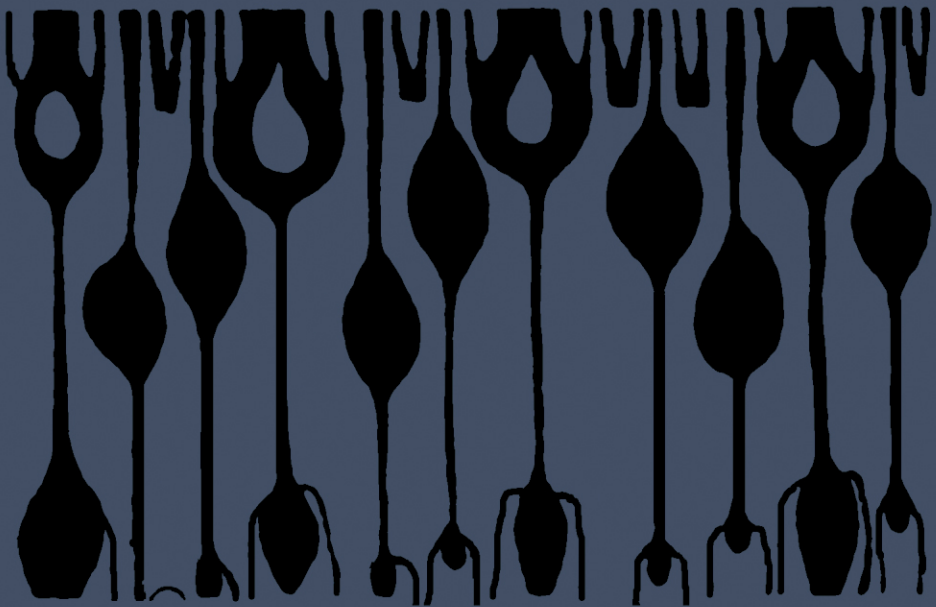


The Physiology of the Eye

Hugh Davson



Third Edition

ACADEMIC PRESS

THE PHYSIOLOGY OF THE EYE

To
SAMUEL L. SALTZMAN

THE PHYSIOLOGY OF THE EYE

by

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London*

THIRD EDITION

With 453 illustrations



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PREFACE

IT was in 1948 that I called at the offices of Messrs. Churchill with a brown paper parcel containing the manuscript of *Physiology of the Eye*, and offered it to them for publication, and the first edition appeared in 1949. A second edition appeared in 1963, and in the preface to this I wrote: 'The task (of revision) has now been completed and has resulted in about a 50 per cent increase in size, an increase that is the necessary consequence of the tremendous advances made in those aspects of the physiology of the eye that are dealt with in Sections I and II. Thus, it is true to say that in 1948 our knowledge of the vegetative physiology and biochemistry of the eye was rudimentary in the extreme. Now, thanks to the establishment of numerous ophthalmological research organizations—mainly in the U.S.A.—it is safe to say that our knowledge in this branch of ocular science is abreast of our knowledge in comparable fields of physiology and biochemistry. Although, in 1948, the field covered by the title *Mechanism of Vision* rested on a much firmer basis of accurate scientific investigation, the striking improvements in photochemical and electrophysiological techniques that have since taken place have permitted just as rapid progress in elucidating basic problems. Consequently, because I have tried to maintain the same sort of treatment as I had in mind when I wrote the first edition of this book—namely, to present a simple yet thorough exposition of the fundamental principles of ocular physiology—I have had to double the amount of space devoted to these first two sections. The muscular aspects covered by Section III have been expanded a little to take account of the important advances made possible by the application of modern methods to the analysis of the eye movements, pupillary function, and so on. Sections IV and V rest on the firm theoretical and practical foundation laid by the work of Helmholtz and other classical research workers in the realm of physiological optics, so that they have been tampered with least'.

To this I need only add that further advances have required the addition of some 150 pages, and these have been fairly equally divided between the first four sections; perhaps the most striking feature of the progress made between this and the previous edition is the successful application of modern microelectrode techniques to the recording of activity at all stages in the visual pathway pioneered by Hubel and Wiesel; this has already necessitated a considerable expansion of Section IV by virtue of our increased understanding of the neuronal basis of higher interpretative processes in visual physiology.

London, 1971

HUGH DAVSON

ACKNOWLEDGEMENTS

IN preparing this new edition I have been helped in the way only an author can appreciate by the kindly and skilful assistance of the head librarian of the Thane Library at University College, Mr. C. F. A. Marmoy. In addition, it is a pleasure to acknowledge the secretarial assistance of Mrs Jane Barnett, and the co-operation of my publishers who, in the person of Mr. A. S. Knightley, have made the task of seeing the book through the press so agreeable.

To the authors and publishers from whose works illustrations have been reproduced, I convey my sincere thanks, particularly to Drs. de Robertis, Fine, Gavin, Ishikawa, Jakus, Kleifeld, Pappas, Pirie, Sjöstrand, Smelser, Tousimis, Lasansky, Wanko, Bloemendal, Tripathi, and Kayes, for generously providing originals of micrographs.

H. D.

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ANATOMICAL INTRODUCTION

The Three Layers. The globe of the eye consists essentially of three coats enclosing the transparent refractive media. The outermost, protective tunic is made up of the *sclera* and *cornea*—the latter transparent; the middle coat is mainly vascular, consisting of the *choroid*, *ciliary body*, and *iris*. The innermost layer is the *retina*, containing the essential nervous elements responsible for vision—the *rods* and *cones*; it is continued forward over the ciliary body as the *ciliary epithelium*.

Dioptric Apparatus. The dioptric apparatus (Fig. 1) is made up of the transparent structures—the cornea, occupying the anterior sixth of the surface of

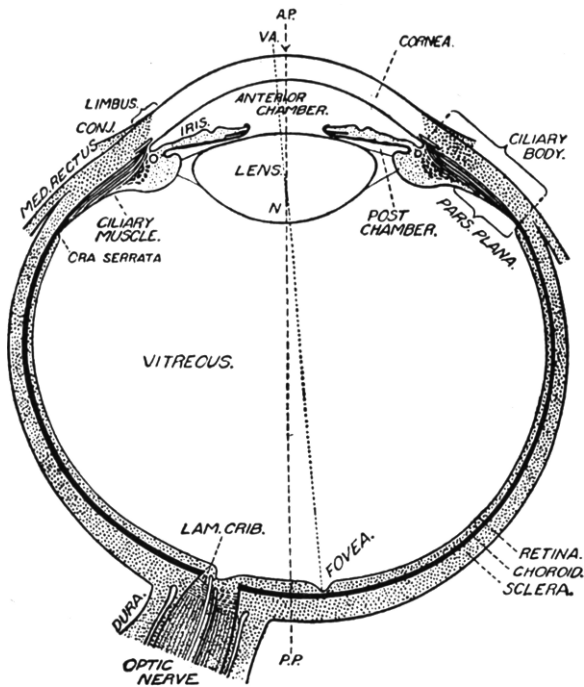


FIG. 1. Horizontal section of the eye. P.P. = Posterior pole; A.P. = Anterior pole; V.A. = Visual axis. (Wolff, *Anatomy of the Eye and Orbit*.)

the globe, and the *lens*, supported by the *zonule* which is itself attached to the ciliary body. The spaces within the eye are filled by a clear fluid, the *aqueous humour*, and a jelly, the *vitreous body*. The aqueous humour is contained in the *anterior* and *posterior chambers*, and the vitreous body in the large space behind the lens and ciliary body. The posterior chamber is the name given to the small space between the lens and iris.

The iris behaves as a diaphragm, modifying the amount of light entering the eye, whilst the ciliary body contains muscle fibres which, on contraction, increase the refractive power of the lens (accommodation). An image of external objects

is formed, by means of the dioptric apparatus, on the retina, the more highly specialized portion of which is called the *fovea*.

Visual Pathway. The retina is largely made up of nervous tissue—it is an outgrowth of the central nervous system—and fibres carrying the responses to visual stimuli lead away in the *optic nerve* through a canal in the bony orbit, the *optic foramen* (Fig. 2); the visual impulses are conveyed through the optic

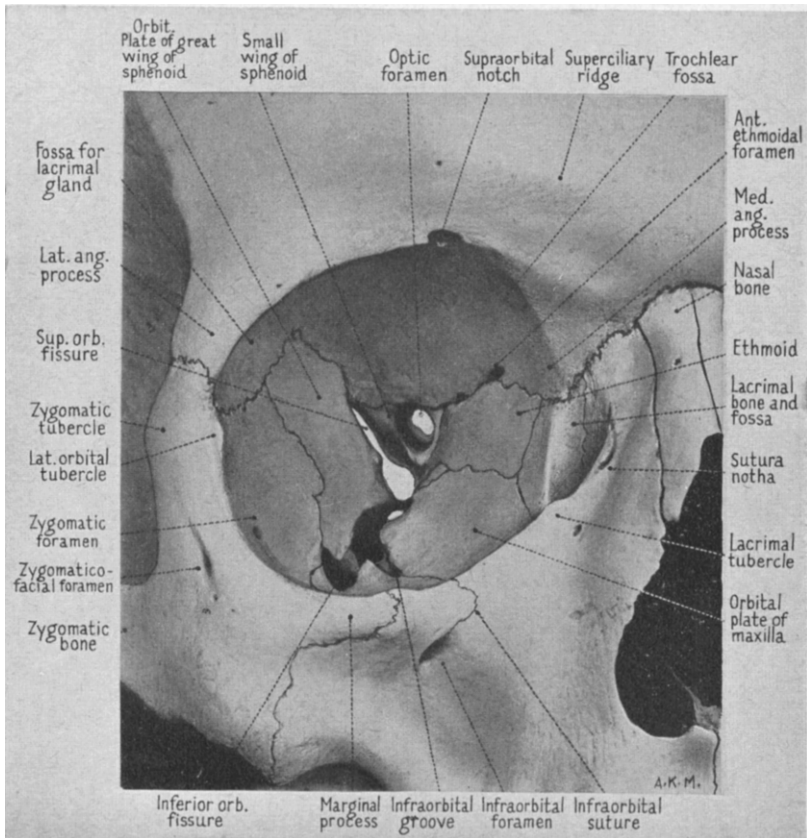


FIG. 2. The orbit from in front. (Wolff, *Anatomy of the Eye and Orbit*.)

nerve and tract to the lateral geniculate body and thence to the cerebral cortex; on their way, the fibres carrying messages from the medial, or nasal, half of the retina cross over in the *optic chiasma*, so that the lateral geniculate body of the left side, for example, receives fibres from the temporal half of the left retina and the nasal half of the right. The nerve trunks, proximal to the chiasma, are called the *optic tracts*. This partial decussation may be regarded as a development associated with binocular vision; it will be noted that the responses to a stimulus from any one part of the visual field are carried in the same optic tract (Fig. 3), and the necessary motor response, whereby both eyes are directed to the same point in the field, is probably simplified by this arrangement. It will be noted also that a right-sided event, i.e. a visual stimulus arising from a point in the right half of

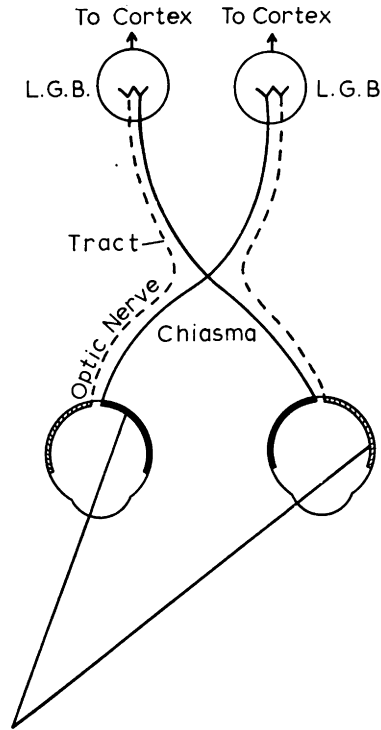


FIG. 3. The decussation of the optic pathway.

the field, is associated with impulses passing to the left cerebral hemisphere, an arrangement common to all peripheral stimuli.

Vascular Coat

The nutrition of the eye is taken care of largely by the capillaries of the vascular coat; let us examine this structure more closely.

Choroid. The choroid is essentially a layer of vascular tissue next to the retina; it is separated from this nervous tissue by two membranes—the structureless *membrane of Bruch* and the pigment epithelium. The retina comes to an end at the ciliary body, forming the *ora serrata* (Fig. 4), but the vascular coat continues into the ciliary body as one of its layers, the *vessel layer*, which is separated from the eye contents by membranes—the two layers of ciliary epithelium which, viewed embryologically, are the forward continuations of the retina and its pigment epithelium, and the *lamina vitrea*, which is the continuation forward of Bruch's membrane.

Ciliary Body and Iris. The ciliary body in antero-posterior section is triangular in shape (Fig. 5) and has a number of processes (seventy) to which the zonule is attached; viewed from behind, these processes appear as radial ridges to which the name *corona ciliaris* has been given (Fig. 4). The relationship of the iris to the ciliary body is seen in Fig. 5; the blood vessels supplying it belong to the same system as that supplying the ciliary body. Posteriorly, the stroma is

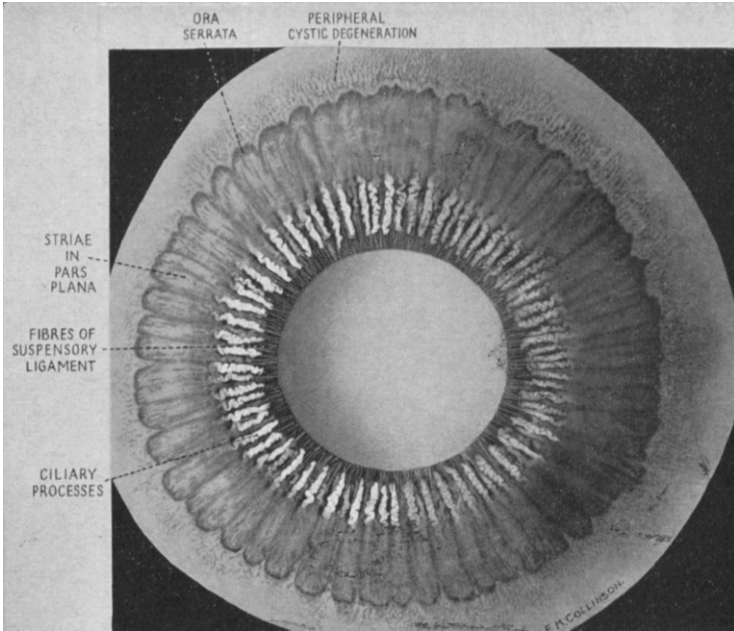


FIG. 4. Posterior view of the ciliary body showing ora serrata and corona ciliaris. (Wolff, *Anatomy of the Eye and Orbit.*)

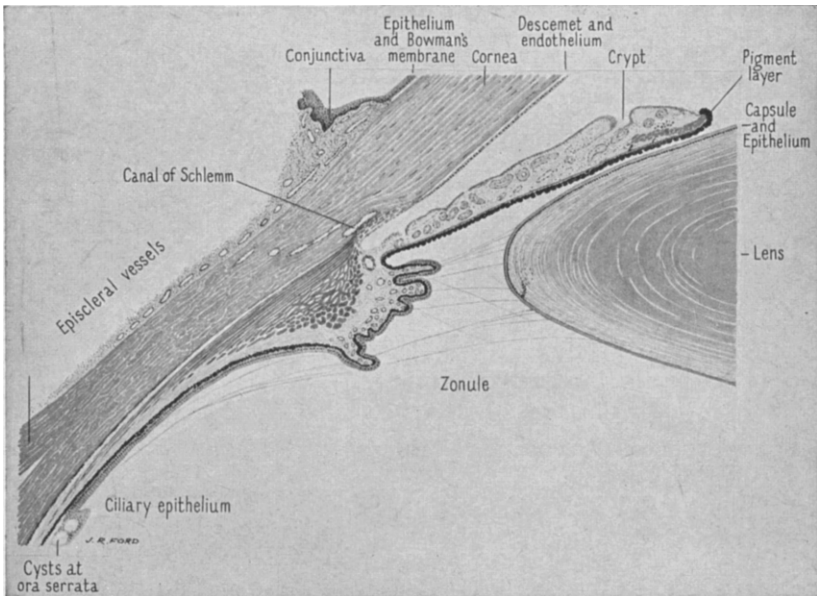


FIG. 5. Antero-posterior section through the anterior portion of the eye. (Wolff, *Anatomy of the Eye and Orbit.*)

separated from the aqueous humour by the *posterior epithelium*, a double, heavily pigmented layer which may be viewed as a prolongation of the ciliary epithelial layers.

Nutrition. The vessels of the vascular coat nourish the internal structures of the eye; so far as the lens is concerned, this process must take place by diffusion of dissolved material from the capillaries through the aqueous humour and vitreous body. The inner (nearest the vitreous) nervous elements of the retina, however, are provided for by a functionally separate vascular system derived from the *central artery of the retina*; this artery, a branch of the *ophthalmic*, enters the globe with the optic nerve and it is its ramifications, together with the *retinal veins*, that give the fundus of the eye its characteristic appearance. The choroid, ciliary body, and iris are supplied by a separate system of arteries, also derived from the ophthalmic—the *ciliary system of arteries*.

The anterior portion of the sclera is covered by a mucous membrane, the *conjunctiva*, which is continued forward on to the inner surfaces of the lids, thus creating the *conjunctival sac*. The remainder of the sclera is enveloped by *Tenon's capsule*.

Muscle. Movements of the eye are executed by the contractions of the six extra-ocular muscles; the space between the globe and orbit being filled with the orbital fat, the movements of the eye are essentially rotations about a fixed point in space.

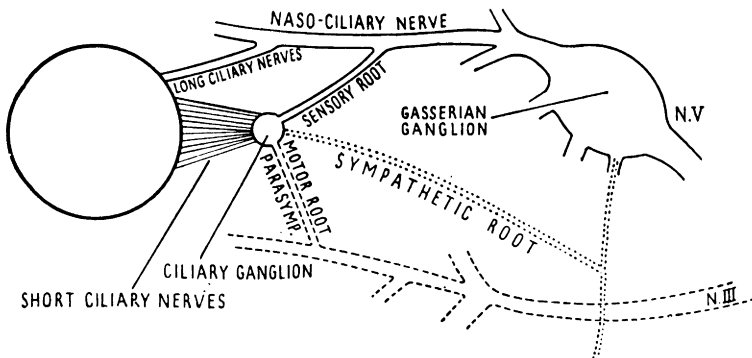


FIG. 6. Nervous supply to the eyeball.

Nerve Supply. The essentials of the nerve supply to the eyeball are indicated in Fig. 6; sensory impulses (excluding, of course, the visual ones) are conveyed through the *long* and *short ciliary nerves*. The long ciliary nerves are composed mainly of the axons of nerve cells in the *Gasserian ganglion*—the ganglion of the trigeminal (N. V); they convey impulses from the iris, ciliary body, and cornea. The short ciliary nerves also contain axons of the trigeminal; they pass through a ganglion in the orbit, the *ciliary ganglion*, into the *nasociliary nerve*; the fibres carry impulses from all parts of the eyeball, but chiefly from the cornea.

The voluntary motor nerve supply to the extraocular muscles is through the cranial nerves III (oculomotor), IV (trochlear) and VI (abducens). Parasympathetic motor fibres to the ciliary muscle and iris travel through the lower division of N. III as the *motor root* of the ciliary ganglion; post-ganglionic fibres to the muscles are contained in the short ciliary nerves.

Sympathetic fibres from the superior cervical ganglion enter the orbit as the sympathetic root of the ciliary ganglion and run in the short ciliary nerves to supply the vessels of the globe and the dilator fibres of the pupil. Other sympathetic fibres avoid the ciliary ganglion, passing through the Gasserian ganglion and entering the globe in the long ciliary nerves, whilst still others enter the globe in the adventitia of the ciliary arteries.*

* Ruskell (1970a, b) has described a second source of parasympathetic fibres to the eye; these are derived from the facial nerve (N. VII) as *rami orbitales* of the pterygopalatine ganglion, and they enter the eyeball mainly with the long ciliary nerves; nerve terminals on all ciliary arteries examined showed degenerative changes after damage to the pterygopalatine ganglion.

SECTION I

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PART I

AQUEOUS HUMOUR AND THE INTRAOCULAR PRESSURE

THE aqueous humour is a transparent colourless fluid contained in the anterior and posterior chambers of the eye (Fig. 1, p. 1). By inserting a hypodermic needle through the cornea, the fluid may be more or less completely withdrawn, in which case it consists of the mixed fluids from the two chambers. As Seidel first showed, the posterior fluid may be withdrawn separately by inserting a needle through the sclera just behind the corneoscleral junction; because of the valve-like action of the iris, resting on the lens, the anterior fluid is restrained from passing backwards into the posterior chamber, so that subsequently another needle may be inserted into the anterior chamber and this anterior fluid may be withdrawn. In the cat Seidel found that the volume was some 14 per cent of the volume of the anterior fluid, whilst in the rabbit it is about 20 per cent, according to Copeland & Kinsey. The fluids from the two chambers are of very similar composition, so that we may consider the composition of the mixed fluid when discussing the relationships between aqueous humour and blood. Thanks largely to the studies of Kinsey, however, it is now known that there are characteristic differences between the two fluids, differences that reflect their histories, the posterior fluid having been formed first and therefore exposed to diffusional exchanges with the blood in the iris for a shorter time than the anterior fluid.

ANATOMICAL RELATIONSHIPS

The nature of the aqueous humour is of fundamental interest for several reasons. There is reason to believe that it is formed continuously in the posterior chamber by the ciliary body, and that it passes through the pupil into the anterior chamber, whence it is drained away into the venous system in the angle of the anterior chamber by way of Schlemm's canal. As a circulating fluid, therefore, it must be a medium whereby the lens and cornea receive their nutrient materials. Furthermore, because it is being continuously formed, the *intraocular pressure* is largely determined by the rate of formation, the ease with which it is drained away, and by the forces behind the process of formation. To understand the nature of the fluid we must consider its chemical composition and variations of this under experimental conditions, whilst to appreciate the drainage process we must examine the detailed micro-anatomy of the structures that are concerned in this process. Since, moreover, the aqueous humour cannot be considered in isolation from the vitreous body, the posterior portion of the eyeball is also of some interest.

The Vascular Coat

The choroid, ciliary body and iris may be regarded as a vascular coat—the *uvea*—sandwiched between the protective outer coat—cornea and sclera—and the inner neuroepithelial coat—the retina and its continuation forwards as the ciliary epithelium (Fig. 7). This vascular coat is made up of the ramifications of the ciliary system of arteries that penetrate the globe independently of the optic nerve.

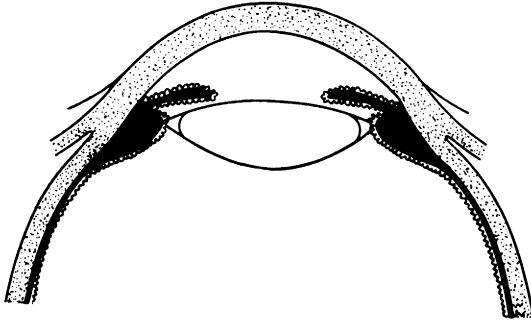


FIG. 7. Illustrating the uvea or vascular coat (black) sandwiched between the sclera on the outside and the retina, ciliary epithelium, etc., on the inside.

Ciliary Arteries. The posterior ciliary arteries arise as trunks from the ophthalmic artery (Fig. 8), dividing into some ten to twenty branches which pierce the globe around the optic nerve. Two of them, the long posterior ciliary arteries, run forward through the choroid to the ciliary body where they anastomose with the anterior ciliary arteries to form what has been incorrectly called the *major circle of the iris*; incorrectly, because the circle is actually in the ciliary body. From this circle, arteries run forward to supply the ciliary processes and iris, and backwards—as recurrent ciliary arteries—to contribute to the choroidal circulation.

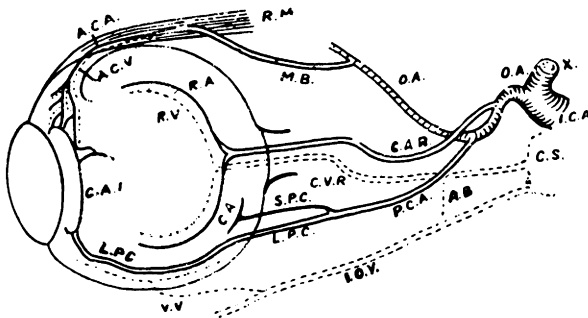


FIG. 8. Physiological plan of the circulation in man. O.A., ophthalmic artery; M.B., muscular branch; A.C.A., anterior ciliary artery; C.A.I., Circulus arteriosus iridis major; L.P.C., long posterior ciliary artery; S.P.C., short posterior ciliary artery; P.C.A., posterior ciliary arteries; C.A.R., central artery of the retina; R.A., retinal artery; V.V., vortex vein; I.O.V., inferior orbital vein; A.B., anastomosing branch; C.S., cavernous sinus. (Duke-Elder, *Brit. J. Ophthalm.*)

By the *choroid* we mean the vascular layer between the retina and sclera; it is made up of the ramifications of the recurrent ciliary arteries, just mentioned, and of the short posterior ciliary arteries, which enter the globe around the posterior pole. The arteries break up to form a well-defined capillary layer—the *chorio-capillaris*—next to the retina, but separated from this by a transparent glassy membrane—the *membrane of Bruch* or *lamina vitrea*. This capillary layer is certainly responsible for nutrition of the outer layers of the retina—pigment

epithelium, rods and cones, and bipolar cells—and may also contribute to that of the innermost layer.

Venous System. The venous return is by way of two systems; the anterior ciliary veins accompany the anterior ciliary arteries, whilst the vortex veins run independently of the arterial circulation; these last are four in number, and they drain all the blood from the choroid, the iris and the ciliary processes, whilst the anterior ciliary veins drain the blood from the ciliary muscle and the superficial plexuses, which we shall describe later. According to a study by Bill (1962) only 1 per cent of the venous return is by way of the anterior ciliary veins.

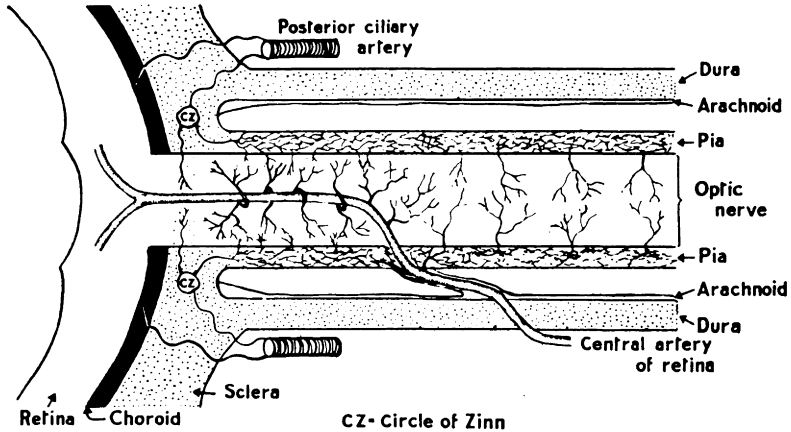


FIG. 9. Schematic section of optic nerve and eyeball showing course and branches of the central retinal artery. (Singh & Dass, *Brit. J. Ophthalm.*)

Retinal Circulation. As indicated earlier, the innermost part of the retina is supplied directly, in man, by the ramifications of the central retinal artery, a branch of the ophthalmic that penetrates the meningeal sheaths of the optic nerve in its intraorbital course and breaks up into a series of branches on the inner layer of the retina, branches that give the fundus its characteristic appearance in the ophthalmoscope. As Fig. 9 indicates, the central artery gives off branches that supply the optic nerve*; moreover, the posterior ciliary arteries may send off branches in the region of the optic disk, forming a circle—*circle of Zinn or Haller*—which may form anastomoses with the branches of the central artery of the retina. To the extent that these anastomoses occur, the uveal and retinal vascular systems are not completely independent. Venous return from the retinal circulation is by way of the central retinal vein which, for a part of its course, runs in the subarachnoid space of the optic nerve and is thereby subjected to the intracranial pressure. For this reason, an elevated intracranial pressure may be manifest as an engorgement of the retinal veins.

So much for the general lay-out of the vascular circulation of the eye; as we

* Some authors, for example François & Neetens, speak of a *central artery of the optic nerve*, derived either as a branch of the central retinal artery or entering separately as a branch of the ophthalmic artery. Wolff describes them as *arteriae collaterales centralis retinae*. The literature relating to this and other points is well summarized in the careful studies of Singh & Dass (1960), whilst Hayreh (1969) has described the capillary supply to the optic disk; a large part of this—the prelaminar—is from cilio-retinal arteries.

have seen, the uveal circulation supplies the ciliary body and iris, the two vascular structures that come into close relationship with the aqueous humour. It is important now that we examine these structures in some detail.

Ciliary Body

In sagittal section this is a triangular body (Fig. 5, p. 4), whilst looked at from behind it appears as a ring, some 6 mm wide in man. Where it joins the retina—the *ora serrata*—it appears smooth to the naked eye, but farther forward the inner surface is ridged, owing to the presence of some seventy to eighty *ciliary processes*, and acquires the name of *corona ciliaris* (Fig. 4, p. 4). As the oblique section illustrated in Fig. 10 shows, the ciliary processes are villus-like

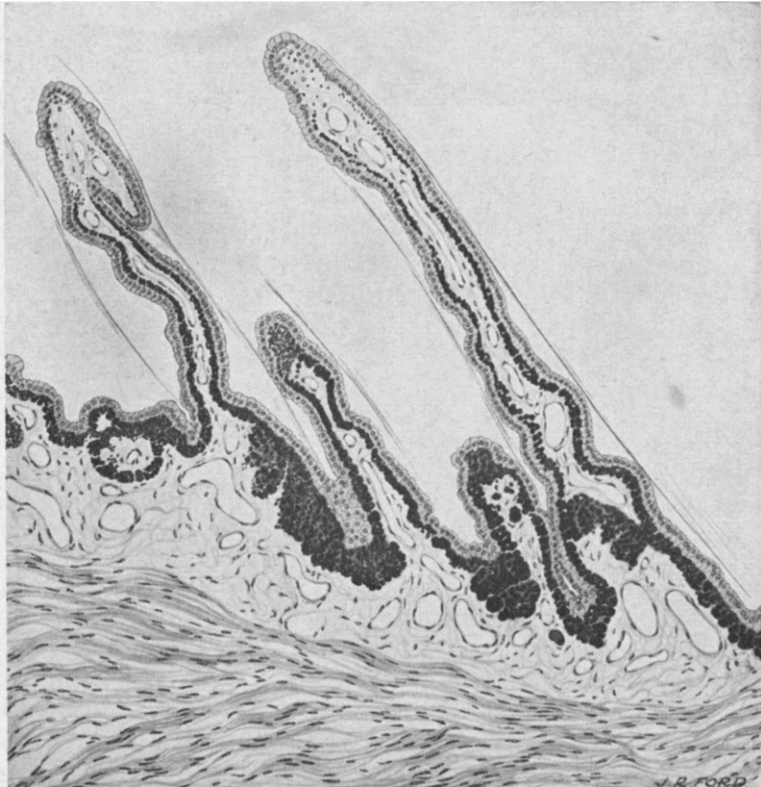


FIG. 10. Oblique section of the ciliary body.
(Wolff, *Anatomy of the Eye and Orbit*.)

projections of the main body, jutting into the posterior chamber. According to Baurmann, the total area of these processes, in man, is some 6 cm² and we may look upon this expansion as subserving the secretory activity of this part of the ciliary body, since there is good reason to believe that it is here that the aqueous humour is formed. The vessel-layer of the ciliary body is similar to the choroid; it extends into each ciliary process, so that this is probably the most heavily

vascularized part of the eye. Each process contains a mass of capillaries so arranged that each comes into close relationship, at some point in its course, with the surface of the epithelium. As stated above, blood from the ciliary processes is carried away by the vortex veins. In the rabbit, the ciliary processes are of two kinds—*posterior principal processes* projecting from the posterior region, and the *iridial processes*, located more anteriorly, and projecting towards the iris. These last have no zonular connections and may be those that are most closely concerned in production of the aqueous humour since they are the only processes to show significant morphological changes after paracentesis (p. 40), according to Kozart (1968).

Ciliary Epithelium. The innermost coat, insulating the ciliary body from the aqueous humour and vitreous body, is the *ciliary epithelium*, a double layer of cells, the inner layer of which, i.e. the layer next to the aqueous humour or vitreous body, is non-pigmented, whilst the outer layer is heavily pigmented. These cells, which are considered to be responsible for the secretion of the aqueous humour, have been examined in the electron microscope by several workers; a striking feature is the interdigitation of the lateral surfaces of adjacent cells, and the basal infoldings (Fig. 11, Pl. I), which are characteristic features of secretory epithelia concerned with fluid transport. The relations of the two epithelial cell layers are of importance, since the secreted aqueous humour must be derived from the blood in the stroma of the ciliary body, and thus the transport must occur across both layers. This relation has been studied in the electron microscope by Bairati & Orzalesi (1966); the two layers, which face apex-to-apex, are united at frequent intervals by a variety of junctional complexes including zonulae occludentes, which would restrict diffusion through the intercellular space; the fusion of cell membranes brought about in this way would provide a relatively unrestricted passage of material from one cell layer to the other. Localized expansions of these intercellular spaces occur, and are called ciliary channels. Diffusion from stroma towards the aqueous humour is restricted by lateral zonulae occludentes between adjacent pigmented cells, but the spaces between the non-pigmented cells are apparently open.

The Iris

This is the most anterior part of the vascular coat; in a meridional section it is seen to consist of two main layers or *laminae*, separated by a less dense zone, the *cleft of Fuchs*. The posterior lamina contains the muscles of the iris, being covered posteriorly by two layers of densely pigmented cells, the innermost being the posterior epithelium of the iris which is continuous with the inner layer of the ciliary epithelium. The blood vessels, derived from the major circle of the iris (p. 9), run in the loose connective tissue of the laminae. Both arteries and veins run radially; venous return is by way of the vortex veins.

On its anterior surface the iris is in contact with the aqueous humour, so that it is of some interest to determine exactly how the fluid is separated from the tissue. It is customary to speak of an *anterior endothelium*, continuous with the corneal endothelium anteriorly and the posterior iris epithelium posteriorly, covering the anterior surface of the iris and thus insulating the aqueous humour from the underlying spongy tissue. The weight of recent evidence, however, bears against this so that it would seem that, in man at any rate, the aqueous humour has direct access to the stromal tissue.

PLATE I

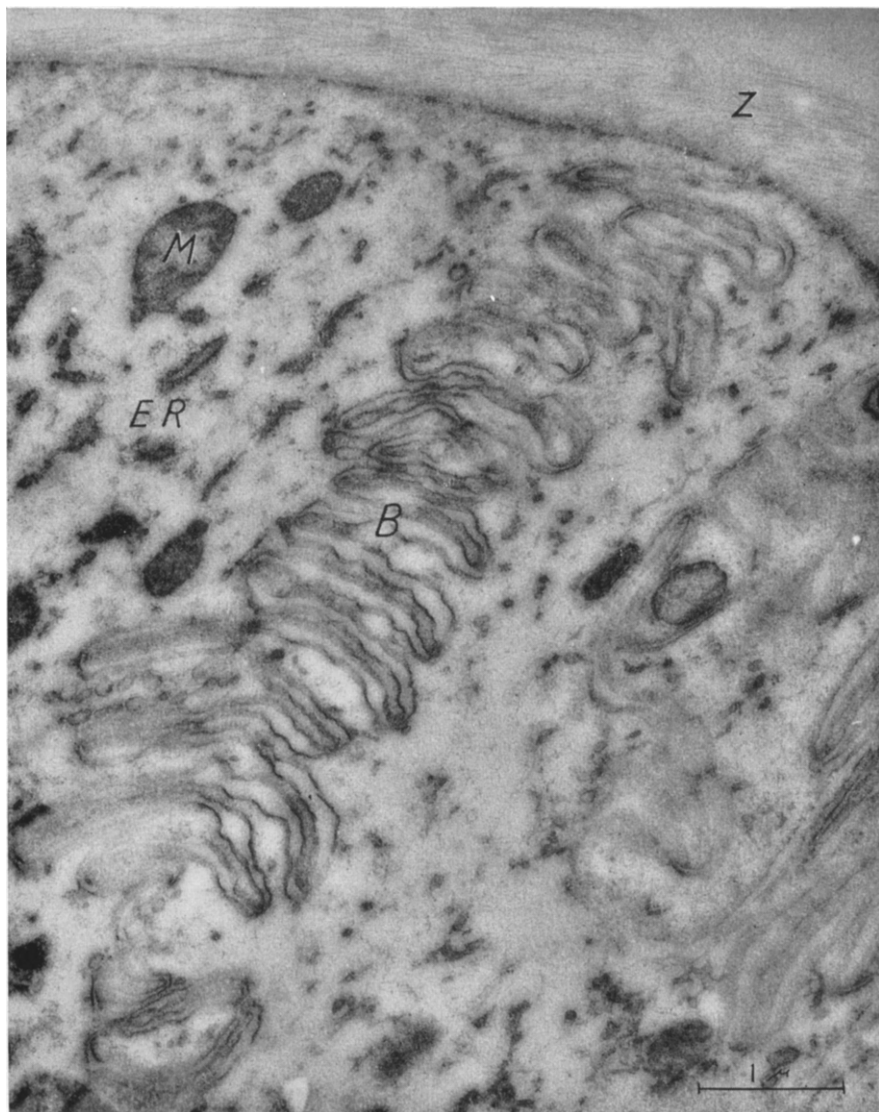


FIG. 11. Electron micrograph of a section of portions of two adjacent ciliary epithelial cells of the rabbit showing complex interdigitations (B) of their boundaries. Zonular fibres (Z) can be seen in close approximation to the surface of these cells. ER, endoplasmic reticulum; M, mitochondrion. Osmium fixation. $\times 19,000$. (Pappas & Smelser, *Amer. J. Ophthalm.*)

To face p. 12.

PLATE II

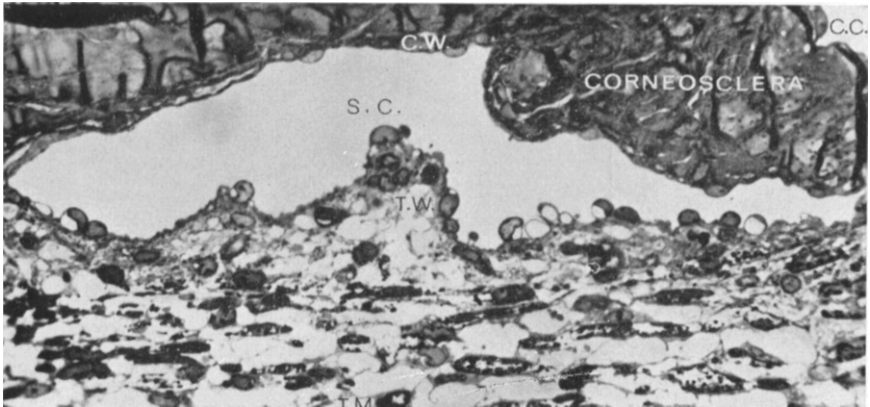


FIG. 14. Meridional section of Schlemm's canal and adjacent trabecular meshwork of rhesus monkey. Osmium fixed; toluidine blue stained. C.C., Collector channel; C.W., corneo-scleral wall of Schlemm's canal; S.C., Schlemm's canal; T.M. trabecular meshwork. Light micrograph. $\times 610$. (Tripathi, *Exp. Eye Res.*)

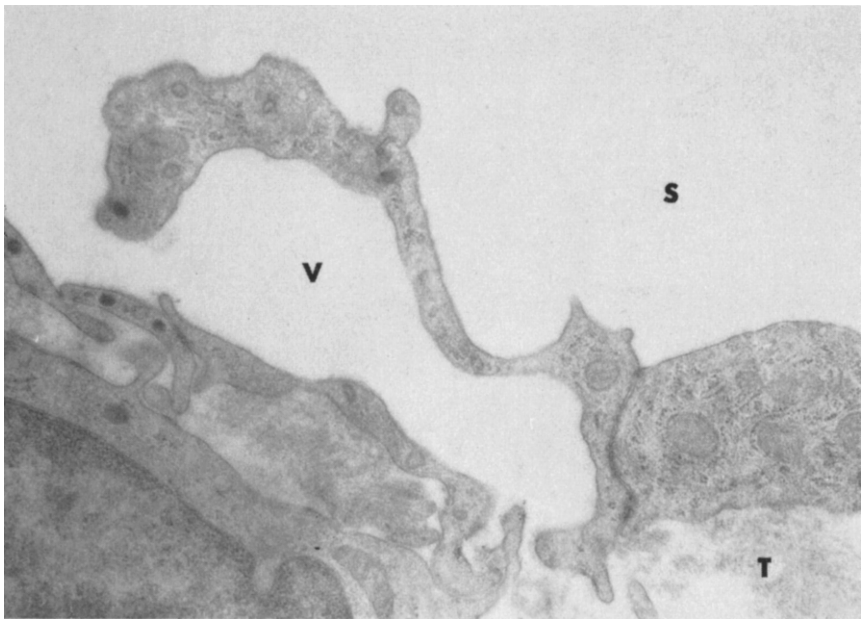


FIG. 24. Section through vacuole, V, of the endothelium lining Schlemm's canal, S. Note communication between Schlemm's canal and trabecular meshwork, T, through the vacuole. $\times 19,500$. (Kayes, *Invest. Ophthalm.*)

The Drainage Route

We have said that the aqueous humour is most probably secreted continuously by the cells of the ciliary epithelium; to make room for the new fluid there must obviously be a continuous escape, or drainage, and this occurs by way of the *canal of Schlemm*. This is a circular canal in the corneo-sclera of the limbus (Fig. 5, p. 4) which comes into relation with the aqueous humour on the one hand and the *intrasceral venous plexus* on the other, as illustrated by Figs. 12 and 13.

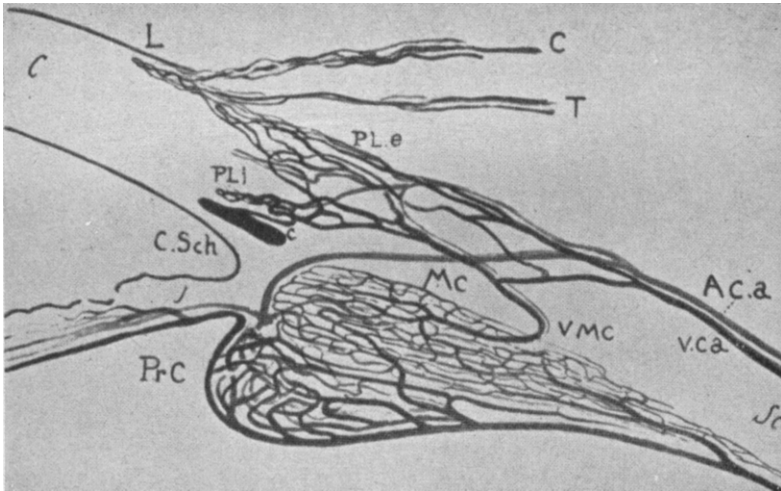


FIG. 12. Illustrating the canal of Schlemm and its relation to the plexuses of the anterior segment of the eye. C, conjunctival plexus; T, Tenon's capsule plexus; PLe, episcleral plexus; PLi, intrasceral plexus; Mc, ciliary muscle; VMc, vein of ciliary muscle; Ac.a, anterior ciliary artery; v.ca, anterior ciliary vein; Pr C, ciliary process; C, cornea; c, collector; L, limbus. (Maggiore, *Ann. Ottalm.*)

Plexuses of the Anterior Segment. The intrasceral plexus is largely made up of the ramifications of branches of the anterior ciliary veins, but, as Maggiore showed, there is also an arterial contribution, branches of the anterior ciliary arteries passing directly to the plexus and breaking up into fine vessels that come into direct continuity with the finer vessels of the plexus. It connects with the canal of Schlemm by some twenty fine vessels—*collectors*—which thus transport aqueous humour into the venous system. The blood from the plexus is drained away by large trunks into the *episcleral plexus*; from here large veins, also draining the more superficial plexuses—conjunctival and subconjunctival—carry the blood to the insertions of the rectus muscles in the sclera and accompany the muscular veins.

Canal of Schlemm and Trabecular Meshwork. The canal of Schlemm is usually represented as a ring lying in the corneo-sclera, which on cross-section (as in the meridional section of Fig. 13) appears as a circle or ellipse; its structure is, in fact, more complex, since it divides into several channels which, however, later reunite; hence the appearance of a cross-section varies with the position of the section. The canal is essentially an endothelium-lined vessel, similar to a

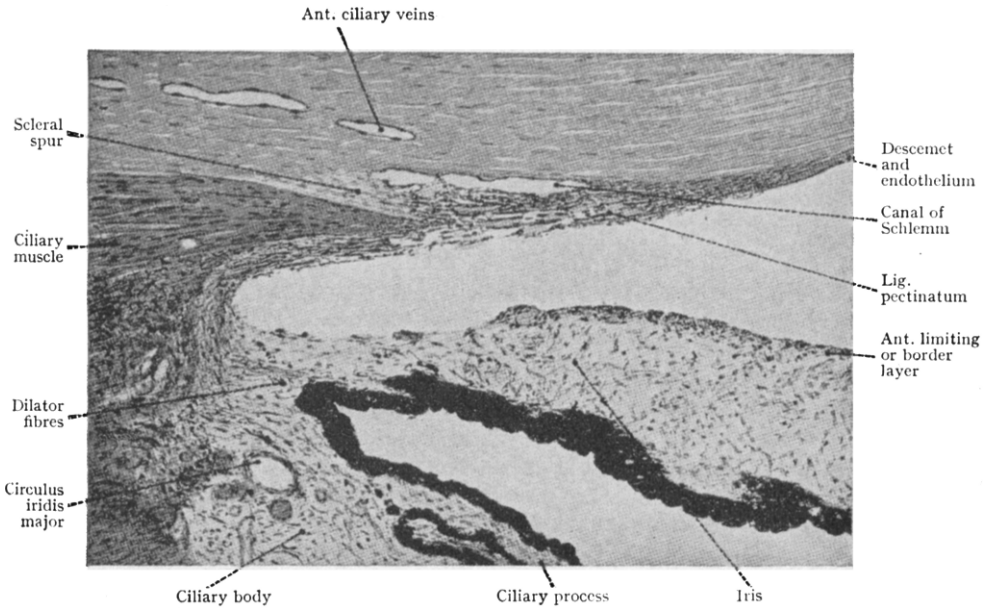


FIG. 13. Section of the angle of the anterior chamber.
(Wolff, *Anatomy of the Eye and Orbit.*)

delicate vein; on the outside it rests on the scleral tissue whilst on the inside, nearest the aqueous humour, it is covered by a meshwork of endothelium-covered trabeculae—the *trabecular meshwork* or *pectinate ligament* (Fig. 14, Pl. II). Aqueous humour, to enter the canal, must percolate between the trabeculae and finally cross the endothelial wall. On meridional section the meshwork appears as a series of meridionally orientated fibres (Fig. 13), but on tangential section it is

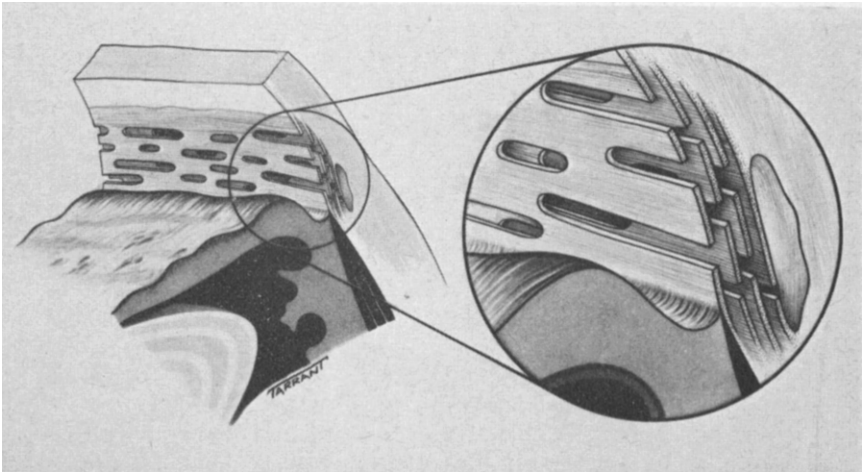


FIG. 15. Schematic illustration of lamellae of scleral meshwork.
(Ashton, Brini & Smith, *Brit. J. Ophthalm.*)

seen to consist of a series of flat lamellae, piled one on top of the other, the fluid-filled spaces between these lamellae being connected by holes, as illustrated schematically in Fig. 15. The meshwork has been divided into three parts with characteristically different ultrastructures; the innermost portion (1 of Fig. 16) is the *uveal meshwork*; the trabeculae making up the lamellae here are finer than those of the outer or *corneoscleral meshwork*, whilst the meshes are larger. Each

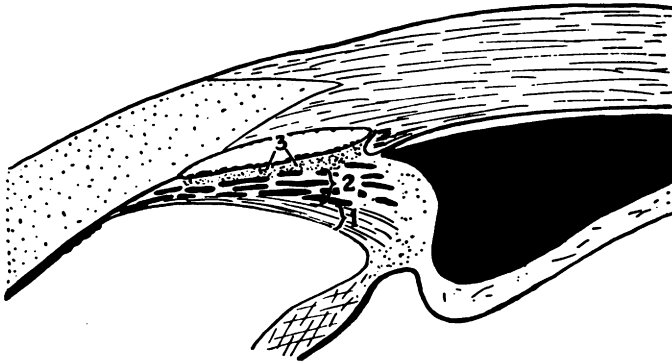


FIG. 16. Schematic drawing of the chamber angle in primates, showing the three distinct parts of the trabecular meshwork. 1, uveal meshwork; 2, trabeculum corneosclerale; 3, inner wall, or pore area. (Rohen, *Structure of the Eye*.)

lamella of the uveal meshwork is attached anteriorly to the corneal tissue at the end of Descemet's membrane, constituting *Schwalbe's ring*,* and posteriorly to the meridional fibres of the ciliary muscle. A pull of these fibres may well operate to open up the meshes of this trabecular structure, thereby favouring passage of fluid. The third portion, revealed by the electron-microscope, immediately adjacent to the canal, is called the *pore area* or *pore tissue* and is made up of endothelial cells with an intervening ground substance. Thus the inner wall of Schlemm's canal, facing the trabecular meshwork, consists of a double layer of endothelial cells, which are closely connected by tight junctions, whilst beneath this is the pore-tissue or what Rohen (1969) calls the "cribriform meshwork".

THE DRAINAGE PROCESS

Experimental Study. In 1921 Seidel established beyond reasonable doubt that the aqueous humour was continually formed and drained away. He inserted a needle, connected to a reservoir containing a solution of a dye, into the anterior chamber of a rabbit (Fig. 17). By lowering the reservoir below the intraocular pressure a little aqueous humour was drawn into the needle and then, when the reservoir was raised, this fluid, mixed with dye, was returned to the anterior chamber. Soon the dye mixed with the rest of the fluid. Seidel observed that the dye stained the blood vessels in the surface of the globe—episcleral vessels—indicating that aqueous humour was being carried into the venous system. This

* *Iris processes* are made up of an occasional lamina of the uveal meshwork that crosses posteriorly to attach to the root of the iris.

passage out would only occur, however, if the pressure in the eye, determined by the height of the reservoir, was at or above 15 mm Hg; when the pressure was reduced below this it was presumed that drainage of aqueous humour ceased. Since the pressure within the eye is normally above 15 mm Hg, we may conclude that fluid is being continuously lost to the blood; moreover, the loss presumably depends on the existence of a pressure-gradient between the aqueous humour and the venous system. Since the episcleral vessels are derived from the anterior ciliary system, we may conclude that the dye was not being absorbed from the iris, the venous return from which is by way of the vortex veins which were uncoloured in these experiments. More recent studies, in which isotope-labelled material is introduced into the aqueous humour and the venous blood collected from both ciliary and vortex veins, have confirmed that at least 99 per cent of drainage is by the anterior route (Bill, 1962).

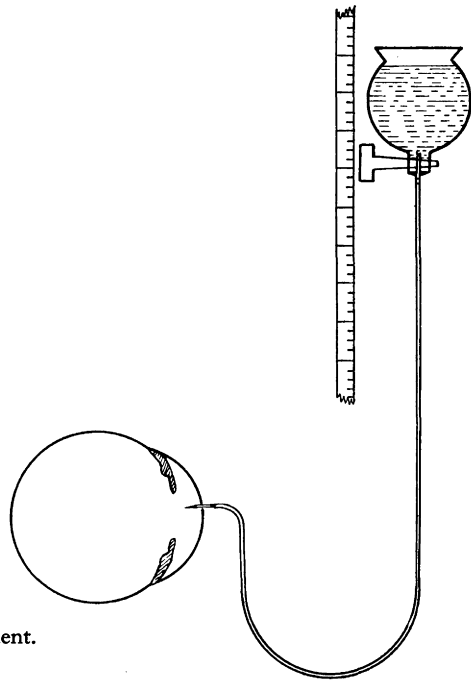


FIG. 17. Illustrating Seidel's experiment.

Aqueous Veins. Confirmation of Seidel's view was provided in a striking manner by Ascher in 1942; when examining the superficial vessels of the globe with the slit-lamp microscope, he observed what appeared to be empty veins but they turned out to be full of aqueous humour, and he called them *aqueous veins*. Usually one of these veins could be followed till it joined a blood vessel, in which event the contents of the two vessels, aqueous humour and blood, did not mix immediately but often ran in parallel streams forming a *laminated* aqueous vein, as illustrated schematically in Fig. 18. If the blood-vein beyond the junction was compressed, one of two things happened; either the blood drove the aqueous humour out of its channel or the aqueous humour drove the blood out.

The latter situation was described as the *positive glass-rod phenomenon*, whilst the former, with the blood driving aqueous humour out, was called the *negative glass-rod phenomenon*. These superficial vessels, full of aqueous humour, are probably derived from the deeper vessels of the intrascleral plexus, the pressure-relationships in the collectors from Schlemm's canal being such as to favour displacement of blood throughout the course of the fluid to the surface of the globe as illustrated by Fig. 19.

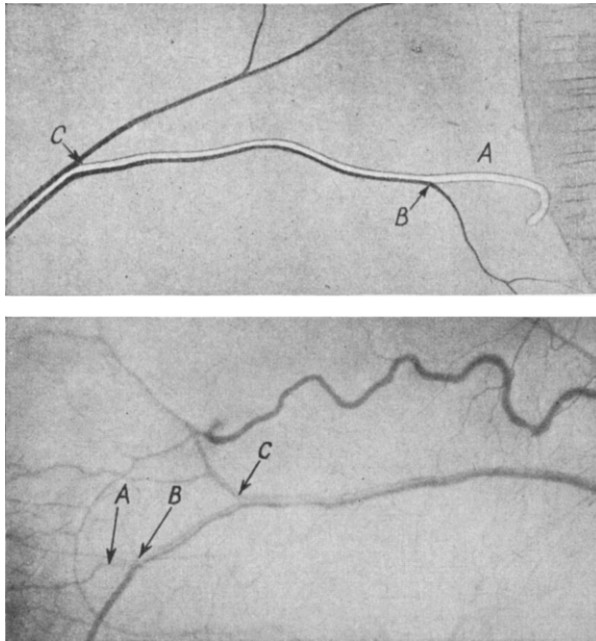


FIG. 18. Typical aqueous veins. *Above*: Sketch made by Ascher (*Amer. J. Ophthalm.*) in his original description. *Below*: Untouched photo taken by Thomassen and Perkins. The aqueous vein emerges from the deeper tissue and is visible at A. At B it joins a blood-vein so that the latter has two strata. At C the stratified vessel joins another vein to give three laminae.

Goldmann proved conclusively that these vessels contained aqueous humour by injecting fluorescein intravenously. This substance passes very slowly from blood into aqueous humour so that one would not expect any vessel containing aqueous humour to fluoresce immediately after the injection, whilst vessels full of blood or plasma should so so; in fact only the blood vessels did fluoresce. Later, Ashton identified an aqueous vein in a human eye that was about to be enucleated; a wire was tied round the vein and, after enucleation, the canal of Schlemm was injected with Neoprene. After digesting the tissue away a cast of the canal and its connecting vessels remained, and examination showed that the aqueous vein did, indeed, take origin from the canal of Schlemm. Subsequent studies of Jocson & Sears (1968), employing a silicone vulcanizing fluid, have shown that the connections of the canal of Schlemm with the vascular system are of two main kinds, large (aqueous veins) to the episcleral vessels and much finer connections to the intrascleral vessels. In addition, Rohen (1969) has described

FIG. 19. Ascher's view of the origin of an aqueous vein.



bridge-like channels running parallel with Schlemm's canal, which branch off and later rejoin it; these make connections with the intrascleral plexus.*

PHYSIOLOGY OF THE VASCULAR SYSTEM

The vascular circulation of the eye has attracted a great deal of interest because of its close relationship to the formation and drainage of aqueous humour. Space will not permit a detailed description of this aspect of ocular physiology, and we must be content with a few salient points.

Pulses. With the ophthalmoscope an arterial pulse may be observed in the retinal vessels; if the intraocular pressure is increased by compressing the globe the pulse may be exaggerated, since the collapse of the artery during diastole becomes greater; if the pressure is raised sufficiently the pulse will cease, at which point the pressure in the eye is equal to the systolic pressure in the artery from which the retinal artery is derived, namely, the ophthalmic artery. The retinal veins also show a pulse; it is best seen where the large veins lie on the optic disk; it appears as a sudden emptying of this portion of the vein, progressing from the central end towards the periphery followed by a pronounced dilatation, beginning at the periphery and passing centrally. The pulse is not simply a reflexion of events taking place in the right auricle, and is closely related to ventricular systole. The rise in intraocular pressure associated with systole will tend to compress the veins; and a collapse of the latter will take place where the pressure is least, i.e. most centrally. The subsequent refilling of the vein will occur in diastole, or late in systole, and will proceed in the reverse direction. The exact time-relationships of the pulse were established cinematographically by Serr.

Pressures. These were studied experimentally by Seidel and later by Duke-Elder; according to the latter author the following values (mm Hg) are associated with an intraocular pressure of 20 mm Hg:

Ophthalmic artery	99.5	Retinal vein	22.0
Retinal arteries	75.5	Intrascleral vein	21.5
		Episcleral vein	13.0

* The outer wall of Schlemm's canal has been described by Rohen & Rentch (1969); the tissue immediately adjacent to the endothelium is differentiated from the sclera proper; the regions of confluence of the canal with the collector ducts may be regarded as out-pouchings of this outer wall, whilst the septa that partially occlude the canal at various points are to be regarded as extensions of the outer wall into the lumen. In old eyes there is an accumulation of amorphous material in the outer wall, but its significance for drainage is doubtful.

Of most importance are the values in the anterior ciliary or episcleral veins; these are probably not independent of the intraocular pressure, however; thus in human subjects Weigelin & Löhlein found the following empirical relationship: $P_{ev} = 0.48 \times P_{oc} + 3.1$, where P_{ev} is the episcleral venous pressure and P_{oc} the intraocular pressure. In animals, too, Macri (1961) found a linear relationship between the two.

THE INTRAOCULAR PRESSURE

On the basis of Seidel's studies, we may expect the flow of aqueous humour to be determined by the difference of pressure between the fluid within the eye—the *intraocular pressure*—and the blood within the episcleral venous system into which the fluid must ultimately flow to reach the surface of the globe. Thus, according to Seidel's formulation we should have:

$$\text{Flow} = (P_{oc} - P_{ev})/R$$

if the flow follows Poiseuille's Law, R being a resistance term determined by the frictional resistance through the trabecular meshwork and along the various vessels through which the fluid flows. To understand the dynamics of flow of aqueous humour, then, we must consider in some detail the nature of the intraocular pressure, P_{oc} , and its relationships with the other factors in the above equation, namely, the episcleral venous pressure, P_{ev} , and the resistance term, R .

Measurement of the Intraocular Pressure

On inserting a hypodermic needle into the anterior chamber the aqueous humour flows out because the pressure within is greater than atmospheric; we may define the intraocular pressure as that pressure required just to prevent the loss of fluid. Manometric methods have been developed that permit the measurement of this pressure with a minimal loss of fluid, this being necessary since, as we shall see, loss of fluid *per se* may upset the normal physiology of the eye.

Manometry. The general principle of the manometric methods employed for measuring the intraocular pressure is illustrated by Fig. 20. The fluid-filled chamber is connected to a reservoir, R , which is of variable height, and also to the hypodermic needle. The end of the chamber is covered by a membrane, and it is essentially the movements of the membrane, caused by changes in pressure, that are recorded. If the membrane consists of a latex skin, it may be made to move a small mirror in contact with it, so that movements of the membrane can be magnified into movements of a spot of light reflected from the mirror. Alternatively, the membrane may be made of metal and act as the plate of a condenser, as in the Sanborn electromanometer, or it may be connected to a transducer valve, i.e. a valve whose anode may be moved from outside, so that a change in its position is converted into a change of voltage. The reservoir serves to fill the system with a saline solution and may be employed to calibrate the system; thus, with the needle stopped and the tap open, raising and lowering the reservoir will establish known pressures in the chamber.

Tonometry. For studies on man, the introduction of a needle into the anterior chamber is rarely permissible, so that various *tonometers* have been developed permitting an indirect measure of the pressure within the eye. With the *impression*

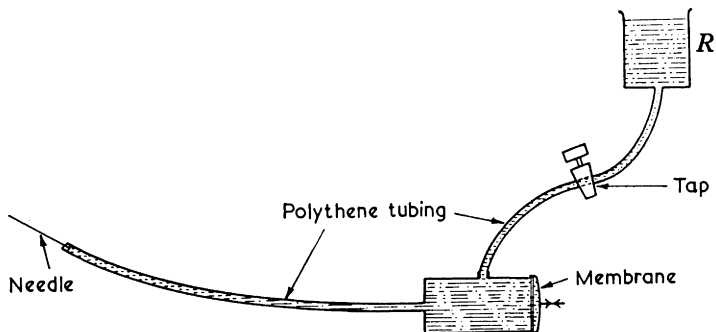


FIG. 20. Illustrating the general principle on which manometric measurement of the intraocular pressure is based. The reservoir serves to fill the system with saline. When the needle is in the anterior chamber, and the tap is closed, changes in pressure cause movements of the membrane.

type of tonometer, such as the Schiøtz instrument, the depth to which a weighted plunger applied to the cornea sinks into the eye is measured, whilst with the *applanation tonometer* the area of flattening of the cornea, when a metal surface is applied with a controlled force, is measured. The two principles are illustrated schematically in Fig. 21; the greater the intraocular pressure the smaller will be the depth of impression, or area of applanation.

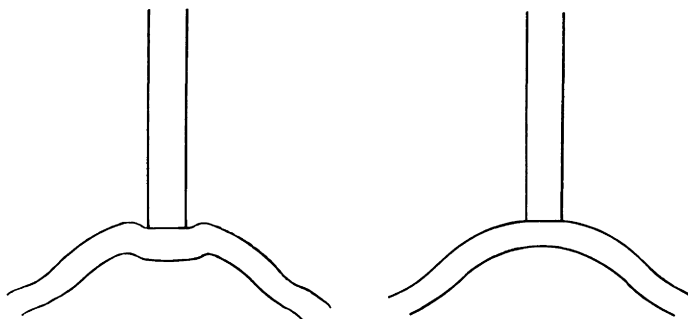


FIG. 21. Illustrating the principles of impression tonometry (*left*) and applanation tonometry (*right*).

SCHIØTZ TONOMETER

So widespread is the use of this instrument, or its electronic adaptations, that it may profitably be described in some detail. An actual instrument is illustrated in Fig. 22, whilst the mechanical features are shown schematically in Fig. 23. The footplate, F, is curved to fit the average curvature of the human cornea. The weighted plunger, P, passes through the footplate; movements of this plunger operate on the hammer, H, which converts vertical movements into readings of the pointer on the scale. This scale reads from 0 to 20, the greater the indentation the lower the intraocular pressure and the *larger* the scale-reading. The frame, Y, serves to hold the instrument upright on the eye, and because the footplate can move freely within the cylindrical part of the frame, the actual

weight resting on the eye is that of the plunger, footplate, hammer and scale (17.5 g), the frame being held by the observer. With the smallest weight on the plunger, the total effective thrust on the eye amounts to 5.5 g, and the readings made with this are referred to as the "5.5 g readings". By using heavier weights the thrust may be increased to 7.5 or 10 g, thereby allowing the instrument to give reasonable scale-readings at higher levels of intraocular pressure.

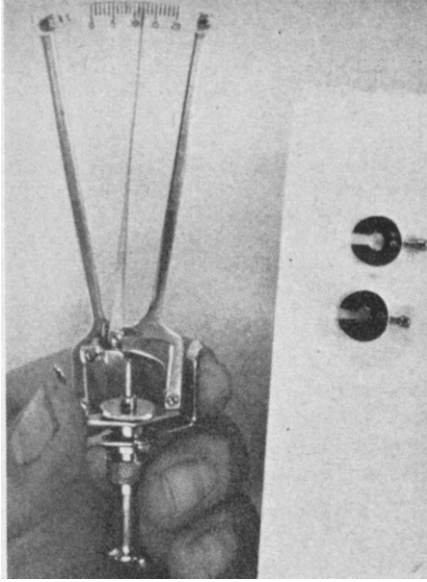


FIG. 22. The Schiötz tonometer. (Davson, *The Eye*.)

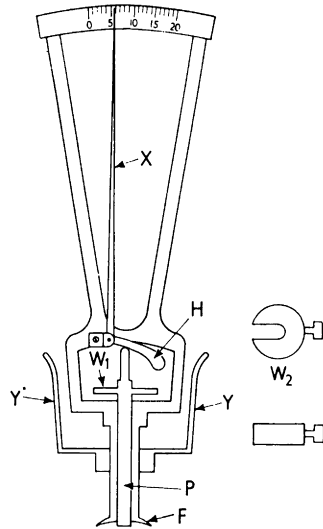


FIG. 23. Diagrammatic drawing of the Schiötz tonometer. (Davson, *The Eye*.)

Calibration. To calibrate the tonometer, the scale-reading, R , must be converted to the actual pressure within the eye before the tonometer was applied, P_o . The detailed procedure has turned out to be very complex and not completely satisfying*; it is impossible to enter into details of the procedures here, so we must content ourselves with the general principles. When the tonometer is on the eye, the pressure within it obviously rises because of the weight of the instrument; and the pressure within the eye with the tonometer on it is referred to as P_t . P_t may be related to the scale-reading, R , by taking an excised eye, and inserting a needle connected to a reservoir and manometer into the anterior chamber. Different pressures may be established in the eye, and tonometer readings corresponding to these may be made, Friedenwald found the relationship:

$$W/P_t = a + bR$$

so that with a and b determined experimentally we have the relationship between P_t and scale-reading, R . To convert P_t to P_o , we require to know by how much the indentation, corresponding to the scale-reading, R , has raised the pressure; and

* The literature on calibration scales and ocular rigidity is quite large and cannot be summarized here; some key references are Friedenwald, 1957; McBain, 1960; Drance, 1960; Perkins & Gloster, 1957; Hetland-Eriksen, 1966).

this depends on the distensibility of the sclera, i.e. the extent to which a change in volume of the eye will raise the pressure. Thus, if we know the volume of displacement, V_c , associated with a given scale-reading, and if we can relate V_c to a change in pressure of the eye, we can finally establish a relationship between R and P_o . Friedenwald considered that there was a logarithmic relationship between pressure and volume of the globe, to give an equation:

$$\text{Log } P_2/P_1 = k(V_2 - V_1)$$

whence he defined a *rigidity coefficient*, k , characteristic of a given eye. Experimentally he measured the volumes of displacement, V_c , for different scale-readings, and making use of an average rigidity coefficient he was able to construct a table relating scale-readings to values of P_o , the intraocular pressure corresponding to the scale-reading. As subsequent work has shown (Perkins & Gloster; Macri, Wanko & Grimes; McBain), the weakness in this calibration is the assumption that the rigidity coefficient is a constant characteristic of each eye, i.e. that it is independent of pressure; in fact values ranging from 0.003 to 0.036 could be obtained in a given eye according to the intraocular pressure. Moreover, there is no doubt that the distensibility of the globe varies from one individual to another, so that unless this can be allowed for, it is not very sound to use a single calibration scale.*

Because of these difficulties in accurate calibration, the Schiøtz instrument is slowly being superseded by an applanation type of manometer, since with this instrument the deformation of the eye during applanation is very small, with the result that calibration is independent of scleral extensibility (Goldmann, 1955; Armaly, 1960).

APPLANATION TONOMETER

This measures, in effect, the force required to produce a fixed degree of applanation when a flat surface is pressed against the cornea. The earliest instrument (Maklow) consisted of a cylindrical piece of metal with a flat base weighing 5–15 g. A drop of a concentrated dye-solution was spread over the cornea, the instrument was allowed to rest a moment on the corneal surface and a print of the area of contact between cornea and metal was obtained by placing the foot of the instrument on a piece of paper. Goldmann's (1955) instrument is a refinement on this procedure, in which the degree of applanation is kept fixed and the instrument indicates the force required to produce this. There is no doubt that the calibration of this instrument involves far fewer uncertainties than does that of the Schiøtz indentation type. Other applanation instruments are the Mackay-Marg (1959) tonometer and the pneumatic applanation tonometer of Durham *et al.* (1965).

Because of the superiority of the Goldmann applanation tonometer to the indentation type, it seems reasonable to calibrate the Schiøtz tonometer by measuring pressure on the same eye with both instruments successively, taking care that the head is in the same position for both measurements. The most recent calibration carried out in this way has shown that the pressure deduced

* If the pressure is measured on the same eye with different weights on the tonometer, the same result should be read off the calibration scales. If this did not happen it was attributed to the circumstance that the ocular rigidity was abnormal in the eye being studied and Friedenwald, and later Moses & Becker, actually devised a nomogram and tables from which the ocular rigidity could be estimated from paired readings on the same eye using different weights. It will be clear, however, that the scales must be rigidly consistent within themselves if deviations from them are to be interpreted as the correlates of the mechanical properties of the eye rather than as errors in the scales themselves. Subsequent studies summarized by McBain (1960) have shown that they were not sufficiently consistent to warrant their use in this way.