior cerebral trunk (or anterior communicating artery or arteries according to species and anomalies).

The antero-posterior anastomosis. The posterior communicating artery on either side connects the internal carotid system (or its substitute) and the vertebral-basilar system. In this channel, the two sources of blood meet and oppose each other because the pressure on either side of the interface is the same. This point will oscillate if the pulse waves are out of phase in arriving or if the influence of respiration differs in the two systems. This was seen when the interface was artifically moved back into the basilar artery under vision. The position of this 'dead point' in an anastomotic channel can only be determined experimentally. The mere existence of a vessel, to many, naturally implies a flow of blood through it. In fact, no such through-current need occur. For flow to start, an adequate pressure difference must exist between two points along the tube, and blood will therefore flow freely in the posterior communicating artery only when an event, such as the obstruction of a major artery, lowers the pressure in one of the opposing systems. It should be mentioned that one posterior communicating artery may be absent in 6 % and both in 4 % of human brains. There may also be considerable variation in both their absolute and relative calibres (Stopford, 1916).

An additional, and possibly significant, part of the antero-posterior anastomosis is seen in the much smaller vessels that connect the middle cerebral with the posterior cerebral artery branches on the surface of the hemisphere. Here similar 'dead points' have been observed. The only mixing that will occur at such points will be by diffusion over the cross-sectional area of the vessel.

The side-to-side anastomosis. The part played by the anterior and posterior mid-line brain arteries has received little comment as there have been no experiments adequate to demonstrate the physiological behaviour of the blood they carry. They have of course their counterparts in the mid-line elsewhere in the body although on a considerably smaller scale. It is this relatively large size perhaps that has made their study difficult, by allowing too ready a flow across them. This may explain the seemingly incongruous results obtained by both Kramer and ourselves in the anterior cerebral artery territory. A discrepancy in size between the internal carotids, by shifting the 'dead point' across the mid-line, may also be a factor; for we have seen this operate in the vertebral-basilar system. Kramer (1912), having elucidated the antero-posterior anastomotic function, must surely have been disappointed in his failure to demon-

strate that occurring in the mid-line. For he takes, as examples of other functioning anastomoses, those in the mid-line across the thyroid isthmus and the tongue, which do not allow blood across unless one carotid is tied.

The basilar artery must itself be considered as an anastomotic channel of a special kind, connecting the two vertebral arteries. The interface here is much larger, for it occupies the longitudinal section of the artery. Normally no flow occurs across it owing to the streamlined (laminar) nature of the flow. Because of its large size, it allows transgression of the mid-line at smaller pressure differences than in the previously considered anastomoses, but this is a matter of degree only. Since a 'dead point' or interface formed between layers of streaming blood is perhaps a somewhat unusual concept, a brief comment on this type of flow in the basiliar artery is required.

Starting with the experiments of Osborne Reynolds (1883), it has been shown that a pure fluid flowing smoothly through a glass tube does not become turbulent until the value of the expression $Rv\rho/\eta$ (the Reynolds number) exceeds about 1000; R being the radius of the tube, v the mean velocity, ρ the density of the fluid and η its viscosity coefficient. It has been assumed many times since that the heterogeneous substance blood behaves similarly in its system of elastic blood vessels.

Coulter & Pappenheimer (1949), however, from experiments *in vitro*, suggest that, while the plasma sleeve behaves thus, the more axially flowing red corpuscles still remain orientated after the critical Reynolds number has been considerably exceeded.

If, for the basilar artery of the rabbit, we take the values $R = 0.04$ cm., $v = 40$ cm./sec. (a maximum value, Potter & McDonald, 1950) and $\rho/\eta = 60$ (an arbitrary figure, modified from Green, 1944), we obtain a Reynolds number of 96. So that, even allowing a considerable error for the problematical viscosity value, we are, in this artery, well within the theoretical region for the streamline flow that we have always observed. It has been stated that, among mammals, the rabbit has blood of exceptionally high fluidity (Hübner, quoted by Bingham, 1922), but we have not studied this particular matter.

It may be remembered that inequality in size of the vertebral arteries resulted in a corresponding difference in the width of the two main basilar streams and a shift from the mid-line. In man, some such inequality is present in 92 %, and in 72 % it is marked (Stopford, 1916). In the basilar artery the most relevant anomaly is the rare presence of a median septum. This would provide an anatomical barrier, preventing the basilar from acting as an anastomosis. We have watched for this, but have not observed it in our rabbits, although we have encountered an incomplete one in man.

There is little to discuss concerning the anterior cerebral artery region, for we have not studied this so thoroughly. By analogy, where a common anterior cerebral trunk occurs (in the rabbit) the same principles should be applicable as in the case of the basilar artery, but our results have been insufficiently conclusive to test this supposition. Where an anterior communicating artery (or arteries) exists, as in man, a similarity to the posterior communicating artery is suggested.

Thus, where both carotid and vertebral arteries contribute, the brain is seen

to be supplied by four separate sources of blood, each running into the capillary bed of its proper tissue region. To be aware of possible variations and anomalies is essential in any consideration of the complex haemodynamics of this region. In man, a 'normal' circle of Willis occurs in barely 50% (Dandy, 1945). The elaborate system of readily functioning connexions between these arterial systems may be regarded as evidence of the survival value of having such a blood supply to the brain as will not fail in any minor disaster. The efficiency of these safeguards is a matter for further study.

SUMMARY

1. The distribution of blood from the four main arteries to the brain of the rabbit has been studied. A dye-coagulation method has been used and certain brain arteries have also been observed microscopically during the introduction of dye during life.

2. With all four arteries patent, the internal carotid artery sends blood to the middle cerebral artery territory and to that of the anterior part of the posterior communicating artery of its own side. It also appears to send blood to the bilateral territory of the common anterior cerebral artery but with ipsilateral preponderance.

3. Similarly, the vertebral artery supplies its own side of the spinal cord and contributes a strictly unilateral stream to the basilar artery. Its blood is thence distributed ipsilaterally to brain stem, cerebellum, posterior cerebral artery territory and as far as the caudal part of the posterior communicating artery territory.

4. The two systems meet and oppose each other in the posterior communicating artery, where a 'dead point' or interface is formed without mixing. They also meet in much smaller anastomoses on the cerebral hemisphere.

5. If both internal carotid or both vertebral arteries are occluded, blood passes forwards or backwards respectively from the pair which are still patent. There is then a functioning antero-posterior anastomosis in each posterior communicating artery.

6. Occlusion of one internal carotid or one vertebral artery results in the supply of the defrauded territory by its contralateral fellow. There is therefore also a side-to-side anastomosis in both the common anterior cerebral and basilar arteries themselves.

7. Previous work, mainly that of Kramer (1912), and methods for investigating these problems are discussed and criticized. Anatomical factors, including species variations, are also considered.

8. From present knowledge it is not possible to attribute to the circle of Willis any role other than that of collaborator in an unusually elaborate system of anastomoses at the base of the brain. In this system the vertebral and basilar arteries play an integral part.

REFERENCES

Batson, O. V. (1944). *Fed. Proc.* **3**, 139.

Bingham, E. C. (1922). *Fluidity and Plasticity.* New York: McGraw-Hill.

Coulter, R. A. & Pappenheimer, J. R. (1949). *Amer. J. Physiol.* **159**, 401.

Curtis, J. B. (1949). *J. Neurol. Neurosurg. Psychiat.* **12**, 167.

Dandy, W. E. (1945). *Intracranial Arterial Aneurysms.* New York: Comstock.

Elliott, K. A. C. & Jasper, H. H. (1949). *J. Neurosurg.* **6**, 140.

Elvidge, A. R. (1938). *Res. Publ. Ass. nerv. ment. Dis.* **18**, 110.

Green, H. D. (1944). In *Medical Physics*, ed. by O. Glasser. Chicago: Year Book Publishers.

Kramer, S. P. (1912). *J. exp. Med.* **15**, 348.

Lima, P. A. (1950). *Cerebral Angiography.* London: Oxford University Press.

McDonald, D. A. & Potter, J. M. (1949a). *J. Physiol.* **108**, 34P.

McDonald, D. A. & Potter, J. M. (1949b). *J. Physiol.* **109**, 17P.

McDonald, D. A. & Potter, J. M. (1950). *J. Anat., Lond.,* **84**, 327.

Moniz, E. (1927). *Rev. Neurol.* **2**, 72.

Moniz, E., Pinto, A. & Alves, A. (1933). *Bull. Acad. Méd. Paris,* **109**, 758.

Potter, J. M. & McDonald, D. A. (1950). *Nature, Lond.,* **166**, 596.

Reynolds, O. (1883). *Philos. Trans.* **174**, 935.

Rogers, L. (1947). *Brain,* **70**, 171.

Schmidt, C. F. (1950). *The Cerebral Circulation in Health and Disease.* Oxford: Blackwell.

Stopford, J. S. B. (1916). *J. Anat., Lond.,* **50**, 131.

Willis, T. (1664). *Cerebri Anatome.* London: Martin & Allestry.

Willis, T. (1684). *Practice of Physick.* London: Dring, Harper & Leigh.

Wolff, H. G. (1938). *Res. Publ. Ass. nerv. ment. Dis.* **18**, 29.