CERTAIN ASPECTS OF THE VASCULAR ANATOMY OF THE OCULAR CIRCULATION AND THEIR SIGNIFICANCE IN DISEASE.

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Thesis for Degree of Ch.M.

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GENERAL INTRODUCTION.

A study of the vascular pattern of non-living tissues may be undertaken in two fundamentally different ways.

First, a composite picture of the distribution of the blood vessels may be built up by examining histologically a series of sections cut at regular intervals throughout the tissue. The examination may be facilitated by a preliminary injection of the vessels with some dye substance such as indian ink. It is only necessary to cut fairly thick sections, but even so this method is extremely laborious and time-consuming and it is difficult in a densely vascular tissue to reconstruct the vascular pattern with accuracy.

Secondly, the vessels may be observed within the tissue after preliminary injection with some dye substance. Many such substances have been tried; lead acetate and potassium bichromate which form an intravascular precipitate of lead chromate - it is interesting to note that this was the method adopted by Bowman (1842) in his classical study of the renal circulation; gelatin dyes; starch pastes incorporating some colouring material like red lead; celloidin; metal alloys; indian ink; melted tallow with vermillion; heavy oil paint; shellac coloured with prussian blue; poly-allyl-ester resin with styrene as a monomeric diluent with benzoyl peroxide as a polymerization catalyst and with sudan red as a colouring agent; vinolyte; etc.

All these substances, however, due to defects in their composition, impose certain restrictions on the final exposure of the vessels in the region to be studied. Some substances, like gelatin, are too fragile so that during dissection of the tissues, or even during a simple prising apart of the tissues, the continuity of the injected vessels is readily lost. Other substances, like vinolyte, form a rigidly hard precipitate within the vessels which, although not susceptible to the action of digestive ferments so that a complete cast of the injected vessels may be obtained free from supporting tissues, is unsuitable for dissection.

It is, of course, not always necessary during a study of the circulation to be able to dissect the injected vessels. In some thin tissues the vessels may be viewed directly, and in thicker tissues it is possible to produce a transparent effect by suitable methods of dehydration and clearing, but in densely vascular tissues it is necessary to dissect the preparation if the finer details of individual vessels are to be revealed clearly.

In an attempt to overcome the disadvantages of previous injection substances Batson (1939) used a synthetic rubber preparation, and his work was followed by that of Lieb (1940) who used Neoprene latex, a similar synthetic material, in a study of the renal circulation.

/ Many other

Many other workers have elaborated on the use of Neoprene in studies of the renal circulation, for example, Trueta and others (1947), Duff and More (1944) and Shonyo and Mann (1944) ; and Ashton (1951 and 1952) adapted the technique so as to be suitable for studies of the ocular circulation. This is an admirable method for the study of densely vascular tissues because it permits detailed dissection of the injected vessels owing to the cohesive and elastic properties of Neoprene.

A large part of the work to be described in this thesis is concerned with the use of Neoprene, and to a great extent it is based on the techniques of Ashton under whose direction this work was carried out at the Institute of Ophthalmology.

AIM AND SCOPE OF PRESENT STUDY.

This study of the ocular circulation is limited to two particular regions; the choroidal vessels and the vessels in and around the optic nerve head. In the main it represents a re-assessment of the vascular anatomy of these regions, and particularly of the more controversial aspects of the circulation, in the light of more recent methods of examination, but at the same time the findings will be reviewed in relation to certain hypotheses.

The vascular anatomy of the choroid has been examined in relation to two hypotheses. First, in relation to the hypothesis that the choroidal arteries act as functional end-arteries and that there are specialised vascular districts within the choroid; an hypothesis which is important in a consideration of the selective localisation of certain ocular diseases, and in a consideration of the effect on the choroid of surgical procedures which involve resection of the posterior ciliary arteries or damage to a localised part of the choroid, either directly by incision or indirectly by diathermy. Secondly, in relation to the hypothesis that there are choroidal arterio-venous anastomoses which have an importance in the pathogenesis of chronic simple glaucoma.

The vascular anatomy of the optic nerve head has been examined in relation to the hypothesis that there are anastomoses in that region between the uveal and retinal arterial and venous circulations, and that these anastomoses have an important bearing on the pathological events which follow occlusion of the central retinal artery or vein.

These two aspects of the ocular circulation will be considered separately.

NOTE:

Practically all the observations which are recorded in this thesis were made on the human eye. In a short appendix to Section I details are given of experimental work on the eye of the rabbit but this is recorded as a separate entity. It may be assumed, therefore, that throughout this thesis all observations are related to the human eye unless stated otherwise.

SECTION I

VASCULAR ANATOMY OF CHOROID IN RELATION TO SELECTIVE LOCALISATION OF OCULAR DISEASE.

Introduction.

The choroidal coat of the eye consists of a dense continuous network of vessels and yet it is a striking feature of choroidal disease that the lesions often remain remarkably circumscribed. It is for this reason that many clinical, pathological and experimental facts have been brought forward which would appear to establish two important concepts regarding the choroidal circulation. First, that the choroid is divided into many discrete radially arranged sectors each of which extends from the peri-papillary region to the peripheral limit of the choroid and that the choroidal arteries have, therefore, the characteristics of end- arteries. Secondly, that within the choroid there are several specialised and distinct vascular zones which include the equatorial, peripheral, peripapillary and submacular regions. The observations which have led to these hypotheses will be considered in more detail.

Previous Theories in Literature.

Theory of division of choroid into sectors.

The experimental investigations of Wagenmann (1890) on the rabbit, gave rise to the belief that the short posterior ciliary arteries are functional end-arteries and that the vessels within the choroid have a strictly segmental distribution. Wagenmann found that when he sectioned a few short posterior ciliary arteries behind the globe in the living animal a localised area of choroidal obliteration occurred which corresponded in situation to the field of distribution of the affected vessels and which was sharply demarcated from the surrounding healthy choroid. There was a tendency for some of the vessels in the affected zone to re-open within a few days, but a sector of permanent vascular obliteration remained in most of the rabbits. The detailed study of the choroidal circulation by Leber (1903) contributed to this concept by the emphasis which was laid on the absence of anastomoses between the various branches of the short posterior ciliary arteries except in the immediate vicinity of the optic disc and in the extreme periphery of the choroid.

Certain clinical observations have been advanced to substantiate Wagenmann's findings of a segmental pattern of the choroidal vascular supply. A wedge-shaped area of choroidal infarction was described by Coats (1907) in a case of posterior scleritis, due, he presumed, to occlusion of a short posterior ciliary artery within the inflammatory tissue of the sclera. If Coats' hypothesis is correct it must follow that there are an insufficient number of anastomotic twigs from the unaffected choroidal vessels to restore the circulation in the sector dependent on the occluded vessel.

Hepburn (1912) also believed that blockage of a short posterior ciliary artery might produce a wedge-shaped defect in the choroid based on his interpretation of the changes in the visual fields which occurred in certain cases of localised choroiditis. In these cases a sector-shaped scotoma reaching to the periphery of the visual field extended from the scotoma which corresponded in situation to the patch of choroiditis, and Hepburn considered that this was evidence of a circulatory failure within the whole choroidal sector on the peripheral side of the inflammatory focus due to the involvement of a short posterior ciliary artery in the patch of choroiditis.

There is evidence that the anterior part of the choroidal circulation may also have a segmental distribution. After optico-ciliary section there was atrophy of extensive areas of the choroid in the posterior part of the globe (Berlin, 1871), but it was noted by Birch-Hirschfeld (1910) that when, in addition to the /optico-ciliary optico-ciliary section, one of the rectus muscles was tenotomised thus cutting off part of the anterior ciliary arterial circulation, an area of atrophy occurred in the anterior part of the choroid corresponding in situation to the region supplied by the recurrent branches of the affected anterior ciliary arteries.

Theory of division of choroid into zones.

(1) Equatorial choroid.

The equatorial part of the choroid was considered by Leber (1903) to be a peculiar region of the choroid in that it represents the meeting place of the terminal twigs of the short posterior ciliary arteries running forwards, and of the recurrent choroidal arteries from the anterior part of the uveal tract running backwards. Leber concluded that, although the two arterial systems are bridged by an intervening capillary junction, the anastomosis is insufficiently well marked to enable the posterior part of the choroidal circulation to maintain the anterior part in the absence of a functioning recurrent circulation. In this way the equator marks the division between two fairly separate circulations.

Leber's view has been maintained by other observers. Gonin (1903) regarded the equator as a zone of defective vascularisation because it marks the dividing line between two arterial systems and, therefore, is insufficiently served by either system. Hepburn (1910) doubted whether the anastomosis at the equator is sufficiently well developed to have any significance from a visual point of view. It is difficult to know exactly what Hepburn meant by this statement but it is likely that he based it on his belief that the equatorial region is placed so far forward that it corresponds in situation to the extreme periphery of the retina, a part which does not have any great visual significance. The rather unusual views of Hepburn will be discussed in greater detail later. More recently, Marín-Amat (1952) stated that the choroid is divided at the equator into a central and peripheral part each of which maintains its own independence.

Certain clinical observations have been advanced to substantiate these anatomical viewpoints. For example, Coats (1913 d) was impressed by the independent ways in which the anterior and posterior choroidal circulations are influenced by pathological processes, and he regarded this as a sign of their anatomical isolation from one another. Gonin (1903) , Nettleship (1903) and Hepburn (1910) considered that the occurrence of a ring scotoma in the visual field in the early stages of retinitis pigmentosa indicates a preferential disturbance of the equatorial part of the choroid owing to its greater liability to disease on account of its defective vascularisation. This theory, of course, assumes that the retinal degeneration in retinitis pigmentosa is due to some defect in the underlying choroidal circulation. Still further evidence was

/produced by

produced by Nettleship (1903) in his interpretation of the ring scotoma which may be found in the visual field in certain cases of syphilitic retinitis. He considered that the scotoma indicates a preferential affection of the terminal twigs of the choroidal vessels at the equator by the endarteritic process.

(2) Peripheral choroid.

The choroid in the extreme periphery of the fundus has been considered to be a specialised area; indeed, this conclusion is the logical outcome of an acceptance of the view that the anterior vascular supply of the choroid is to a large extent isolated from the rest of the choroid by the imperfect anastomosis between the posterior and recurrent vascular systems at the equator. Evidence suggesting a peculiarity in the structure of this region was advanced by Hancock (1908) who pointed out that the function of the extreme periphery of the retina, particularly on the nasal side where the retina extends farther forwards than on the temporal side, may be retained in certain cases of total occlusion of the central retinal artery. Hancock regarded this as an indication of a specialisation of the chorio-capillaris in the extreme periphery of the choroid so that it is capable of nourishing the whole thickness of the retina, in contrast to the chorio-capillaris elsewhere which can maintain the viability of the outer retinal layers only. The occasional ability of the peripheral retina to retain its function despite blockage of the central retinal artery was previously demonstrated by Coats (1905) who found retention of a small part of the extreme temporal periphery of the visual field in such cases. Histological proof that this part of the retina could survive occlusion of the retinal arterial circulation was given by Komoto (1915).

A further fact has come to light which may be interpreted as indicating a peculiarity of function of the peripheral part of the choroid. It was shown by Duke-Elder (1948) that transudate may filter from the anterior part of the choroid through the peripheral retina where it joins with the rest of the aqueous humour. This is in contrast to the choroid elsewhere which does not contribute to aqueous humour production.

(3) Peripapillary choroid.

The choroid immediately surrounding the optic disc has been considered by Duke-Elder (1940) to be a specialised zone of the choroid. A continuous arterial network composed of arterioles which supply an area within one disc diameter of the optic disc and which are quite distinct from the other vessels in the rest of the posterior part of the choroid was described by Marín-Amat (1952), and also by Bartolozzi (1952) who found that the fine arteries are derived from two sources; from the short posterior ciliary arteries, and from the intra-scleral arterial circle of Zinn.

/Bartolozzi

Bartolozzi suggested that certain forms of contusion by suddenly stretching and twisting the globe may rupture the fine vessels in this discrete arterial network with the formation of a localised zone of peripapillary atrophy. Furthermore, it was shown by Klien (1950) that sclerosis of the vessels in the circle of Zinn produced an atrophy of the choroid immediately surrounding the optic disc.

(4) Submacular choroid.

The choroid underlying the macula has been regarded as different from the rest of the choroid owing to its greater vascularity, and this increased blood supply has been attributed to two separate characteristics of the circulation. In the first place, the capillaries of the submacular part of the choroid have been considered to be more densely packed than the capillaries in any other part of the choroid (Sattler, 1876; Leber, 1903; Nettleship, 1903; Salzmann, 1912; and Lauber, 1931) . Stress was laid by Leber (1903) on the great width of the capillaries in this area as compared with the rest of the choriocapillaris, and Lauber (1931) pointed out that as a result of this increase in diameter of the capillaries there is a marked reduction in the inter-capillary meshwork so that when the submacular capillaries are distended with blood they become a solid vascular mass.

In the second place, the submacular part of the choroid has been considered to be different from the rest of the choroid owing to its greater thickness (Wolfrum, 1908; Salzmann, 1912; Lauber, 1936; Mörike, 1949; and Hartridge, 1950). For example, Wolfrum (1908) showed that the submacular choroid was 0.30 - 0.35 mm. in thickness whereas the choroid away from this region shaded off to a thickness of 0.25 mm. in the peripapillary region and to a thickness of 0.15 mm. in the periphery. Lauber (1936) gave values of 0.35 - 0.55 mm. for the submacular choroid decreasing to 0.10 mm. in the periphery, and Mörike (1949) for the same area gave measurements of 0.26 mm. and 0.02 - 0.05 mm. respectively.

Salzmann (1912) put forward the view that the greater thickness of the submacular choroid is due solely to the fact that the short posterior ciliary arteries are larger and more numerous in that region, and Cordes (1944) found this to be an acceptable hypothesis because it explains why the posterior pole of the eye should be the site of election for neoplastic metastases within the choroid. On the other hand, Mörike (1949), although in agreement with Salzmann's finding of an increased aggregation of vessels in the submacular region, considered that it has a biological significance , and is not due merely to the greater number of posterior ciliary arteries which perforate the globe in the

/ neighbourhood

neighbourhood of the posterior pole and so traverse the submacular area on their way to other parts of the choroid.

The hypothesis put forward by Mörike that the greater vascularity of the submacular choroid is the result of a physiological response to the higher metabolic demands of the complex and specialised macula, has re-stated the dictum of Nettleship (1903) that the structural peculiarity of the submacular choroid is the direct effect of a functional stimulus from the macula. Hartridge (1950) has also assumed that the unusual physiological responses of the macula necessitate the postulation of structural peculiarities in the underlying choroid. This view of Mörike's was based on a study of the bifoveal eye of the sea-swallow (sterna). The bird's eye was removed and fixed rapidly after death to minimise, as far as possible, post-mortem alterations in the state of the circulation. It was found that the choroid under each macula was thicker than at any other part of the choroid. (Temporal submacular choroid 0.21 mm; nasal submacular choroid 0.19 mm; remainder of choroid 0.10 - 0.15 mm. except for extreme periphery 0.02 mm.) The interesting feature of these results, however, is the fact that the maculae in the sea-swallow are far away from the site of perforation of the posterior ciliary arteries, and that in the region of these perforating vessels the choroid measured only 0.09 - 0.14 mm.

The concept of a specialised structure of the choroidal vascular bed at the macula is of particular interest in view of the frequency with which certain pathological processes affecting the uveal tract remain confined to the posterior pole of the eye. For example, choroidal haemorrhage may impair the function of the retina in certain senile eyes and in some cases of high myopia where it occurs characteristically in this region. Similarly cystoid degeneration of the retina, which follows a degeneration of the underlying chorio-capillaris, is often limited to the macular region.

It was shown by Ashton (1953) that the basic pathological lesion in a case of central areolar choroidal sclerosis was an atrophy of the chorio-capillaris in the macular and paramacular areas without any sclerosis of the underlying choroidal vessels and without any similar involvement of the chorio-capillaris in other parts of the choroid. Other observers have noted clinically in similar cases an extension of the atrophic process into the peripapillary region (Klien, 1950) and even into other regions of the choroid (Cowan, 1951) but such cases are rare and characteristically the lesion is limited to the posterior pole.

It is interesting to note that this finding by Ashton of a loss of the submacular chorio-capillaris in central areolar choroidal sclerosis confirms the speculation of Nettleship (1884) that the basic cause of the condition lies in the chorio-capillaris, although Nettleship (1903) amplified his hypothesis by attributing the condition of the capillaries to a narrowing of the lumen of a specific short posterior ciliary artery which, in his opinion, supplies the submacular part of the choroid.

All this evidence, apparently pointing to a rigid segmentation of the short posterior ciliary arteries and to a regional characterisation of certain areas of the choroid, forms a particularly attractive thesis in considering the selective localisation of choroidal disease. If correct it fits in admirably with the hypothesis of Nettleship (1903) that a narrowing of the lumen of one or more short posterior ciliary arteries affects the integrity of particular areas of the choroid without affecting the rest of the choroid. Furthermore, if correct it fits in with the doctrine put forward by Hepburn (1910) that the vascular network of the choroid reacts as a series of terminal vascular systems the individual branches of which may be affected separately, and may show varying degrees of liability to disease or obstruction. Thus the extent of a lesion in the choroid depends on the size or on the number of arteries involved in the pathological condition of the circulation.

On the other hand there are many facts of a clinical, pathological or experimental nature which conflict with such a simple hypothesis. For this reason the details of the vascular anatomy of the choroid have been re-assessed and the contradictory facts will be reviewed in relation to the findings of the present investigation.

Present Investigation.

Materials.

1) Eyes.

The vascular pattern of the choroid was examined in 31 human eyes, and, as far as could be ascertained, each eye was free from local ocular disease, or from any gross change of a systemic nature. It is assumed, therefore, that this study as far as can be determined represents the anatomy of the normal choroid.

The eyes together with their associated orbital structures were removed at post-mortem examination through an intra-cranial approach by the following technique :-

A sagittal incision was made in the scalp in the region of the vault of the skull, and, after reflection of the scalp anteriorly and posteriorly, the bony cranium was removed by a coronal incision. The brain was then lifted out of the skull by incising its covering membranes and by severing its neuro-vascular connections with the extra-cranial structures. During this manoeuvre great care was taken to avoid any damage to the optic nerves and internal carotid artery. The optic nerves and chiasma were left intact in their normal position in the base of the skull by cutting through the optic tract, and the internal carotid artery including the origin of the ophthalmic artery was maintained in the base of the skull by severing the artery after its emergence from the cavernous sinus at the origin of its two terminal branches, the anterior and middle cerebral arteries.

The orbital contents were then exposed by removing the anterior clinoid process, the lesser wing of the sphenoid including the roof of the optic canal, and the orbital plate of the frontal bone, and great care was taken during removal of these bony structures to avoid opening the periorbital membrane. The bulbar conjunctiva was incised around the limbus and, after severing the fibrous and muscular bands passing from the orbit to the eyelids, the whole orbital mass including the eyeball, the optic nerve, the ophthalmic artery and the cavernous portion of the internal carotid artery, was removed in one block and placed in a dry sterile container.

2) Instruments and appliances.

Most of the instruments and appliances used in this study were of value only during a particular phase in the preparation or examination of the eyes, and it is more convenient to describe them in the subsequent sections dealing with the technical methods, but certain instruments which were in practically constant use are described now.

a) Microscope. (Fig. 1.)

This was a wide-field stereoscopic microscope with eye-piece lenses of x7 and x15, and objective lenses of x1.25, x5 and x10, giving

/ a magnification range

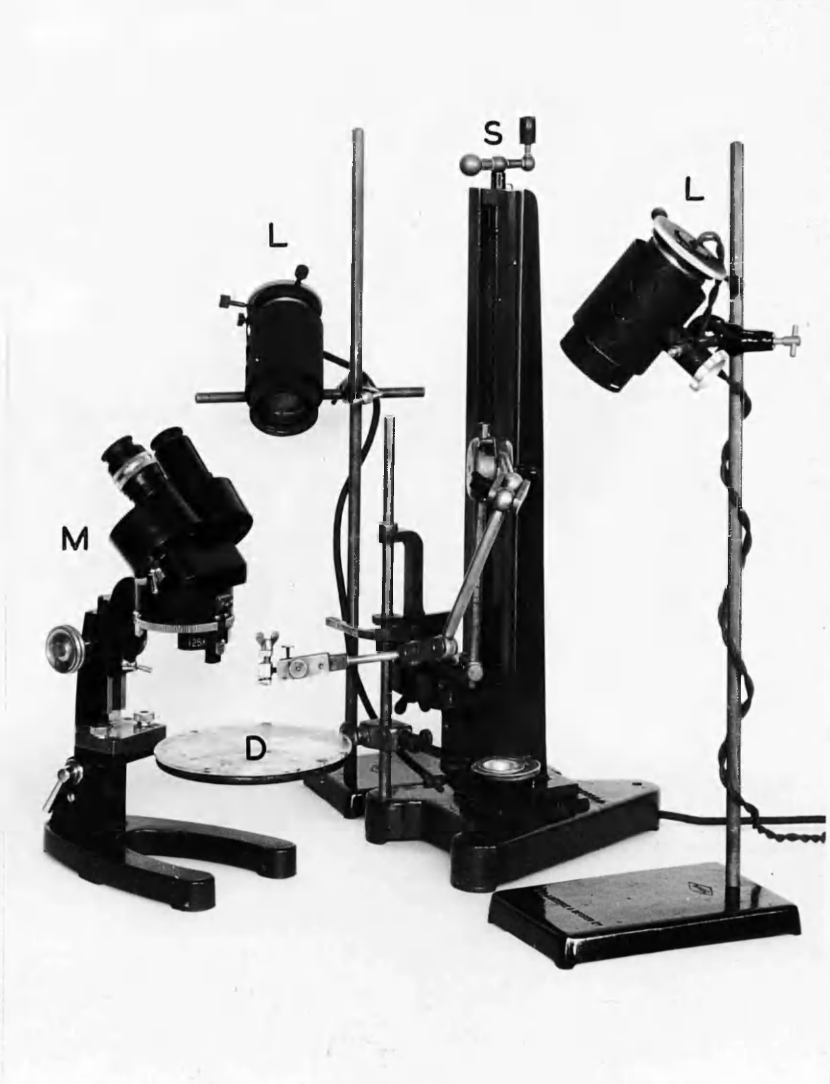


FIG. 1. Wide-field stereoscopic microscope (M) with stand (S) for perspex platform (D). Direct illumination from two high-power low-voltage filament lamps (L) .

a magnification range of x8.75 to x150. The stage of the microscope was removed and replaced by a transparent perspex platform which was mounted independently on a screw stand. In this way it was possible to move the microscope without disturbing the specimen under observation.

b) Illuminating lamps (Fig.1.)

Direct illumination from one or two high-power low-voltage filament lamps.

c) Dissecting instruments (Fig. 2)

The initial stages of the dissections were carried out with ordinary plain forceps and sharp or blunt-pointed scissors, but thereafter the dissections were continued with very fine watchmaker's forceps and fine straight or curved spring scissors, so that it was possible to handle each vessel individually.

Technical methods.

1) Methods of injection.

a) Injection of uveal tract with Neoprene. (20 eyes).

The ophthalmic artery, identified as it left the internal carotid artery to run under the optic nerve, was incised through half its circumference, and a glass cannula was inserted into the artery through the incision and ligatured in position. (Fig. 3.) The vessels of the eye and orbit were then irrigated with tap water through this cannula for 60 minutes. Provided the orbital mass had been removed in a reasonably intact condition, this procedure was associated with only a gentle uniform capillary ooze, but in a few eyes when large superficial vessels were exposed it was necessary to ligate them before proceding with the irrigation. The ocular mass was then placed in the refrigerator where it was left for 12 hours. After thawing, the specimen was finally irrigated with water for 15 minutes, thus ensuring complete removal of any small residual particles of blood clot from the ocular circulation. A thorough preliminary irrigation was found to be an essential step in the successful injection of the uveal circulation with Neoprene.

Neoprene latex 572 was prepared for injection. This synthetic rubber preparation, an emulsion of polymerised 2 chlorbutadiene with a particle size of 0.1 - 1.0 microns, was obtained from the B.B. Chemical Company. Neoprene was obtained normally with a consistency similar to that of milk, and this was suitable for injection purposes, but sometimes it was received in a more concentrated form and it was necessary then to dilute it with a suitable amount of water. Neoprene was unsuitable for injection when too concentrated because of the tendency for the formation of clots within the smaller vessels thus preventing complete injection of the circulation in all its ramifications.

/ Neoprene was

FIG. 2. Dissecting instruments.

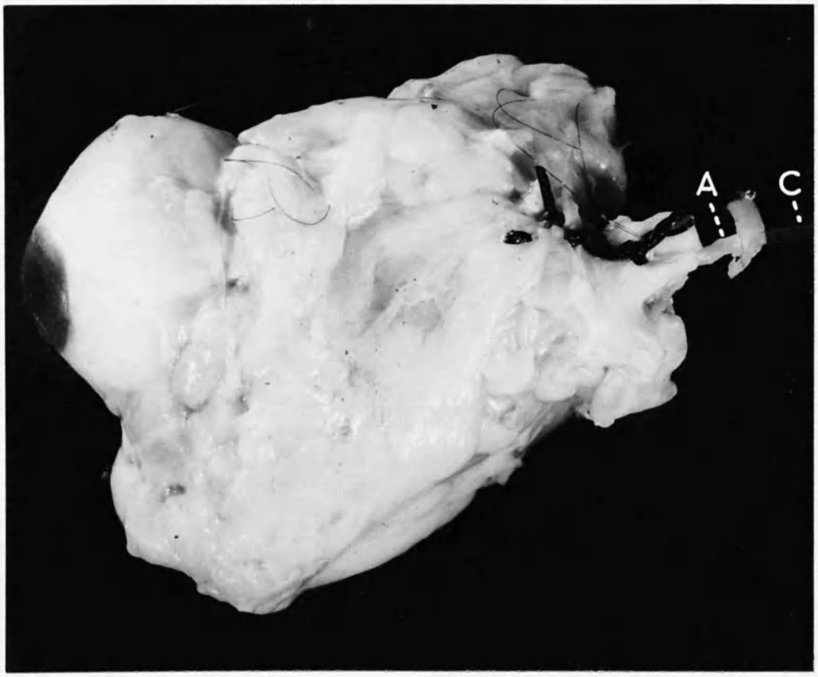


FIG. 3. Cannula (C) used for irrigation and injection shown in position within ophthalmic artery (A) .

Neoprene was normally used in its natural white state, but in some eyes a red-coloured Neoprene was injected and this was prepared by incorporating carmine with the Neoprene.

The cannula in the ophthalmic artery was connected to a Woulff's bottle containing about 50 ml. Neoprene, and this was then injected into the ocular circulation under a pressure of 5 - 10 lbs using a small electric pump (Edward's rotary vacuum pump and compressor, type IV). Neoprene was found to coagulate rapidly on entry into the circulation, and it was essential to commence the injection at a reasonably high initial pressure. This was achieved by releasing the clamps on the rubber tube connecting the Woulff's bottle to the cannula in the ophthalmic artery a fraction of a second after switching on the electric pump. By this technique Neoprene was more likely to pass right along the whole length of the circulation into the finest terminal vessels and capillaries without forming a block in any of the narrow vessels. Another manoeuvre which was of value in ensuring adequate intra-vascular injection was to lower the intra-ocular pressure by a stab incision of the central part of the cornea before switching on the electric pump.

It is interesting to note, however, that although it is necessary to observe the technique detailed above in order to obtain consistently good injections of the ocular circulation with Neoprene, satisfactory results may also be obtained by simpler methods. In a few eyes the irrigation with water and injection with Neoprene were carried out solely by a hand syringe (following a mechanical failure of the electric pump) and in most eyes the results were wholly satisfactory.

The change-over of Neoprene from a stable emulsion in the bottle to an irreversible colloid system within the circulation is probably due solely to a change in Ph values. Neoprene is stable in the presence of alkali (as in the bottle) but precipitates in an acid medium (as in the tissues) to form a solid, resilient, acid-resisting and alkali-resisting substance. It is these properties which make Neoprene so useful in a detailed study of a densely vascular tissue.

b) Injection of uveal tract with indian ink. (2 eyes).

After thorough irrigation of the ocular circulation with water through the ophthalmic artery, 50 ml. indian ink was injected into the artery from a hand syringe or through a Woulff's bottle using an electric pump, as described above.

c) Injection of uveal tract with Neoprene or indian ink after occlusion of one short posterior ciliary artery. (7 eyes).

After thorough irrigation of the whole ocular circulation with water through the ophthalmic artery, as described above, 1 ml.1% methylene blue solution was injected into the ophthalmic artery.

/ It was found

It was found that the easiest way of doing this, without disturbing the cannula in the artery, was to inject dye directly into the rubber tube near the junction of the tube with the cannula.

A careful blunt dissection was then made of the orbital tissues near the globe until a few of the short posterior ciliary arteries were exposed; the methylene blue greatly assisted in their identification. One artery was freed from its surrounding fatty tissues, and , after ligaturing it securely in two places, was severed between the ligatures. It was important to cause the minimum of trauma to the surrounding tissues during this manoeuvre, so that the other short posterior ciliary arteries were undamaged.

The ocular circulation was then injected through the ophthalmic artery with Neoprene (4 eyes) or indian ink (3 eyes) as described above.

d) Injection of one short posterior ciliary artery with indian ink. (2 eyes).

After thorough irrigation of the ocular circulation with water followed by an injection of methylene blue, as previously described, a dissection was made of the tissues of the orbit behind the globe until several short posterior ciliary arteries were clearly identified. One artery was firmly ligated about 20 mm. behind the globe and cut on the proximal side of the ligature. Using this ligature as a retractor the artery was carefully freed from its surrounding tissues, and then incised through half its circumference at a point about mid-way between the ligature and the site of entry of the artery into the globe, using a pair of fine curved spring scissors. A capillary glass cannula of the bulb type (Fig. 4) was inserted through this opening in the wall of the artery, and indian ink injected under pressure by a technique similar to that described above.

2) Methods of examination.

a) Examination of injected choroid in situ.

Following the injection of the ocular circulation through the ophthalmic artery with Neoprene or indian ink, all the extra-ocular tissues were removed by dissection and the eye fixed in 10% formol saline for 24 hours. After fixation the globe was opened by a sweeping cut through the coronal plane just distal to the equator, so that the lens was removed with the discarded anterior segment. Some of the vitreous became detached by the influence of gravity and this could be aided by the use of blunt forceps, but no effort was made to remove it completely because any vitreous which was left came away simultaneously with retina. The retina was separated from the choroid by placing the half-globe under water and detaching its peripheral part in towards the centre of the globe. This detachment was extended until the retina remained attached only at the optic disc, where it was freed without any damage to the peripapillary choroid by stripping it away with fine forceps or by the use of a thin narrow swab of cotton wool on the end of a fine pointed stick.

/ The pigment layer

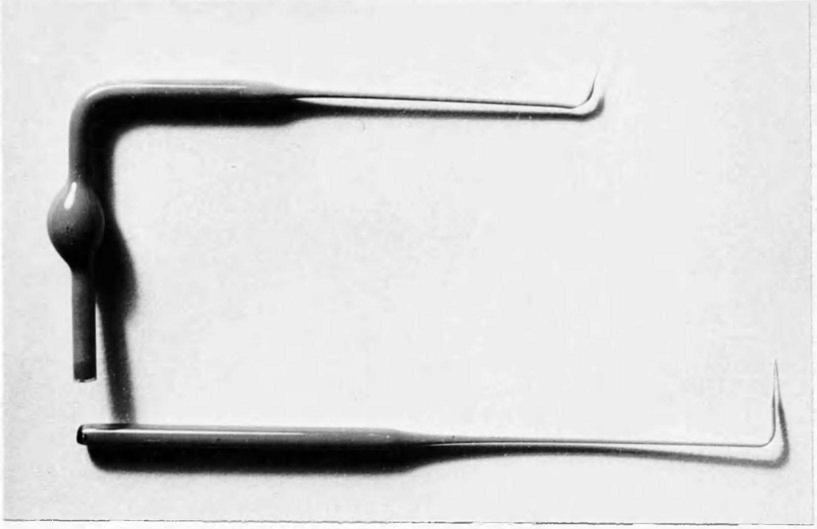


FIG. 4. Capillary glass cannulae, one of bulb type, for injection of short posterior ciliary artery.

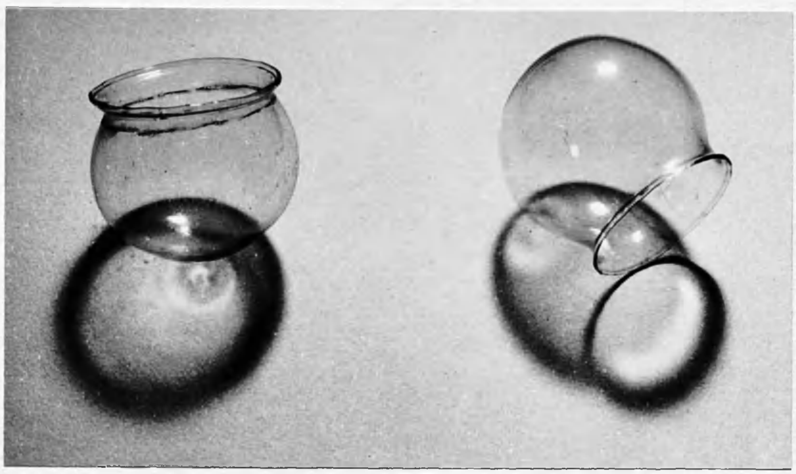


FIG. 5. Hemispherical glass viewing chamber for examination of choroid.

The pigment layer of the retina remained attached to the choroid but this pigment could be removed by gentle brushing under water so that the injected vessels of the choroid could be viewed in their natural position in the posterior part of the globe.

b) Examination of isolated injected choroid.

In most eyes the choroid was removed from the globe for further study. After exposure of the injected choroid, as described above, the choroid was gently separated from the underlying sclera under water. Each individual vessel or nerve passing between the sclera and choroid was carefully cut within the suprachoroidal space to avoid damage to the choroid during this separation, until finally the choroid only remained adherent around the optic disc. This zone of attachment was freed by gently tearing the choroid away with fine forceps or by gently stroking it away from the globe with a swab of cotton wool on the end of a fine pointed stick.

The isolated choroid was fixed in 10% formol saline for a further 24 hours, and thereafter bleached by immersion in 2% potassium permanganate for 30-60 minutes followed by washing in oxalic acid. It was then examined in three different ways. First, the choroid was examined without further interference to its structure by floating it under water into a glass hemisphere, designed to resemble the shape and size of the scleral cup (Fig.5). On removal of the water from the hemisphere the choroid was gently forced to line the inner surface of the glass. In this way it was possible to view clearly the choriocapillaris surface of the choroid (by looking directly at the choroid within the hemisphere) or to view the external surface of the choroid (by looking indirectly at the choroid through the outer surface of the hemisphere). This method provided a composite view of the choroidal vessels and capillaries. Secondly, the choroid was examined by making a series of radial incisions along the whole length of the choroid, except in the peripapillary region, so that it could be spread out flat on a large glass slide. It was then possible to obtain a detailed view of the relationships of the various choroidal vessels to one another. In the case of those eyes injected with Neoprene it was easier to view the specimens against a background of black photographic paper, and in the indian ink injected eyes to view against a background of white filter paper.

Thirdly, the details of individual vessels and capillary areas were examined by careful dissection. This method, of course, was applied only to the eyes injected with Neoprene, and it was found in those eyes that the elasticity and high tensile strength of Neoprene together with its cohesive properties permitted detailed dissections even within such a densely vascular tissue as the choroid. The dissections were carried out under water, and the casts were viewed through the stereoscopic microscope against a black background. This method, although laborious and time-consuming, yielded most of the information to be reported in this thesis.

c) Examination of isolated injected uveal tract.

The following technique was adopted in those eyes in which it was desired to examine the uveal tract along its whole length.

The cornea was removed by a circumcorneal incision using a pair of fine curved spring scissors, and then, after making a radial incision in the iris, the lens was removed followed by as much as possible of the vitreous and retina. These structures were pulled out gently by forceps with great care to prevent damage to the underlying uveal tract. The rest of the dissection was carried out under water. The root of the iris was separated by blunt dissection from its scleral attachments particularly in the region of the scleral spur, and this separation of the uveal tract from the sclera was gradually extended back by opening up the supra-choroidal space. This was facilitated by simultaneously cutting concentric strips from the sclera. Each vessel or nerve crossing the suprachoroidal space and linking the sclera to the uvea was cut individually. Finally, the peripapillary part of the choroid was separated from its attachment around the optic disc, as described above, and the entire uveal tract was thus obtained as an isolated mass. This was then fixed and bleached by the methods given above.

The isolated uveal tract was examined by cutting it into sectors by a series of longitudinal incisions, and these strips were then examined by direct view. In the case of those eyes injected with Neoprene a detailed dissection of each sector was carried out under water.

Findings.

1) Arteries of choroid.

The choroid is supplied by two arterial systems; the more posterior part by the short posterior ciliary arteries and by a few fine branches from the intrascleral arterial circle of Zinn , and the more anterior part by the recurrent choroidal arteries which arise within the ciliary body from the major arterial circle of the iris, from the long posterior ciliary arteries, and from the anterior ciliary arteries. The two arterial systems approach one another and meet at the equator of the eye. This description of the choroidal arteries will now be considered in more detail.

NOTE:

It is not difficult to distinguish between arteries and veins in Neoprene casts of the choroidal vessels. In an examination of a composite picture of such casts (figs. 6 & 7), there would not appear to be any clear distinction between arteries and veins except in the case of those veins which can be traced to their termination in one of the main vortex veins. A more detailed examination shows, however, that the arteries have a whiter, more rounded appearance than the veins which appear greyer and flatter (fig.8). This distinction may be emphasised by using red Neoprene in which case the arteries have a more densely red colour than the veins which appear pink (fig.9) .

a) Short posterior ciliary arteries.

The short posterior ciliary arteries arise from the ophthalmic artery in the posterior part of the orbit either as one or two trunks or as a series of 4-6 branches. They run forward to the posterior part of the globe where they divide into other branches so that in all about 15-20 branches perforate the sclera around the optic nerve. On passing through the sclera each branch undergoes further sub-division, and from these branches others are given off within the choroid.

Each definitive branch then runs forward within a narrow sector of the choroid to terminate in a series of arteriolar-capillary networks at some point between the peripapillary and equatorial regions. It is a significant feature of the choroidal arteries that these arteriolar-capillary networks do not occur along the whole length of the longer arteries, so that those arteries which reach the equator contribute to the chorio-capillaris there without contributing to the chorio-capillaris in the other parts of the choroid.

/Similarly

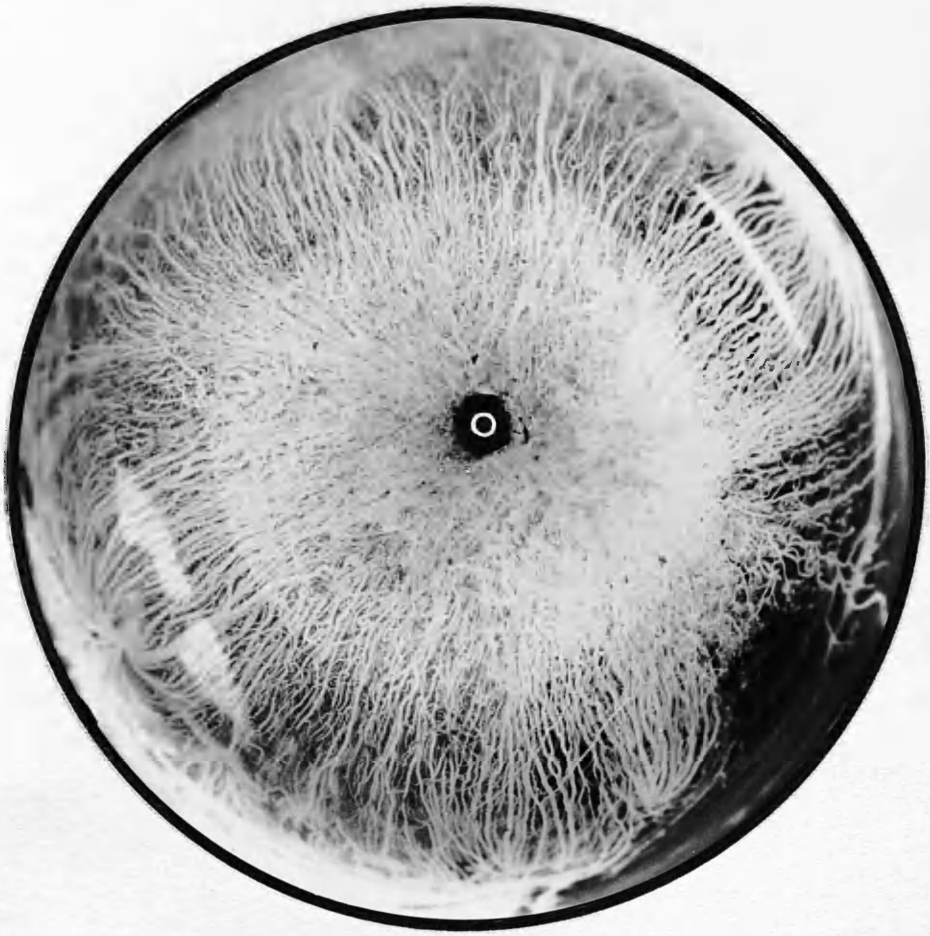


FIG. 6. White Neoprene cast of whole choroid mounted in glass hemisphere and viewed from within, (choriocapillaris surface nearest camera). Optic disc (O)lies in centre. x 6.

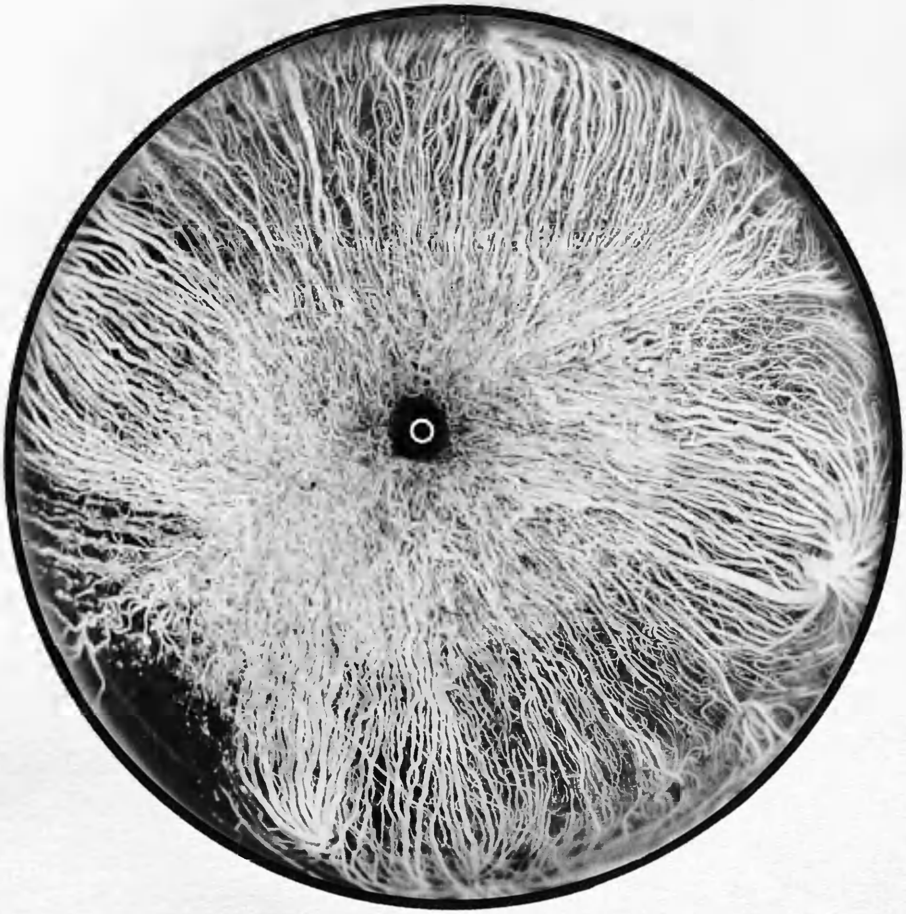


FIG. 7. White Neoprene cast of whole choroid mounted in glass hemisphere and viewed from without, (layer of larger vessels nearest camera). Optic disc (0) lies in centre. x 6.

FIG. 8. White Neoprene cast of sector of choroid to show distinction between arteries(A) and veins (V). x 33.

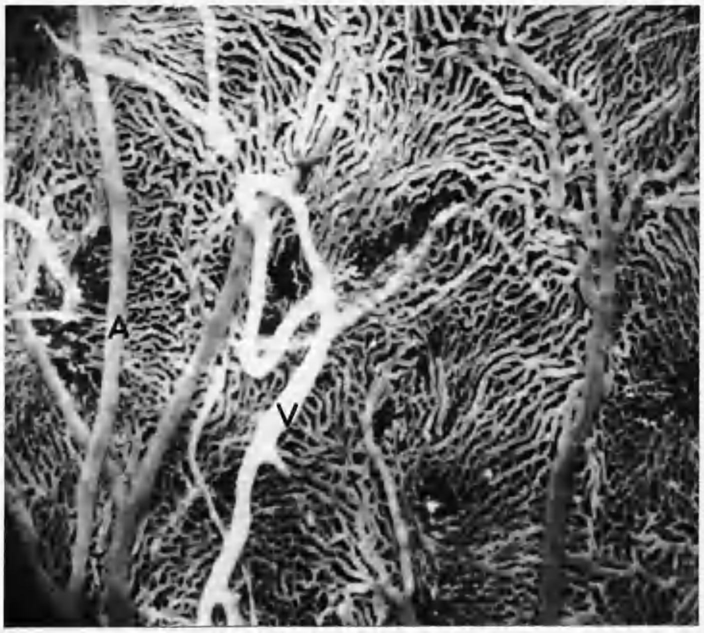


FIG. 9. Red Neoprene cast of sector of choroid to show distinction between arteries (A) and veins (V). x 33 .

Similarly, the smaller short posterior ciliary arterial branches limit their networks to the posterior part of the choroid and do not reach forward to the equator. The arteries are not connected to one another by direct arterial branches except in the more posterior part of the choroid. These features are illustrated in fig.10.

The short posterior ciliary arterial branches radiate out from their point of entry into the choroid to their point of termination in a fairly uniform manner so that the density of arteries in a particular area of the choroid is equivalent to that in any other area situated an equal distance from the optic disc. The submacular part of the choroid is an exception to this, however, in that it contains a greater aggregration of arterial branches (fig.11); in Neoprene casts this feature is apparent only after removal of the extensive network of choroidal veins many of which sweep round in the posterior part of the globe before passing to the vortex veins.

The short posterior ciliary arteries give off other branches in addition to those which pass directly into the choroid. Within the orbit, branches pass from the arteries to the sheaths of the optic nerve where they contribute to the formation of the arterial plexus of the pia mater, and, within the sclera, small branches unite to form the intrascleral arterial circle of Zinn. These branches will be discussed in greater detail in Section II of this thesis because they are of more concern in a consideration of uveo-retinal arterial anastomoses, but the circle of Zinn is also of interest in a study of the choroid because small arterial branches pass from the circle to the choroid immediately surrounding the optic disc where they are associated with the most posterior branches of the short posterior ciliary arteries.

An examination of the 7 eyes which were injected with Neoprene latex (4 eyes) or with indian ink (3 eyes) through the ophthalmic artery after occlusion of a single short posterior ciliary artery in the orbit revealed the following features. In 4 eyes (two injected with Neoprene latex and two with indian ink) there was complete filling of the vessels of the choroid and ciliary body (fig. 12), but in the 3 other eyes (two injected with Neoprene and one with indian ink) a partial sectorial filling defect occurred in the choroid corresponding in situation to the occluded short posterior ciliary artery (figs.13 and 14). It is noteworthy, however, that in the three eyes which showed a sectorial defect the anterior part of the uveal circulation was not well injected, and this is in contrast to the four eyes without a sectorial defect, which showed a uniform filling of the whole uveal circulation.

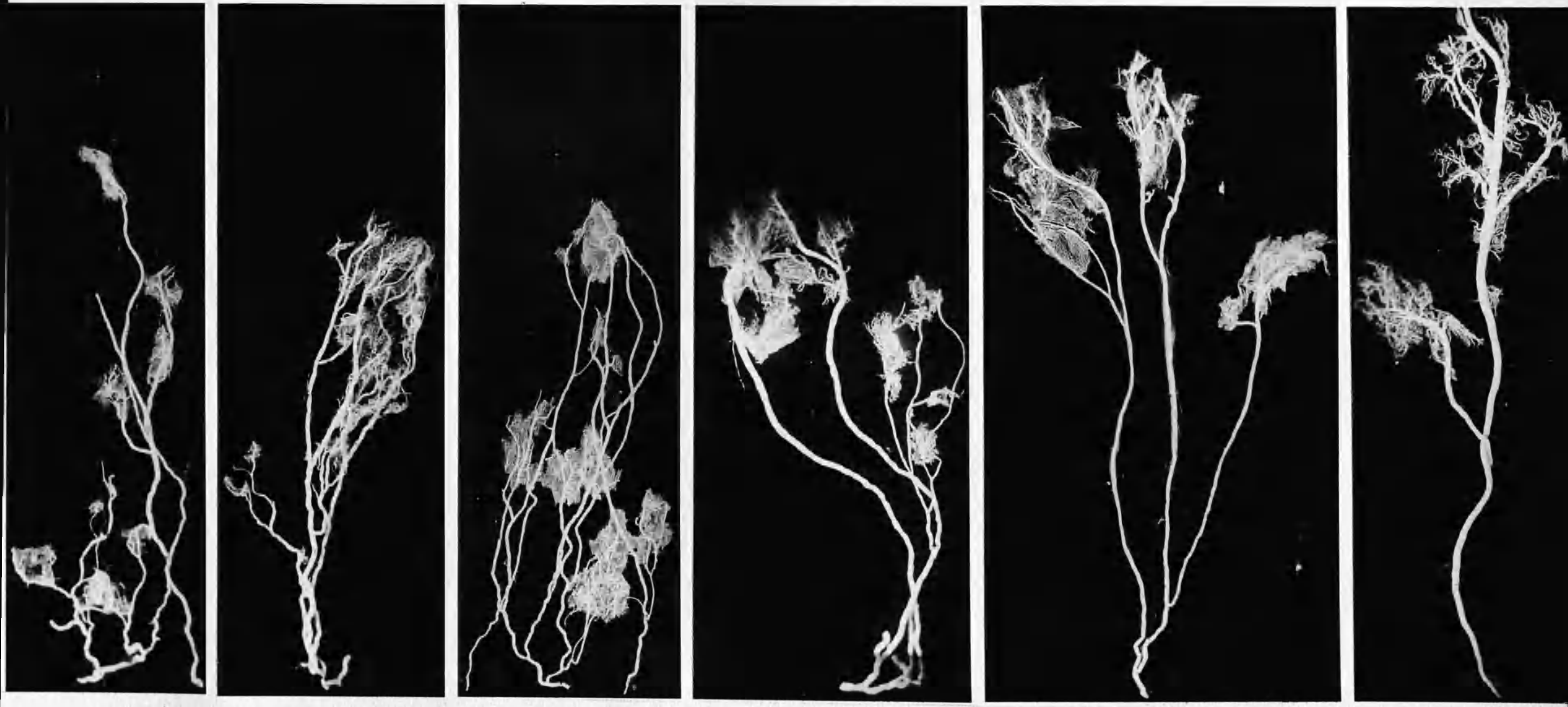


FIG. 10. White Neoprene casts of several individual posterior choroidal arteries. (Dissected specimens). x 12.

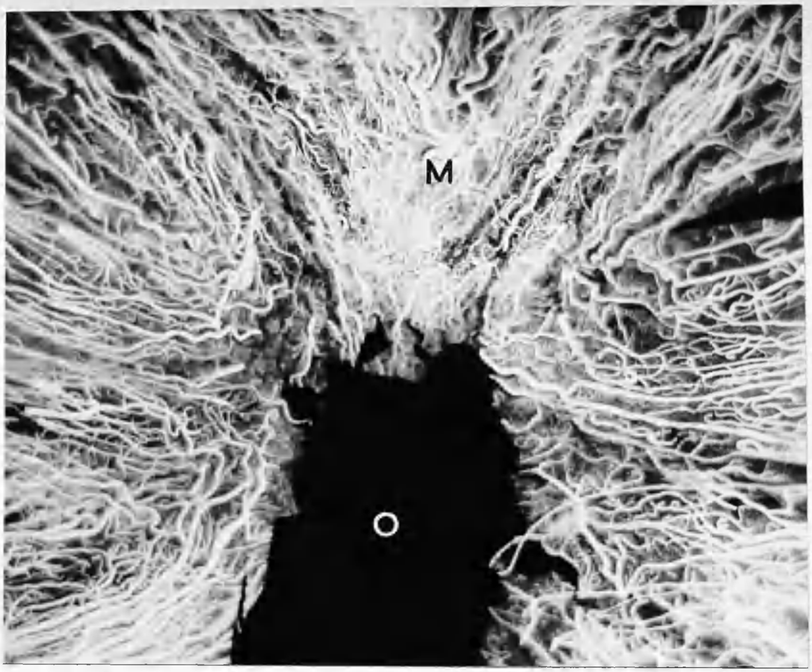


FIG. 11. White Neoprene cast of part of choroid near optic disc (O) to show greater aggregation of arterial branches in submacular area (M). (Dissected specimen in which majority of choroidal veins have been removed) . x 8.

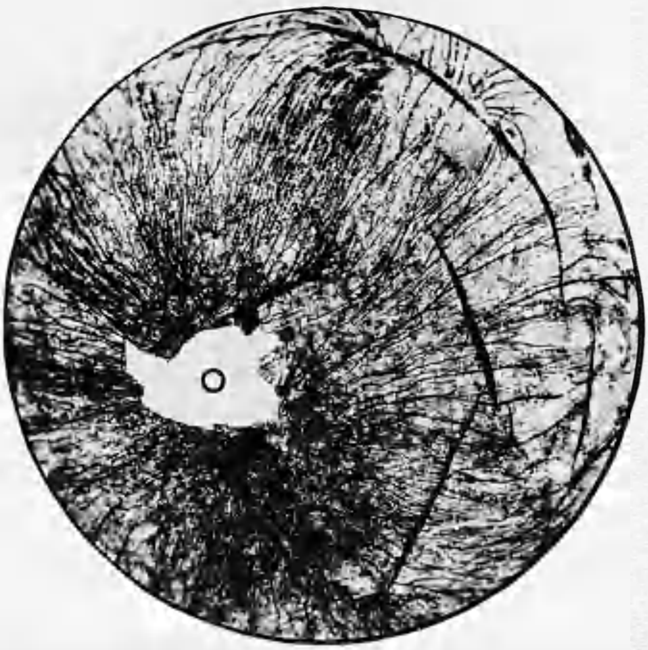


FIG. 12. Indian ink injection of whole choroid mounted in glass hemisphere. Optic disc (O) lies in centre. x $4\frac{1}{2}$.

FIG. 13. White Neoprene injection of part of choroid lying within globe to show large incompletely injected sector (below) corresponding in situation to area of distribution of short posterior ciliary artery occluded before injection. (Anterior part of globe not available for photography). x $4\frac{1}{2}$.

FIG. 14. Indian ink injection of part of uveal tract to show large incompletely injected sector corresponding in situation to area of distribution of short posterior ciliary artery occluded before injection. Position of occluded artery relative to globe indicated by notch (N) in iris. x $4\frac{1}{2}$.

An examination of the two eyes which were injected with indian ink through a single short posterior ciliary artery within the orbit showed that in each eye more than two-thirds of the vessels of the ciliary body and choroid became filled with the dye (fig.15).

b) Recurrent choroidal arteries originating from major arterial circle of iris.

The major arterial circle of the iris is formed in the anterior part of the ciliary body near the root of the iris by the terminal parts of the long posterior ciliary arteries and of the anterior ciliary arteries. Recurrent choroidal arteries arise from the major arterial circle and pass backward through the ciliary body into the choroid to reach the equator (fig.16a).

c) Recurrent choroidal arteries originating from long posterior ciliary arteries.

The two long posterior ciliary arteries arise from the ophthalmic artery, in the posterior part of the orbit, either separately or by a common trunk which divides after a short course into the two final branches. One artery passes laterally to perforate the sclera a short distance from the lateral aspect of the optic nerve head, and the other artery passes medially to perforate the sclera an equivalent distance away from the optic nerve on the medial side. In both cases the sites of perforation lie outside the perforating short posterior ciliary arteries.

The lateral and medial long posterior ciliary arteries perforate the sclera in an oblique way so that they enter the suprachoroidal space farther away from the optic nerve head than the site of their entry on the external scleral surface. Each artery runs in the suprachoroidal space in the horizontal meridian of the eye and passes straight to the ciliary body without contributing directly to the vascularity of the choroid. In the anterior part of the ciliary body the long posterior ciliary arteries break up into several terminal branches which join with the anterior ciliary arteries to form the major arterial circle of the iris, but before this happens, each branch sends off a recurrent branch which passes back through the ciliary body into the anterior part of the choroid to reach the equator (fig.16b).

d) Recurrent choroidal arteries originating from anterior ciliary arteries.

The anterior ciliary arteries are the continuations of the muscular arteries of the four rectus muscles beyond the insertions of these muscles. It has been shown by Ashton and Smith (1953) that each anterior ciliary artery divides in the episcleral tissues into several medium-sized vessels which, after giving off small twigs to the episcleral limbal plexus and to the region of Schlemm's canal, perforate the sclera and cross over the suprachoroidal space to enter the ciliary

/body where

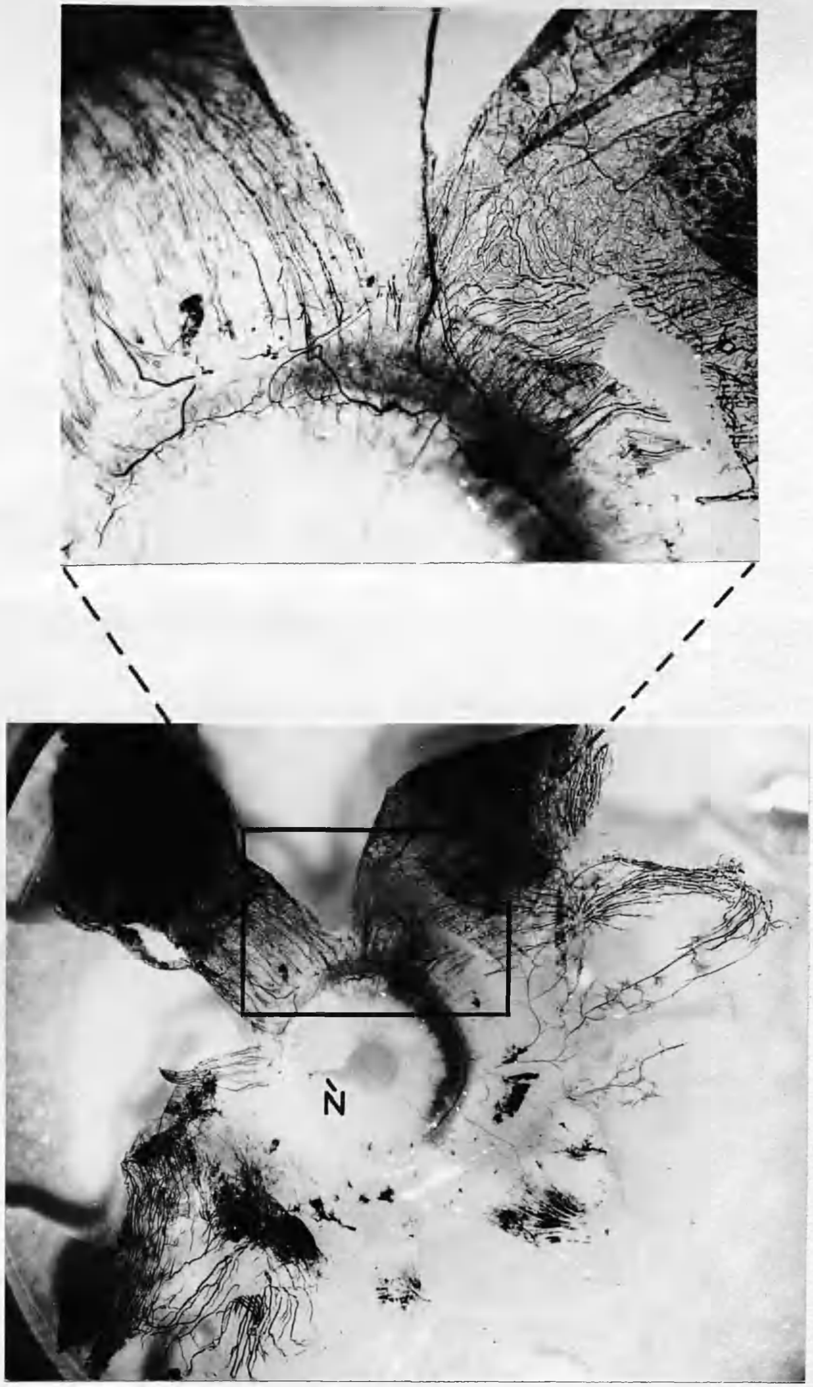
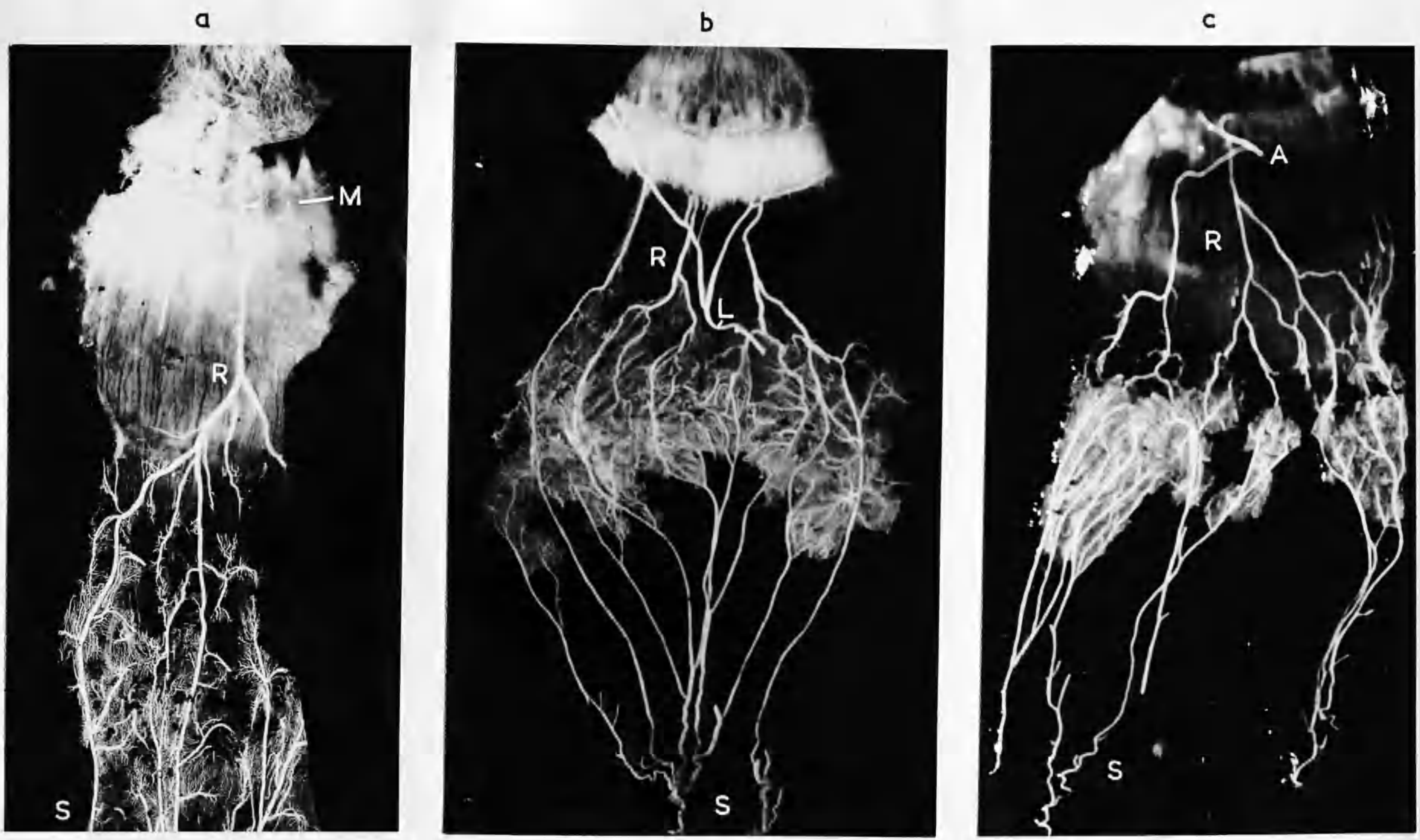


FIG. 15. Indian ink injection of extensive area of uveal tract after injection into single short posterior ciliary artery. Position of injected artery relative to globe indicated by notch (N) in iris. Uveal tract cut into sectors except for iris. x $2\frac{1}{2}$ and x 8.



FIGS. 16 a,b,and c. White Neoprene casts of three strips of uvea to show recurrent choroidal arteries (R)arising:

a) from the major arterial circle of the iris (M) ;
b) from a long posterior ciliary artery (L) ;
c) from an anterior ciliary artery (A) .

Terminal parts of short posterior ciliary arterial branches (S) shown below. (Dissected specimens).
a) x14, b) x10 and c) x10.

body where they terminate by joining the long posterior ciliary arteries to form the major arterial circle of the iris. Within the ciliary body the anterior ciliary arteries give off small twigs which pass to the sclera, to the region of Schlemm's canal and to the ciliary muscle, and they also give off several large recurrent branches which run back through the ciliary body into the anterior part of the choroid to reach the equator (fig.16c).

e) Anastomoses between posterior and recurrent choroidal arteries at equator.

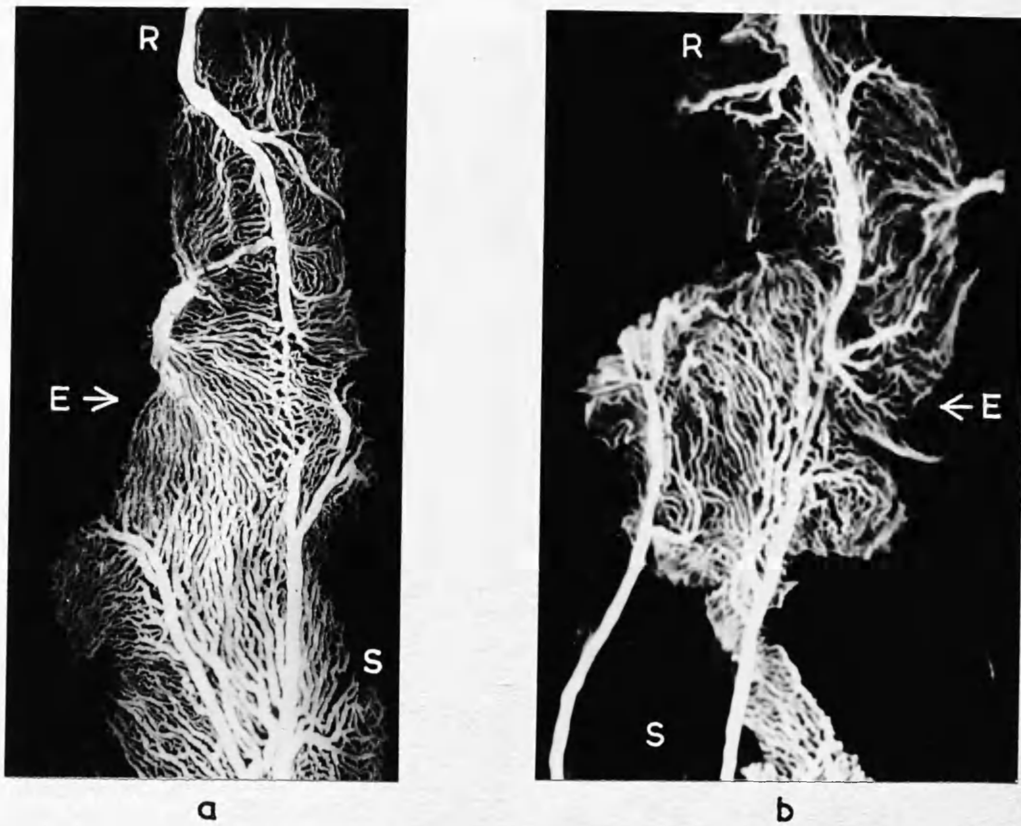
The short posterior ciliary arteries which extend forward meet at the equator the recurrent choroidal arteries from the major arterial circle of the iris, from the long posterior ciliary arteries and from the anterior ciliary arteries which extend backward. The two opposing systems may anastomose through a narrow intervening capillary network (fig.17), but in many places the anastomosis is a direct one (figs.18 & 19). When the opposing arteries are in direct continuity the point of union may be determined by a slight narrowing of the arterial trunk, but it may be determined also by the direction in which the branches arise from the artery; branches of the posterior choroidal arteries point forward and branches of the recurrent choroidal arteries point backward.

2) Capillaries of choroid.

The capillaries, which form a single layer on the inner aspect of the choroid, are not uniform in calibre throughout the chorio-capillaris. Posteriorly, they are smaller with a closer inter-capillary network and anteriorly they become wider with a more open network (fig.20). The capillaries are, therefore, more dense in that part of the choroid which lies under the macula as compared with capillaries in a more peripheral part of the choroid, but there is no detectable structural difference between the chorio-capillaris underlying the macula and any other part of the chorio-capillaris situated an equivalent distance from the optic disc. It would appear, therefore, that the density and calibre of the capillaries within the chorio-capillaris are purely expressions of the distance of the capillaries from the optic disc, and that although there is a marked difference between scattered areas of the chorio-capillaris there are no specific features of the submacular chorio-capillaris.

In the extreme periphery of the choroid, the capillaries become wide and irregular and then disappear at the junction of the choroid with the ciliary body (fig.21). There is, therefore, no capillary layer, corresponding to the chorio-capillaris, in the ciliary body (fig.22).

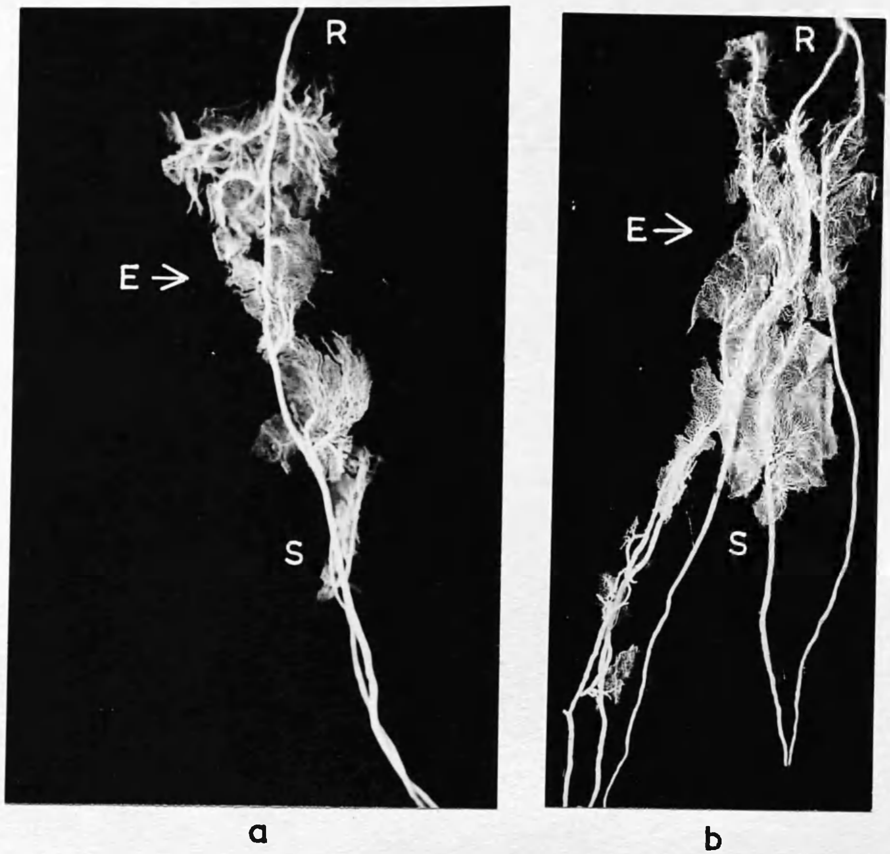
It is significant to note that in none of the Neoprene casts was there any evidence that the chorio-capillaris had been damaged during the intravascular injection of the Neoprene.



FIGS. 17 a and b.

White Neoprene casts of the terminal parts of recurrent choroidal arteries (R) and of short posterior ciliary arterial branches (S), to show intervening capillary network at equator (E).

(Dissected specimens). (a) and (b) x 19.



FIGS. 18 a and b.
White Neoprene casts of recurrent choroidal arteries (R) and of short posterior ciliary arterial branches (S) to show the occurrence of direct arterial anastomoses at equator (E). (Dissected specimens). (a) and (b) x 8.

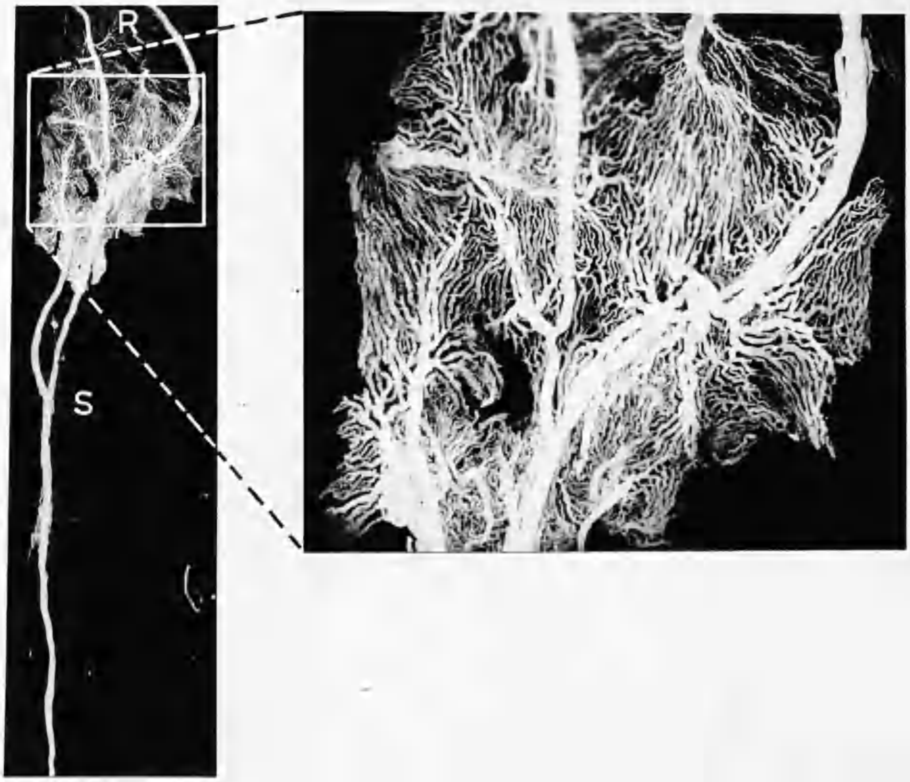


FIG. 18 c. White Neoprene cast of recurrent choroidal arteries (R) and of short posterior ciliary arterial branches (S) to show occurrence of direct arterial anastomoses at equator(E). (Dissected specimen). x 8 and x 22.

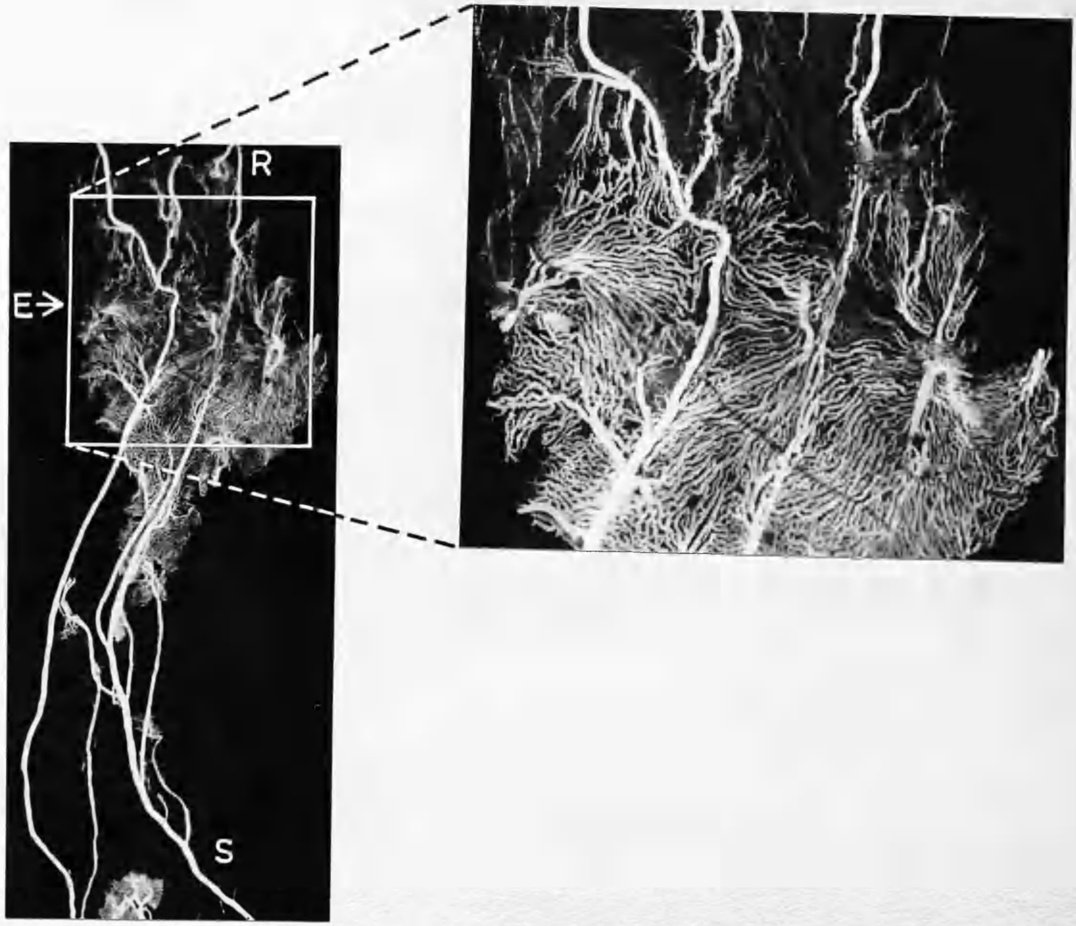


FIG. 18 d. White Neoprene cast of recurrent choroidal arteries (R) and of short posterior ciliary arterial branches (S) to show occurrence of direct and capillary arterial anastomoses at equator (E) .

(Dissected specimens). x 8 and x 16.

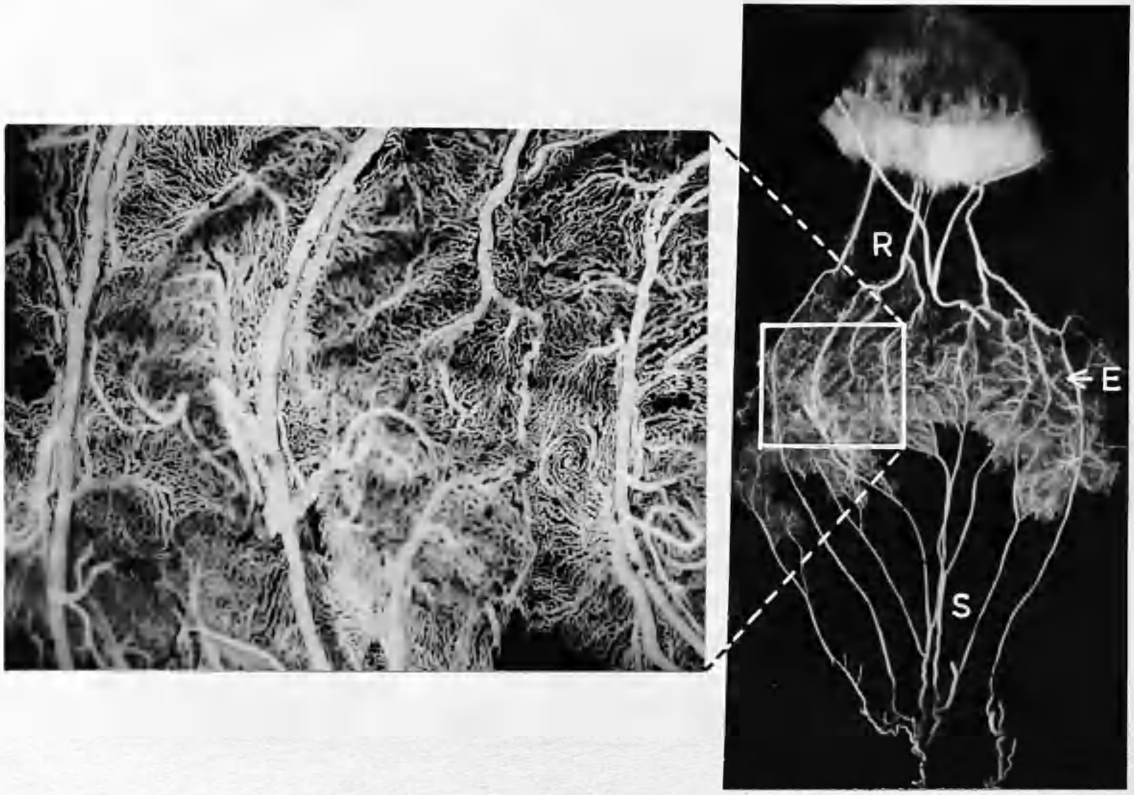


FIG. 18 e. White Neoprene cast of recurrent choroidal arteries (R) and of short posterior ciliary arterial branches (S) to show occurrence of direct and capillary anastomoses at equator (E). (Dissected specimens). x 7 and x 24.

FIG. 18 f. White Neoprene cast of recurrent choroidal arteries (R) and of short posterior ciliary arterial branches (S) to show occurrence of direct and capillary anastomoses at equator (E). (Dissected specimens). x 16.

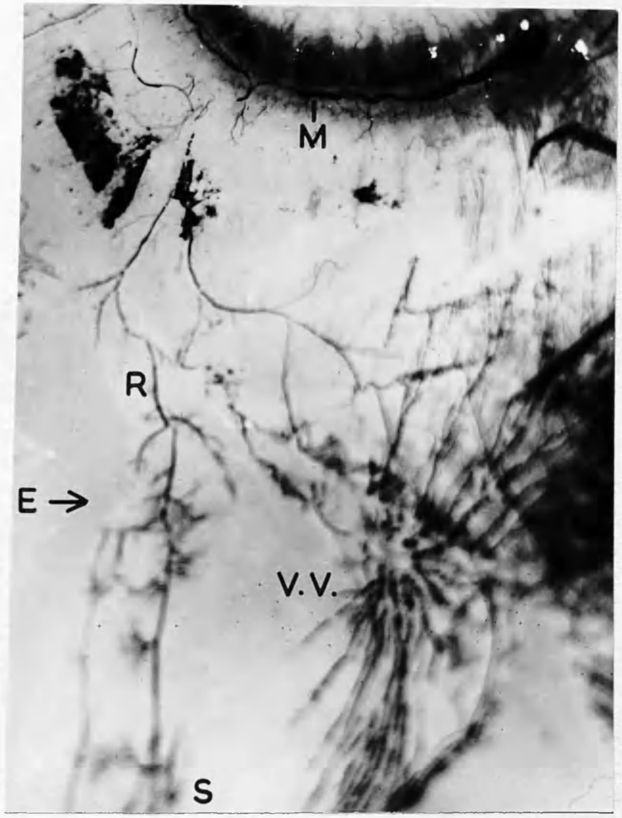


FIG. 19. Indian ink injection of uveal vessels to show direct anastomosis between a recurrent choroidal artery (R) and a short posterior ciliary arterial branch (S) at equator (E).
Note major arterial circle of iris (M) and formation of a vortex vein(V.V.)
x 16.

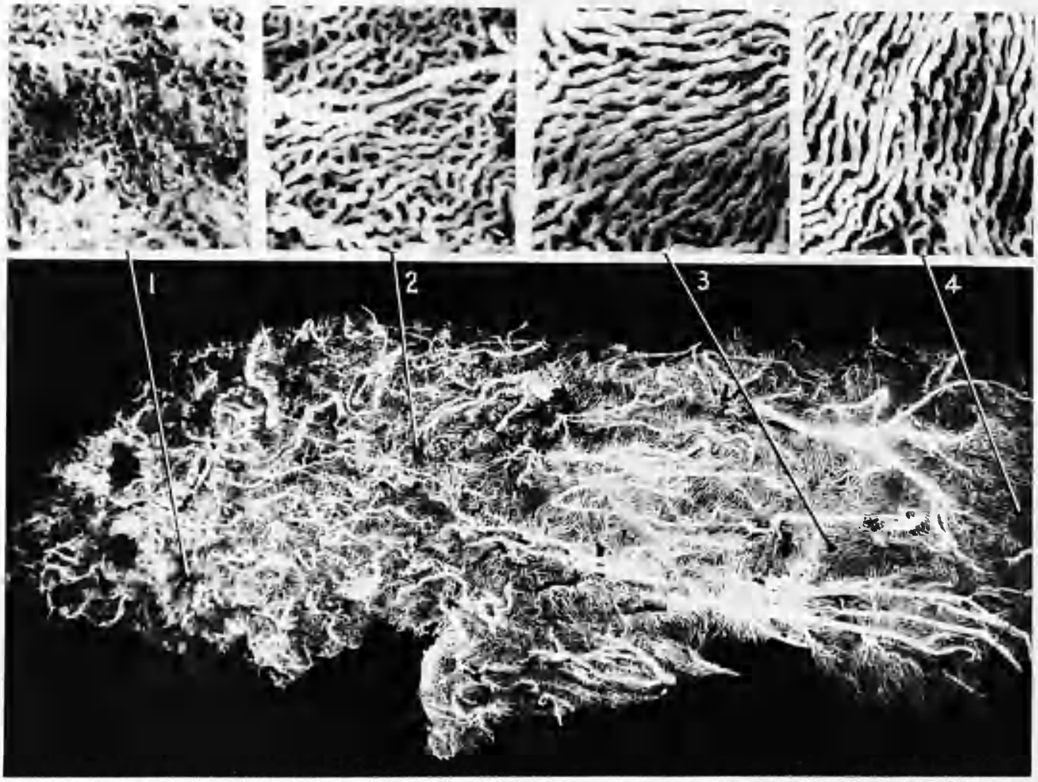


FIG. 20. White Neoprene cast of choroid to show increase in calibre of capillaries and opening up of intercapillary spaces in passing from posterior to anterior regions, that is, from areas marked 1 to 4. (Dissected specimen). x 8 and x 32.

FIG. 21. White Neoprene cast of anterior part of uveal tract to show termination of chorio-capillaris at anterior end of choroid.
(Dissected specimen). x 22.

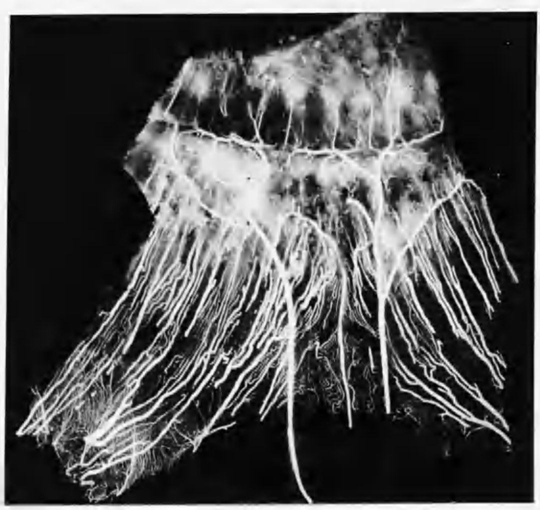


FIG. 22. White Neoprene cast of anterior part of uveal tract to show absence of chorio-capillaris in ciliary body.
(Dissected specimen). x 14.

3) Veins of choroid.

The venules arise abruptly from the chorio-capillaris and form a characteristic loop before they are joined by neighbouring venules (fig.23). The larger venous channels are formed by an aggregation of these venules and they pass toward the equator where they converge at four points to form the four main vortex veins. Some of the venous tributaries pass directly forward from their origin in the chorio-capillaris to the nearest vortex vein, but others pass backward towards the peripapillary region before sweeping round to join the main stream of vessels (fig.24). Occasionally there is a subsidiary vortex vein which is formed independently of the main ones (fig.25), and this subsidiary vein leaves the globe by a separate channel to join one of the main veins outside the sclera.

An examination of the Neoprene casts showed small localised dilatations of the choroidal veins particularly at the site of crossing of the vein by an artery (fig.26), but these swellings were not associated with any arterio-venous communication, and no evidence was found in the choroid of any arterio-venous anastomoses, except through the normal chorio-capillaris. (fig.27).

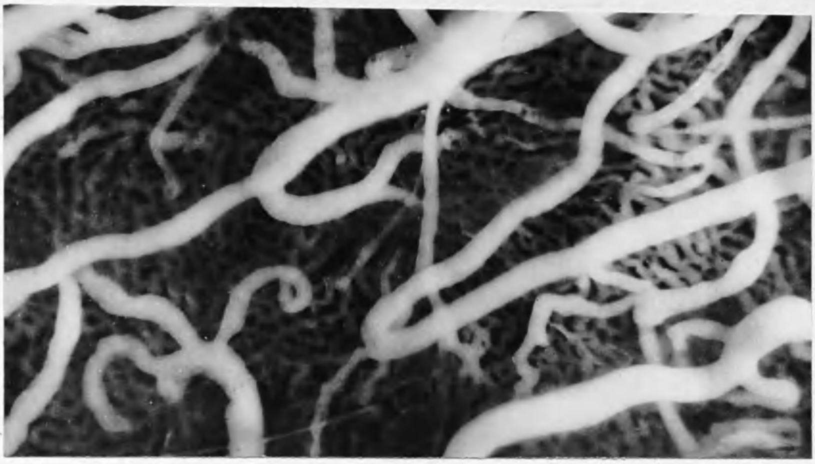


FIG. 23. White Neoprene cast of sector of choroid to show looping of venules at origin from chorio-capillaris.

x 33.

FIG. 24. White Neoprene cast of choroid to show formation of two vortex veins (V.V.). (Dissected specimen). x 5.

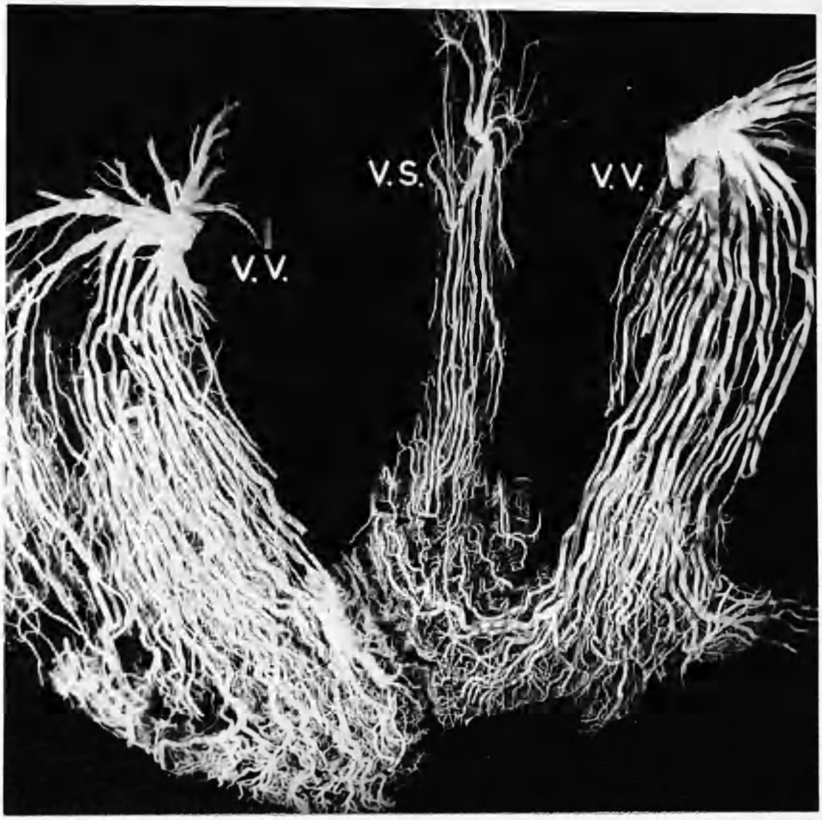


FIG. 25. White Neoprene cast of choroid to show formation of two main vortex veins (V.V.) and one subsidiary vortex vein (V.S.).
(Dissected specimen). x 7.

FIG. 26. White Neoprene cast of sector of choroid to show swelling of vein (V) at site of arterial (A) crossing. x 33.

FIG. 27. White Neoprene cast of sector of choroid to show capillary bed between terminal arteriole (A) and commencing venule (V). x 36.

Discussion.

It is apparent that some of the findings of this investigation conflict, in part or in whole, with certain of the more accepted views regarding the vascular anatomy of the choroid which subdivide it into a series of more or less rigidly isolated sectors or zones. These previous theories will now be re-examined in the light of the present study.

First, there is doubt regarding the validity of the hypothesis that the choroid has a segmentally arranged arterial blood supply, and that the choroidal arteries have the characteristics of end-arteries. There is, therefore, doubt regarding the theory that the choroid is sub-divided into isolated sectors.

It has been shown that although each definitive branch of the short posterior ciliary arteries runs forward in a narrow sector of the choroid to form a terminal arteriolar-capillary network in some particular area of the choroid between the peripapillary and equatorial regions, these individual choroidal arteries are not wholly isolated from one another. The connections which link the various arteries to one another take two forms. In the first place, the direct anastomosis at the equator between the posterior and recurrent choroidal circulations establishes a direct link between many of the short posterior ciliary arteries and the major arterial circle of the iris. This circle in turn is in communication with other short posterior ciliary arteries through the recurrent choroidal arteries from the circle and from the arteries which contribute to the formation of the circle (that is, from the anterior ciliary arteries and from the long posterior ciliary arteries). In the second place, the chorio-capillaris forms a continuous capillary network over the inner surface of the whole choroid, so that the capillary district of one terminal short posterior ciliary arterial branch is in direct continuity with the capillary districts of all the neighbouring arterial branches.

Further evidence that the short posterior ciliary arteries are not true end-arteries is provided by the four eyes in which the entire choroid became filled with intravascular injection material following injection through the ophthalmic artery in spite of the preliminary ligation of a single short posterior ciliary artery. This, of course, is easily understood if it is accepted that the area of choroid dependent on the ligated posterior ciliary artery may be filled from the recurrent choroidal arteries and from the neighbouring chorio-capillaris. On the other hand there were three eyes subjected to the same technique in which there was a sector-shaped area of inadequately filled choroid corresponding in situation to the ligated short posterior ciliary artery. It would appear

/most likely

most likely, however, that these inconsistent results are purely expressions of the degree of success of the injection technique. When material is injected into the ophthalmic artery it passes, in the first place, into the arteriolar-capillary networks of the patent vessels, but, at a later stage, it enters the zone dependent on the occluded artery by way of the alternative pathways through the anterior uveal circulation and through the chorio-capillaris. It will be remembered that the three eyes with a partial filling defect were less well injected, quite apart from the sectorial defect, than the four eyes without a filling defect, and this is in keeping with the view outlined above.

It is postulated, therefore, that although each short posterior ciliary arterial branch has its own area of supply, there is no rigidly determined anatomical segmentation of the choroidal arterial circulation, and that the short posterior ciliary arteries are not true end-arteries, at least from an anatomical point of view. It would be reasonable to expect on these grounds that in the event of a circulatory failure within the choroidal sector, following the occlusion of a short posterior ciliary artery, the circulation may be restored rapidly from the other intact vessels.

This doubt regarding the rigid segmentation of the choroidal arteries was also expressed by Nicholls (1938) who failed to confirm the experimental findings of Wagenmann (1890) of a sectorial defect in the choroid of the rabbit following occlusion of part of the posterior ciliary circulation. Nicholls did not detect any structural changes within the choroid of the rabbit after occlusion of the short posterior ciliary arteries unless at least two-thirds of the arteries were obliterated, and in such cases a phthisical condition of the eye was a more likely development than a sectorial atrophy of the choroid.

In some rabbits Nicholls noticed the occurrence of a sector-shaped area of retinal pallor extending to the ora serrata after section of a few short posterior ciliary arteries, but it was purely a temporary phenomenon and passed off within a few hours. This retinal oedema is presumably a reflection of a disturbance of the circulation in the underlying choroidal sector, but its transient nature is evidence of a sufficiently well marked collateral circulation between the various sectors of the choroid to prevent any extensive permanent area of vascular obliteration within the choroid.

It is possible that Wagenmann (1890) in his experimental work produced a more widespread disturbance of the short posterior ciliary arteries than that produced by Nicholls (1938), and, therefore, the apparently contradictory results may be due purely to a difference in technique. It is interesting to note that Wagenmann observed that within a few days of the section of the ciliary arteries the area of sectorial disturbance became smaller and this is surely evidence for the existence of some choroidal anastomoses.

There is also evidence that the clinical cases, which have been used to illustrate the concept of a segmentation of the choroid, have been misinterpreted; these cases were mentioned in the earlier part of this thesis. For example, in the case described by Coats (1907) it is more likely that the wedge-shaped area of choroidal atrophy, which was found in association with the patch of posterior scleritis, was due to the direct involvement of the choroidal sector in the scleral inflammation. This would account for the obliteration of the vessels and capillaries in that sector, in a more likely way than to postulate an indirect circulatory failure within the choroidal sector due to the involvement of a short posterior ciliary artery in its passage through the diseased sclera. Even Coats who put forward the latter hypothesis admitted that it is peculiar for infarction to follow blockage of one artery in such a vascular tissue as the choroid. In fact it would appear likely that such a hypothesis is valid only if the thrombotic process in the artery has spread into all the vessels and capillaries of the affected sector, because the continuity of the chorio-capillaris over the whole surface of the choroid ensures the survival of individual areas even after the occlusion of a few feeding arteries.

Furthermore, in the case described by Hepburn (1912) the sector-shaped scotoma extending to the periphery of the visual field following a circumscribed patch of deep choroiditis, may be explained solely on the basis of involvement of the retina overlying the choroiditis, without the necessity of postulating a circulatory failure in the whole sector of the choroid corresponding in shape to the sectorial field defect. When a focus of choroiditis involves only the outer layers of the overlying retina, the defect in the visual field is a localised scotoma corresponding in size and position to the choroiditis, but when the inner retinal layers are implicated, the function of a whole sector of retina is affected with the production of a scotoma extending right out to the periphery of the visual field. Additional evidence that this is the probable interpretation of such cases may be derived from the observation of Wolff and Penman (1950) that a narrow functional area of visual field may remain between the localised and sectorial field defects. This finding is understandable on the basis that the sector defect is due to the involvement of the retinal nerve fibre layer, but it is contrary to the concept of a circulatory failure within a whole sector of the choroid extending from the choroidal focus of inflammation. There is, therefore, no sound evidence from Hepburn's observations on choroiditis or from Coat's' observations on scleritis to justify the hypothesis that the choroid is made up of many isolated vascular sectors.

Secondly, there is doubt regarding the validity of the hypothesis that the equator is a specialised area of the choroid in that it represents a zone of ineffective anastomosis between the posterior and recurrent choroidal circulations.

It has been shown in this thesis that many of the arteries in the opposing posterior and recurrent choroidal circulations are in direct continuity with one another at the equator, and that even when there is no direct continuity the intervening capillary network is narrow. There is, therefore, no sound anatomical basis for the concept of a defective circulation at the equator, and it is interesting to examine more closely how this hypothesis was put forward. To a limited extent the hypothesis was based on the anatomical studies of Leber (1903) but in the main it obtained its chief support from an interpretation of the visual field changes in retinitis pigmentosa with the fundamental supposition that the retinal changes are secondary to choroidal degeneration (Gonin,1903, and Nettleship, 1903). It is now known, however, that although patches of choroidal angio-sclerosis may occur in retinitis pigmentosa (Greeves,1912) they are not an essential part of the pathological picture (Cogan,1949), and, indeed, may even be completely absent (Collins,1919,and Verhoeff,1931).

In a study of a hereditary pigmentary degeneration of the retina in rats (Bourne, Campbell and Tansley,1938) and in dogs (Parry,1953) , a condition which appears to be closely allied to retinitis pigmentosa in the human, it has been shown that the retinal disturbance is the primary lesion without any underlying choroidal lesion.

Furthermore, as pointed out by Hancock (1906), the ring scotoma of retinitis pigmentosa is not in the correct position for a scotoma due to a lesion at the anatomical equator because it does not lie far enough out in the periphery of the field, nor is it concentric with the blind spot. Hepburn (1908) in an attempt to overcome the difficulties raised by Hancock postulated that the short posterior ciliary arteries do not necessarily reach as far as the equator because their terminations are determined primarily by the site of exit of the vortex veins. There is, however, no anatomical evidence for this view.

There would not appear to be any sound basis for drawing conclusions regarding the pattern of the choroidal circulation from a study of the retina in retinitis pigmentosa, and the finding, in this present investigation, of an effective anastomosis between the posterior and recurrent choroidal circulations at the equator does not conflict with modern views on the pathogenesis of the disease. It is most likely that, as originally suggested by Lister (1903), retinitis pigmentosa is a primary neuro-epithelial degeneration and the occurrence of a ring scotoma in the early stages of the condition represents a selective degeneration of a particular region of the retina (Collins, 1919).

In any case doubt may be cast on the hypothesis that because an area lies between the terminal parts of two opposing and anastomosing circulations it is ineffectively supplied by blood. It may even be that such an area is particularly well served because it can draw on blood from two circulations.

It is convenient at this stage to discuss the view put forward by Hepburn (1910) that the choroid is a series of terminal vascular systems which, in disease, may be separately affected without necessarily involving neighbouring vessels; a view which was based to a large extent on an interpretation of the visual field changes in retinitis pigmentosa in the belief that the disease is a primary choroidal affection. The choroid was divided by Hepburn into three main zones - first, the macular, secondly, the mid-peripheral and, thirdly, the extreme peripheral zones - with further subdivisions within each zone so that the choroid was regarded as a series of isolated areas each of which may respond to disease in an individual manner. It should be remembered, however, that these zones refer only to the ophthalmoscopically visible choroid, and do not denote any exact anatomical location. The "macular" zone, according to Hepburn, lies between fixation point and the 20° circle concentric with the fixation point, the "mid-peripheral" zone lies between the 20° and 60° circles, and the "extreme peripheral" zone lies between the 60° circle and the region of the anatomical equator. Hepburn regarded each zone as a separate entity with only a few intervening capillary anastomoses, but as has been shown above his conclusions would not appear to be based on sound premises.

There is further evidence against the concept of a defective anastomosis at the equator. It has been shown that after optico-ciliary resection many areas of the choroid behind the equator may be spared (Komoto, 1915, and Cogan, 1949), particularly if the anterior ciliary arteries are left intact (Berlin, 1871; Studer,1906; and Birch-Hirschfield, 1910). This may be explained readily on the basis of an effective anastomosis between the posterior and recurrent choroidal circulations at the equator, so that even after total occlusion of the short posterior ciliary arteries it is possible for at least part of the pre-equatorial region of the choroid to be maintained from the anterior circulation. It is, therefore, unnecessary to postulate, as has been done by Komoto (1915), that retention of part of the posterior choroidal circulation in such cases indicates a failure to secure complete obliteration of all the short posterior ciliary arteries during the optico-ciliary resection.

Thirdly, there is doubt regarding the validity of the hypothesis that the periphery is a specialised area of the choroid in that it represents a distinct zone isolated from the rest of the choroid.

Indeed, the idea of an isolation of the peripheral part of the choroid is untenable in view of the direct anastomoses which have been /demonstrated between demonstrated between the anterior and posterior parts of the choroid at the equator. Furthermore, it is not necessary to endow the periphery of the choroid with any special features in order to explain the fact that after blockage of the central retinal artery the whole thickness of the retina in the extreme periphery may remain viable, whereas elsewhere the inner half of the retina becomes degenerate. It has been shown by Michaelson (1950) that the choroid in general supplies nourishment to the retina to a depth of about 130 microns. This thickness covers the pigment layer, the layer of rods and cones, and the outer nuclear and plexiform layers over the whole of the retina except in the extreme periphery and at the macula where the retina narrows to about that thickness.

It is not surprising, therefore, that the retina in the extreme periphery may be nourished exclusively by the choroid, and that part of the transudate from the peripheral choroid may even pass through the attenuated retina to contribute to the formation of the aqueous humour, but these unusual features would appear to be attributable to peculiarities of retinal rather than of choroidal structure.

This is in keeping with the failure to find any specific features in the peripheral part of the choroid in an examination of casts of the choroid prepared by the intravascular injection of Neoprene. It is true that the capillaries of the choroid are not uniform in calibre throughout the chorio-capillaris - posteriorly they are smaller with a narrow intercapillary network and anteriorly they are wider with a more open network - but this variation in calibre is a gradual transition which occurs in passing from the central to the peripheral parts of the choroid and there is no sharp distinction between individual areas.

> Fourthly, there is doubt regarding the validity of the hypothesis that the peripapillary region is a specialised area of the choroid in that it is supplied by an exclusive system of arteries isolated from the rest of the choroid.

It is true that within the peripapillary region of the choroid, unlike the other parts of the choroid, there are many fine arterial branches which pass from the intrascleral arterial circle of Zinn, but there are also many fine arterial branches which arise directly from the short posterior ciliary arteries. Other branches of the same short posterior ciliary arteries pass to the rest of the posterior part of the choroid, and, therefore, it is difficult to postulate that the vessels in the peripapillary choroid are divorced from the other choroidal vessels. There is certainly no anatomical evidence to substantiate the view of Klien (1950) that peripapillary choroidal atrophy is due to sclerosis of the circle of Zinn. Furthermore, the capillaries of the peripapillary region are directly continuous with the main mass of the chorio-capillaris so that they also are not isolated from the rest of the choroid.

Fifthly, there is doubt regarding the validity of the hypothesis that the submacular region is a specialised area of the choroid in that it has distinctive features particularly in its capillary layer.

An examination of the casts of the choroidal circulation failed to reveal any structural distinction of the submacular chorio-capillaris as compared with any other part of the chorio-capillaris situated an equivalent distance from the optic disc. There is, of course, a marked difference between scattered areas because of the gradual opening of the capillaries on passing from the central to the peripheral parts of the choroid, but the density and calibre of the chorio-capillaris in any area appear to be purely expressions of the distance away from the optic disc without any reference to particular zones like the submacular region. It is interesting to note that Mörike (1949) found a uniform thickness of the chorio-capillaris throughout the choroid in the bifoveal eye of the sea-swallow.

The fact that the macular part of the retina is avascular does not necessarily mean that there must be unusual features in the submacular choroid for similar reasons to those discussed in the review of the peripheral part of the choroid. The macula is an attenuated part of the retina (Michaelson,1950; and Denton and Pirenne, 1952) - it is about 130 microns in thickness - and this is a depth which can be catered for exclusively by the normal choroid without postulating any additional choroidal blood supply. There is also no necessity to postulate on anatomical grounds a secondary oxygen-carrying system within the macula, like the suggestion of Dartnall and Thomson (1949) that the yellow retinal pigment mediates an oxygen-carrying system which prevents anoxia of the macula. There is no reason why the macula should not be adequately nourished simply by the submacular choroid.

There are, of course, an increased number of arterial vessels in the submacular choroid, and it is interesting to speculate whether this is due merely to the greater number of short posterior ciliary arteries which perforate the globe in the neighbourhood of the posterior pole of the eye, or whether it is determined by some basic physiological stimulus. Both Nettleship (1903) and Mörike (1950) postulated that there is greater preponderance of choroidal arteries in the submacular region in response to the higher metabolic demands of the specialised macula.

In view of the retinal attenuation at the macula, however, there is certainly no evidence for this assumption on anatomical grounds, and in any case there is no reason why a mere increase in arterial branches should affect the nutrition of the macula in the absence of associated specialised features of the submacular chorio-capillaris. As was shown in an examination of the Neoprene casts many of the arteries in the submacular choroid pass on to other areas of the choroid without contributing anything to the capillaries under the macula.

There is no evidence for the view of Nettleship (1903) that certain ocular diseases are limited to the posterior pole because of

/ the implication

the implication of a particular short posterior ciliary artery in the disease process. In the first place, the submacular choroid is not supplied by one special artery, and, in the second place, the submacular chorio-capillaris is in direct continuity with the rest of the chorio-capillaris. This means that even if there was a special artery to the submacular region a localised patch of atrophy would follow arterial block only if the obliterating process extended into the chorio-capillaris. This view that survival of the chorio-capillaris is compatible with obliteration of a few feeding arteries has been discussed earlier, and it is interesting to note that Berlin (1871) was impressed by how little the chorio-capillaris was affected by extensive optico-ciliary section.

Similarly, benign melanomata of the choroid may affect quite a large area of the vessel layer without encroaching on the chorio-capillaris (Cogan, 1949). In these cases the function of the overlying retina remains normal, evidence that the chorio-capillaris is unaffected despite the involvement of some of the feeding arteries. When, however, malignant change supervenes the chorio-capillaris becomes obliterated by direct spread and the overlying retina ceases to function.

There does not appear, therefore, to be any clear-cut anatomical evidence of a peculiarity in the vascular architecture of the submacular choroid to account for the circumscribed lesions which occur in that region. The answer to the problem must lie in the chorio-capillaris because, as has been shown, an area of choroid becomes atrophic only when its capillaries are affected, and yet it is difficult to understand the underlying mechanism of capillary involvement.

It has been suggested by Ashton (1953) that although circumscribed areas of choroidal capillary loss may be attributed purely to some primary degenerative process, such areas may also occur as a result of a rise in the normal tissue pressure in the submacular area. A haemorrhagic or exudative extravasation exerts a definite effect within the choroid because expansion of the choroid is greatly limited by the force of the normal intra-ocular pressure on the inner side, and the lack of elasticity of the rigid sclera on the outer side. The choroidal capillaries, by virtue of their delicate structure, are more affected by such a rise in tissue pressure than the more resistant vessels.

It is interesting to recall a case described by Klien (1950) of heredo-degeneration of the macula which showed on pathological examination a localised detachment of the macula due to a serous extravasation in the submacular space. It may be that this represents the early stage of the disease, and that the degeneration of the chorio-capillaris follows as a result of a pressure effect from an extravasation. It is also of interest to note that Sorsby and Crick (1953) claimed that the earliest pathological change in cases of central areolar choroidal sclerosis is an exudative reaction.

This hypothesis provides a possible explanation for the isolated patches of choroidal atrophy which occur not only in the submacular region but also in other parts of the choroid during the course of certain traumatic, inflammatory or degenerative conditions. On such a basis the the peripapillary atrophy which may follow severe blunt trauma of the globe is not due solely to the rupture of the fine vessels within the peripapillary region, as suggested by Bartolozzi (1952), but is also due to the effect of the pressure of the associated haemorrhagic extravasation on the chorio-capillaris.

Similarly, the loss of the chorio-capillaris within the chorio-retinal scar which follows an application of diathermy to the surface of the sclera during an operation for detachment of the retina may be determined primarily by the pressure on the capillaries of the sterile exudate which forms in response to the electro-stimulus. On the other hand a simple serous detachment of the choroid, whether occurring spontaneously or as a result of a perforating wound of the globe, is seldom associated with any permanent damage to the choroidal vessels or capillaries despite the presence of a serous exudate in the supra-choroidal space. In this type of condition, however, there is a well marked hypotonia of the globe, and consequently a reduction in the effective pressure of such an exudate.

An attempt has been made to investigate experimentally the effect on the choroidal vessels and capillaries of a localised rise in tissue pressure, and this will be reported in a separate appendix to this section.

In conclusion it must be emphasised that although the anatomical findings of this investigation of the choroid permit the establishment of certain hypotheses, they do not necessarily give any indication of the extent to which circulatory conditions may be modified in the living eye. The choroid is subjected to many neuro-vascular influences, and, although there is no anatomical evidence of choroidal segmentation, it may be that certain areas of the choroid assume functional distinctions.

APPENDIX A.

EXPERIMENTAL CHOROIDAL LESIONS.

Introduction.

This appendix contains a short account of certain experimental observations which are being made on the ocular circulation. It is included in the thesis because of its bearing on the hypothesis, put forward at the end of section I, that a circumscribed area of choroidal degeneration may follow an increase in the tissue pressure within a localised part of the choroid due, for example, to a haemorrhagic or exudative extravasation.

The method involves the introduction of activated plasma into a particular area of the suprachoroidal space of the rabbit's eye, and subsequent determination of the effect of the pressure of this clot on the surrounding choroid.

Materials.

1) Rabbits.

14 young rabbits which varied between 1.5 and 2.5 kgs. in weight were used in the experiment. They were fed on a Blue Cross No.41 diet.

2) Activated plasma.

Two substances, a chick extract and a fowl or rabbit plasma, were used in the preparation of the activated plasma.

The chick extract was obtained from a 10 day-old chick embryo by mincing the embryo in 3-4 ml.physiological saline and then, after allowing the mixture to stand for 10-15 minutes, centrifuging it to remove the cells. The extract was diluted with physiological saline (1 part extract to 3 parts saline) and used in its fresh state.

The plasma was obtained from fowl or rabbit blood collected under sterile conditions in a chilled vessel containing heparin (2 units/ml. blood). The blood was centrifuged to remove the cells, and the plasma stored in waxed bottles at-20°C. It was diluted before use with physiological saline (1 part plasma to 1 part saline).

The plasma was activated by adding it to the chick extract (1 part plasma to 1 part extract), and once activated the plasma formed a clot within a few minutes.

3) Instruments and appliances.

The instruments and appliances used in the production of the choroidal lesion are described under technical methods, and those used in the examination of the choroidal lesion are similar to those described in section I of this thesis (p.p.15 - 16).

Technical Methods.

1) Formation of localised choroidal lesion.

The rabbit was anaesthetised by the intravenous administration of nembutal (0.45 ml.nembutal / Kg.body weight - each ml. nembutal

/ contained

contained 60 mg. 10% nembutal alcohol and 60 mg. 20% propylene glycol). The anaesthetised rabbit was laid on its left side and the right eye proptosed by exerting gentle but firm backward pressure on the under-surface of the globe with the handle of a small scalpel. This manoeuvre provided good exposure of the upper surface of the eyeball, and at the same time ensured a reasonable degree of immobility of the globe.

The upper aspect of the sclera behind the equator was exposed through a conjunctival incision by clearing away the overlying subconjunctival and episcleral tissues, and a very small radial incision was made with the point of a narrow Graefe knife through the sclera on the medial side of the superior rectus muscle about 7-10 mm. behind the limbus. Great care was taken to prevent any serious damage to the underlying choroid, but in a few eyes the completion of the scleral incision was associated with a small amount of choroidal haemorrhage. An iris repositor was then inserted through the scleral incision into the suprachoroidal space. It was difficult to enter this space without causing some haemorrhage from the choroid and in a few eyes there was even a small escape of vitreous. However, once the repositor was within the suprachoroidal space it was relatively easy to open up the space further by passing the repositor in a forward direction for about 5 mm. with care to maintain the repositor against the inner surface of the sclera. The iris repositor was then withdrawn and 0.05 - 0.10 ml. activated plasma, prepared by the method described above, was injected into that part of the suprachoroidal space opened up by the repositor from a tuberculin syringe through a lacrimal cannula connected to the syringe. It was essential to carry out this injection without delay after activation of the plasma, by the addition of chick extract, otherwise a clot would have formed before the injection was completed.

The effect of these procedures was observed ophthalmoscopically and this was facilitated by previous instillation of gutt.atropin 1% into the conjunctival sac.

2) Examination of choroidal lesion.

The eye was observed ophthalmoscopically on several occasions following the production of the choroidal lesion, and, after an interval of 5 - 39 days (average interval 17 days), the eye was removed for pathological investigation.

The rabbit was anaesthetised by the intravenous administration of nembutal, as described above, and the right carotid artery exposed in the neck through a vertical median incision. On exposure of the artery gutt.pantocaine 1% was applied to its surface to reduce the tendency for the development of arterial spasm during its manipulation. Two ligatures were placed round the artery, and the proximal one tied to stop the circulation within the artery. The artery was held in position by the distal untied ligature, and a small incision made through the upper surface of the artery between the two ligatures with a pair of fine spring scissors. A glass cannula was passed in a cephalic direction into the artery through the incision and maintained in place by tightening the untied ligature.

The blood vessels of the head and neck region were irrigated thoroughly by injecting 100 ml. water through the cannula from a large hand syringe connected to the cannula by rubber tubing. Immediately after starting the irrigation one of the large superficial veins in the neck was cut to facilitate complete removal of the blood by the irrigating fluid. The syringe containing the water was then replaced by another syringe containing Neoprene (the rubber tubing near the syringe was clamped during this change-over), and 50 ml. Neoprene were injected into the circulation. Both eyes were removed by enucleation and fixed in 10% formol saline. The right eye was examined to determine the nature of the choroidal lesion and the left eye was examined as a control in certain cases where there was doubt regarding the efficiency of the Neoprene injection.

After fixation, the globe was opened by a coronal incision through the posterior part of the ciliary body, and the lens removed with the discarded anterior segment. The vitreous was separated from the globe by carefully dislodging it with blunt forceps aided by the influence of gravity. The retina was removed under water by detaching its peripheral part in towards the centre of the globe, and gradually extending the detachment so that the retina remained adherent only at the optic disc. This attachment was freed by careful dissection with fine forceps. The choroid also was separated from the sclera under water, starting at the periphery and working in towards the centre, with careful division of any vessels or nerves crossing the suprachoroidal space. The attachment of the choroid at the optic disc was freed with fine forceps.

The choroidal lesion was examined under the wide-field stereoscopic microscope with direct illumination from two high-power low-voltage filament lamps, both before and after removal of the choroid from the globe. Any small remnants of clot which remained in the area of the lesion were removed in order to expose completely the architecture of the vessels within that region.

Findings.

None of the eyes developed any clinical manifestations of uveitis or other intra-ocular inflammation during the interval between the production of the choroidal lesion and the removal of the eye for examination, and on opening the eyes after fixation, there were no macroscopic signs of any gross inflammatory process.

Only remnants of the clot remained at the time the globes were opened for examination, and to a large extent these fragments were present within the suprachoroidal space. There were also, however, some particles within the choroid and in the subretinal space, and in a few eyes a small amount of plasma was found within the vitreous on the inner surface of / the retina.

the retina. In 9 eyes a small hole was found in the choroid corresponding in situation to the scleral wound (figs.28 and 30) and in 5 eyes another small hole was present in the choroid at the point where the tip of the cannula lay during the suprachoroidal injection (figs. 28 and 29). In addition to the occurrence of choroidal holes each eye injected with activated plasma showed an area of defective choroidal filling corresponding to the region of the choroid occupied by the plasma clot. This filling defect was limited mainly in some eyes to the chorio-capillaris (figs.28 and 29), but in other eyes the vessels also failed to fill either partially (fig.30) or completely (fig.31). Even those eyes, however, which showed a complete filling defect were unassociated with any rupture of the choroid in that area. Furthermore, there was no evidence of any sectorial filling defect of the choroid extending from the circumscribed defective region. The findings are tabulated in fig.32.

Discussion.

It is apparent that two different types of lesion occurred in the choroid following the suprachoroidal injection of activated plasma.

The first type of lesion consisted of one or sometimes two small choroidal holes which were found in certain eyes in relation to the perforating scleral wound or in relation to the position occupied by the tip of the cannula during the suprachoroidal injection. There is little doubt that these holes were produced by direct trauma at the time of the operative interference. It is difficult to avoid damaging the choroid during the final stages of the scleral incision, and even more difficult to prevent some disturbance of the choroid during the insertion of the iris repositor into the suprachoroidal space. These difficulties presumably account for the occurrence of small tears of the choroid below the scleral opening. Similarly, the choroid may be damaged by the force of the injection causing a small choroidal tear at the farthest end of that part of the suprachoroidal space opened up by the iris repositor. This mechanism probably accounts for the second small choroidal hole found in some eyes, and it may have contributed also to the formation of the hole underlying the scleral wound.

The second type of lesion consisted of a fairly large circumscribed area of defective choroidal filling with a predominant effect on the chorio-capillaris. This area corresponded in position to the area occupied by the plasma clot, and, in the eyes in which there were also choroidal tears, it lay between the holes. This filling defect is due to a partial or even complete obstruction of the circulation within a localised area of the choroid. It is not due merely to a mechanical pressure of the plasma clot preventing the Neoprene from entering the affected area, because, in practically all eyes, the plasma clot persisted in only a fragmented form at the time of the Neoprene injection.

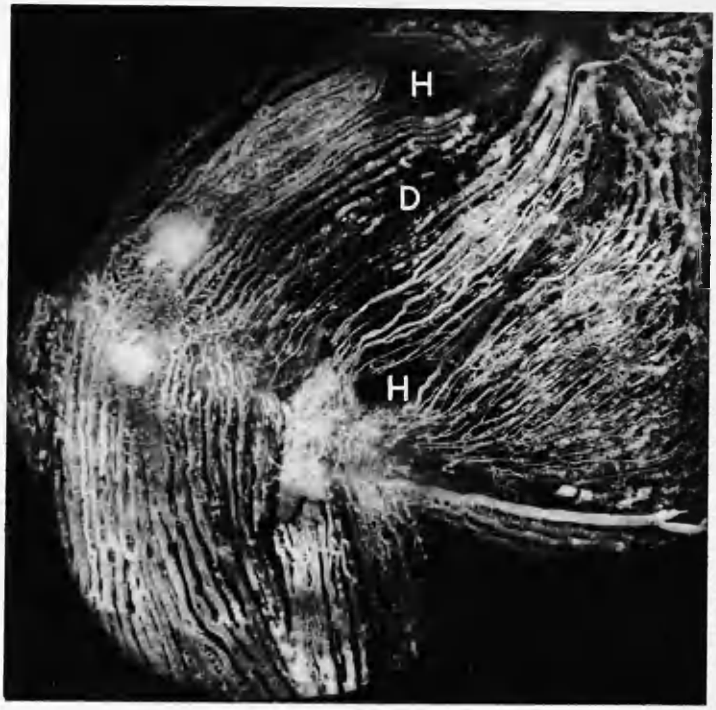


FIG. 28. White Neoprene cast of isolated choroid of rabbit to show circumscribed area of partially defective choroidal filling (D), particularly affecting choriocapillaris, between two small choroidal holes (H). x 15. (Rabbit no. 1021.)

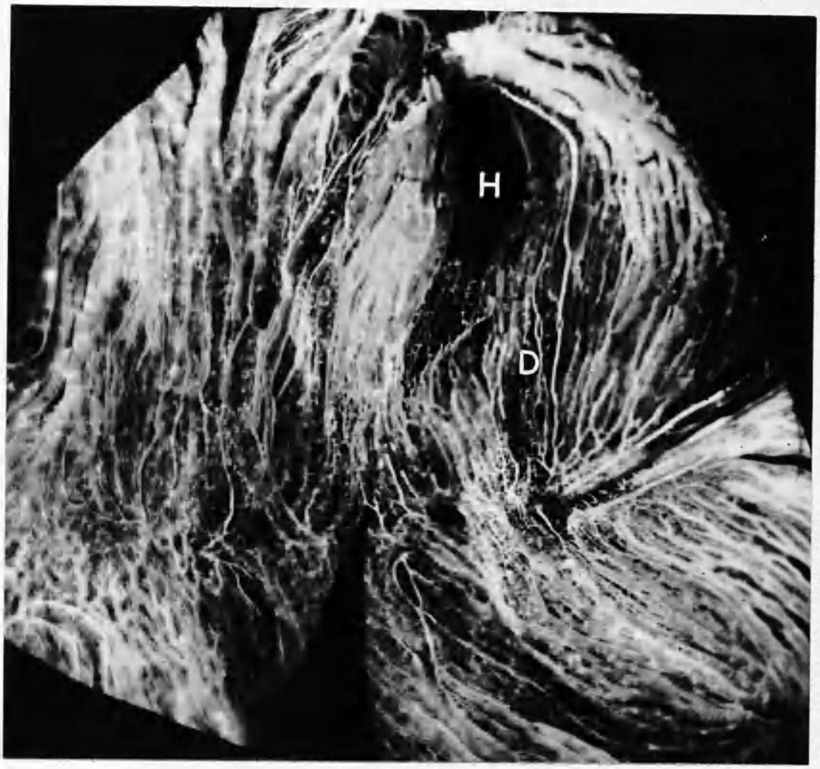
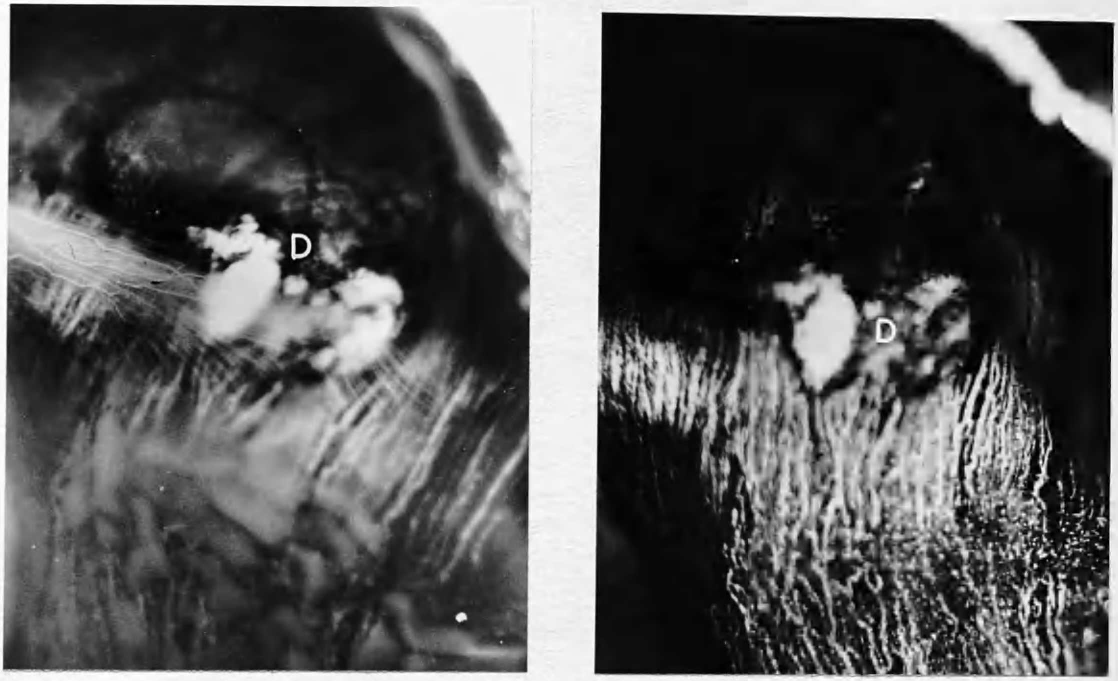


FIG. 29. White Neoprene cast of isolated choroid of rabbit to show circumscribed area of defective filling of chorio-capillaris (D) adjacent to choroidal hole (H). (This hole was inadvertently enlarged during removal of choroid from globe.)

x 15.

(Rabbit no.1161).



a b

FIGS. 30 a and b. White Neoprene injection of ocular vessels of rabbit to show circumscribed area of choroidal filling defect (D), before (fig.30 a) and after (fig.30 b) removal of retina.

(a) and (b) x 12.

(Rabbit no.24).

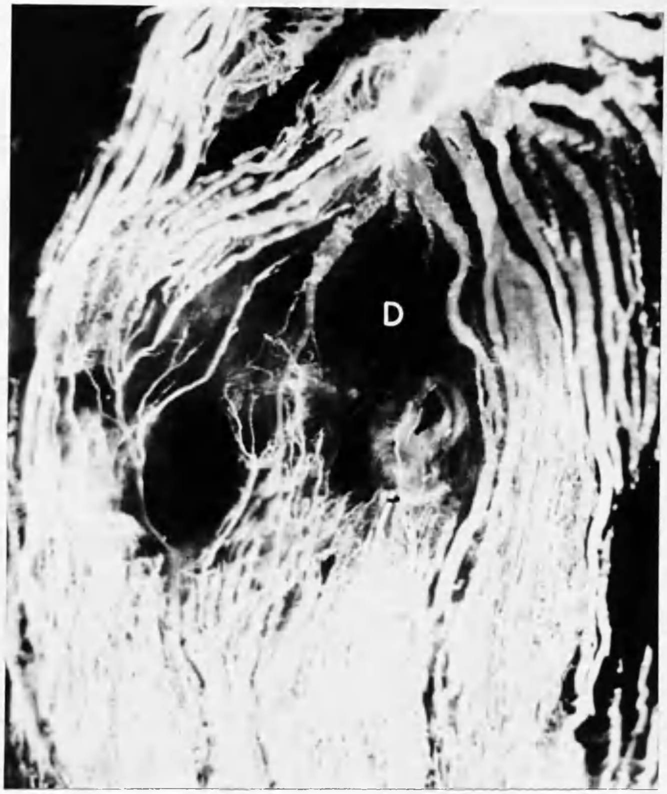


FIG. 30 c. White Neoprene cast of isolated choroid of rabbit to show circumscribed area of partially and completely defective choroidal filling (D). x 22. (Rabbit no.24).

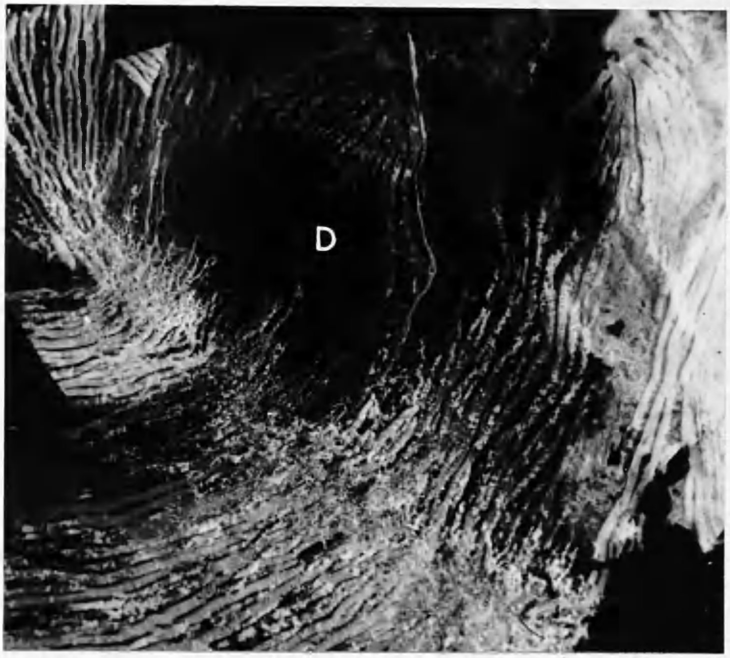


FIG. 31. White Neoprene cast of isolated choroid of rabbit to show extensive area of partially and completely defective choroidal filling (D). x 15. (Rabbit no.1162).

FIG. 32. Table to show effect on choroid of activated plasma in suprachoroidal space.

Rabbit No.	Volume of activated plasma in supra-choroidal space.	Time interval between injection and final examination.	Type of choroidal lesion.
1021.	0.05 ml.	5 days.	Circumscribed partial filling defect.
1161.	0.05 ml.	6 days.	Circumscribed partial filling defect.
1162.	0.05 ml.	6 days.	Circumscribed partial and complete filling defect.
1020.	0.05 ml.	7 days.	Circumscribed partial filling defect.
833.	0.05 ml.	10 days.	Circumscribed partial filling defect.
825.	0.10 ml.	11 days.	Circumscribed partial and complete filling defect.
782.	0.10 ml.	13 days.	Circumscribed partial and complete filling defect.
277.	0.05 ml.	21 days.	Circumscribed partial and complete filling defect.
207.	0.10 ml.	21 days.	Circumscribed partial filling defect.
826.	0.05 ml.	22 days.	Circumscribed partial filling defect.
827.	0.05 ml.	22 days.	Circumscribed partial filling defect.
783.	0.05 ml.	28 days.	Circumscribed partial and complete filling defect.
276.	0.05 ml.	31 days.	Circumscribed partial filling defect.
24.	0.10 ml.	39 days.	Circumscribed partial and complete filling defect.

Furthermore, the filling defect is not due to rupture of that area of the choroid during the suprachoroidal injection because, except for the occurrence of small choroidal holes as described above, the choroidal "membrane" was intact over the area occupied by the plasma clot. Any plasma which entered into the subretinal or vitreous space is likely to have done so through one of the choroidal holes.

This short experimental investigation would appear to substantiate the hypothesis put forward in the preceding section, that a haemorrhagic or exudative extravasation within and around the choroid may exert a pressure effect on a localised area of the choroidal vascular bed, particularly the chorio-capillaris, with the production of a circumscribed region of partial or complete choroidal atrophy, without the formation of any sectorial defect.

APPENDIX B.

EXAMINATION OF HYPOTHESIS THAT ARTERIO-VENOUS ANASTOMOSES ARE PRESENT IN THE CHOROID.

In a study of the normal choroid Kiss and Orbán (1951) noted the occurrence of small swellings (bulbiculi) in the walls of the venules which they believed to be the site of arterio-venous anastomoses. They also postulated that these anastomoses perform an important function in the control of the choroidal circulation, a view which had been put forward earlier by Loewenstein (1949), although Loewenstein did not demonstrate the actual site of any such anastomosis.

In a more recent study of the choroid, Ashton (1952) confirmed the presence of the bulbiculi but he showed that they were simply the result of compression of the venule by the overlying arteriole, and that they were not the site of any arterio-venous communication. His view is confirmed in this investigation because no evidence was found of any arterio-venous anastomosis in any part of the choroid despite careful examination and dissection of 20 Neoprene casts of the choroidal vessels.

This does not exclude, of course, the occurrence of arterio-venous anastomoses in certain pathological conditions of the choroid. Cristini (1950) put forward the hypothesis that the reduction in the capillary bed of the choroid, which occurs in chronic simple glaucoma, is associated with the development of arterio-venous anastomoses. It may be that in such cases a capillary channel between a terminal arteriole and a commencing venule dilates sufficiently to constitute a direct anastomosing vessel between the artery and vein, and it is of interest to note that Ashton, Ward and Serpell (1954) found peripheral arterio-venous anastomoses in the retina of kittens following severe vaso-obliteration of the retinal circulation induced by exposure to oxygen. There is, however, no evidence that arterio-venous anastomoses are a feature of the normal choroid.

SECTION II.

ANASTOMOSES BETWEEN UVEAL AND RETINAL CIRCULATIONS AND THEIR SIGNIFICANCE IN VASCULAR OCCLUSION.

Introduction.

Bruch's membrane, in its healthy intact state, forms an impenetrable barrier to the passage of blood vessels and, as a result, there are no anastomoses within the normal globe between the uveal and retinal circulations. Under certain pathological conditions when the continuity of Bruch's membrane is disturbed, direct anastomoses may occur between the uveal and retinal vessels as, for example, in the case of thrombosis of the central retinal vein described by Michaelson (1950) where a direct channel was established between the retinal and choroidal veins through a dehiscence in the elastic lamina.

The region of the ora serrata was investigated by Leber (1903) as a possible site for uveo-retinal vascular anastomoses with entirely negative results, and, all subsequent searches for such anastomoses have centred around the region of the optic nerve head where the ciliary and retinal blood vessels pass close to one another as they enter or leave the globe.

Previous Descriptions of Uveo-retinal Vascular Anastomoses.

Uveo-retinal arterial anastomoses.

Anastomoses between, first, the arterial circle of Zinn and the central retinal artery, and, secondly, the choroidal arteries and the central retinal artery, have been postulated in the region of the optic nerve head by Nettleship (1876), Leber (1903) and Coats (1905). Nettleship (1876) considered that the first of these anastomoses is purely a capillary one but that the second is of a more direct nature. On the other hand, Leber (1903) regarded both anastomoses as capillary in type, although it is interesting to note that he was not too happy about this conclusion because he qualified it by saying that the whole matter merited a further and more detailed investigation.

Coats (1905) shared Leber's view that both anastomoses are capillary in nature although he believed that, following occlusion of the central retinal artery, the fine capillary anastomoses may dilate sufficiently to become visible ophthalmoscopically as fine arterial networks around the optic disc. Coats substantiated his viewpoint by the hypothesis that the haemorrhages which he found in the peripapillary part of the retina in certain of these cases were due to the rupture of the fine anastomotic vessels during the process of dilatation. Gonin(1905) also described similar anastomotic channels in cases of central retinal arterial block; vessels which emerged from the disc margin and passed into the retina to join the attenuated retinal arteries. The retinal arteries lost their thread-like appearance distal to this point of union.

Coats (1913b) showed that, after total occlusion of the central retinal artery, an area of light perception may remain around the blind spot particularly on its temporal aspect. It is possible, of course, for the retina immediately adjacent to the optic disc to derive a certain amount of nourishment from the normal capillaries of the optic nerve head,

/ but Coats considered

but Coats considered that the area of sparing was too great for such an explanation and he postulated that the retention of light perception in the peripapillary field was further evidence for the existence of uveo-retinal arterial anastomoses. Some years earlier, Se Schweinitz and Holloway (1908) put forward a similar hypothesis to explain the retention of light perception around the blind spot in cases of retinal artery block.

It is important to distinguish clearly these uveo-retinal arterial anastomoses from the so-called cilio-retinal arteries which have been described by many observers (Nettleship 1877; Randall, 1887; etc.). Uveo-retinal arterial anastomoses constitute a direct link between the ciliary arterial circulation and the main stem of the retinal artery, whereas cilio-retinal arteries are small retinal arteries which occur in a certain number of normal eyes (23% according to Lang and Barrett,1888) and which are derived, not from the retinal circulation, but from the ciliary circulation through the circle of Zinn. It follows, therefore, that in the event of a sudden blockage of the central retinal artery although blood ceases to circulate in the main retinal arteries it continues to flow in a cilio-retinal artery. However, a cilio-retinal artery is a true end-artery which supplies only a localised segment of the retina, commonly on the temporal aspect of the optic disc, and its presence is of no avail in the restoration of the circulation within the main retinal arteries. This is in contrast to a uveo-retinal arterial anastomosis which, if present, provides an alternative pathway for the passage of blood into the whole retinal circulation, despite the continuance of the occluding process in the central artery of the retina. It is, of course, essential for such an anastomosis to lie on the distal side of the arterial occlusion .

A further type of anastomosis which must be distinguished from a uveo-retinal arterial anastomosis is the so-called inter-retinal arterial anastomosis which occurs as a rare event after occlusion of a single branch of the retinal artery within the retina. Coats (1913c) described such a case in which a collateral artery linked a patent retinal arterial branch to the occluded one with consequent restoration of circulation in the affected branch distal to the point of union. An inter-retinal arterial anastomosis is not relevant, however, in a discussion of the pathological events which may follow occlusion of the main stem of the central retinal artery.

In addition to the importance of uveo-retinal arterial anastomoses from a pathological point of view, evidence has been put forward recently by Sautter and Seitz (1952) that such anastomoses may also have a physiological significance. In an experimental investigation on the rabbit, Sautter and Seitz found, under normal conditions, that a vital dye injected intravenously passed along the retinal artery to the lamina cribosa where it was diverted to the arterial circle of Zinn within the sclera, but

/ after the use of

after the use of a sympatholytic agent, the dye passed along the retinal artery into the retina without being diverted to the circle of Zinn. This was regarded as evidence for the existence of an anastomosis between the central retinal artery and the circle of Zinn, at the level of the lamina cribrosa, under vegetative control through the mediation of a glomus apparatus at the point of origin of the anastomotic channel from the central retinal artery.

Sautter and Seitz regarded the flow along the anastomotic channel as a uni-directional one so that the blood only passes from the central retinal artery to the circle of Zinn, and never in the reverse direction. They described the existence of two arterial rings within the circle of Zinn, a lower one formed by branches from two or three short posterior ciliary arteries, and an upper one connected to the lower ring from which it obtains its blood by a process of suction. Both rings are connected to the central retinal artery by anastomotic branches. According to Sautter and Seitz these anastomotic channels divert blood from the retinal artery to the circle of Zinn and act as a mechanism which protects the retina from an excess of blood; the arterial rings, by virtue of their free connection with the choroid and with the arterial plexus to the pia mater surrounding the optic nerve head, are less likely to be embarrassed by an additional volume of blood than the retinal arteries which are functional end-arteries.

This is an interesting study and it gives the arterial circle of Zinn a hitherto unknown physiological significance, but it does not provide any information regarding the exact site and nature of the uveo-retinal anastomotic channels. The existence of such channels has been inferred from the results of the experiment rather than from anatomical observation. In fact Sautter and Seitz merely restated the original hypothesis of Leber (1903) that the anastomoses are only of capillary dimensions, and it is difficult to relate the physiological implications of their experimental work to such a poorly developed anastomosis. Parsons (1906), who also agreed with Leber's finding of a capillary anastomosis, considered that this type of anastomosis is of little or no physiological significance. Furthermore, it is uncertain to what extent observations on the rabbit may be related to the human eye with its obvious structural and physiological differences.

It is interesting to note that Moffat (1952) described an analagous type of glomus apparatus in the dog. In this animal the retinal artery is a branch of a ciliary artery and, at its point of origin, Moffat found a subendothelial cushion of smooth muscle within the circular muscle of the ciliary artery, which he believed acts as a regulator of the blood passing into the retina, so that the retinal blood flow may be maintained even when the ciliary circulation is diminished.

There is, therefore, a considerable amount of evidence of an anatomical, pathological and physiological nature to suggest that there are uveo-retinal arterial anastomoses within the optic nerve head, but there is also some evidence which conflicts with such a concept.

Magitot (1908), Beauvieux and Ristitch (1924) and Behr (1935) failed to demonstrate any anastomosis between the ciliary and retinal arteries and, furthermore, they all considered that such anastomoses are impossible on the grounds that no branches arise from the central retinal artery within the optic nerve tissue. At one time the view that the central retinal artery continued through the optic nerve without giving off any branches was supported by Wolff (1938 and 1939), but later Wolff (1948) showed, in a histological preparation of the optic nerve, that a small branch arose from the central artery in the region of the lamina cribrosa. He did not demonstrate any anastomosis of this arterial branch with any other artery in the optic nerve head but he considered that it was presumptive evidence of at least a capillary anastomosis between the retinal and ciliary circulations.

Bignell (1953) described branches which came off the central retinal artery just behind the lamina cribrosa but which came to an end in the nerve tissue of that region without forming any anastomosis with the other arteries in the optic nerve head derived from the arterial circle of Zinn. Branches of the central retinal artery in the laminar part of the optic nerve were also shown by François and Neetens (1954), but the branches were considered to pass directly to the retina without taking part in any anastomosis. In this way all the branches of the central retinal artery, whether arising within the optic nerve or at the optic nerve head, were regarded as strictly terminal arteries to the retina.

François and Neetens found, however, another artery - the central optic nerve artery - which arose from the ophthalmic artery as a separate branch, accompanied the central retinal artery into the optic nerve and then divided, first, into an anterior branch passing forwards to the lamina cribrosa in company with the central retinal artery and, secondly, a posterior branch passing backwards towards the optic foramen in the axial part of the optic nerve. They considered that the central optic nerve artery is nutritive to the deeper parts of the optic nerve, and that the anterior branch forms an anastomosis with other arterial branches in the laminar part of the optic nerve derived from the ciliary circulation. However, it is not possible to restore the retinal circulation, after occlusion of the central retinal artery by means of such an anastomosis, and, therefore, it is unimportant in relation to the study of anastomoses between the main retinal and ciliary circulations.

The central optic nerve artery would appear to be analagous to the collateral branch of the central retinal artery described by Beauvieux and Ristitch (1924), Behr (1935) and Wolff (1948). These observers found a collateral artery which arose from the central retinal artery within the orbit, accompanied the central retinal artery into the optic nerve and then divided into an anterior branch running forwards and a posterior branch running backwards in the axial part of the optic nerve. They did not consider, however, that any anastomosis was formed between the anterior collateral artery and any arterial branches of the ciliary circulation within the optic nerve head, and in this respect they differed from the conclusion of François and Neetens.

It is apparent, therefore, that not only is there a considerable amount of doubt regarding the exact situation and size of arterial uveo-retinal anastomoses, but there is even doubt as to their very existence, and in view of this uncertainty it was decided to investigate the whole arterial pattern in and around the optic nerve head.

Uveo-retinal venous anastomoses.

The existence of anastomoses within the optic nerve head between the uveal and retinal venous circulations is widely recognised, and several different anastomoses have been described. In the first place, a direct anastomosis was demonstrated by Elschnig (1888) at the level of the optic disc between the choroidal and central retinal veins. This anastomosis was confirmed by Coats (1906) who also described a second anastomosis which, unlike the first one, is of a more indirect nature. Coats showed that some of the choroidal veins in the peripapillary part of the choroid drain back into the pia mater surrounding the optic nerve head, and that the venous plexus in this part of the pia mater is in communication with the central retinal vein in the optic nerve through the trabecular venous branches. In this way a second although indirect channel of communication is formed between the uveal and retinal veins. Many other observers (for example, Beauvieux and Ristitch, 1924; Wolff, 1939 ; Sautter and Seitz, 1952, etc.,) have confirmed these two anastomoses.

A third anastomosis was claimed by Beauvieux and Ristitch (1924) between a venous circle which they described within the peripapillary part of the sclera and the central retinal vein at the level of the lamina cribrosa. This venous circle was regarded as a derivative of the uveal system, so that it represents the venous equivalent of the arterial intrascleral circle of Zinn. The existence of such a venous circle has not been confirmed by other observers and there is doubt, therefore, regarding the existence of this third type of anastomosis.

In most normal eyes the uveo-retinal venous anastomotic channels are believed to be only of capillary dimensions but as a rare phenomenon they may be sufficiently dilated to be visible with the ophthalmoscope. A clinical description was given by Lawford (1895) of a vein which corresponded in situation to the direct anastomotic channel described by Elschnig (1888), and Lawford's account was amplified by Coats (1906) who called the anastomotic channel an optico-ciliary vein. That part of the indirect anastomosis which joins the choroidal veins to the venous plexus in the pia mater has also been observed ophthalmoscopically in a few eyes (Thomson and Ballantyne, 1903) and named a chorio-vaginal vein.

/ It was shown

It was shown by Coats (1906) that chorio-vaginal veins occur more frequently in myopic than in hypermetropic eyes, and he believed this to be due to the embarrassment of the venous drainage in the posterior part of the choroid in the myopic eye following the excessive stretching of that part of the eye.

In a discussion of uveo-retinal venous anastomoses it should be noted that the so-called cilio-retinal veins are not really relevant to the main argument. Cilio-retinal veins were described originally by Nettleship (1876 and 1877), and are of relatively rare occurrence. They are small retinal veins which drain a localised area of retina but which, instead of draining back into the main central retinal vein, join directly with the choroidal veins. In the event of an occlusion of the central retinal vein the cilio-retinal vein is unaffected but the presence of this vein in no way facilitates venous drainage from the rest of the retina which is dependent on the central vein. In this way cilio-retinal veins are analagous to the arteries of the same name, and they do not assist in establishing any collateral uveo-retinal venous pathways.

Apparently there is a fairly general agreement on the existence of uveo-retinal venous anastomoses in the region of the optic nerve head, but it was decided to investigate them, partly, because the study is in any case complementary to the investigation of the uveo-retinal arterial anastomoses, and, partly, because of the great importance of such anastomoses in an understanding of the pathological events which follow occlusion of the central retinal vein.

Present Investigation.

Materials.

1) **Eyes.**

The uveo-retinal vascular anastomoses were examined in human eyes removed at post-mortem, but the eyes may be divided into two groups according to the method by which they were obtained.

First, 46 eyes were removed together with their orbital coverings, including the whole length of the optic nerve and the cavernous part of the internal carotid artery. This method has been described in detail in Section 1 (p.15). Each eye in this series was considered to be free from any local ocular disease or from any gross changes of a systemic nature, and the findings to be reported are regarded as those of the normal eye.

Secondly, 51 eyes were removed without their orbital coverings by simple enucleation. In this method the extra-ocular muscles were exposed by a circumcorneal conjunctival incision, and then severed close to their attachments to the globe. The optic nerve was cut as far behind the globe as possible. The eyes in this group were removed from diabetic subjects and in 30 of the 51 eyes there was clinical or pathological evidence of diabetic retinopathy. There is no direct evidence, however, that the diabetic condition seriously affected the results with regard to the occurrence of uveo-retinal vascular anastomoses. In any case the diabetic eyes may be completely excluded from consideration without affecting the conclusions of this investigation; they were used simply because they happened to be available, and because they provided corroborative evidence for certain of the findings of the normal eye.

2) Instruments and appliances.

The same instruments and appliances were used as described in Section I (pp.15-16).

TECHNICAL METHODS.

1) Methods of injection.

a) Injection of indian ink, carmine jelly, or Neoprene into central retinal vessels. (81 eyes).

The eyes subjected to this technique may be divided into two groups according to whether they were obtained together with their orbital coverings or whether they were removed by enucleation.

First, 30 of the eyes which were removed with their orbital

/coverings

coverings were irrigated thoroughly with water through the ophthalmic artery, and then dealt with in the following ways: -

In 28 of the eyes the optic nerve was exposed by dissection and cut transversely across at a point distal to the entry of the central retinal vessels into the nerve. These vessels were identified in the cut end of the nerve, and in most eyes it was relatively easy to distinguish the thicker-walled artery from the thinner-walled vein, particularly under conditions of good illumination and magnification. In certain eyes identification of the vessels was facilitated by placing a drop of Van Gieson's stain on the cut end of the nerve; this stain is taken up intensely by the vessel wall. A fine glass cannula, similar to that described for the injection of individual posterior ciliary arteries (p.18), was then inserted into the central retinal artery or vein. If any difficulty was experienced in this manoeuvre due to a tendency for the mouth of the vessel to collapse, it was found to be helpful to lightly swab the cut end of the nerve with 10% formol saline which increased the rigidity of the vessel wall. The retinal vessels of these 28 eyes were then injected as follows: -

In 17 eyes indian ink was injected into the central retinal artery and into the central retinal vein.

In 5 eyes carmine jelly was injected into the central retinal artery and indian ink into the central retinal vein.

In 5 eyes indian ink was injected into the central retinal vein only.

In 1 eye Neoprene was injected into the central retinal vein only.

The injections were carried out under pressure of about 70 mm. of water using a similar apparatus to that described for the Neoprene injections, and were continued for a period of about 3 - 5 minutes.

In the remaining 2 of the 30 eyes which were irrigated by way of the ophthalmic artery, 2 ml. of a weak solution of methylene blue were injected into the ophthalmic artery after completion of the irrigation. The orbital tissues were removed except in the region of the optic nerve which was dissected carefully to reveal the central retinal artery as it lay below the nerve prior to its entry into the nerve. The faintly blue colour of the methylene blue in the artery greatly facilitated its identification. A ligature was then passed round the artery and, using this as a retractor to keep the artery taut, a small cut was made through half the circumference of the vessel. A fine cannula was inserted through this incision and indian ink injected into the artery.

Secondly, the 51 eyes which were removed by enucleation were irrigated with tap water for 60 minutes through the central retinal vessels, placed in the refrigerator for 12 hours, irrigated again after being allowed to thaw, and then dealt with in the following ways:-

In 23 eyes indian ink was injected into the central retinal artery and into the central retinal vein.

In 18 eyes carmine jelly was injected into the central retinal artery and indian ink into the central retinal vein.

In 10 eyes indian ink was injected into the central retinal vein only.

b) Injection of Neoprene into entire ocular circulation. (16 eyes) .

The 16 eyes, which were removed together with their orbital coverings were irrigated with water and injected with Neoprene exactly as described in Section I (pp.16-17).

2) Methods of Examination.

a) Examination of choroidal vessels after injection of central retinal vessels. (79 eyes) .

79 of the 81 eyes which were irrigated with water either through the ophthalmic artery (28 eyes) or through the central retinal vessels (51 eyes) and injected through one or both of the central retinal vessels with indian ink, carmine jelly or Neoprene were fixed in 10% formol saline, and then the choroids were examined within the globe or after their removal from the globe, by the methods described in Section I.(pp18-19).

b) Examination of Neoprene casts of ocular vessels. (13 eyes).

Following the completion of the injection of Neoprene through the ophthalmic artery, 13 eyes were subjected to the action of digestive ferments. In order to accelerate this process all the extra-ocular tissues were cut away except in the region of the optic nerve where great care was taken to prevent any damage to the nerve or to the nearby posterior ciliary and retinal vessels. The injected eye in its fresh state was placed in a saturated solution of pepsin in N/10 hydrochloric acid for 7- 14 days at 37° C, and then in a saturated solution of trypsin in 1% sodium bicarbonate for 3 - 7 days at the same temperature. Neoprene is not susceptible to the action of digestive ferments so that a complete cast of the ocular vessels may be obtained, but it was found to be important to stop the digestive process before it was quite complete, otherwise, due to the loss of all supporting structures, it was extremely difficult to identify the various vessel groups within the tangled network of Neoprene injected vessels.

Each partially digested cast was placed in a large Petri dish which contained a thin layer of black paraffin wax, and enough water was poured on to the wax to cover the cast completely. The vessel groups were then identified and, if necessary pinned in position to the paraffin wax. (Fine glass pins were used in preference to steel ones because the latter cause contamination of the casts with rust particles after a few days under water). The remnants of the ocular tissues were carefully removed to complete the exposure of the Neoprene cast. It was found that the optic nerve offered most resistance to the action of the digestive ferments, and, therefore, even in well digested specimens it was necessary to remove some of the nerve tissues by dissection. This was not a difficult procedure, however, because the nerve became friable and fragments were removed piece by piece without disturbing the Neoprene injected vessels in and around the nerve.

The Neoprene cast was then subjected to a detailed dissection using the stereoscopic microscope and good direct illumination. In order to expose the fine vessels within the optic nerve head it was necessary, after removal of many of the surrounding vessels, to complete the dissection under fairly high magnification.

c) Examination of Neoprene injected vessels in situ. (3 eyes).

3 eyes which were irrigated with water and injected with Neoprene through the ophthalmic artery were fixed in 10% formol saline, and a dissection was made of the tissues in the region of the optic nerve head. By this method it was possible to expose the central retinal vessels within the optic nerve and the arterial circle of Zinn within the sclera, but the toughness and density of the fixed scleral and optic nerve tissues were such that a detailed dissection was only carried out with great difficulty and it was not possible to preserve the continuity of the finer vessels. The method has the advantage of showing the ocular vessels in their correct positions relative to one another (unlike the digested specimens wherein the spatial relationships are lost), but this advantage is greatly outweighed by the difficulties of the dissection.

d) Examination of indian ink injected vessels in situ. (2 eyes).

2 eyes which were irrigated with water through the ophthalmic artery and injected with indian ink through both central retinal vessels (one eye) and through the central retinal artery only prior to its entry into the optic nerve (one eye), were cleared, after fixation in 10% formol saline, by the Spalteholz method. This technique was devised

/originally

originally for the clearing of the tissues of small embryos to show up the blood vessels which had been injected with some dye substance, and the method may be applied to a study of the vessels of the eye.

The eyes were dehydrated by passing them through 80% alcohol (1 day), 90% alcohol (1 day), absolute alcohol (1 day) and fresh absolute alcohol (1 day). They were then placed in a mixture of benzol and absolute alcohol, 1 part of each, (1 day), pure benzol, (1 day), fresh pure benzol (1 day), and finally cleared by immersion in oil of wintergreen (3 parts of methylated spirits to 1 part of benzyl benzoate). The specimens were maintained in oil of wintergreen during examination and storage. The injected vessels were examined through the semi-transparent globes with the stereoscopic microscope and under direct illumination.

Findings.

Uveo-retinal arterial anastomoses.

In 10 of the 23 normal eyes which were irrigated with water through the ophthalmic artery, injected with indian ink or carmine jelly through the central retinal artery and examined for the presence of intravascular injection material in the isolated choroid, there was some filling of the choroidal arteries by the injection material. In 6 eyes this filling was limited to a few vessels in the immediate peripapillary region (fig.33), but in the other 4 eyes the filling was more extensive and involved several of the larger arteries within a particular sector of the choroid (figs.34 a and b).

There were also several other eyes in which the choroidal filling was limited to such a narrow area around the optic disc, or was of so scanty a nature, that it was impossible to distinguish arteries from veins with certainty (fig.35). The injected vessels appeared more like veins than arteries, and they have been recorded, therefore, as eyes showing venous filling only. On the other hand there may also have been some arterial filling, so the number of eyes showing choroidal arterial filling may be somewhat higher than recorded above.

In 8 of the 41 eyes removed from diabetic persons which were irrigated with water and injected with indian ink or carmine jelly through the central retinal artery and examined for the presence of intravascular injection material in the isolated choroid, there was some filling of the choroidal arteries by the injection material. This intravascular filling of the choroidal arteries was limited in 4 eyes to a few vessels adjacent to the optic disc (fig.36), but in the other 4 eyes the filling extended into several larger choroidal arteries lying within a sector of the choroid (fig.37). Of these 41 eyes, 23 showed evidence of diabetic retinopathy and 18 showed a normal retina, and of the 8 eyes which showed choroidal arterial filling after injection of the central retinal artery, 4 were associated with diabetic retinopathy and 4 were associated with a normal retina. The same difficulty arose in this diabetic series, as in the normal series, of clearly defining the choroidal arteries from the veins when the injection was limited to a small area of the peripapillary part of the choroid. For this reason the true figure for the incidence of choroidal arterial filling may be higher than stated.

Thus, when the non-diabetic and diabetic series are considered together, at least 18 of the 64 eyes which were injected through the central retinal artery showed some injection material within the choroid. It is important to notice that the choroidal arteries which became injected were not in direct relationship to injected veins (figs.34a, 34 b and 37), so that it may be assumed that the arteries were filled by direct arterial connections and not merely by an over-spilling from the injected veins through the intervening chorio-capillaris.

/ The findings

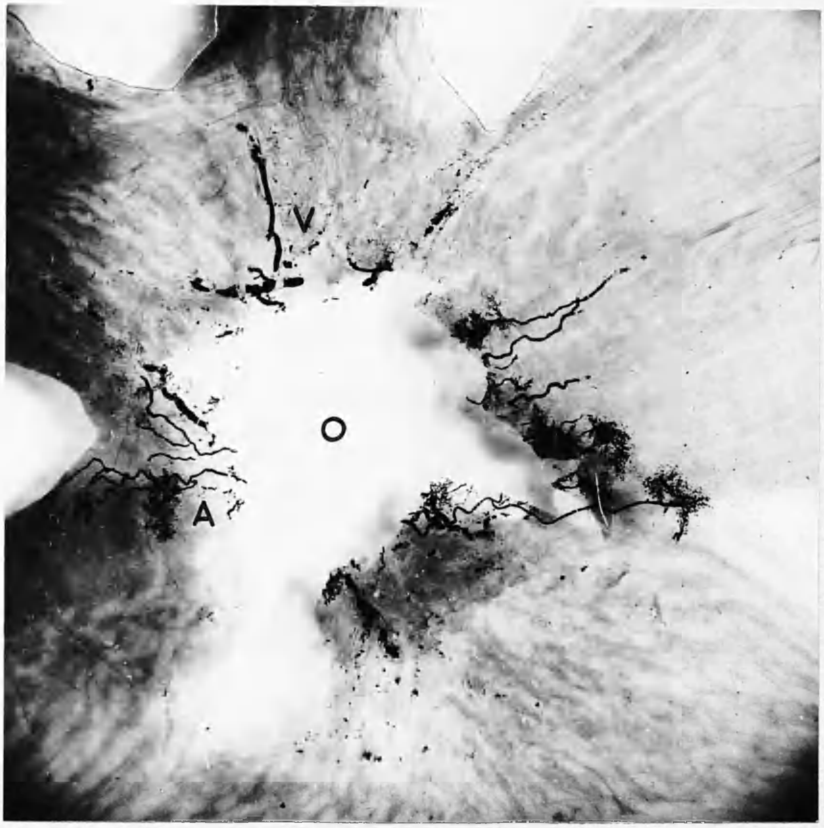
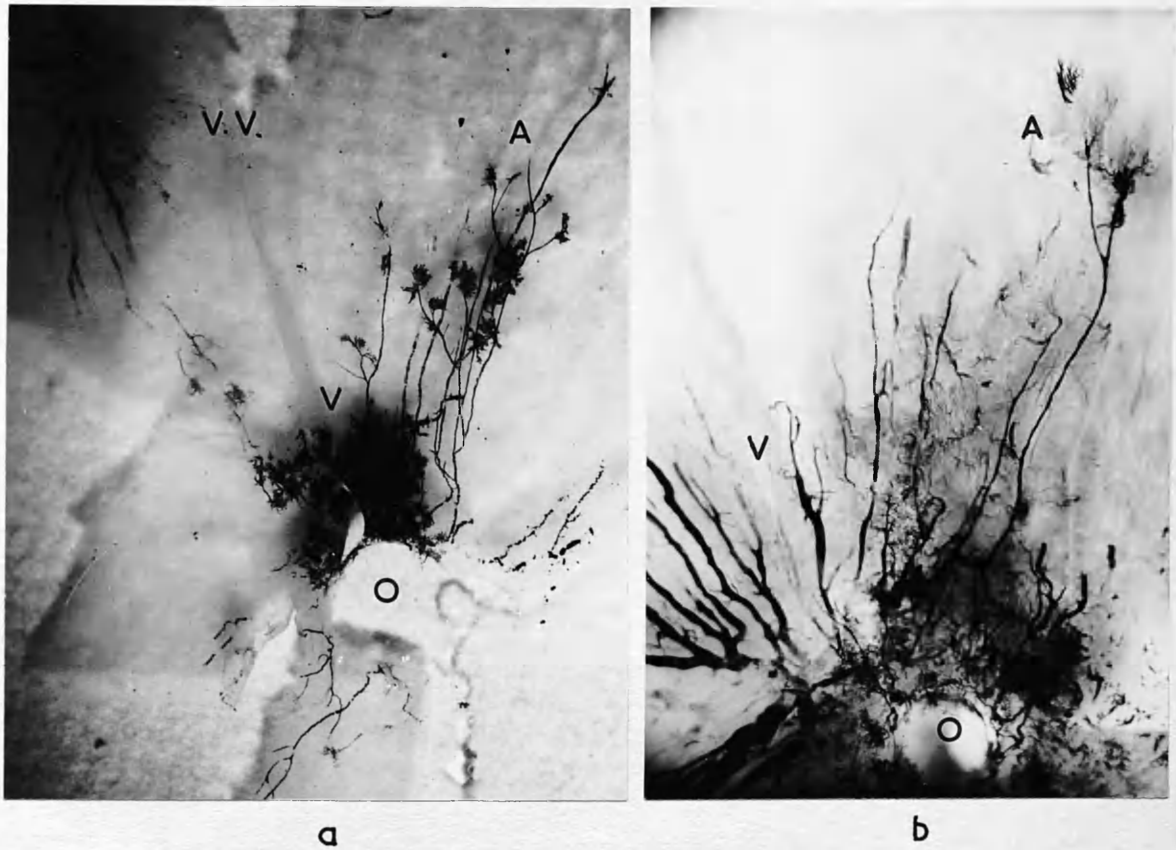


FIG. 33. Part of isolated choroid to show filling of a few small arteries (A) and veins (V) with indian ink in region of optic disc (O). x 12.



FIGS. 34 a and b. Parts of isolated choroid to show filling of several large arteries (A) and veins (V) with indian ink in sectors of choroid.
Note optic disc (O), and formation of vortex vein (V.V.) in (a).
(a) x 8 and (b) x 10.

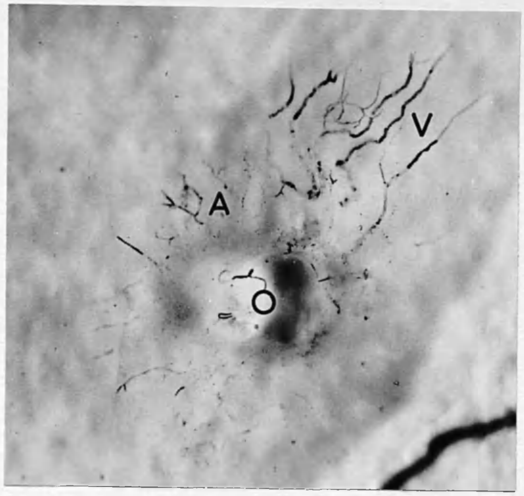


FIG. 35. Part of isolated choroid to show scanty filling of a few vessels with indian ink. Most of vessels are veins (V) but a few may be arteries (A). Note optic disc (O). (Black line in lower right corner is an artefact). x 8.

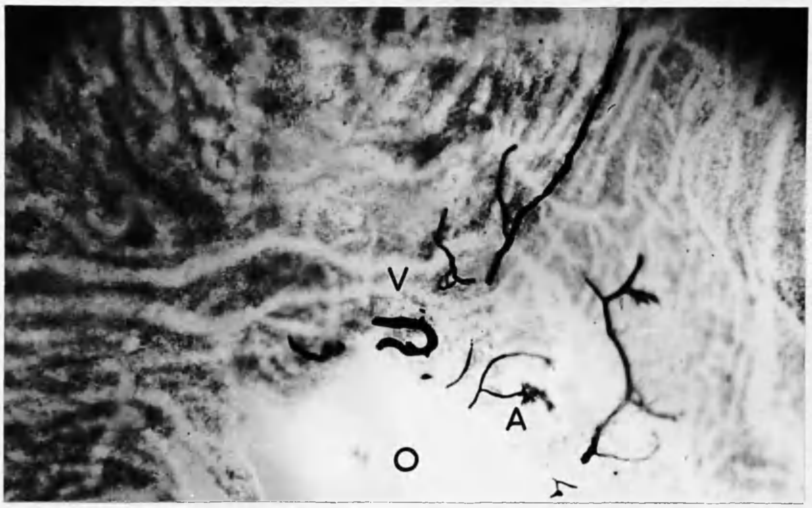


FIG. 36. Part of isolated choroid to show filling of a few small arteries (A) at veins (V) with indian ink in region of optic disc (O). x 22.

FIG. 37. Part of isolated choroid to show filling of several medium-sized arteries (A) and large veins (V) with indian ink in sectors of choroid. Note optic disc (O). x 10.

The findings of this part of the investigation give presumptive evidence, therefore, for the existence of uveo-retinal arterial anastomoses.

Examination of the Neoprene casts of the ocular vessels of the 13 eyes irrigated with water and injected with Neoprene through the ophthalmic artery and then subjected to digestion in pepsin and trypsin, revealed many details of these uveo-retinal arterial anastomoses. It is important to remember, however, that the findings are the result of the pooled data obtained from an examination of all the eyes, and that it is not possible to state how often certain features occurred throughout the series. A complete cast of the ocular circulation presents a dense mass of vessels (fig.38), particularly in the region of the optic nerve head (fig. 39), wherein lay the main objective of this study. The preliminary steps in the dissection of the cast shown in fig. No.39 are illustrated in figs. 40, 41 and 42, and it is apparent that in order to expose a particular area it is necessary to discard many vessels in the surrounding fields. Each cast was approached, therefore, in a special way in order to demonstrate a definite aspect of the circulation, and as a result certain other features of interest had to be sacrificed.

The following features were determined in an examination of the dissected Neoprene casts : -

a) Central retinal artery.

The central retinal artery arises as one of the first branches of the ophthalmic artery in the orbit either alone or in common with one of the two long posterior ciliary arteries. It runs below the optic nerve until it reaches about 15 mm. from the globe where it turns upwards at 90^{o} to perforate the optic nerve. In many of the casts at the point where the central retinal artery enters the optic nerve there is a marked reduction in its calibre (figs. 43,44 and 47). It is not felt, however, that any definite conclusion can be drawn from this regarding the calibre of the artery in life, because it is possible that this calibre variation is merely the result of the injection technique. Neoprene is injected into the ophthalmic artery under pressure and it is natural that, in the case of the central retinal artery, the artery should expand more where it is unsupported (as in the orbit) than where it lies within a dense mass of tissue (as in the optic nerve). After its entry into the nerve the artery passes to the centre of the nerve where it turns forwards at 90^{o} to travel along the axial part of the nerve to the optic disc where it divides into its definitive retinal branches.

The central retinal artery during its course within the orbit and optic nerve gives off the following branches :-

i) Branches which arise from the central retinal artery at any point between the origin of the artery from the ophthalmic artery and the entry of the artery into the optic nerve, and which contribute to the arterial plexus of the pia mater which surrounds the optic nerve within the orbit (figs.43,45,46 and 48).

FIG. 38. White Neoprene cast of ocular vessels viewed from in front to show retinal vessels (R) lying within uveal vessels (U). Note major arterial circle of iris (M). x 12.

(Digested specimen).

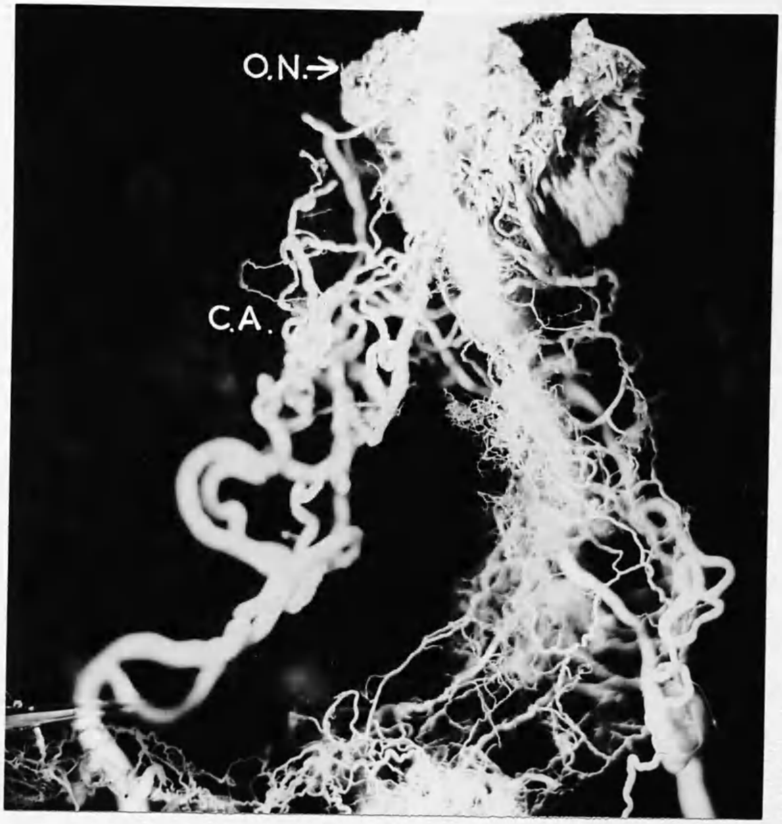


FIG. 39. White Neoprene cast of ocular vessels viewed from behind to show vessels in neighbourhood of optic nerve.
Note density of ciliary arteries (C.A.) around optic nerve (O.N.). x 12.
(Digested specimen).

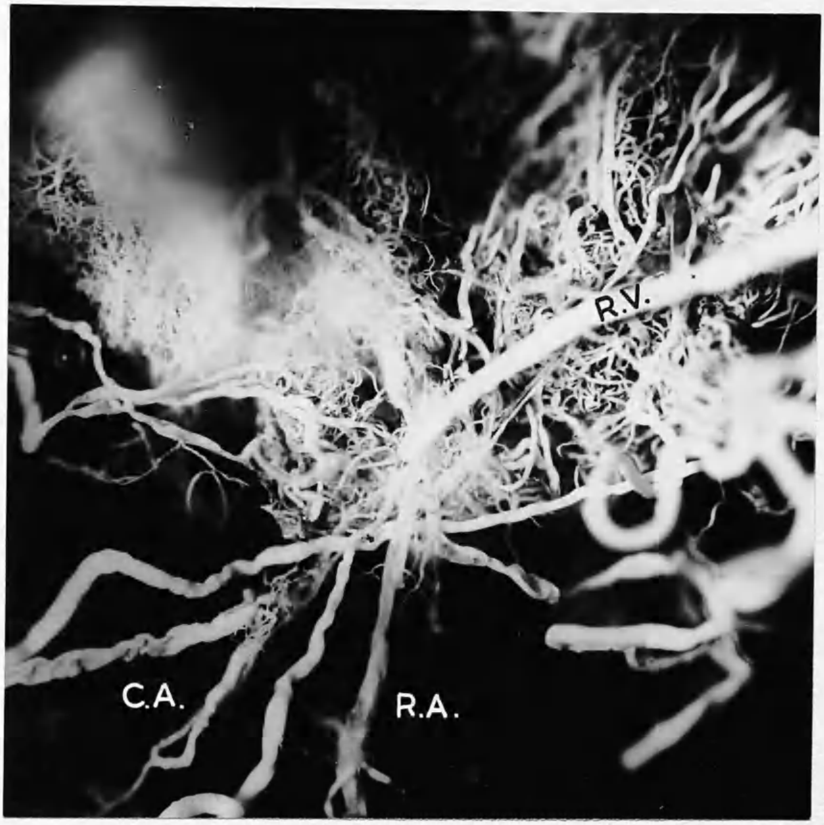


FIG. 40. White Neoprene cast of vessels in and around optic nerve head to show first stage in dissection of cast shown in fig. 39.
Note central retinal artery (R.A.), central retinal vein (R.V.) and short posterior ciliary arteries (C.A.).
(Digested and dissected specimen). x 20.

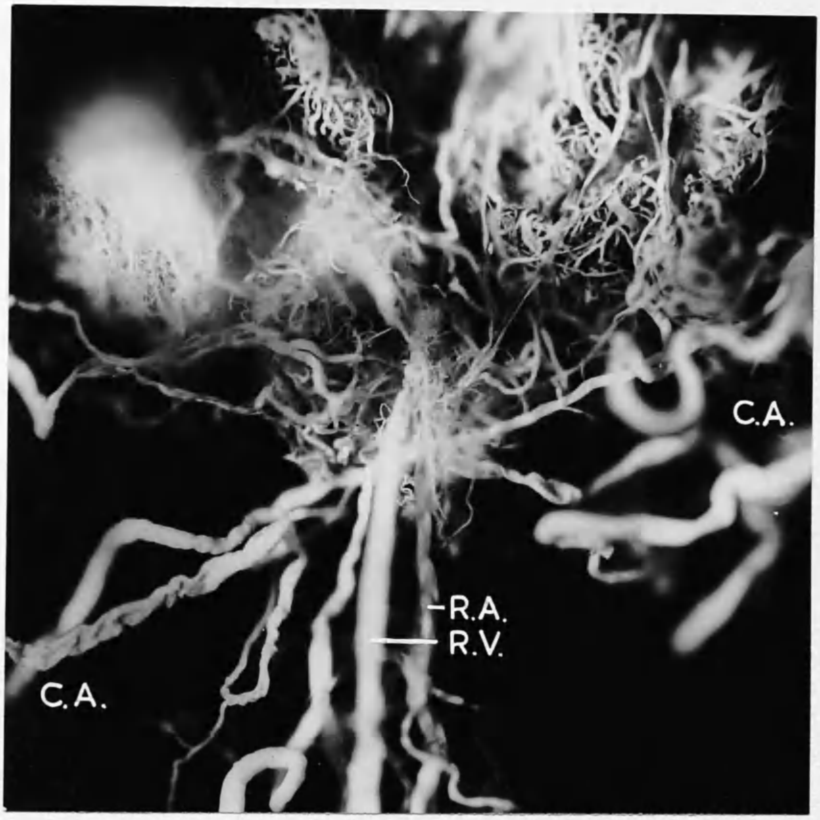


FIG. 41. White Neoprene cast of vessels in and around optic nerve head to show second stage in dissection of cast shown in fig.40.
Note central retinal artery (R.A.), central retinal vein (R.V.) and short posterior ciliary arteries (C.A.).
(Digested and dissected specimen). x 20.

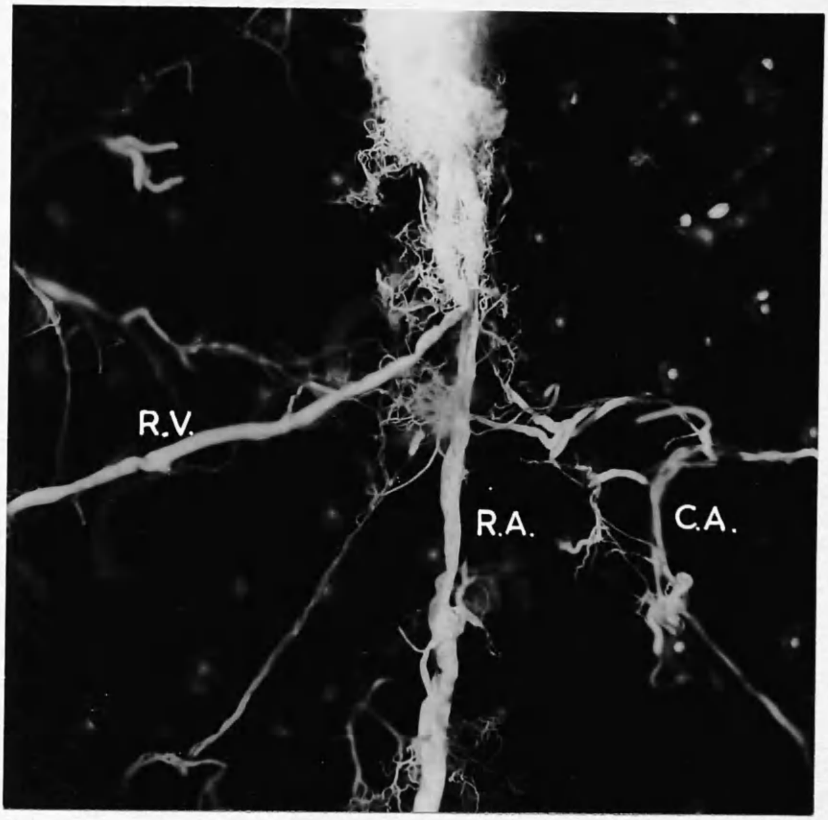


FIG. 42. White Neoprene cast of vessels in and around optic nerve head to show third stage in dissection of cast shown in fig. 40.
Note central retinal artery (R.A.), central retinal vein (R.V.) and short posterior ciliary arteries (C.A.).
(Digested and dissected specimen). x 20.

FIG. 43. White Neoprene cast of ocular vessels to show:-

i) Branches from central retinal artery (R.A.), before entry into optic nerve, to arterial plexus of pia mater (P.M.).

ii) Narrowing of central retinal artery (R.A.) at entry into optic nerve (N).

iii) Collateral central retinal artery (C.R.A.).

iv) Anastomosis between central retinal artery (R.A.) and arterial plexus of pia mater (P.M.) behind lamina cribrosa (L).

v) Anastomosis between central retinal artery (R.A.) and circle of Zinn (C.Z.) at lamina cribrosa (L).

vi) Anastomosis between circle of Zinn (C.Z.) and arterial plexus of pia mater (P.M.).

vii) Branches from posterior ciliary arteries (C.A.) to circle of Zinn (C.Z.) and to arterial plexus of pia mater (P.M.).

(Digested and dissected specimen). x 12 and x 30.

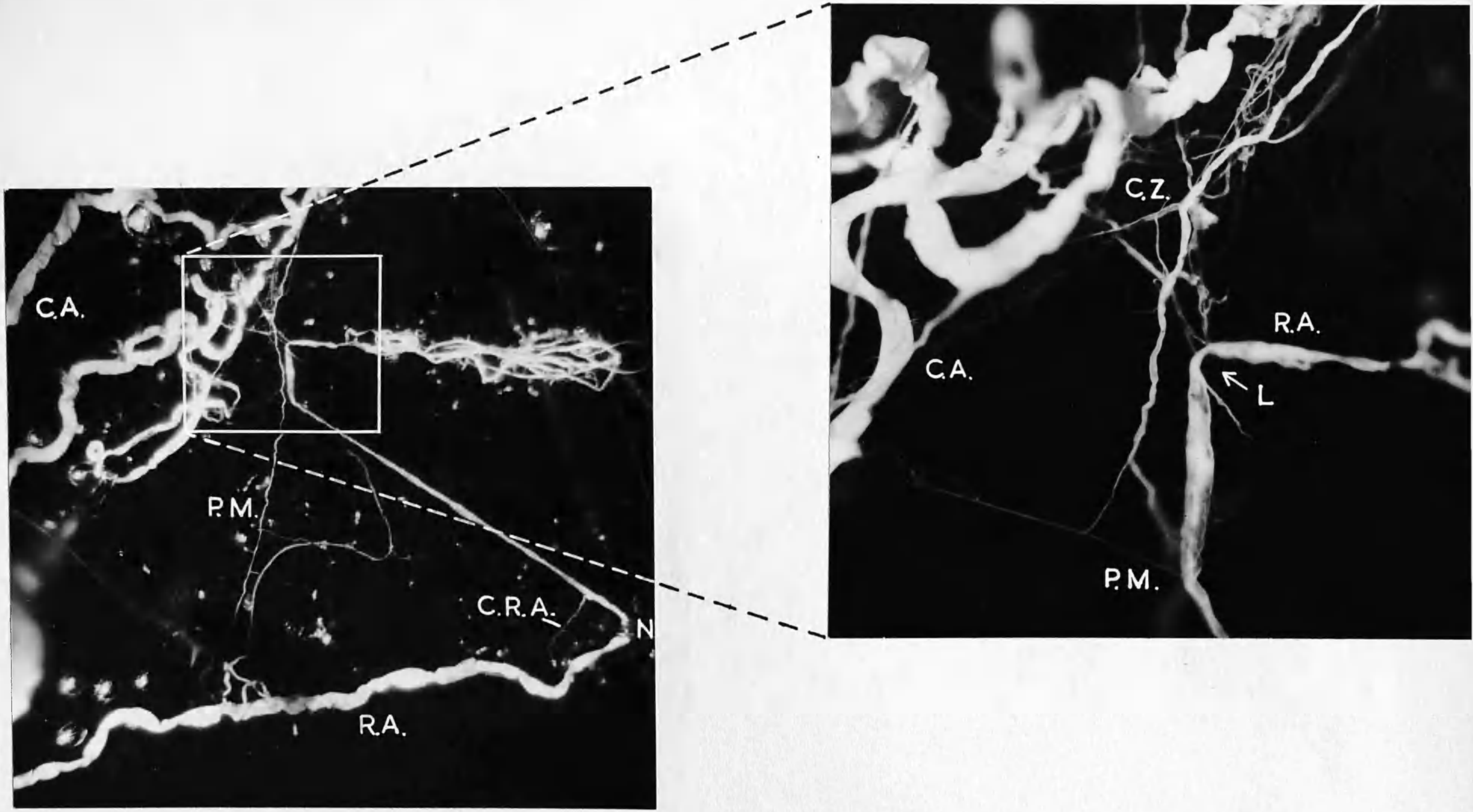


FIG. 43. For description see opposite page.

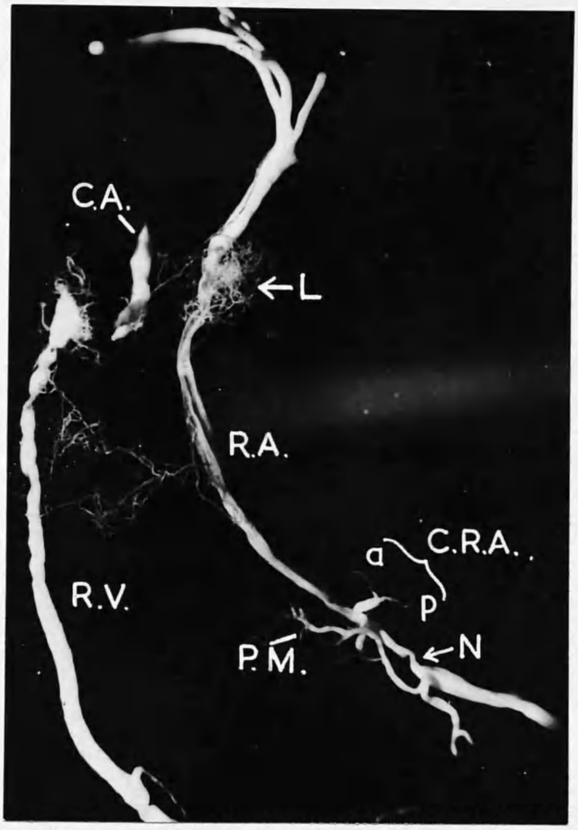


FIG. 44. White Neoprene cast of ocular vessels to show:-

i) Branches from central retinal artery (R.A.), before entry into optic nerve, to arterial plexus of pia mater (P.M.).

ii) Narrowing of central retinal artery (R.A.) at entry into optic nerve (N).

iii) Anterior and posterior collateral central retinal arteries (a and p. C.R.A.).

iv) Branches from central retinal artery (R.A.) at lamina cribrosa (L), showing capillary anastomosis with short posterior ciliary artery (C.A.).

v) Branches from central retinal vein (R.V.) at lamina cribrosa (L), showing capillary anastomosis with central retinal artery (R.A.).

(Digested and dissected specimen). x 12.

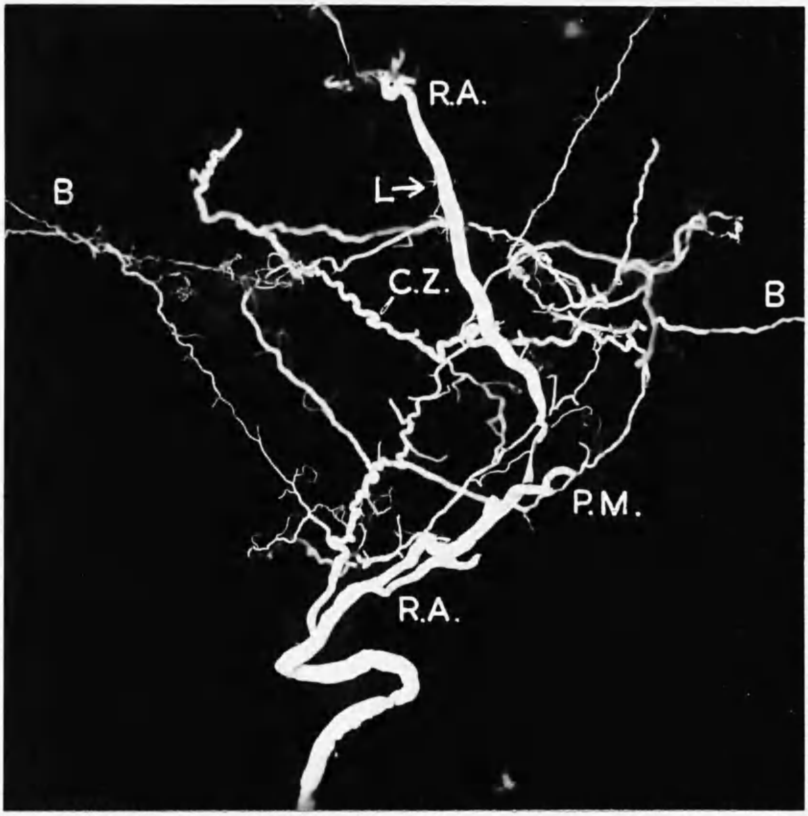


FIG. 45. White Neoprene cast of ocular vessels to show:-

i) Branches from central retinal artery (R.A.), before entry into optic nerve, to arterial plexus of pia mater (P.M.).

ii) Branches from central retinal artery (R.A.) at lamina cribrosa (L).

iii) Branches from circle of Zinn (C.Z.) to optic nerve head.

iv) Anastomosis between circle of Zinn (C.Z.) and arterial plexus of pia mater (P.M.).

v) Branches (B) from ciliary arteries to circle of Zinn (C.Z.) and arterial plexus of pia mater (P.M.).

(Digested and dissected specimen). x 12.

FIG. 46. White Neoprene cast of ocular vessels to show:-

i) Branches from central retinal artery (R.A.), before entry into optic nerve, to arterial plexus of pia mater (P.M.).

ii) Anastomosis between central retinal artery (R.A.) and arterial plexus of pia mater (P.M.) behind lamina cribrosa (L).

iii) Anastomosis between central retinal artery (R.A.) and circle of Zinn (C.Z.) at lamina cribrosa (L).

iv) Anastomosis between circle of Zinn (C.Z.) and arterial plexus of pia mater (P.M.).

v) Branches from posterior ciliary arteries (C.A.) to circle of Zinn (C.Z.) and to arterial plexus of pia mater (P.M.).

vi) Central retinal vein (R.V.).

(Digested and dissected specimen). x 11 and x 22.

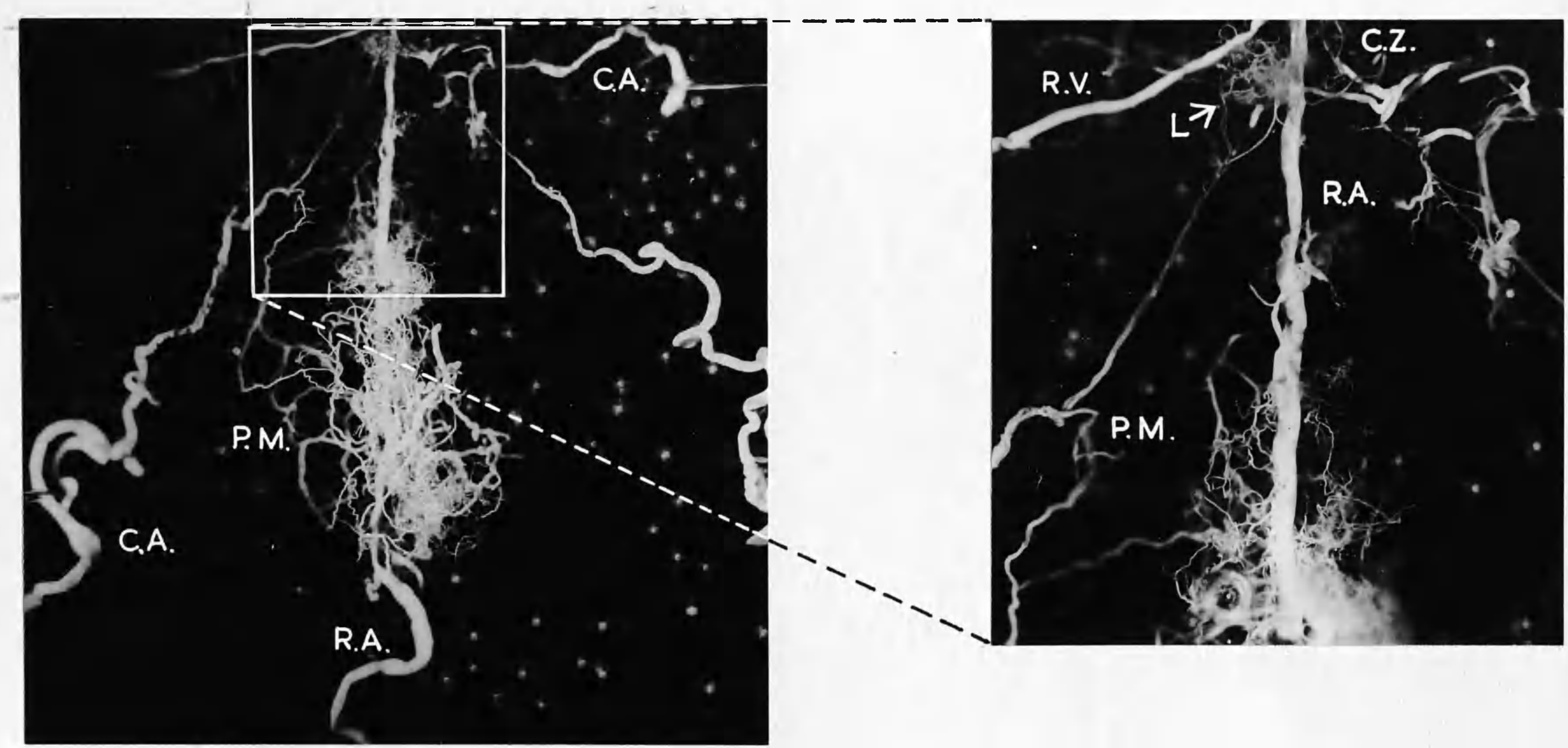


FIG. 46. For description see opposite page.

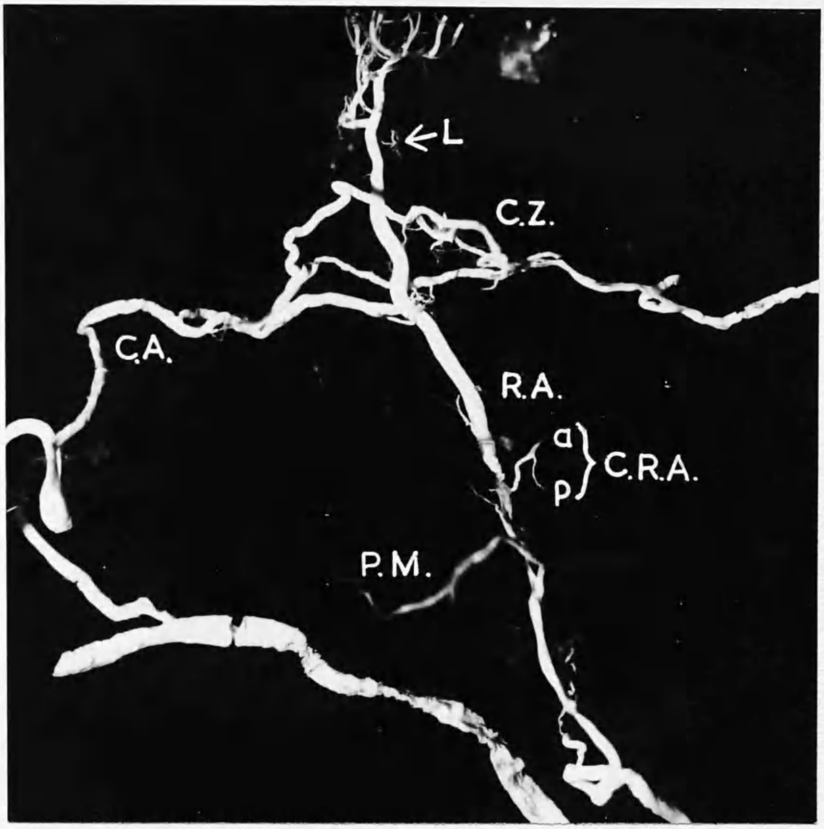


FIG. 47. White Neoprene cast of ocular vessels to show:-

i) Branches from central retinal artery (R.A.), before entry into optic nerve, to arterial plexus of pia mater (P.M.).

ii) Narrowing of central retinal artery (R.A.) at entry into optic nerve.

iii) Anterior and posterior collateral central retinal arteries (a and p. C.R.A.).

iv) Branches from central retinal artery (R.A.) at lamina cribrosa (L).

v) Branches from circle of Zinn (C.Z.) to optic nerve head.

vi) Branches from posterior ciliary arteries (C.A.) to circle of Zinn (C.Z.).

(Digested and dissected specimen). x 12.

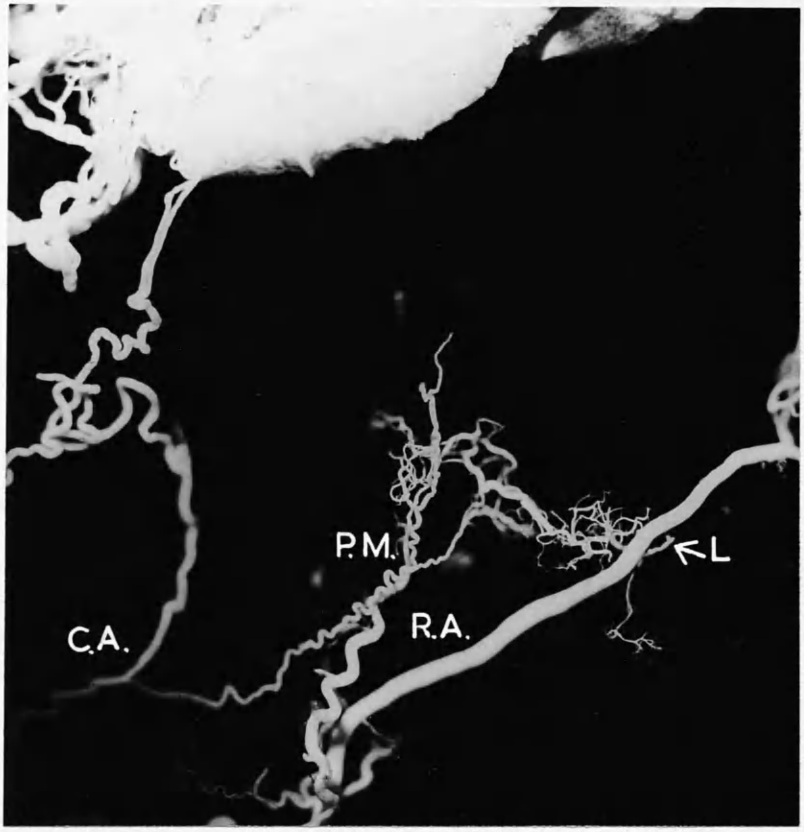


FIG. 48. White Neoprene cast of ocular vessels to show:-

i) Branches from central retinal artery (R.A.), before entry into optic nerve, to arterial plexus of pia mater (P.M.).

ii) Anastomosis between central retinal artery (R.A.) and arterial plexus of pia mater(P.M.) behind lamina cribrosa (L).

iii) Branches from posterior ciliary arteries (C.A.) to arterial plexus of pia mater (P.M.).

(Digested and dissected specimen). x 12.

ii) Branches which arise from the central retinal artery at the point where the artery pierces the optic nerve to pass to its centre (figs.43,44 and 47). There are two such branches and they may arise separately or by a common trunk. One of the arteries passes forwards in the axial part of the optic nerve to end somewhere behind the lamina cribrosa, and the other artery runs backwards in the axial part of the optic nerve towards the optic foramen. These are the anterior and posterior collateral central retinal arteries.

iii) Branches which arise from the central retinal artery during its course within the optic nerve. Some of these branches appear to terminate within the tissues of the optic nerve, but others form anastomoses with branches from the arterial plexus of the pia mater (figs. 43,46 and 48). Many branches are given off in the region of the lamina cribrosa and although some of them end within the tissues of the optic nerve head, other laminar branches form anastomoses with the laminar branches from the ciliary arteries (fig.44). These latter branches are derived to a large extent from the intrascleral arterial circle of Zinn, so that the anastomosis is primarily with the circle of Zinn (figs.43 and 46).

b) Arterial plexus of pia mater of optic nerve.

The arterial plexus of the pia mater is formed from three sources :-

i) Branches from the short posterior ciliary arteries (figs. 43,45,46 and 48).

ii) Branches from the central retinal artery before the entry of the artery into the optic nerve (figs.43,45,46 and 48).

iii) Branches from the circle of Zinn (figs.43,45 and 46).

Branches which arise from this arterial plexus (essentially a derivative of the ciliary circulation) passinto the optic nerve and some of them form anastomoses with branches of the central retinal artery within the optic nerve (figs.43 and 46).

c) Arterial circle of Zinn.

The arterial circle of Zinn lies within the sclera surrounding the optic nerve head and is made up of branches which are derived from the short posterior ciliary arteries during their passage through the sclera. These branches unite to form a continuous intrascleral arterial ring, and from the ring the following branches are given off into the optic nerve particularly in the region of the lamina cribrosa.

i) Branches which pass into the optic nerve head in the region of the lamina cribrosa(figs.43,45,46 and 47). It has been shown above that anastomoses are formed between some of these branches and the laminar branches of the central retinal artery (figs. 43 and 46).

ii) Branches which pass backwards to contribute to the formation of the arterial plexus of the pia mater (figs.43,45 and 46).

iii) Branches which pass forwards into the peripapillary part of the choroid. These have been described in Section I(p.22).

iv) Occasionally a branch passes directly into the retina, a so-called cilio-retinal artery (fig.49), which thus constitutes a retinal artery derived from the ciliary circulation. A cilio-retinal artery is, however, an end-artery, like the true retinal arteries, and it supplies only a localised segment of the retina.

Examination of the 3 eyes irrigated with water and injected with Neoprene through the ophthalmic artery and then dissected after fixation in 10% formol saline, confirmed the presence of fine branches arising from the central retinal artery as it passes along the optic nerve. Fine branches were detected also passing into the nerve from the arterial plexus of the pia mater and from the intrascleral arterial circle of Zinn, but no direct anastomoses were found between these derivatives of the retinal and ciliary circulations. The dissection was particularly difficult, however, owing to the density of the optic nerve and scleral tissues.

Examination of the 2 eyes irrigated with water through the ophthalmic artery, injected with indian ink through both central retinal vessels (one eye) and through the central retinal artery only (one eye) and cleared by the Spalteholz method, confirmed the presence of the anastomoses, described above, between the central retinal artery and the arterial plexus of the pia mater and between the central retinal artery and the intrascleral arterial circle of Zinn. In both eyes there was some intravascular injection of the choroidal arteries (fig.50), but, owing to the dense pigmentation of the choroid and retina and owing to the density of the tissues of the optic nerve head even after prolonged clearing, this is not a suitable method for photographic representation.

Uveo-retinal venous anastomoses.

1) In 19 of the 27 normal eyes which were irrigated with water through the ophthalmic artery, injected with indian ink through the central retinal vein and examined for the presence of intravascular injection material in the choroid, there was some filling of the choroidal veins. In 7 of the 19 eyes this injection of the choroidal veins was limited to a few small ones in the peripapillary region (fig.51), but in 8 other eyes it extended into a whole sector of the choroid (figs.52 a and b), and in the remaining 4 eyes it covered a wide area of the choroid (fig.53).

2) In 30 of the 51 eyes removed from diabetic persons which were irrigated with water and injected with indian ink or Neoprene through the central retinal vein and examined for the presence of intravascular injection material in the choroid, there was some filling of the choroidal veins. In 9 of the 30 eyes this injection of the choroidal

/ veins was

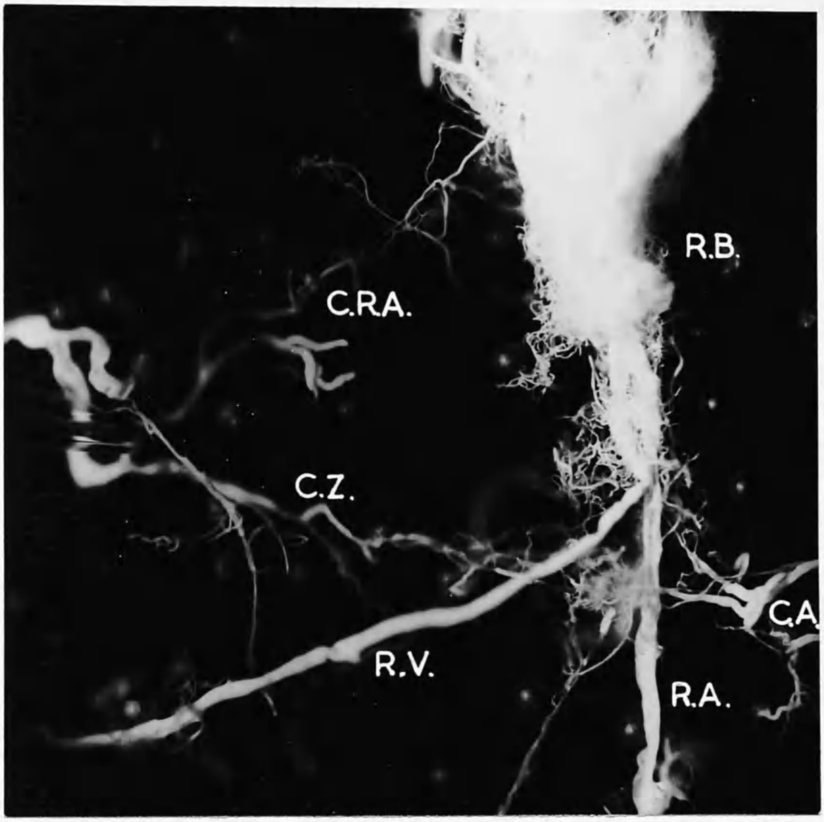


FIG. 49. Neoprene cast of ocular vessels to show cilio-retinal artery (C.R.A.).
Note central retinal artery(R.A.), central retinal vein (R.V.), short posterior ciliary arteries (C.A.), circle of Zinn (C.Z.), and definitive retinal branches (R.B.).
(Digested and dissected specimen). x 24.

FIG. 50. Posterior view of globe to show indian ink within circle of Zinn (C.Z.) and a choroidal artery (Ch.A.).

(Spalteholz method - unsatisfactory reproduction due to dense choroidal pigmentation).

x 10.

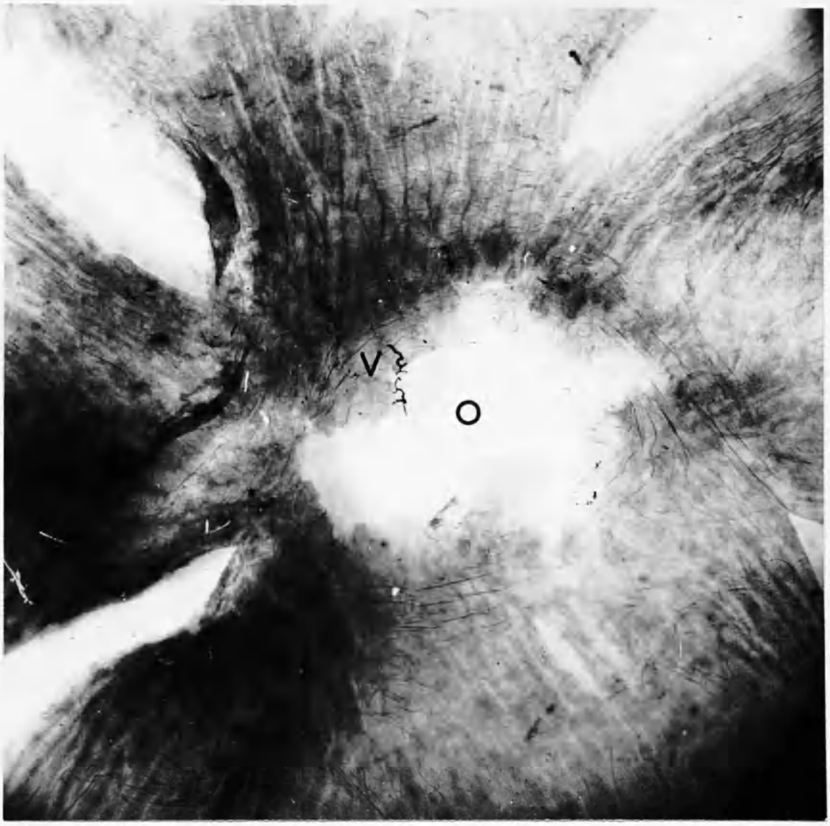
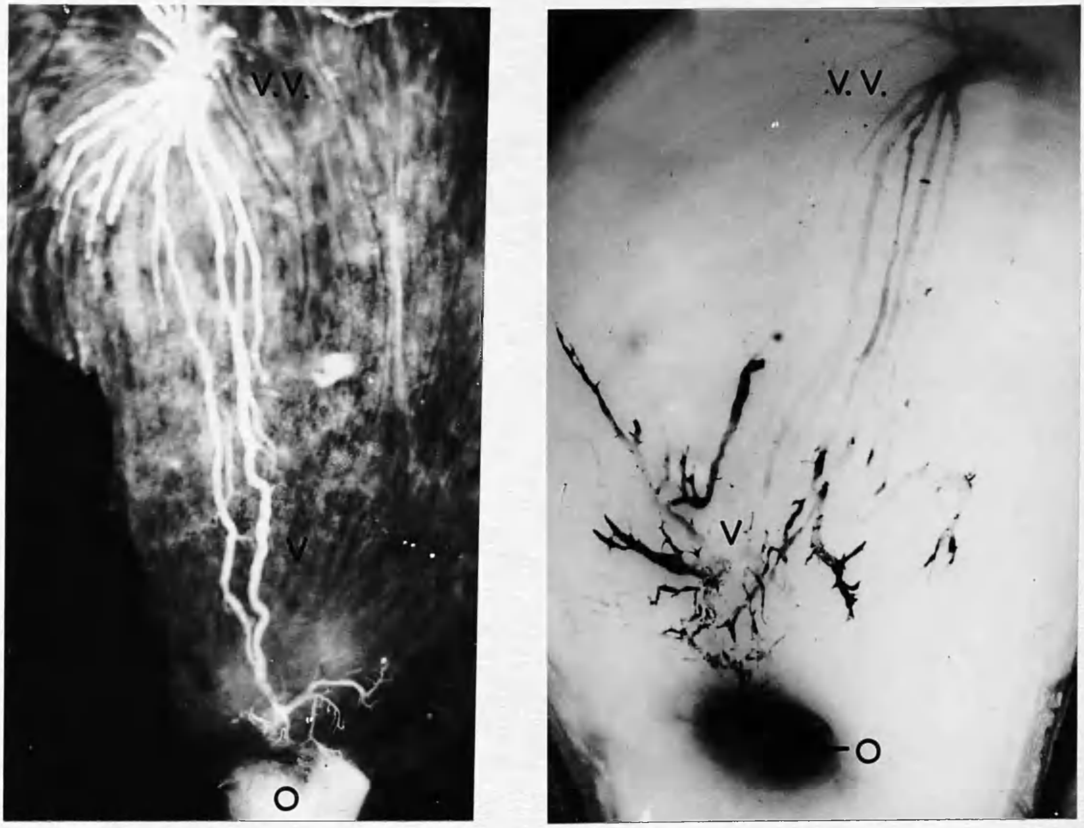


FIG. 51. Part of isolated choroid to show filling of a few small veins (V) with indian ink in region of optic disc (O). x 12.



a b

FIGS. 52 a and b. Parts of isolated choroid to show filling of several veins (V) with Neoprene in (a) and with indian ink in (b) in sectors of choroid. Note optic disc (O) and formation of vortex vein (V.V.).

(a) x 12 and (b) x 10.

FIG. 53. Part of isolated choroid to show extensive filling of veins (V) with indian ink.
Note optic disc (O) and formation of vortex vein (V.V.). x 12.

veins was limited to a few small ones in the peripapillary region (fig.54), but in 16 other eyes it extended into a whole sector of the choroid (fig.55), and in the remaining 5 eyes it covered a wide area of the choroid (fig.56). Of these 51 eyes, 30 showed evidence of diabetic retinopathy and 21 showed a normal retina, and of the 30 eyes which showed some choroidal venous filling 20 were associated with diabetic retinopathy, and 10 were associated with a normal retina.

In a few eyes in which the choroids were examined in situ, it was possible to make out fine connecting links from the central retinal vein in the optic nerve head to the injected peripapillary choroidal veins (fig.57).

3) Examination of the Neoprene casts of the ocular vessels of the 13 eyes irrigated with water and injected with Neoprene through the ophthalmic artery and then subjected to digestive action of pepsin and trypsin, confirmed the presence of uveo-retinal venous anastomoses in the optic nerve head. These anastomoses occur directly between the central retinal vein and the choroidal veins, and a particularly large one is shown in fig.58. There was no evidence of any intrascleral venous circle, such as has been described on the arterial side of the circulation.

FIG. 54. Part of isolated choroid to show filling of a few veins (V) with indian ink. Note optic disc (O). x 12.

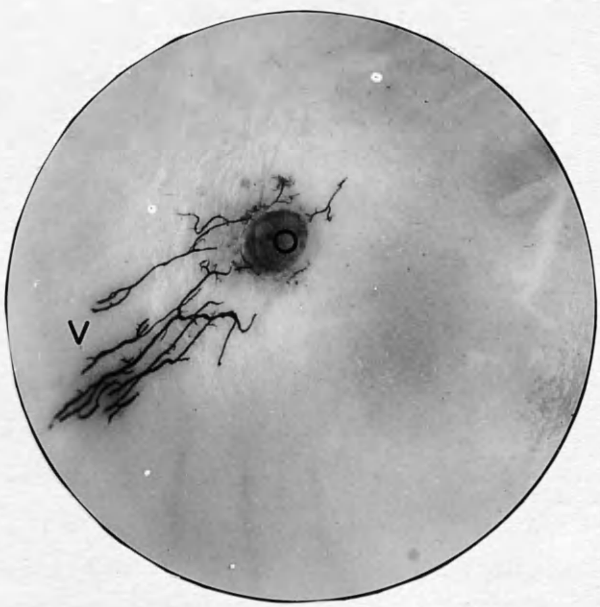
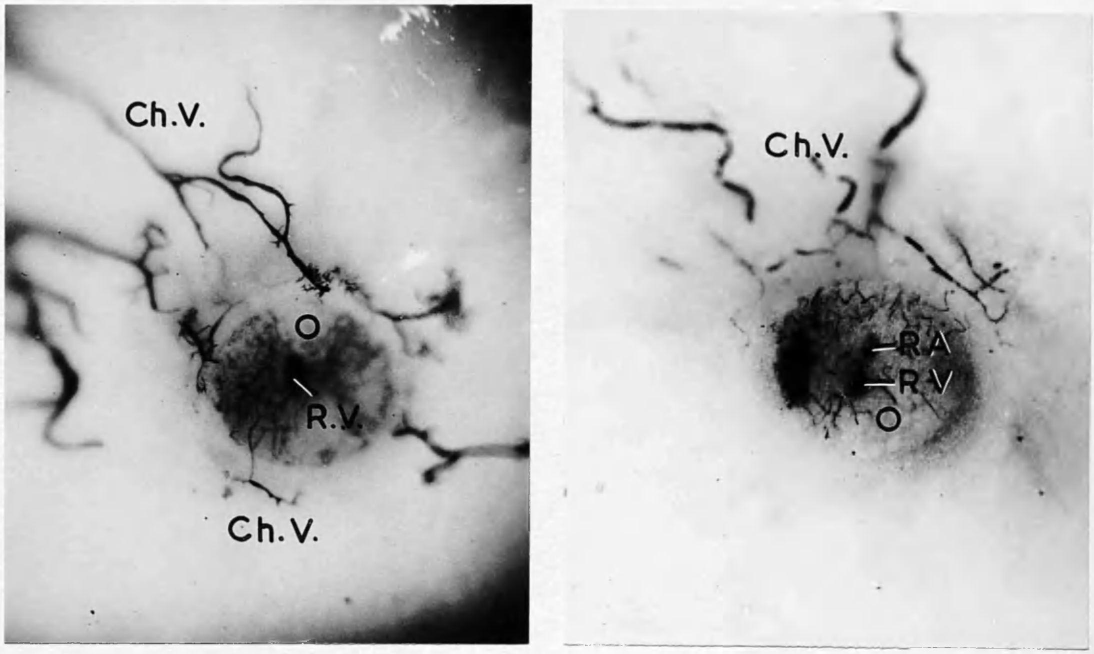


FIG. 55. Choroid in situ within globe to show filling of veins (V) with indian ink in one sector. Note optic disc (O). x 4.

FIG. 56. Part of isolated choroid to show extensive filling of veins (V) with indian ink.
Note optic disc (O) and formation of vortex veins (V.V.). x 7.



a b

FIGS. 57 a and b. Choroid in situ within globes to show filling of connections across optic disc (O) between central retinal vein (R.V.) and choroidal veins (Ch.V.) with indian ink.
Note central retinal artery (R.A.) in (b). (a) and (b) x 14.

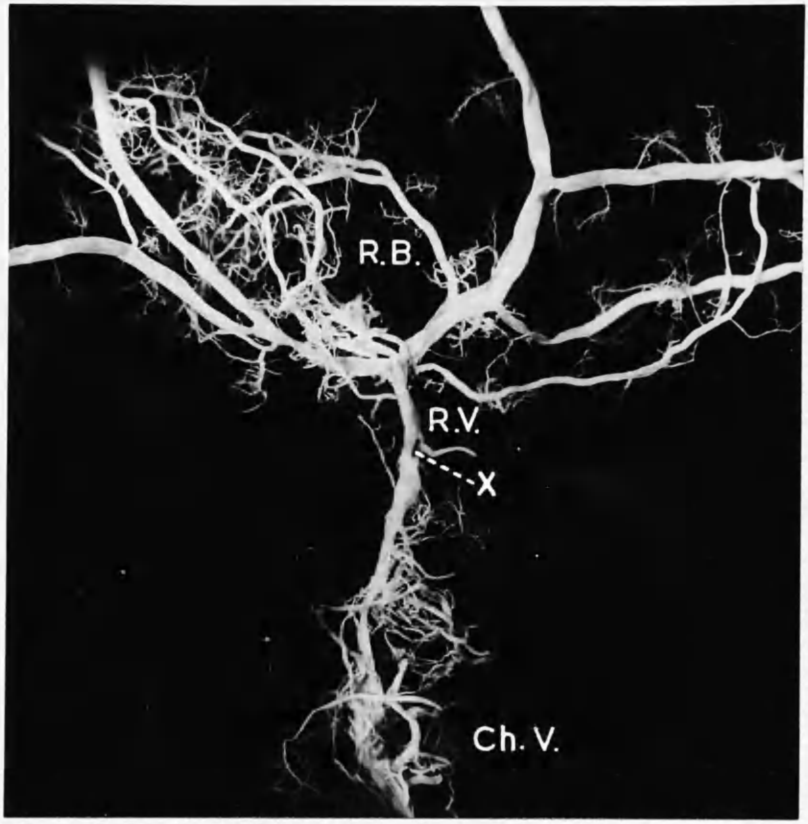


FIG. 58. White Neoprene cast of central retinal vein (R.V.) and its retinal branches (R.B.) to show anastomotic branch from vein to a choroidal vein (Ch. V.). Note that main stem of central retinal vein broke off at point marked X. (Digested and dissected specimen). x 24.

Discussion.

General assessment of results.

It has been shown that the problem of determining the presence and nature of uveo-retinal arterial and venous anastomoses in the anterior part of the optic nerve was approached in two entirely different ways.

In the first place, an indirect approach was made by injecting some dye substance into the central retinal vessels and then examining the choroid for the presence of intravascular injection material, on the assumption that those eyes in which the dye was found in any of the choroidal arteries or veins indicate the existence of some form of uveo-retinal arterial or venous anastomosis. It is known that there are no such anastomoses within the eye (that is across Bruch's membrane) so it is assumed that the anastomosis must lie within the optic nerve.

It is doubtful, however, whether those eyes in which no dye was found in the choroidal vessels may be interpreted as evidence for the absence of anastomotic channels because there are certain difficulties inherent in injection techniques, especially when, as in the case of the present study, the channels to be examined are narrow and lie in a dense connective tissue framework between two main vascular systems. These difficulties will be discussed now:-

1) The results are influenced by the efficiency of the preliminary irrigation of the vessels with water. This irrigation attempts to remove completely all the blood clots from even the finest ramifications of the circulation, but if there is any failure to achieve this successfully, it is natural that the vessels are less effectively prepared for the final injection.

   It is of interest to compare the results of the series in which the preliminary irrigation was carried out through the ophthalmic artery with the series in which it was carried out through the retinal vessels. There was arterial filling of the choroid in 43% of the eyes in the first series as compared with 20% in the second series, and for venous choroidal filling the figures were 70% as compared with 59% respectively. It is likely that the difference in these figures is a reflection of the more thorough irrigation which was possible by way of the ophthalmic artery.

2) The results are influenced by the efficiency of the injection of the dye substance or other injection material into the vessels. It is essential that a large enough quantity of material is used, and that it is introduced at a sufficiently high pressure to ensure an adequate filling of even the smallest vessels of the vascular pattern.

   In this connection it is interesting to note that Beauvieux and Ristitch (1924), who denied the existence of any branches from the central retinal artery within the optic nerve, used a technique which involved the injection of only 2 ml. of

/ prussian blue

prussian blue into the central retinal artery without any preliminary irrigation (at least no mention is made in their paper of any preliminary irrigation). It is questionable whether such a technique is sufficiently energetic to reveal the presence of fine inter-vascular connecting links and it may explain their negative findings. On the other hand, criticism may be levelled against the methods used in this investigation in that the irrigation and injection involved considerable quantities of water and injection material which were forced into the circulation under relatively high pressures. This is undoubtedly true, but it is important to note that there was never any evidence of rupture of the fine vessels or capillaries in the specimens examined; Duff and More (1944) had a similar experience when they found no damage to the renal vessels or capillaries despite injections of water and Neoprene at high pressures.

In the second place, a direct approach was made to the problem of the existence of uveo-retinal vascular anastomoses. This involved an examination of the vessels within the optic nerve, after their injection with Neoprene and exposure by digestion or dissection of the surrounding tissues, or after their injection with indian ink and exposure by clearing the covering tissues (Spalteholz method). This approach was intended to show up the true position of the anastomoses which were assumed from the results of the indirect method of study.

Once again, it is difficult to know how much weight to place on negative results because the identification of fine communicating channels between the two main vascular systems was dependent on an injection technique which has certain inherent disadvantages.

1) The results are influenced by the efficiency of the preliminary irrigation of the circulation, as outlined above.

2) The results are influenced by the efficiency of the intravascular injection of the dye substance or other injection material, as outlined above. This is particularly so in the case of a substance like Neoprene which readily forms a block within the smaller vessels unless injected fairly rapidly and at a reasonably high pressure.

3) The results are influenced by the ease with which the injected vessels may be exposed to direct view. In the Neoprene casts of the whole ocular circulation there is a vast network of injected vessels, and it is possible to isolate the anastomotic vessels in the optic nerve head only after a

/ prolonged series

prolonged series of dissections involving the removal of many surrounding vessels. The absence of an anastomotic channel in any one specimen may represent, therefore, a failure in technical skill. Similarly, in the Neoprene injected eyes fixed in 10% formol saline it is extremely difficult to maintain the integrity of the fine vessels during dissection of the tissues of the optic nerve and sclera.

The eyes dealt with by the Spalteholz method also present a problem because, although it is possible to obtain a moderately clear view through the tissues of the optic nerve head, it is possible only to examine for anastomoses after injection through the central retinal vessels. This limits the likelihood of showing up the anastomoses, but if an attempt were made to examine the cleared optic nerve head after injection with indian ink through the ophthalmic artery, the density of injected vessels within the optic nerve head would prevent any view of the anastomotic channels.

It is felt, therefore, that because of the technical difficulties outlined above, it is not possible to submit the results of this investigation to a statistical analysis or to give any clear indication of how frequently uveo-retinal arterial and venous anastomoses occur in the healthy eye. It would appear that the venous anastomoses are more common than the arterial ones, but it may be only that the venous ones are injected more easily.

Uveo-retinal Arterial Anastomoses.

It is a common finding that some time after occlusion of the central retinal artery there is at least a partial restoration of the retinal circulation (Coats,1905; De Schweinitz and Holloway, 1908; etc.). Coats (1913 b) reported a series of 6 such cases and in all of them there was a complete re-establishment of the retinal circulation. There are several interpretations of this phenomenon.

First, the vascular occlusion may be due solely to a spasm of the central retinal artery, so that when the spasm passes off the circulation is restored in the retina. This is the most likely explanation for those cases in which there are transient periods of loss of vision associated with constriction of the retinal arterial circulation.

Secondly, the vascular occlusion may be due to the lodgement of an embolus within the central retinal artery, and the circulation may be restored, at least in part, when the embolus is moved away from the central artery into one of its more peripheral branches, or when the blood is able to pass round the embolus into the peripheral circulation. When an embolus becomes lodged in the central retinal artery there is a spasm of the surrounding arterial wall. The shifting of the embolus to another part of the circulation or the ability of the blood to by-pass the embolus is the result presumably of a decrease in the spasm of the vessels wall.

Thirdly, the vascular occlusion may be due to a thrombosis within the central retinal artery, and the circulation may be restored by canalisation of the thrombus. Coats (1905) has suggested also that in certain cases of thrombosis where there is a more rapid re-establishment of some retinal circulation, blood may be forced round a weak area of the thrombus, following a rise in the systemic blood pressure.

There are, however, certain cases showing restoration of the retinal circulation which do not fit in easily with any of the three mechanisms outlined above; cases in which the occlusion is too prolonged for pure spasm of the vessel wall, in which there is no evidence of any embolic focus, and in which there is histological proof of the permanence of the thrombosis without any attempt at canalisation (Coats, 1913 a). The most likely mechanism in such cases is the re-establishment of the circulation in the retina through uveo-retinal arterial anastomoses in the optic nerve head.

The establishment of a collateral circulation was suggested by Lawson (1898) and also by Coats (1905) who emphasised the capillary nature of the anastomotic channels so that, although the circulation is restored in the retina, the retinal arteries do not return to their original calibre but remain narrow as an adaptation to a diminished blood flow. Even Beauvieux and Ristitch (1924), who denied the existence of a collateral circulation between the retinal and uveal arteries, considered that the opening up of the retinal circulation after occlusion of the central artery must be due, in certain cases, to the existence of some pre-formed channel. This would appear to be a contradiction of their main conclusion.

It has been shown in this present investigation that without doubt uveo-retinal arterial anastomoses exist in a certain number of normal eyes, although, for the reasons outlined at the beginning of this discussion, it is difficult to assess the frequency of such anastomoses. On the other hand, in spite of the existence of these collateral channels and in spite of the other mechanisms by which an arterial block may be overcome, the visual prognosis after occlusion of the central retinal artery is extremely poor.

Coats (1905) has suggested that in such cases the block must have occurred so far forward that it lay on the distal side of the collateral circulation, but this is not a likely explanation because there are collateral channels between the central retinal artery and the circle of Zinn quite far forward in the optic nerve head, and because the commonest site for the occluding process in the central retinal artery is in the retro-laminar region (Verhoeff, 1908). Behr (1935) stated that from the standpoint of the restoration of the retinal circulation, it does not matter where the blockage occurs within the artery, but no emphasis can be placed on this conclusion because it was based on a denial of the existence of any uveo-retinal arterial anastomoses within the optic nerve.

It is probably more reasonable to assume that the poor visual prognosis in blockage of the central retinal artery is related to the rapid degeneration of the inner retinal layers which follows any disturbance of the retinal circulation, so that by the time the function of the retinal arteries is restored to an adequate level the ganglion cells of the retina have suffered permanent damage. Some cases have been reported in which there was a gradual improvement of vision over a period of several days; for example, De Schweinitz and Holloway (1908) gave details of a case in which vision was reduced to a vague perception of light after the occlusion, with a restoration to 6/60 within 40 minutes, and a further gradual improvement to 6/9 within 4 days. It is not clear, however, whether this represents a gradual re-opening of the retinal circulation with a similarly gradual restoration of retinal function, or whether the initial recovery from perception of light to 6/60 represents a re-establishment of retinal circulation and the subsequent improvement in vision represents a subjective adaptation to the presence of some paracentral visual disturbance, probably in association with a subsidence of oedema of the central retina. The presence of a paracentral scotoma, although perhaps minimal in size, is indicated by the failure of the vision to reach an absolutely normal level. If this is the correct interpretation of the case then it is an indication of how rapidly damage can occur to the integrity of the retina even when there is a fairly rapid restoration of the circulation.

It is difficult, therefore, to arrive at a definite conclusion regarding the frequency and nature of uveo-retinal arterial anastomoses in the optic nerve head from a study of the events which follow occlusion of the central retinal artery, and the poor visual prognosis may be more a reflection of the rapidity of retinal degeneration rather than of the poverty of such anastomoses. Of course, come of the cases in which vision is fully and rapidly restored after occlusion of the artery, and which are generally attributed purely to arterial spasm, may, in fact, be cases of true blockage in which there is a well-marked collateral circulation capable of maintaining an adequate level of retinal nutrition within a short time of the occlusion of the main trunk.

In any case the known existence of uveo-retinal arterial anastomotic channels in even a few eyes warrants the use of any measure which will promote vaso-dilatation and thus facilitate the opening up of a collateral circulation. This includes such procedures as the retro-bulbar injection of acetyl-choline, and the sudden lowering of the intra-ocular pressure by paracentesis of the anterior chamber.

It is interesting to speculate on what might happen to the vision in cases of central artery occlusion if they were maintained for a short time in an atmosphere rich in oxygen. It has been shown by Ashton, Ward and Serpell (1954) that in new-born kittens subjected to high oxygen levelsthe integrity of the retinal function is unimpaired despite the disappearance of the retinal vessels. If, in cases of occlusion

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of the central retinal artery the function of the retina could be maintained by supplemental oxygen until the retinal circulation became restored by the opening up of collateral channels, it might greatly alter the prognosis of such cases, provided, of course, that the oxygen therapy was initiated at a sufficiently early stage before the onset of irreparable retinal damage. (This hypothesis is at present under experimental investigation).

Uveo-retinal venous anastomoses.

The existence of an anastomosis between the choroidal and retinal veins provides an alternative channel for the drainage of blood from the retina, and it is likely that this collateral circulation is of great significance in those cases of occlusion of the central retinal vein in which the blockage occurs behind the site of the anastomotic channels. In some cases of thrombosis of the central retinal vein new vessels may be seen ophthalmoscopically on the optic disc passing from the main stem of the retinal vein in towards the choroid. These are undoubtedly dilated anastomotic channels.

It may be that the presence of an adequate collateral circulation is an important factor in preventing the occurrence of secondary glaucoma after thrombosis of the central retinal vein. Thrombotic glaucoma is the result of obliteration of wide areas of the filtration angle due to the development of peripheral anterior synechiae, an event brought about by the formation of a new fibro-vascular membrane on the anterior surface of the iris. Recently, Ashton, Ward and Serpell (1954) showed that new vessel formations occur in the retina of the kitten as a result of hypoxic conditions, and they postulated that the lack of oxygen favours the accumulation within the retina of some unknown substance which in turn is responsible for the neo-vascularisation. Following this concept it was suggested by Smith (1954) that the new vessels which form on the iris in certain cases of thrombosis of the central retinal vein may be produced by a similar mechanism.

This seems a reasonable postulation, and, if correct, would indicate that those cases of central retinal vein occlusion which develop an adequate collateral venous circulation in the optic nerve head due to the existence of uveo-retinal venous anastomoses, are less likely to suffer from stagnation of the retinal circulation with consequently less interference in the normal oxygenation of the retina, and less likelihood of the development of new vessels on the iris with its disastrous sequelae. On such a basis it is possible to put forward a hypothesis which may have surgical applications.

Cases of thrombotic glaucoma respond extremely badly to any form of surgical interference designed to restore the patency of the filtration angle, and this is understandable in view of the nature of the pathological changes in the drainage angle which have induced the rise in intra-ocular pressure. For this reason it would appear to be essential to approach the problem of thrombotic glaucoma on a prophylactic rather

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than on a therapeutic basis, and to deal with the iris before the new fibro-vascular membrane on its anterior surface has induced the formation of peripheral anterior synechiae.

This would entail a detailed examination of the iris by slit-lamp microscopy, involving both direct and gonioscopic views at frequent intervals for a considerable period after the occlusion of the central retinal vein. By this means it may be possible to select a group of cases which are destined to terminate in a glaucomatous episode, and to prevent this disastrous occurrence by performing a wide basal irridectomy so that, even if the neo-vascularisation of the remainder of the iris leads to the formation of peripheral anterior synechiae, at least part of the filtration angle will remain open.

SUMMARY

SECTION I

1. Casts of the choroidal vessels of 20 normal human eyes were prepared by the intravascular injection of Neoprene latex through the ophthalmic artery after preliminary irrigation with water, and the cohesive and elastic properties of Neoprene permitted the dissection of individual vessels and isolated capillary areas from the main vascular mass after fixation in 10% formol saline.

2. The choroidal vessels of 2 normal human eyes were injected with indian ink through the ophthalmic artery after preliminary irrigation, and 7 other eyes were similarly injected following occlusion of a single short posterior ciliary artery. In 2 further eyes indian ink was injected into the choroid through a short posterior ciliary artery.

3. The short posterior ciliary arteries are segmentally arranged and each branch supplies a localised zone of the choroid with an arteriolar-capillary network, but there is no anatomical evidence for the concept that these arteries are true end-arteries.

4. The meeting place at the equator of the posterior choroidal circulation (short posterior ciliary arteries) and anterior choroidal circulation (recurrent arteries from the major arterial circle of the iris, from the long posterior ciliary arteries and from the anterior ciliary arteries) may be marked by an intervening capillary network, but many of the vessels in the anastomosing circulations are in direct continuity with one another. This is contrary to the view that the equator is a zone of defective choroidal vascularisation, and to the view that the anterior part of the choroid is isolated from the rest of the choroid.

5. The peripapillary region of the choroid, although supplied, in part, by fine arterial branches from the intrascleral arterial circle of Zinn, is not isolated from the rest of the choroid.

6. The size and density of the capillaries in the chorio-capillaris vary in different regions according to their distance from the optic disc, but there is no evidence for the view that the chorio-capillaris underlying the macula has distinctive anatomical features. There are, however, more arterial branches in the submacular region of the choroid than in other regions.

7. There is no anatomical evidence to suggest that the selective localisation of choroidal disease is purely an expression of anatomical peculiarities of certain vascular districts. There is clinical and experimental evidence to suggest that circumscribed areas of choroidal atrophy are due to compression of the chorio-capillaris by exudative or haemorrhagic extravasations, and this has a bearing on operative procedures involving the choroid.

8. There are no arterio-venous anastomoses in the normal choroid.

SECTION II

1. The choroids of 28 normal eyes were examined after injection of one or both of the central retinal vessels with indian ink, carmine jelly,or Neoprene, following preliminary irrigation of the ocular circulation with water through the ophthalmic artery.

2. The choroids of 51 eyes removed from diabetic persons were examined after injection of one or both of the central retinal vessels with indian ink, carmine jelly, or Neoprene,following preliminary irrigation of the ocular circulation with water through the retinal vessels.

3. Casts of the ocular vessels of 13 normal human eyes were prepared by the intravascular injection of Neoprene latex through the ophthalmic artery after preliminary irrigation with water, and, owing to the cohesive and elastic properties of Neoprene, a detailed dissection was made of the vessels in and around the optic nerve head after removal of the supporting ocular tissue by the action of digestive ferments.

4. Neoprene latex was injected in 3 other eyes, as described above, and the optic nerve head was examined by dissecting the tissues after fixation in 10% formol saline.

5. Indian ink was injected into one or both central retinal vessels in 2 eyes, after preliminary irrigation of the ocular circulation with water through the ophthalmic artery, and the optic nerve head examined by clearing the tissues according to the method of Spalteholz.

6. In a certain number of eyes there are uveo-retinal arterial anastomoses; first, between the central retinal artery and the arterial plexus of the pia mater surrounding the anterior part of the optic nerve, and, secondly, between the central retinal artery and the intrascleral circle of Zinn. These anastomoses are important in a consideration of the pathological events which may follow occlusion of the central artery, and in a consideration of the medical and surgical treatment of such cases.

7. In a certain number of eyes there are uveo-retinal venous anastomoses between the central retinal vein and the choroidal veins. These anastomoses are important to a consideration of the pathological events which may follow occlusion of the central retinal vein, and in a consideration of the medical and surgical treatment of such cases.

ACKNOWLEDGEMENTS

This investigation has been carried out in the Pathology Department of the Institute of Ophthalmology, London, during the tenure of a Moorfields Research Scholarship, and I am grateful to Sir Stewart Duke-Elder, Director of Research at the Institute, for granting me facilities within the Institute.

My thanks are due in particular to Dr. Norman Ashton, Director of the Pathology Department, for introducing me to the technique of Neoprene injection and for his encouragement and advice throughout the whole period of the investigation.

I am also indebted to Messrs. G. Knight and A. McNeil and to the Medical Illustration Department of the Institute of Ophthalmology for their help in the preparation of the specimens and photographs.

BIBLIOGRAPHY.

ASHTON, N. (1951). Brit.J.Ophthal., 35,291.

--- (1952). Ibid., 36,465.

--- (1953). Ibid., 37,140.

ASHTON,N., and SMITH,R.(1953). Ibid., 37,577.

ASHTON,N., WARD,B., and SERPELL,G.(1954). Ibid., 38,397.

BARTOLOZZI, R. (1952). Arch.Soc.oftal.hisp-amer., 12,692.

BATSON, O.V. (1939). Science, 90,519.

BEAUVIEUX, J., and RISTITCH, K. (1924). Arch. d'Ophthal.,41,352.

BEHR, C.(1935). v. Graefe's Arch.Ophthal., 134,227.

BERLIN, R.(1871). Klin. Mbl. Augenheilk., 9,278.

BIGNELL, J.L.(1952). Trans.ophthal.Soc.Austral., 12,105.

BIRCH-HIRSCHFELD,A. (1910). Z.Augenheilk.,24,193.

BOURNE,M.C.,CAMPBELL,D.A., and TANSLEY,K.(1938).Brit.J.Ophthal.,22,613.

BOWMAN,W.(1842). Phil.Trans.roy.Soc.Lond. 132,57.

COATS,G. (1905). Roy.Lond.ophthal.Hosp.Rep., 16,262.

--- (1906). Ophthal.Rev., 25,99.

--- (1907). Trans.ophthal.Soc.U.K., 27,135.

--- (1913[a]). Roy.Lond.ophthal.Hosp.Rep., 19,45.

--- (1913[b]). Ibid., 19,71.

--- (1913[c]). Ibid., 19,78.

--- (1913[d]). Trans.ophthal.Soc.U.K., 33,30.

COGAN, D.G.(1949). Trans.Amer.Acad.Ophthal.Otolaryng.,54,629.

COLLINS, E.T.(1919). Trans.ophthal.Soc.U.K.,39,165.

CORDES, F.C.(1944). Amer.J.Ophthal., 27,1355.

COWAN,H. (1951). Ibid., 34,304.

CRISTINI,G. (1950). "XVI Concilium ophthalmologicum 1950,Britannia", vol.2,865.

DARTNALL,H.J.A., and THOMSON,L.C.(1949). Nature,164,876.

DENTON,E.J., and PIRENNE,M.H.(1950). Ibid.,165,304.

DUFF,G.L., and MORE,R.H. (1944). J.tech.Methods, 24,1.

DUKE-ELDER,S. (1940). "Text-book of Ophthalmology",vol.3,p.2102. Kimpton,London.

--- (1948). Trans.ophthal.Soc.U.K., 68,413.

ELSCHNIG, A.(1888). v. Graefe's Arch.Augenheilk., 18,295.

FRANÇOIS, J. and NEETENS,A. (1954). Brit.J.Ophthal., 38,472.

GONIN, J. (1903). Ann. d'Ocul., 129,24.

--- (1905). Ibid., 133,167.

GREEVES, R.A. (1912). Roy.Lond.ophthal.Hosp.Rep.,18,301.

HANCOCK,W.I.(1906). Ibid., 16,496.

--- (1908). Ibid., 17,428.

HARTRIDGE, H. (1950). Nature, 165,304.

HEPBURN, M.L. (1908). Roy.Lond.ophthal.Hosp.Rep., 17,232.

--- (1910). Ibid., 18,92.

--- (1912). Trans.ophthal.Soc.U.K., 32,361.

KISS,F., and ORBÁN, T.(1951). Acta.morph.Acad.Sci.Hung., 1,23.

KLIEN, B.A. (1950). Amer.J.Ophthal., 33,371.

KOMOTO, G. (1915). Trans.ophthal,Soc.U.K., 35,295.

LANG, W., and BARRETT, J.W. (1888). Ophth. Hosp. Rep., 12,59.

LAUBER, H. (1931). Graefe-Saemisch Handbuch der gesamten Augenheilkunde. Bd.1, Abt.2, 82. Springer, Berlin.

--- (1936). Handbuch der microkopischen Anatomie des Menschen, ed.W. von Möllendorf,Bd.3,Abt.2,105. Springer, Berlin.

LAWFORD, J.B. (1895). Trans.ophthal.Soc.U.K., 15, 195.

LAWSON, A. (1898). Ibid., 18,148.

LEBER, T. (1903). In "Graefe-Saemisch Handbuch der gesamten Augenheilkunde",2nd.ed.,Bd.2,Abt.2. Springer,Berlin.

LIEB, E. (1940). J.tech.Methods, 20,48.

LISTER, W.T. (1903). Roy.Lond.ophthal.Hosp.Rep., 15,258.

LOEWENSTEIN, A.(1949). Amer.J.Ophthal., 32,1651.

MAGITOT, A. (1908). These de Paris. Vigot Frères.

MARÍN-AMAT, M. (1952). Amer.J.Ophthal., 35,1700.

MICHAELSON, I.C.(1950)."XVI Concilium ophthalmologicum 1950 Britannia", vol.1, 605.

MOFFAT, D.B. (1952). J.Anat.(Lond.), 86,490.

MÖRIKE, K.D. (1949). Klin.Mbl.Augenheilk., 114,308.

NETTLESHIP, E. (1876). Brit.med.J., 1,161.

--- (1877). Roy.Lond.ophthal.Hosp.Rep.,9,161.

--- (1884). Trans.ophthal.Soc.U.K., 4,165.

--- (1903). Roy.Lond.ophthal.Hosp.Rep.,15,189.

NICHOLLS, J.V.V.(1938). Brit.J.Ophthal., 22,672.

PARRY, H.B. (1953). Ibid., 37,487.

PARSONS, J.H. (1906). "Pathology of the Eye", vol.3, p.950. Hodder and Stoughton, London.

RANDALL, B.A. (1887). Trans.Amer.ophthal.Soc., 7,511.

SALZMANN, M. (1912). " The Anatomy and Histology of the Human Eyeball", p.57. University of Chicago Press.

SATTLER, H. (1876). v. Graefe's Arch. Ophthal., 22,(Abt.2), 1.

SAUTTER,H. and SEITZ, R. (1952). Ibid., 152,413.

de SCHWEINITZ, G.E., and HOLLOWAY, T.B. (1908). Trans.Amer.ophthal.Soc., 11,471.

SHONYO, E.S., and MANN, F.C. (1944). Arch.Path., 38,287.

SMITH, R. (1954). "XVII Concilium ophthalmologicum 1954". (In press).

SORSBY, A., and CRICK, R.P. (1953). Brit.J.Ophthal., 37,129.

STUDER, T.F. (1906). Arch.Ophthal.(Chicago), 35,333.

THOMSON, W.E. and BALLANTYNE, A.J. (1903). Trans.ophthal.Soc.U.K., 23,273.

TRUETA, J., BARCLAY,A.E., DANIEL, P.M.,FRANKLIN, K.J., and PRICHARD,M.M.L. (1947). "Studies of the Renal Circulation", p.45. Blackwell Scientific Publications, Oxford.

VERHOEFF, F.H. (1908). Trans.Amer.ophthal.Soc., 11,501.

--- (1931). Arch.Ophthal.(Chicago), 5,392.

WAGENMANN, A. (1890). v. Graefe's Arch.Ophthal., 36, (Abt.4), 1.

WOLFF, E. (1938). Trans.ophthal.Soc.U.K., 58,70.

--- (1939). Ibid., 59,157.

--- (1948). "The Anatomy of the Eye and Orbit", p.310. Lewis, London.

WOLFF, E., and PENMAN, G.G. (1950). "XVI Concilium ophthalmologicum 1950, Britannia", vol.1, p.625.

WOLFRUM, M. (1908). v. Graefe's Arch.Ophthal., 67,307.

Many of the findings illustrated in this thesis have been have been reported in the following papers:-

WYBAR, K.C. (1954). J.Anat.(Lond.), 88, 94.

--- (1954). Brit.J.Ophthal., 38,513.

--- (1954). "XVII Concilium ophthalmologicum 1954". (In press) .