VASCULARIZATION OF THE OPTIC PATHWAY*

III. STUDY OF INTRA-ORBITAL AND INTRACRANIAL OPTIC NERVE BY SERIAL SECTIONS

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IN previous papers we have pointed out some new facts concerning the vascularization of the optic nerve (François and Neetens, 1954; François and others, 1955a, b). In the present paper a new technique is introduced to confirm and amplify our previous findings.

Technique

The tissues to be studied were preferably taken from patients who had died of congestive heart failure, the blood being pressed towards the regions under study. All the surrounding large vessels were ligated and afterwards the optic nerve was dissected over its whole length from the orbital, intracanalicular, and intracranial contents.

The technique employed was that of Pickworth (1934), as modified by Fazio and Farina (1940). The tissue, after irrigation, is wrapped in hydrophilic gauze and immersed from 3 to 5 days in a fixative of saturated sodium chloride (15 ml.), saturated glucose (15 ml.), and formol 10 per cent. (5 ml.). Frozen sections are then cut of approximately 50μ thickness and treated as follows:

A sodium nitro-prussate solution, 0.5 per cent. (20 parts) is mixed with 25 parts of a 0.5 per cent. benzidine solution; the latter, containing 2 per cent. acetic acid, gives a cloudy precipitate. After filtration, 80 parts aq. dist. are added to the filtrate. The sections are immersed in this preparation for 20 to 30 minutes at 37°C . After irrigation by tap-water they are immersed for a further 10 minutes at 37°C . in oxygen water (12 vol.), rinsed in tap-water, and treated with absolute alcohol (to dehydration). Thereafter they are ready to be examined microscopically. In order to see the small capillaries it is advisable to cover the preparation with Canada balsam.

Results

In addition to confirming our previous results, the following facts emerged from our studies of the arteriolar and capillary vascular pattern.

I. Arteriolar Vascular Pattern

(1) *Central Artery of the Optic Nerve.*—The existence of this artery can be considered as a well-established fact. After piercing the optic nerve sheaths it runs towards the centre of the proper nerve tissue, where it divides into an anterior

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and a posterior branch, both running longitudinally (Figs 1 and 2). It is accompanied by the central retinal artery and vein (perhaps by other venous branches) as it runs towards the lamina cribrosa, where it ravel out into a capillary system; the posterior branch divides similarly; and from the entire lengths of both, branches are given off which curve widely between the bundles in the interfascicular spaces.

FIG. 1.—Optic nerve, middle part, horizontal. $\times 6$. After preparing the central artery of the optic nerve up to its point of penetration into the nerve, horizontal sections were cut.

- A. Central retinal artery.
- B. Central artery of the optic nerve dividing into an anterior branch (B_1) and a posterior branch (B_2).

FIG. 2.—Optic nerve, middle part, horizontal. $\times 6$. This section immediately follows that shown in Fig. 1.

- A. Central retinal artery.
- B. Division of central optic nerve artery, with posterior branch (B_2).
- C. Venous channel.

(2) *Central Retinal Artery*.—At the level of the lamina cribrosa or just behind it, the central retinal artery may give off important branches which immediately curve anteriorly at an angle of nearly 90° , lying in the longitudinal axis of the optic nerve and running towards the retina (Fig. 3, opposite). Initially non-nutritive arterioles, these branches never supply the optic nerve itself, being destined for the retina.

(3) *Central Vessels in the Posterior Part*.—These have already been discussed (François and others, 1955a).

(4) *Intracranial Part*.—The precapillary vascular pattern changes markedly in this region. Although fine independent arteriolar branches are rarely encountered in the intra-orbital part of the optic nerve, they are relatively frequently observed in the intracranial part: most of them, after penetrating the nerve from the periphery, run for a short distance transversely and then in the longitudinal axis, when they divide into branches. There are thus no large central vessels, but an

FIG. 3.—Optic nerve, anterior part, horizontal. $\times 6$. This fortunate section shows the central retinal artery (A) over a very long distance at the level of the lamina cribrosa and just behind it; only one large branch (B), with origin at C, curving anteriorly towards the papilla is found. No other collateral is visible.

increasing number of arterioles which ramify without an appreciable diminution in calibre.

Most of these penetrating arterioles enter the temporal aspect of the optic nerve (internal carotid artery), and some enter the superior aspect (anterior cerebral artery), but here these arterioles give off only a very small number of feeding capillaries.

II. Capillary Vascular Pattern

(1) *Intra-Orbital Region in the Middle Third of the Nerve.*—Here the typical configuration of the capillary pattern is again found. Two formations are apparent:

First, transverse vascular units of pentagonal shape, as a complete or apparently incomplete ring, encircle a single nerve bundle, which is thus embraced over its whole length at approximately regular intervals (Fig. 4).

FIG. 4.—Optic nerve, middle part, transverse. $\times 6$.

- A. Transverse vascular system (pentagon).
- B. Black spots indicate sections of longitudinal capillary system.

Secondly, longitudinal capillary units (L.C.U.) run antero-posteriorly and give rise to variegated vascular patterns so that rectangles, squares, or irregular circles may be seen (Fig. 5, overleaf). These vessels scrupulously respect the conducting tissue of the nerve bundle.

FIG. 5.—Optic nerve, middle part, horizontal. $\times 6$. Regular pattern of longitudinal capillary system (A), the collaterals of which give rise to rectangles, and irregular circles (B).

(2) *Lamina Cribrosa and Posterior Intra-Orbital Part.*—So far our previous findings were confirmed, apart from the fact that longitudinal capillaries run towards the retina around the papilla, where, after a radial course, they anastomose with the true retinal capillaries. A continuity thus exists between the capillaries of the optic nerve and those of the retina (Fig. 6).

FIG. 6.—Optic nerve, papilla, and lamina cribrosa, horizontal. $\times 6$. Longitudinal capillaries coming from optic nerve (A) are continued towards retina (B) where they anastomose with the retinal capillaries.

(3) *Intracranial Part of the Nerve.*—Several longitudinal capillaries may be present in a single interfascicular space, but the transverse vascular units do not give off transverse branches at regular intervals in approximately the same frontal plane; instead, collaterals run out for some distance, curving over more than one bundle of fibres. The rectangular pattern seen in the intra-orbital part of the nerve on horizontal section is thus progressively lost, the change beginning at the posterior part of the intra-orbital part of the nerve and extending to the intracranial part. Here the capillary pattern undergoes two marked changes (Fig. 7):

- (a) the course of the capillaries is generally straight;
- (b) the branching is quite irregular, showing, for example, angular divisions like fishtails or forks.

FIG. 7.—Optic nerve, intracranial part, horizontal. $\times 6$. The vessels have a generally straight course, with a complicated pattern of fishtails, forks, and angular subdivisions (A). Note how capillaries curve back upon themselves in hairpin bends (B).

In transverse preparations only the sections of vessels of varying sizes are seen which appear as points; the units encircling the bundles seem to disappear because they are drawn out in an antero-posterior direction. In this region also the capillaries are of reduced calibre. As the chiasma is approached the curvatures become less angular and rounded.

A curious appearance is seen particularly on the temporal side: the longitudinal capillaries arriving from the intra-orbital part of the optic nerve tend to curve back upon themselves in hairpin bends (Fig. 8). Most of the other capillaries from the temporal side make a wide curve towards the nasal side. From the top or the sides of these hairpin curves, anastomotic branches may run either towards the chiasma or towards the nasal side of the nerve; such branches are scarce in the temporal aspect of the nerve. The vascularization is thus denser on the nasal side of the nerve than on the temporal side.

FIG. 8.—Optic nerve, intracranial part, horizontal. $\times 6$. Note hairpin curves (A) on temporal side, scarcity of capillaries, and presence of large vessels with no nutritive function (B).

Comparative Anatomy

With the same technique we also studied the optic nerve of the ox and the pig. In the centre of the optic nerve of the ox no artery was found comparable to the central retinal artery in man. In the periphery of the nerve, embedded in mesodermal tissue at the level of the concavity of the kidney-shaped nerve (lamina cribrosa), a large artery penetrates close to the globe and enters the eye where it rapidly divides into end-branches to supply the retina. It seems probable that the arterioles in the optic nerve of the ox correspond with the central artery of the optic nerve of man, and the greater peripheral artery corresponds with the central retinal artery. In addition, ciliary vessels invade the optic nerve from the periphery, entering at the concavity filled with mesodermal tissue and also on the opposite side. This increased vascularity is normally found in the region of the papilla. In these animals there is also a continuity between the capillaries of the nerve and the retina.

In the pig, large arterioles are more frequent in the optic nerve. The vascular supply to the optic nerve comes from the periphery from large arterioles forming a peripheral and axial system, and again the central retinal artery is destined for the retina only. The longitudinal capillary elements predominate, but, instead of giving off regularly occurring transverse branches to encircle the nerve bundles, they usually intermingle between the bundles without interruption. They also give off collaterals running antero-posteriorly, curving around different bundles over a long distance. Such an arrangement resembles the vascular pattern in the posterior part of the intra-orbital portion of the human optic nerve, but the rectangular and pentagonal shapes are absent; these shapes sometimes occur by chance, as the intermingling of the capillaries may occur almost at right angles in the anterior part of the nerve.

In the pig, it is remarkable that the capillaries may penetrate towards the centre of the bundles themselves, where they again take up a longitudinal course (Fig. 9).

FIG. 9.—Optic nerve of pig, transverse. $\times 6$. The pattern should be compared with that of the human optic nerve (posterior part). Note presence of vessels in centre of bundles (X).

Discussion

Our transverse sections each contain a system of transverse pentagons: Since the former are $50\ \mu$ thick, it can be said that a transverse vascular unit

occurs at fairly regular intervals of 50μ ; this only applies to the middle portion of the intra-orbital part of the optic nerve.

Throughout the optic nerve as far as the chiasm there is an uninterrupted network of capillaries, in which the peripheral and axial systems anastomose intimately. It is legitimate to speak of a terminal blood supply when the anastomosis between systems is confined to capillaries; but since precapillaries anastomose with the capillaries in the intracranial part of the optic nerve, a terminal supply in the true sense does not exist.

We did not find corpora arenacea or amylacea.

In the intracranial part the association between myelo- and angio-architecture seems to break down. It is important to note that arterioles derived from the short posterior ciliary arteries, together with vascular channels from the pial plexus, forming the circle of Zinn-Haller, ramify in the optic nerve and send capillary prolongations into the papilla and retina; this constitutes an anastomotic circulation between the vessels of the uvea, optic nerve, and retina.

Several authors have conclusively shown that collateral branches from the central retinal artery may exist; but after the injection of thorotrast into the central retinal artery alone, provided eventual return *via* the capillary system of the retina through the central retinal vein has been blocked (injection of concentrated Duco), no trace can be seen in the optic nerve itself.

Bignell (1952), injecting Indian ink into the central retinal artery without blocking the vein, obtained a coloration of some parts of the optic nerve: the dye, having traversed the capillary meshwork of the retina, may return by the vein; this vessel receives many branches which are filled up and colour the optic nerve. In spite of this, we accept the suggestion that collaterals of the central retinal artery may exist in the optic nerve, but they all run directly to the retina; there are larger vessels which may be regarded as precocious retinal branches, and smaller vessels occurring at the level of the papilla.

The vascular arrangements described in this paper at the level of the intracranial temporal part of the optic nerve, where a rarefaction of the capillaries occurs and where the penetrating larger arterioles can yet have no nutritive function, may have some importance in vascular diseases, intracranial tumours, and infective processes. It may be concerned with the aetiology of some defects of the visual field arising in the optic nerve. We are indeed dealing with a region where the vascular supply seems to get easily out of order. While micro-angiography demonstrates the entire vascular structure in broad survey, with the method of Pickworth we are able to delineate details which show clearly the differences in vascular supply in the several parts of the optic nerve.

The whole optic nerve is supplied by pial vessels (peripheral system), but the anterior, middle, and posterior regions of the intra-orbital part are also supplied by an axial system (central optic nerve artery). At the level of the lamina cribrosa, the axial system diminishes in importance, while, at

the same time, branches of the short posterior ciliary arteries appear. The same change occurs in the intracranial part of the nerve where the axial system completely disappears and numerous peripheral vessels penetrate the nerve to give it a vascular supply. The central retinal artery takes no share in the vascularization of the optic nerve; but vessels from the optic nerve supply a vasa vasorum to the central retinal artery.

Summary

The staining method of Pickworth, modified by Fazio (sodium nitroprussate, benzidine, and oxygen water) and the study of serial sections of the optic nerve give the following results:

(1) At and behind the level of the lamina cribrosa, collateral branches of the central retinal artery occur, but they are destined only for the retina.

(2) In the optic nerve itself there is a complete absence of nutritive collaterals of the central retinal artery.

(3) Capillaries may come into close contact with the central artery and vein, but have no direct communication with it; they occupy the role of vasa vasorum.

(4) The existence of the transverse and longitudinal capillary systems is confirmed and their intimate structure is described in detail.

(5) A central artery of the optic nerve undoubtedly exists.

(6) Arterial branches run antero-posteriorly and venous branches run radially.

(7) In the intracranial part of the optic nerve the axial system disappears and is replaced by several small independent arterioles.

(8) The continuation of the capillaries of the optic nerve to meet the retinal circulation is proved; in this way cilio-retinal capillary anastomoses are effected.

(9) A special type of capillary pattern is described in the intracranial part of the optic nerve; here the capillary system is irregular, showing hair-pin-like bends on the temporal aspect of the nerve from which the vessels run mostly to the chiasma.

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