VASCULAR PATTERNS IN THE CHOROID PLEXUS

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The central position in the field of research into the circulation of the cerebrospinal fluid has long been occupied by the controversy as to whether the fluid is a filtrate or a secretion. The evidence on both sides has been comprehensively reviewed by Weed (1922) and Flexner (1933). In the presence of this controversy, other problems which may be germane to the whole question of the production of the cerebrospinal fluid have been largely overlooked.

Although it is generally accepted at the present time that the choroid plexuses are the main source of the cerebrospinal fluid, little is to be found in the literature concerning the blood vessels of these plexuses. Neither Weed nor Flexner make any reference to the arrangement of the choroidal vessels or to the presence or absence of arteriovenous anastomoses in the plexuses.

The experiments of Dandy (1919) and the criticism to which his findings have been subjected by Flexner (1933) have shown the difficulties which beset attempts to draw conclusions as to the nature and method of production of the cerebrospinal fluid from experimental operations upon the choroid plexuses. The situation and relationships of the plexus must always make the performance of such physiological experiments difficult and the interpretation of the results uncertain and inconclusive.

The work of Trueta, Barclay, Daniel, Franklin & Prichard (1947) has shown that fresh light may be thrown upon a problem, which direct experimentation appears unlikely to solve, by a study of the vascular patterns of the organs concerned. It has appeared therefore that the nature of the vascular patterns of the choroid plexuses may be equally pertinent to the question of the production of the cerebrospinal fluid. An examination of the literature has failed to disclose any description of the general arrangement of the blood vessels of the choroid plexus, and this has encouraged the study of whole cleared preparations of injected plexuses as being fundamental to the further investigation of the possible control of the production of the cerebrospinal fluid by nervous or other mechanisms.

In the present study attention has been confined to the choroid plexuses of the lateral ventricles, as these have been the subject of most physiological investigation and are usually considered to be the main source of production of the cerebrospinal fluid.

MATERIALS AND METHODS

In this investigation the brains of fourteen rabbits, four human foetuses and twelve human adults were examined. The rabbits were injected immediately after death with coloured substances into the common carotid or brachiocephalic arteries. The whole head was then fixed in 10% formalin for 4 days, after which the choroid plexuses of both the lateral and third ventricles were removed entire and cleared before mounting in balsam. The human foetuses were of varying periods of gestation. Injection was made through the common carotid arteries of both sides, and the subsequent treatment was similar to that followed in the rabbits. The adult human brains were obtained from the post-mortem room as fresh as possible. They were injected directly into the anterior choroidal artery of each side. The whole brain was then fixed for 4 days in 10 % formalin, and at the end of this period the choroid plexuses were dissected out. After further fixation, the plexuses were dehydrated through graded alcohols, cleared in xylol, and preserved for examination in methyl salicylate.

Various injection media were employed—indian ink in plasma, colloidal carbon, and red and blue dispersion media.* The blue and red dispersion media employed were those normally used for colouring neoprene latex. They were prepared by ball-milling pigments with a small quantity of a highly active surface wetting agent. The blue pigment used was copper phthalocyanine, and the red was a dispersion of a red lake pigment. It was found that both the carbon suspensions and the red dispersion medium passed rapidly over to the venous side of the plexus and gave a complete picture of the venous pattern, but little if any remained on the arterial side. On the other hand, the blue dispersion under the pressures employed tended to remain on the arterial side and outlined fully the arteries and arterioles. The larger veins in these latter specimens could usually be identified by the presence of contained blood. It was decided therefore to inject the red dispersion from the arterial side and to follow this immediately by an injection of the blue dispersion. This red-blue method was found to give a very satisfactory injection of both the arterial pattern (blue) and the venous pattern (red). There was little mixing of the dispersions, and the junction of the blue and red dispersions at the arteriovenous connexions in the fronds was clearly distinguishable.

OBSERVATIONS

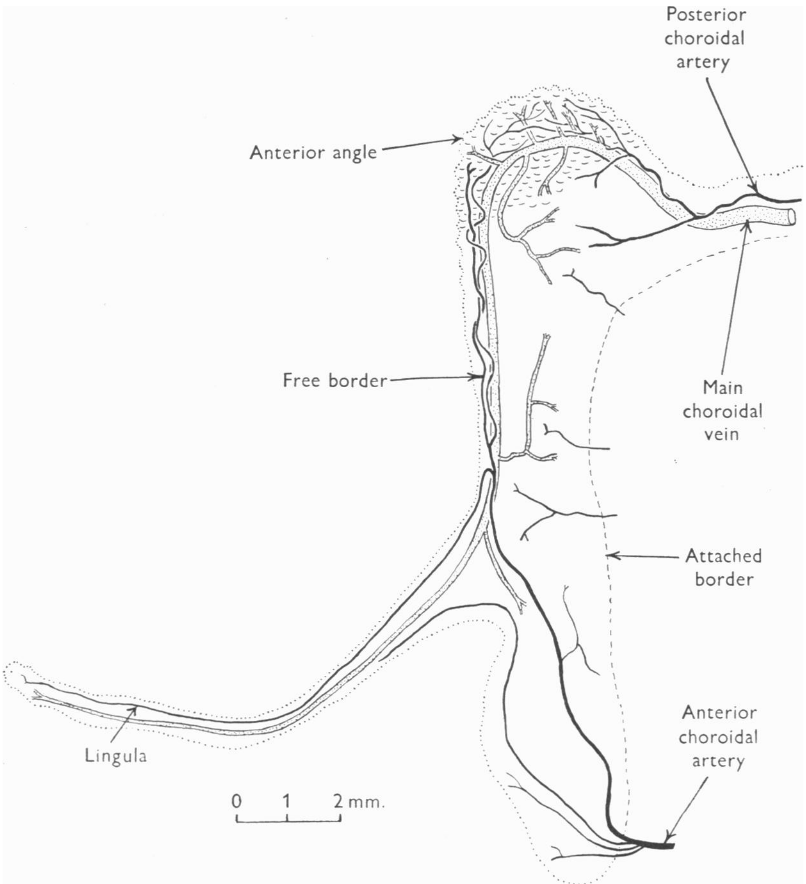
In the descriptions of the choroid plexuses both in the rabbit and in man, the convention is adopted throughout of considering the plexus as though it was situated in a single plane. Thus, the part of the plexus occupying the most anterior part of the inferior horn of the ventricle is described as the posterior end of the plexus, and the superior surface is taken as the whole of that surface which is continuous with the superior surface in the body of the ventricle.

The choroid plexus of the rabbit (Text-fig. 1)

In the rabbit the elaborate folding into villous processes of the ependymal layer covering the choroid plexus is restricted to a limited area of the free margin of the plexus. It is most marked anteriorly, near the interventricular foramen, where the free border shows a marked forward angulation. Behind this, at a point corresponding roughly to the trigone of the ventricle, a curious tongue-like process projects laterally. The name of *lingula* is suggested for this process. This area is not an example of villous thickening of the plexus. It is not covered with folded layers of ependyma, and its vascular relations differ from those of the anterior part of the plexus (Pl. 1, fig. 1). In some plexuses there is a second projection posterior to the lingula.

* The dispersion media were obtained from the B.B. Chemical Co., Ltd., Ulverscroft Road, Leicester.

The anterior choroidal artery enters the inferior horn of the ventricle and divides usually into two main branches, one of which runs along the free and the other along the attached border of the choroid plexus (Pl. 1, fig. 2). The branch along the free border continues along this border to the posterior aspect of the lingula where it ends. It is often accompanied in its course by another branch of the parent stem which is very convoluted. The branch along the attached border gives off short



Text-fig. 1. Diagram to illustrate the principal features of the choroid plexus of the rabbit. (Lateral ventricle: left side.)

stems which divide immediately into branches which pass anteriorly and posteriorly in the attached margin of the plexus. Just after it passes beyond the lingula this branch gives off a recurrent branch to the process which runs along the anterior border of the lingula. Having given off the branch to the lingula, the main branch reaches the free border of the plexus. As it approaches the anterior end where the villous processes are most numerous, it becomes more convoluted and tortuous and ends by becoming continuous with one of the posterior choroidal arteries (Pl. 1, fig. 3).

There are generally two to four posterior choroidal arteries, branches of the posterior cerebral artery. One thick branch enters the plexus at the interventricular foramen and runs along the free margin of the plexus towards the angle of the free border, giving off in its course a branch to the attached border of the plexus and ends by becoming continuous with the anterior choroidal artery (Pl. 1, fig. 3). A more posterior branch from the posterior cerebral artery frequently runs forwards in the attached border. The main choroidal vein starts at the anterior end of the plexus and runs forwards, gaining tributaries as it progresses towards the interventricular foramen (Pl. 1, fig. 4). It is continuous with the venous network which forms a vein or series of veins leaving the posterior end of the plexus and accompanying the anterior choroidal artery. A constant large vein runs in the free margin of the plexus, and joins the main choroidal vein anteriorly.

The choroid plexus of man (Text-fig. 2)

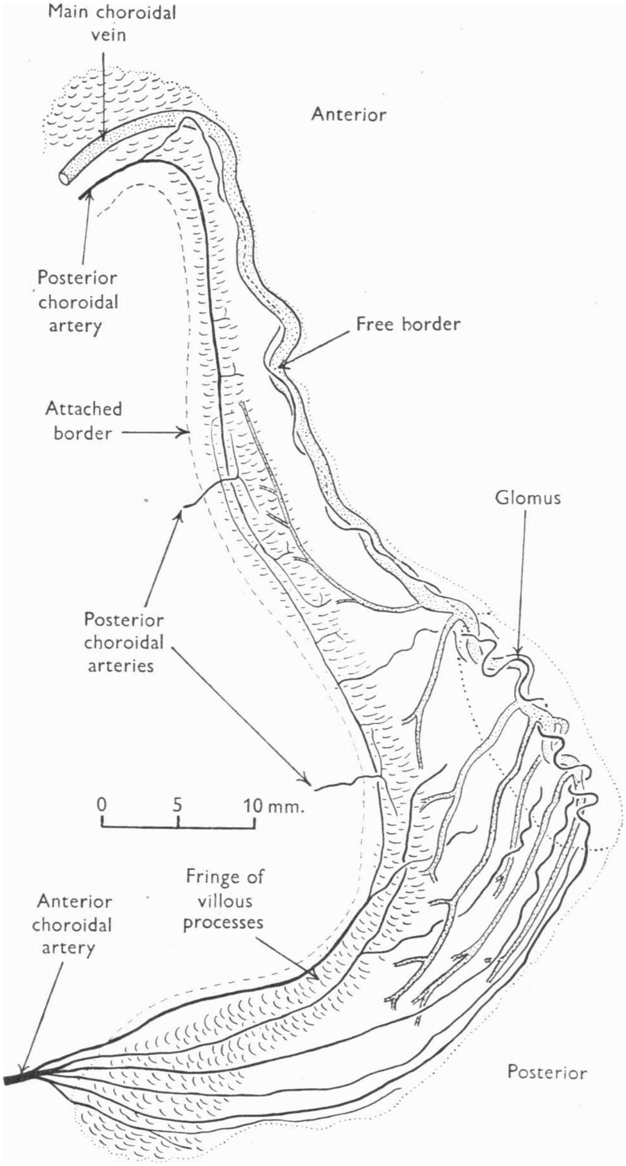
The choroid plexus of the lateral ventricle has the general appearance of a thin undulating membrane (Pl. 1, fig. 5). On macroscopic examination, a well-marked swelling is seen on the free edge of the plexus at the junction of the body and posterior horn of the lateral ventricle. Following Findlay (1899), the term *glomus* has been adopted for this swelling. Both surfaces of the plexus exhibit frond-like villous processes. These processes are mainly aggregated into two fringes, one on the superior and the other on the inferior surface of the plexus, close to the attached border. The fringes form the rounded posterior end of the plexus, and anterior to the glomus where the plexus narrows, the fringes approach the free border and are continuous through the interventricular foramen with the plexus of the third ventricle. The free border of the plexus, except at its posterior end, shows very few villi.

The plexus is supplied by anterior and posterior choroidal arteries. The anterior choroidal artery is constantly given off from the internal carotid artery between the posterior communicating artery and the division of the internal carotid artery into its middle and anterior cerebral branches. The anterior choroidal artery gives off branches to structures in the neighbourhood, and the branch which runs to the plexus crosses the optic tract and enters the choroidal fissure at the anterior end of the inferior horn of the ventricle. Immediately before entering the plexus the artery breaks up into a variable number of branches, usually six to eight.

The posterior choroidal arteries are branches of the posterior cerebral artery. There are usually from three to five branches entering through the choroidal fissure from the tela choroidea. One branch constantly enters the plexus in the region of the interventricular foramen, and anterior branches to the right and left plexuses may arise from a single stem. In some specimens a posterior choroidal branch enters the plexus in the posterior part of the inferior horn of the ventricle.

Free communications between the anterior and posterior choroidal arteries are to be found within the tela choroidea (Pl. 2, fig. 6), in the villous fringe and at the glomus.

Within the plexus both the anterior and posterior arteries give branches which may be broadly divided into branches to the villous fringe and branches to the glomus region. The anterior choroidal branches which enter the hinder end of the plexus are of fairly uniform size. Four or five branches pass towards the free border of the plexus and run parallel to one another towards the glomus (Pl. 2, fig. 7). These vessels give off few side branches and terminate at the glomus. Approaching the glomus they become very tortuous and often appear to form a spiral around the glomus (Pl. 2, fig. 7). Sometimes a branch of the anterior choroidal artery runs



Text-fig. 2. Diagram to illustrate the principal features of the human choroid plexus. (Lateral ventricle: right side.)

directly across the plexus towards the glomus. One or two large branches run forwards in the base of the villous fringe towards the interventricular foramen, and give off branches which enter the fronds (Pl. 2, fig. 8). The anterior branch of the posterior choroidal artery breaks up on entering the plexus. Fine parallel branches, three to four in number, similar to those of the anterior choroidal artery, run posteriorly along the free border, closely related to the large vein in its edge, and end in the region of the glomus. A large branch runs along the base of the villous fringe and shares with the corresponding vessel from the anterior choroidal artery in the supply of the fronds. The posterior branch of the posterior choroidal artery enters the plexus in the inferior horn and runs forwards close to the attached border supplying the villous fronds. It may give off a branch which runs directly to the glomus. The intermediate branches of the posterior choroidal artery join the plexus from the tela choroidea and assist mainly in the supply of the villous fringe.

From the main vessels in the base of the fringe short stems arise which divide to supply the fronds. The appearance is that of a marginal artery giving off short terminal branches along its length rather than that of an arterial tree with branches of ever-diminishing size (Pl. 2, fig. 8).

In general, the anterior choroidal artery supplies the more posterior part of the plexus while the posterior choroidal arteries supply the more anterior part. The variations seen and the communications observed between these vessels suggest, however, that the plexus is indifferently supplied from both anterior and posterior choroidal arteries.

The plexus shows an extremely rich venous network. The venous radicles begin in the villous fronds and unite to form large venules which run towards the glomus (Pl. 2, fig. 9). At the glomus these vessels are intimately related to branches of the choroidal arteries. The veins join to form a single large stem which runs forwards from the glomus in the free edge of the plexus (Pl. 1, fig. 5), accompanied by fine parallel arteries (vide supra). At the interventricular foramen this vein is joined by the thalamostriate vein and a vein from the septum lucidum before turning into the tela choroidea to form the internal cerebral vein. In some specimens a vein leaves the plexus near the posterior end and joins the basal vein. In one specimen a large vein can be seen running from the glomus to join the internal cerebral vein in the tela choroidea.

On entering a frond the arteriole joins a network of capillary loops (Pl. 2, fig. 10), which connect with the venous radicles. It was noted that with injections of carbon particles and the red dispersion, the injection mass passed rapidly over into the capillaries and veins and was not found in the arteries. On the other hand, the blue dispersion medium tended to remain on the arterial side and was seldom to be found in the veins. Arteriovenous connexions without the intervention of a capillary system were also to be observed in some of the fronds (Pl. 2, fig. 11), but it is not possible to state the frequency with which these occur.

DISCUSSION

The surfaces of the choroid plexus of the lateral ventricle present numerous frond-like processes. The distribution of these processes differs in different animals; in the rabbit the villi are most numerous at the anterior end close to the interventricular foramen, whereas in the human plexus the fronds are aggregated mainly as a fringe close to the attached border of the plexus and extending along its whole length. The remainder of the surface shows only scattered single villi, and even these are absent throughout the greater part of its length. Hudson & Smith (1952) have noted that in the sheep the fronds were most numerous at the rostral end of the plexus. It is to be expected, therefore, that, in accordance with the simpler arrangement of the villous processes, the vascular pattern of the plexus in the rabbit will be of a less complex nature than that of the human choroid plexus where there is a great concentration of villous processes along the attached border. Findlay (1899) has noted the shaggy appearance of certain parts of the choroid plexus but has not stated where these parts are to be found.

In all the human plexuses examined the glomus was a well-defined landmark. It presents as an oval-shaped swelling at the junction of the body and posterior horn of the ventricle. In cleared specimens the glomus has a cystic appearance, and hyaline concentric bodies were found to be constantly present in large numbers in the adult plexuses. They were absent in all the foetal plexuses examined and in one specimen from a 6½-year-old boy. No structure resembling the glomus is to be seen in the choroid plexus of the rabbit, although the vascular relationships suggest that the most nearly corresponding region is that near the interventricular foramen where the free border bends medially at almost a right angle. At this place, in the rabbit, the anterior and posterior choroidal arteries meet and the main choroidal vein begins.

In the rabbit (and also in the rat) there is a curious long tongue-like process for which the term *lingula* has been suggested. A similar process is not found in the adult human plexuses, but in some foetal specimens an indication of such a process is to be found posterior to the glomus. It may be that the lingula is buried in the human choroid plexus by the greater folding and growth of this part of the plexus. It is possible that both the glomus and the lingula play a definite part in the control of the production of the cerebrospinal fluid, perhaps as mechanisms sensitive to the pressure of the fluid in the ventricles, but until further investigations have been made it is not profitable to speculate as to how they might perform such a function.

An interesting point which emerges from the examination of the choroid plexus of the rabbit is the junction of the main continuation of the anterior choroidal artery with the posterior choroidal artery at the anterior angle. This is clearly seen in the illustration (Pl. 1, fig. 3). In several specimens the connexion is not to be seen, but the terminations of the two vessels approach within a millimetre of each other. This suggests that in these cases the injection mass advancing simultaneously along both arteries pushed a small quantity of fluid in front of it so that the continuity of the two arteries was not demonstrated. The connexion observed is comparable in degree of magnitude with the connexions between the meningeal vessels illustrated by Pfeifer (1930). Similar connexions were observed in the human choroid plexuses and their significance is discussed later.

In both the rabbit and man, the vessels become increasingly tortuous as the area of villous thickening is reached. A similar condition has been observed in the choroid plexus of the sheep by Hudson & Smith (1952), and an identical appearance has also been noted in the choroid plexus of the goat. It will be observed in the illustration of the choroid plexus of the rabbit that the anterior choroidal artery becomes most tortuous just at its junction with the posterior choroidal artery (Pl. 1, fig. 3). This mechanism may have some importance as a method of reducing pressure, so that there is not too steep a pressure gradient between the blood entering the villous process and the cerebrospinal fluid.

A point which is not stressed in the standard text-books of anatomy is that there are generally four or five separate posterior choroidal arteries coming from the posterior cerebral artery (Beevor, 1907). Even in the rabbit there are generally two or three separate posterior choroidal arteries to be seen.

The venous supply of the plexus in the rabbit is remarkable for the rich network of venules gathering together at the anterior end of the plexus into one large choroidal vein. There is a very scanty network in the posterior part of the plexus with a few small veins accompanying the anterior choroidal artery. A similar picture is seen in the human, and it appears probable that the bulk of the blood enters the plexus through the anterior choroidal artery at the posterior end of the plexus and leaves through the choroidal vein at the anterior end.

The outstanding feature which emerges from an examination of the specimens is the vascular relations of the frond-like villous processes. The villous process is better developed in man than in the rabbit, and it is supplied by an arteriole which is connected to the venous system by both capillary loops and occasional arterio-venous connexions having a diameter of 20–30 μ.

The vascular relations of this villous frond have aroused both interest and speculation. Putnam & Ask-Upmark (1934) have noted the presence of what they have termed 'unusually coarse thin-walled capillaries'. These appear to be identical with the large capillaries commented upon by Findlay (1899), who has queried whether a sinusoidal mechanism is present in the plexus but has concluded that such a mechanism does not exist. In the present investigation, the capillary loops observed while showing irregularities appeared to be well within the normal range of capillary size. Putnam & Ask-Upmark (1934) have also remarked that between the large arteries and veins and the coarse capillaries they have described, there are few vessels of intermediate size. The question arises whether these authors, who examined the exposed choroid plexus in the living cat, were able to observe the true capillary bed. It is possible that they may have seen the blood passing from the arterioles to the venules through the arteriovenous connexions, whilst the true capillary bed was closed down. This would readily account for the 'unusually little difference in colour between arterial and venous blood as seen under the microscope' which they have noted in their examination of the plexus.

The main object of this investigation was to ascertain whether the arrangement of the vessels in the choroid plexus suggested any point at which nervous control of the plexus might be effected, and thus the production of the cerebrospinal fluid regulated. All the evidence points to such control, if present, being exercised at the periphery of the plexus. It appears unlikely that there is any point at which the anterior choroidal artery or its choroidal branch is controlled, so that the blood flow distal to that point is restricted. The least anatomically variable and clinically most important part of the anterior choroidal artery is the distal part, after the choroidal branch is given off, which supplies the lateral geniculate body (Abbie, 1933). There is unlikely to be an arrangement whereby the blood supply to the geniculate body is determined by the requirements of the choroid plexus. Secondly, as has been noted above, the choroidal branch divides immediately before entering the plexus into five or six branches, each almost as large as the parent stem. This reduces the length of the anterior choroidal artery where its circulation may be effectively controlled by a local nervous mechanism to a bare minimum. When the free communications between the anterior and posterior choroidal arteries and the multiplicity of the choroidal branches of the posterior cerebral artery are also considered, it seems impossible that the cerebrospinal fluid production is effectively altered by any nervous mechanism acting on the main stem of the anterior choroidal artery. In our opinion the anatomical evidence tends to show that if a nervous control is present it must be exercised at the periphery.

SUMMARY

1. The vascular patterns of the choroid plexus of the lateral ventricle have been studied in the rabbit and man by the use of injection masses and the examination of whole cleared specimens.

2. The choroidal villi are not uniformly distributed over the surface of the plexus. Scattered single villi are present over the greater part of both surfaces, but the main aggregations are found, in the rabbit, at the anterior end of the plexus, and, in man, along a fringe close to the attached border and extending the whole length of the plexus.

3. The choroid plexus of the lateral ventricle is supplied by a single branch from the anterior choroidal artery, itself a branch of the internal carotid artery, and by several posterior choroidal arteries arising independently from the posterior cerebral artery. These arteries communicate within the plexus and in the tela choroidea.

4. There is a rich venous plexus whose radicles unite in the region of the glomus to form a single large vein which leaves the plexus at the interventricular foramen to join the internal cerebral vein.

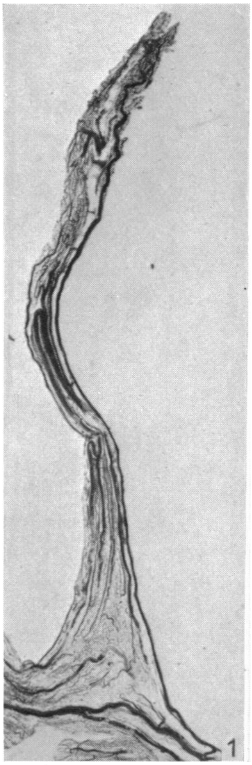
5. Within the choroid plexus in man the branches of the choroidal arteries are of two main varieties—(1) fine parallel vessels with few side branches which run along the free border of the plexus to end in the region of the glomus, and (2) branches which run along the base of the villous fringes close to the attached border of the plexus, giving off short stems to supply the fronds.

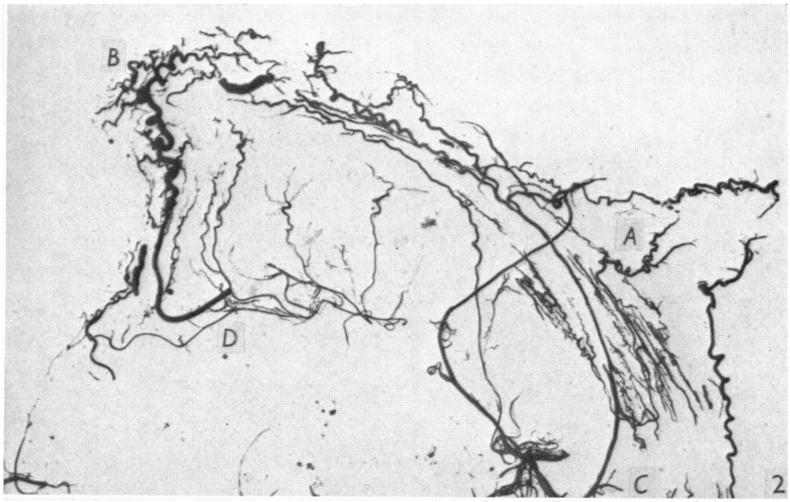
6. Each frond is supplied by an arteriole which breaks up into capillary loops which are connected within the villous process to the terminal venule. Arteriovenous connexions having a diameter of 20–30 μ also occur within the fronds.

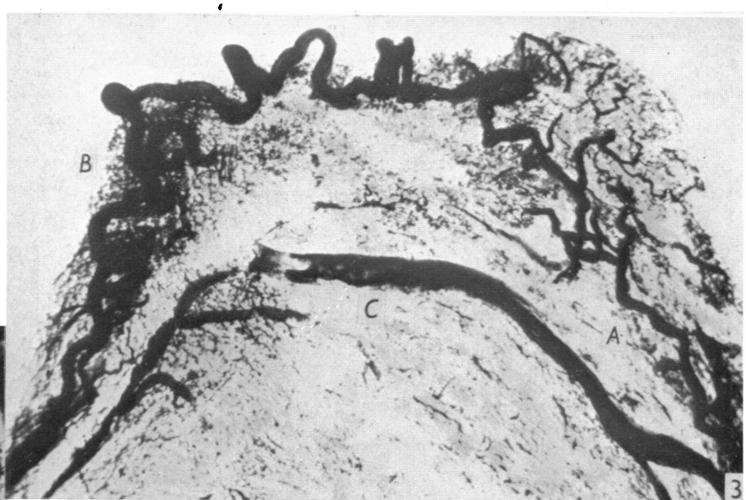
7. A glomus is constantly present in all the human plexuses examined, but cannot be identified in the choroid plexus of the rabbit. In the rabbit, a curious tongue-like process, the lingula, projects from the free border of the plexus behind the 'glomus' region.

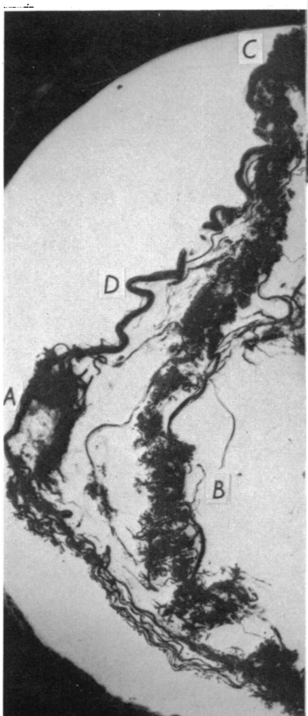
8. The significance of these findings in the interpretation of possible mechanisms for the control of the production of the cerebrospinal fluid is discussed.

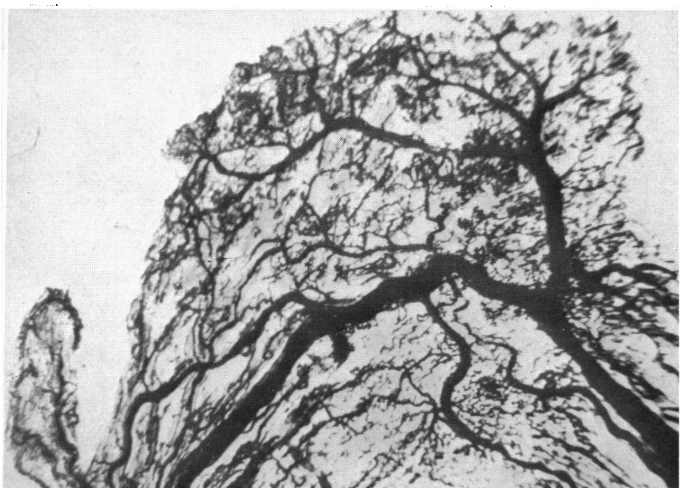
We are greatly indebted to Prof. J. D. Boyd for his constant interest, advice and encouragement. Our thanks are also due to Mr J. A. Fairfax Fozzard for the photographic work.



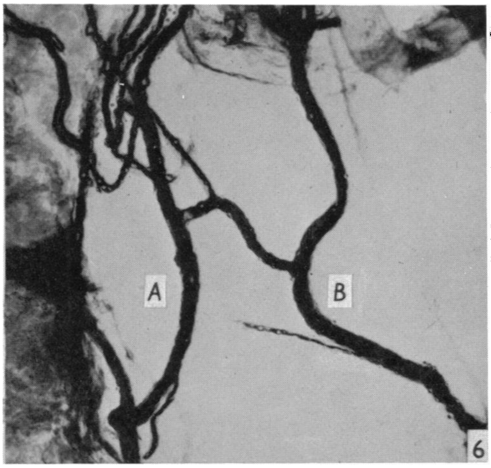








MILLEN AND WOOLLAM—VASCULAR PATTERNS IN THE CHOROID PLEXUS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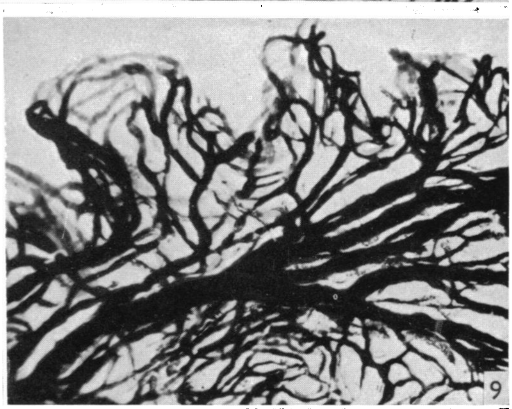
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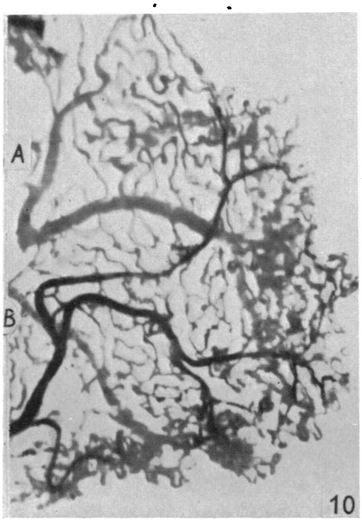
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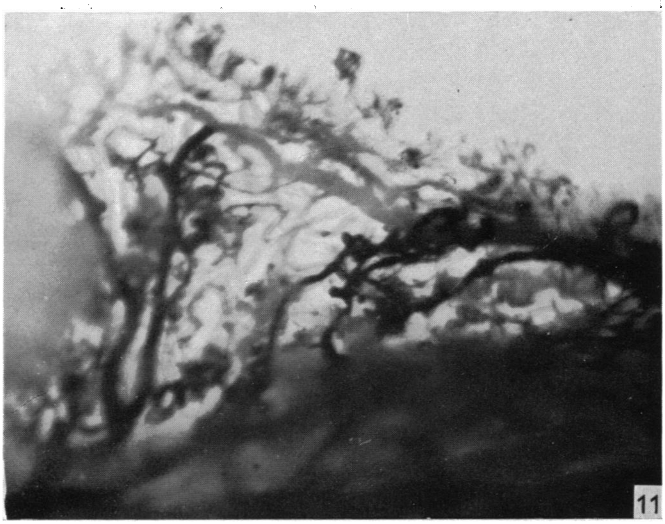
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EXPLANATION OF PLATES

The photographs are all of whole cleared preparations. Figs. 1–4 are of the choroid plexus of the rabbit, fig. 5–11 are of human choroid plexuses.

PLATE 1

Fig. 1. Left choroid plexus showing lingula. Injected with red and blue dispersions. × 8.

Fig. 2. Arteries of right choroid plexus. Injected with blue dispersion. × 7. *A*, base of lingula; *B*, anterior angle; *C*, branches of anterior choroidal artery; *D*, posterior choroidal artery.

Fig. 3. Right choroid plexus showing the junction of the anterior and posterior choroidal arteries at the anterior angle. Injected with red and blue dispersions. × 22·5. *A*, anterior choroidal artery; *B*, posterior choroidal artery; *C*, choroidal vein.

Fig. 4. Left choroid plexus showing the choroidal vein and some of its tributaries. Injected with red dispersion. × 22·5.

Fig. 5. Left choroid plexus showing villous fringe and glomus. Injected with blue dispersion. × 1·3. *A*, glomus; *B*, villous fringe, *C*, site of interventricular foramen; *D*, main choroidal vein.

PLATE 2

Fig. 6. Left choroid plexus showing communication between the anterior and posterior choroidal arteries in the tela choroidea. Injected with blue dispersion. × 5. *A*, anterior choroidal artery; *B*, posterior choroidal artery. × 5.

Fig. 7. Right choroid plexus showing the two main types of branches of the anterior choroidal artery. Injected with blue dispersion. × 4. *A*, branch of anterior choroidal artery in base of villous fringe; *B*, parallel arteries in free border; *C*, glomus.

Fig. 8. A section of the same plexus as fig. 7 at a higher magnification showing short side branches of choroidal arteries supplying fronds of the villous fringe. Injected with blue dispersion. × 8.

Fig. 9. Right choroid plexus of 6 months' foetus showing venous pattern. Injected with Indian ink and plasma. × 22·5.

Fig. 10. A villous frond showing the capillary network. Injected with red and blue dispersions. × 30. *A*, venule; *B*, arteriole.

Fig. 11. Villous frond showing an arteriovenous connexion. Injected with red and blue dispersions. × 52.