COMMUNICATIONS

ANATOMICAL STUDY OF SCHLEMM'S CANAL AND AQUEOUS VEINS BY MEANS OF NEOPRENE CASTS*

III. ARTERIAL RELATIONS OF SCHLEMM'S CANAL

BY

NORMAN ASHTON AND REDMOND SMITH

From the Department of Pathology, Institute of Ophthalmology, London

IN previous studies of this region (Ashton 1951, 1952), it has been shown that the canal of Schlemm and its efferent connections may be clearly demonstrated by Neoprene latex casts, prepared by direct injection of the canal followed by enzyme digestion of the ocular tissues. Over 200 casts have now been studied by this technique and while the preparations in the main confirm the anatomical accounts of earlier workers, who used serial sections or injections of ink and gelatin followed by clearing, they have the advantage of showing the exact anatomy of the canal in its entirety and in a stereoscopic way that can be readily appreciated. The study has revealed some minor but important deviations from the classical descriptions and these will be discussed in a subsequent communication dealing in detail with the structure and connections of the canal itself. It is the purpose of this paper to describe the arterial relationships of Schlemm's canal as observed in cast preparations.

The vessels involved are the anterior ciliary and the long posterior ciliary arteries which originate indirectly from the ophthalmic artery and meet again at the major circle of the iris, the anterior having pursued a mainly extra-ocular and the posterior a mainly intra-ocular course. According to the classical description of Leber (1903), anterior ciliary arteries run forward on the tendons of the rectus muscles; there are usually two on each of the recti, except the lateral on which there is only one. Uncommonly one of the arteries may be derived from the vessels in the eyelid.

As the vessels approach the limbus, they divide and subdivide into smaller and smaller branches. The larger divisions pass into the eye through perforating scleral channels to join the arterial circle of the iris. The smallest remain in the episclera and pass forward to the limbus, where they loop backward to contribute to the anterior conjunctival arteries, while others dip down through the sclera to reach the deeper parts of the corneal limbus immediately external to the canal, or extend more deeply towards the canal itself. The further destination of these latter arterial twigs is a matter of great interest and considerable controversy. According to Maggiore (1917) and Dvorak-Theobald (1934) they tend to run in a circular fashion, accompanying the canal to form an incomplete arterial circle in close association with it, so close, in fact, that they may cause irregularities in the canal wall; indeed, Wolff (1945) has depicted a small artery apparently lying within its lumen.

* Received for publication August 7, 1953.

The great interest of these small arterial twigs, however, lies in the fact that Friedenwald (1936) has stated that a certain proportion of them, approximately six to eight in number, give off branches which pass towards the canal from the ciliary body and supply twigs which connect directly to the canal. This anatomical observation assumed great importance through the hypothesis which Friedenwald constructed upon it, for he believed that, through these minute vessels, plasma (but not red cells) was able to enter the canal, thus attracting water osmotically from the anterior chamber. He further held that in chronic simple glaucoma the primary lesion may be a sclerotic occlusion of these afferent arterioles, the obliteration of which led to a diminished inflow of plasma into the canal and thus to a decreased outflow of aqueous from the anterior chamber. Sugar (1951) has supported this concept from both the physiological and the pathological points of view and it undoubtedly raises questions of unusual interest. Friedenwald's work was based upon a study of serial sections and, since, according to his description, the afferent arterioles were without muscular walls, their arterial nature must of necessity have been inferred from their apparent origin from arteries. It is extremely difficult, however, to be sure of inter-connections in serial sections or to be certain of the arterial or venous origins of minute vessels; indeed, Leber (1903) was unable to convince himself of the existence of arterial afferents to the canal or deep scleral plexus.

The larger divisions of the anterior ciliary artery, having distributed the small anteriorly running branches, perforate the sclera and appear on its inner surface opposite the belly of the ciliary muscle which they immediately enter, and they terminate by anastomosing with the long posterior ciliary arteries at the major arterial circle of the iris. Kiss (1943) however, from his studies on human eyes injected with Indian ink, came to the surprising conclusion that there were no arterial connections between the ciliary body and the episcleral region and that all interconnecting vessels to be found at this point were veins, a view which seems to be totally at variance with the classical description.

Another iconoclastic declaration is that of Henderson (1908), who concluded, from a study of serial sections prepared after the intracameral injection of Indian ink, that all perforating anterior scleral vessels were veins, and since he was able to trace these vessels back to the major arterial circle of the iris he concluded that this vessel was not, in fact, a *circulus arteriosus* but a *circulus venosus*. Histologically, there can be no doubt, however, that the major circle has the structure of an artery, and it is apparent that both Henderson and Kiss, in confining their examination to specimens injected throughout with the same coloured material, were somewhat handicapped by the lack of differentiation between the arteries and veins.

Opinions regarding the arterial relationships of this important region are, therefore, conflicting, and indicate a need for a fresh approach. Indeed, if many interesting clinical and physiological data are not to be misinterpreted,

it would seem to be a matter of great importance that the exact anatomy of the arterial afferents be unequivocally established. With this end in view, we have used a modified form of the Neoprene cast technique, which, by the injection of white Neoprene into the arteries via the ophthalmic artery and red Neoprene into the canal itself, permits an infallible discrimination between the canal with its efferent branches and the adjacent arterial anastomoses.

Material and Methods

All these studies were made on human eyes removed *post mortem*. As soon as practicable after death, the eye, together with its orbital contents and the ophthalmic artery as far back as its origin from the internal carotid, was removed by the trans-cranial route.

A cannula was then inserted into the ophthalmic artery and the specimen was irrigated with tap water for one hour. When the irrigation had been completed the ophthalmic artery was injected with white Neoprene until the latter could be seen in the anterior ciliary arteries and in the iris vessels. When the Neoprene had set, a process which was found to occur within a few minutes, the anterior segment of the eye was removed, the 12 o'clock position of the limbus having been previously marked by a radial scratch incision.

The anterior segment was then inspected under the dissecting microscope to ascertain the degree of uveal and episcleral filling and to see whether any of the injection material had entered the canal of Schlemm. A radial cut was then made from the 12 o'clock position to the centre of the cornea, a sectional view of the canal thus being obtained. The canal was irrigated with tap water and injected with red Neoprene and a further microscopical examination was carried out. As an alternative procedure, the anterior ciliary artery over the rectus tendon was directly injected with white Neoprene (Fig. 1). The specimen was then digested in pepsin and trypsin as previously described (Ashton, 1951) and during the process, which involves partial clearing of the sclera, the specimen was again inspected under the dissecting microscope.

When digestion was complete, the distribution of the white arteries in relation to the red canal and collector channels was fairly easy to follow by microdissection. Finally the casts were mounted in gelatin in a small Petri dish and stored in a tank containing 5 per cent. formalin.

FIG. 1.—Microcannula (M.C.) in position in an anterior ciliary artery (A.C.A.) of the superior rectus muscle (S.R.). The Neoprene has been injected and the tortuous course of the vessel as it approaches the corneal limbus (C.L.) can be followed. $\times 7$ approx.

Fourteen casts prepared by this dual-coloured injection method were examined, and it has been possible to differentiate arteries from veins in two quite different ways and, as we believe, with more accuracy than in histological examinations. The latter method is clearly quite difficult, for, as has been shown, experienced microscopists have expressed divergent opinions as to the arterial or venous nature of moderately large vessels in this particular region.

If it were possible to stop the white arterial injection at the point where Neoprene had arrived at the capillary bed and had gone no further, then the subsequent injection of a venous channel with red material would produce a complete differentiation between arteries and veins. Control as accurate as this, however, is obviously impossible, so that the arterial injection may be either excessive, in which case capillaries and eventually veins are filled, or insufficient, when the subsequent venous injection may overflow into capillaries, arterioles, and arteries. In the final cast we have not, therefore, been content to identify a vessel merely by its colour which, although invaluable for photographic records, is used merely as a gross means of identification. The colour of the vessel is regarded as the "coarse adjustment", while the "fine adjustment", which, if practised with care should be almost infallible, consists in the tracing of a vessel from its source by microdissection. This is particularly easy in the eye because of the highly characteristic early course of the long posterior arteries, which can be identified at their entry into the globe and in their passage through the suprachoroidal space, and of the anterior ciliary arteries, which have a characteristic tortuous course on the tendons of the recti (Fig. 2).

FIG. 2. — Neoprene cast of Schlemm's canal (S.C.) and its vascular connections, showing the tortuous course of an anterior ciliary artery (A.C.A.) as it approaches the limbus, and the delicate network of the limbal capillary plexus (L.P.). $\times 6$ approx.

Findings and Discussion

The long posterior ciliary arteries were found to be exactly as described by Leber (1903) and they undoubtedly terminate in the major arterial circle of the iris; the theory that this circle is venous (Henderson, 1908) is, therefore, untenable.

A typical anterior ciliary artery, after leaving the surface of the rectus tendon, divides in the episclera into several medium sized branches which, as previously described, send small twigs forward to the limbus to supply

the episcleral limbal plexus and to contribute to the anterior conjunctival arteries, while others dip down into the sclera and come to lie near Schlemm's canal (Fig. 3).

FIG. 3.—Neoprene cast and accompanying diagram showing distribution of an anterior ciliary artery (A.C.A.). Superficial branches are given off, for example (S.B.). The artery then perforates the sclera at P., giving off a small vessel (S.C.A.) towards Schlemm's canal (S.C.) (The course of this vessel along the canal is seen in Fig. 4). The artery then enters the ciliary muscle and divides into anterior and recurrent terminal branches to supply the uvea (U.A.). $\times 15$ approx.

A larger branch pierces the sclera near the limbus, crosses the suprachoroidal space, and enters the ciliary body, supplying in its course small twigs to the sclera and to the vascular plexus in the ciliary muscle. Within the ciliary body the anterior ciliary artery divides into terminal branches, which run anteriorly to terminate in the major circle of the iris and posteriorly to contribute to the arterial supply of the anterior choroid. Each of these terminal branches also gives off vessels to the ciliary muscle. The recurrent branch to the choroid was described by Leber (1903), but in his illustrations it is figured as a fairly small vessel, whereas it not infrequently appears to be the major branch. The above findings disprove the contention of Kiss (1943) that there are no arterial connections between the ciliary body and the sclera.

It will be seen that the *small arteries in the region of Schlemm's canal* arise from both the superficial and the deep terminal branches of the anterior ciliary artery, and their final destination appears to be as follows. They either break up into capillaries in the deeper layers of the sclera, or, maintaining a slightly larger size, run right up to the canal, often utilizing the same intra-

scleral channels as the outlets of the canal, and, turning sharply, they proceed to trace out a course parallel and in very close proximity to it (Fig. 4). In areas where the canal is plexiform, they may pass through the gaps, thus explaining their apparent presence inside the canal in histological sections (Fig. 5), or they may weave in between the arches of anastomosing collector channels.

FIG. 4.—Neoprene cast and accompanying diagram illustrating further course of small artery (S.C.A.) along Schlemm's canal (S.C.). A branch (M.B.) can be traced to the vascular plexus of the ciliary muscle in the original cast. Note the close association of the artery with the collector channels (C.C.). ×28 approx.

FIG. 5. — Photomicrograph showing an artery (S.C.A.) in intimate relation to Schlemm's canal (S.C.) and trabeculae (T.R.). ×120 approx.

After a course of variable length, the arteries turn away from the canal and anastomose directly, without capillary division, with a similar vessel, so forming an incomplete arterial circle in close proximity to the canal (Fig. 6, opposite; Figs 7, 8, and 9, overleaf). Occasionally, however, they may terminate by contributing to the ciliary plexus.

FIG. 6.—Drawing of Neoprene cast. The arteries (A) give branches which form an incomplete arterial circle close to the canal.

FIG. 7.—Drawing made from a Neoprene cast in which the ophthalmic artery and Schlemm's canal had been separately injected with different colours. This drawing is one of a series made in the course of microdissection in which all the anterior ciliary arteries in a complete cast were followed branch by branch to their terminations: the picture thus represents the exact anatomical distribution of these vessels. $\times 9$ approx.

(A.C.A.) anterior ciliary artery.	(C.C.) collector channels.
(S.B.) superficial branch.	(A.A.C.) anterior conjunctival arteries.
(S.C.A.) artery near Schlemm's canal.	(M.B.) ciliary muscle branch.
(S.C.) Schlemm's canal.	(C.M.P.) ciliary muscle plexus.
(U.A.) branch to uvea.	

FIG. 8.—Diagram prepared on basis of microdissection shown in Fig. 7. The types of branching found in an anterior ciliary artery (A.C.A.) are shown: a superficial branch (S.B.) or a perforating branch (P.) may give an artery (S.C.A.) which passes near to Schlemm's canal. The perforating branch (P.) then divides in the ciliary muscle into anterior (A.U.A.) and recurrent (R.U.A.) terminal arteries which supply the uveal tract.

FIG. 9.— Neoprene cast of a sector of Schlemm's canal (S.C.) with an artery (S.C.A.) running along its wall, and another coursing towards it and turning away without capillary division. $\times 28$ approx.

Despite very careful microdissection of casts showing these vessels, including some in which the arteries were extraordinarily closely entwined with the canal and deep scleral plexus, it was not possible to demonstrate any arteries terminating at or entering the canal or supplying it with afferent branches. It should be emphasized that in all these specimens the finest capillaries were fully injected, so that the evidence is very strongly against the existence of arterial afferents connected with Schlemm's canal. The findings do not, therefore, confirm Friedenwald's interpretation of his histological material, and consequently do not support his hypothesis of the mechanism of aqueous flow in health and disease.

An interesting feature of the vascular arrangement, strikingly shown in the casts, is that many of the anterior ciliary arteries and their branches run in company with veins. In some places an artery may have two venae comites, in others only one. Such an arrangement is seen throughout the sclera, and, as we have already described, the small arterial branches running towards Schlemm's canal not infrequently utilize the same scleral tunnels as the anastomosing outlets of the canal in the deep scleral plexus (Figs 10 and 11, overleaf). The accompaniment of arteries by veins is common, of course, in other parts of the body, but we are not aware that it has been described previously in scleral vessels. The matter is of some importance, for in an account of the anatomy of the vessels concerned in aqueous drainage Thomassen and Bakken (1951) described similar sets of parallel vessels which they reported as aqueous veins running in company with blood veins. According to these workers, the two vessels ran in a common canal in the rigid

FIG. 10.—Neoprene cast showing an artery (S.C.A.) running in company with Schlemm's canal (S.C.) and a collector channel (C.C.). $\times 25$ approx.

FIG. 11.—Neoprene cast showing an artery (S.C.A.) running in company with a collector channel (C.C.). $\times 25$ approx.

tissue of the sclera, separated from each other only by the wall of the vein and the one-layered endothelium of the aqueous canal, and they assumed that this anatomical arrangement was of great importance, in that a rise of pressure within the vein would compress the canaliculus within the scleral tunnel and so reduce the aqueous flow. Such a mechanism would explain the minimal aqueous content in the aqueous veins when the ocular tension is in an increasing phase, the moderate content when the tension is

normal, and the maximal aqueous flow when the ocular tension is in a decreasing phase as reported by Thomassen (1947) and Thomassen and others (1950), and would harmonize with the assumption of Ascher (1944, 1953) and Ascher and Spurgeon (1949) that the site of obstruction to aqueous outflow is probably located within the scleral channels.

A careful examination of our simple Schlemm's canal casts, however, failed to reveal such an arrangement, and it was not until the double injection technique was performed that the explanation of the findings of Thomassen and Bakken (1951) became apparent. These preparations showed that the vessels which occasionally accompany the canal outlets within the sclera are, in reality, arterioles and we believe that they were erroneously described as venules by Thomassen and Bakken (1951). Since this pattern is an inconstant one and appears to be merely fortuitous, it would seem unlikely to have any particular significance in the control of aqueous flow.

Summary

(1) The arterial relationships of Schlemm's canal have been studied in dual-coloured Neoprene casts, prepared by injecting white Neoprene into the arteries *via* the ophthalmic artery, followed by red Neoprene into the canal itself. By this technique, arteries, veins, and canal efferents may be identified with certainty by tracing their continuity from the parent trunk. The distribution of the arteries in the region is described and the findings are discussed in relation to cognate work.

(2) An incomplete arterial circle was demonstrated in close proximity to Schlemm's canal, and it was found that it consisted of anastomoses between arteriolar twigs converging towards the canal from the superficial or deep terminal branches of the anterior ciliary arteries.

(3) Although there is a very close relationship between the arteriolar branches and the canal, no afferent connections with it could be found; these findings, therefore, do not support Friedenwald's hypothesis of the mechanism of aqueous flow in health and disease.

(4) The anterior ciliary arteries and their branches characteristically run in company with veins. Such an arrangement is seen throughout the sclera, and the small arterial branches running towards Schlemm's canal not infrequently utilize the same scleral tunnels as the anastomosing outlets of the canal.

(5) Aqueous channels were not found in company with blood veins as has been described; they run either alone or in company with arterioles, which histologically may have been erroneously interpreted as venules. In any event, the arrangement is an inconstant one and would seem unlikely to have any particular significance in the control of aqueous flow.

REFERENCES

- ASCHER, K. W. (1944). *Amer. J. Ophthal.*, **27**, 1074.
 — (1953). *Arch. Ophthal.*, Chicago, **49**, 438.
 — and SPURGEON, W. M. (1949). *Amer. J. Ophthal.*, **32**, June (Part 2), 239.
 ASHTON, N. (1951). *British Journal of Ophthalmology*, **35**, 291.
 — (1952). *Ibid.*, **36**, 265.
 DVORAK-THEOBALD, G. (1934). *Trans. Amer. ophthal. Soc.*, **32**, 574.
 FRIEDENWALD, J. S. (1936). *Arch. Ophthal.*, Chicago, **16**, 65.
 HENDERSON, T. (1908). *Trans. Ophthal. Soc. U.K.*, **28**, 167.
 KISS, F. (1943). *Ophthalmologica, Basel*, **106**, 225.
 LEBER, T. (1903). In A. Graefe and T. Saemisch, "Handbuch der gesamten Augenheilkunde", 2nd ed., vol. 2, part 2, ch. 11. Engelmann, Leipzig.
 MAGGIORE, L. (1917). *Ann. Ottalm.*, **40** (n.s. 1), 317.
 SUGAR, H. S. (1951). "The Glaucomas", p. 33. Mosby, St. Louis.
 THOMASSEN, T. L. (1947). *Acta ophthal., Kbh.*, **25**, 369.
 — and BAKKEN, K. (1951). *Ibid.*, **29**, 257.
 —, PERKINS, E. S., and DOBREE, J. H. (1950). *British Journal of Ophthalmology*, **34**, 221.
 WOLFF, E. (1945). *Proc. roy. Soc. Med.*, **38**, 469.

(This study is to be continued in a future issue of this Journal.)