SCHLEMM'S CANAL: ITS ANASTOMOSES AND ANATOMIC RELATIONS*

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In 1830 Friedrich S. Schlemm[1] reported his discovery of the circular canal running equatorially at the border of the sclera and cornea which bears his name, "Schlemm's canal." Since then the anatomic significance and functional importance of this canal have been topics of great interest and controversy to anatomists, physiologists, and clinicians. Numerous original researches have been made, and a fairly large literature on the subject has accumulated.

The anatomists of the early eighteenth century, who gave particular study to the blood circulation of the eyeball, had no precise idea of the disposition and functions of the blood vessels in the vicinity of the limbus. They knew of the existence, in certain animals, of a large circular vessel parallel to the iris insertion. Hovius[2] had described this in 1716, and it was known as the circulus venosus, or the venous circle of Hovius.

The efforts of these early anatomists tended to recognize a venous circle next to an arterial circle, based on the then generally established principle that every arterial vessel might be accompanied by a venous vessel. In 1781 Fontana[3] drew attention to the existence, in animals, of a canal which bears his name, and which is situated between the ciliary body, the sclera, and the cornea in the ciliocorneal trabeculae. During the next half century the existence of Fontana's canal in man was both affirmed and denied by different anatomists. In 1830 Schlemm drew attention to a canal existing in the human eye in almost the same region as that

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of the canal which Fontana had described in animals. Schlemm found it in the eye of a man who had been hung, and because it was filled with blood, Schlemm considered it to be a venous sinus. He described it as "a thin-walled sinus between the layers of the cornea, in the furrow where the cornea is connected with the sclera, on the internal side of the eye." The error of placing the canal in the cornea is still made. Although Schlemm observed that "this canal must not be mistaken for Fontana's canal, which is found in ox eyes," many later anatomists confused these two structures. In 1856 Rouget[4] demonstrated clearly that Schlemm's canal was quite distinct from the structure described by Fontana. Rouget's description was singularly accurate, and is precise enough for general purposes today: "A very rich vascular network occupies the anterior part of the sclera at the junction of the cornea . . . These vessels communicate with the network of the capillary sinus that occupies the anterior extremity of the scleral furrow corresponding to the union of this membrane to the cornea. This plexus, from which emerge the anterior ciliary veins, has no communications with the vessels of the iris; it belongs solely to the vascular system of the sclera and the cornea, which, deprived of its own vessels, has concentrated in its periphery the vascular equipage needed for its nutrition."

Schlemm called the canal the sinus venosus. In 1834 the name circulus venosus Schlemmi was proposed by Retzius,[5] who likened the canal to the dura mater because the thin wall is adherent to the compact scleral tissue so that the lumen remains open even when it is not filled. Although other authors have applied more descriptive terms, such as "scleral sinus" (Rochon-Duvigneaud[6]) and "iridoscleral sinus" (Sondermann[7]), the accepted name is Schlemm's canal.

In 1841 Hueck[8] designated the tissue internal to the canal the "pectinate ligament," and described it as a "series of regular conical continuations which bridge the ciliary edge of the iris with Descemet's membrane." In 1869 Iwanoff and Rolett[9] discovered that in the human eye these iris continuations are much thinner and longer than they are in the ox or pig eye, and that the tissue actually corresponds to Fontana's canal in the human eye, and should be designated as Fontana's spaces. In 1908 Henderson[10] found that the structure forming the outer boundary of the angle of the anterior chamber is not a comb-like ligament for the iris root, but is a perforated or "cribriform" ligament of the ciliary muscle. He suggests that the term "cribriform ligament" is in every way a suitable one, being in absolute conformity with both the anatomic and the physiologic characteristics of the structure, while at the same time it is a term that facilitates the description and simplifies the conception of the filtration angle. Rochon-Duvigneaud (1892) described this tissue as a series of trabeculae of characteristic structure—a sort of grill, having, perhaps for its purpose, the protection of the absorbing surface of the canal against deposits of cellular elements which can pass into the anterior chamber. This description and the name, trabeculae, have been accepted by later authors.

The investigators of Schlemm's canal have been concerned with two main problems: First, to determine whether the canal should be assigned to the venous system or whether it should be regarded as a lymphatic lacuna; and, second, to establish the importance of the canal in the process of elimination of intra-ocular fluids, more especially of the aqueous humor.

In the extensive literature on the subject these two problems and matters arising from them have been the main subjects of controversy. The theory that Schlemm's canal belongs to the blood system and is nothing more than a venous plexus has been sustained by Leber[11] (1873) and his school of thought. Troncoso[12] (1905) and many others support the view of a purely lymphatic function of the canal. There is a third group, composed of Hamburger,[13] Weiss,[14] and others, who, while uninterested in its anatomy, deny any functional value to Schlemm's canal in the elimination of intra-ocular fluids, as they believe that it has fully been demonstrated that there is another path of elimination which is more important, namely, by way of the iris veins, through which the aqueous can be brought out of the globe.

In the first part of this paper I shall endeavor to present a short review of the principal findings by other investigators regarding Schlemm's canal up to the present time, under the following headings:

I. The anatomy and significance of Schlemm's canal in the normal human eye, and its associations.

II. Whether or not Schlemm's canal normally contains blood.

III. The functional significance of Schlemm's canal in relation to the elimination of intra-ocular fluids.

Several authors who have recently written on this subject have to some extent summarized previous investigations. I acknowledge my indebtedness to Maggiore and Sondermann for much that follows; but in every case in which it was possible to do so, I have consulted the original reports, so as to assure myself that the authors cited by others were properly represented.

In the second part of this paper I shall describe some of my own investigations on Schlemm's canal, in which I have been able to verify or to question the findings of other investigators or to discover particulars regarding the canal which, so far as I know, have not previously been mentioned in the literature.

I. ANATOMY AND SIGNIFICANCE OF SCHLEMM'S CANAL AND ITS ASSOCIATIONS

In the normal eye Schlemm's canal appears in the form of a circular duct, situated in the deep part of the limbus, just in front of the corneo-scleral trabeculae which separate it from the anterior chamber. An examination of serial sections shows that the appearance of Schlemm's canal varies in the different sectors of the same eye. Most frequently it is a circular canal, with its margins more or less parallel; or it may present a varicose appearance; in general, the inflections which the concave margin presents are slight and the varicosities are found on the anterior surface. In some sectors the canal is plexiform (Leber, 1865), there being from two to four, very rarely more, narrow lacunae.

Schlemm's canal is attached to a vascular plexus situated in the depths of the limbus. The attachment is effected by vessels of a characteristic aspect, which most investigators term collector trunks or channels. The vascular plexus referred to is composed of a reticulum largely venous in character. In his study of serial sections Henderson described all vessels in the region of Schlemm's canal as veins. He did not differentiate arteries and veins, probably due to the fact that his sections were 25 microns thick and were stained with van Gieson's stain, which infiltrates tissue heavily.

Maggiore,[15] in his important monograph, drew attention to the arteries and capillaries which accompany the veins in the intrascleral plexuses. In general these arteries are extremely fine, and form a series of large and irregular meshes that accompany the venous plexus and are connected with it by means of characteristic loops. Maggiore confirmed Leber's anatomic description of the canal, and his diagram of the circulation of the anterior part of the eyeball differs only slightly from that of Leber. By means of vascular injections of Prussian blue, microscopic examination, and plastic reproduction, Maggiore was able to distinguish four distinct plexuses, which are designated as follows: 1. The conjunctival plexus proper. 2. The plexus of Tenon's capsule. 3. The episcleral plexus. 4. The deeply situated intrascleral plexus.

As has been mentioned, Schlemm's canal is attached to the deep intrascleral plexus by means of a series of characteristic collector trunks or channels that start from the anterior surface or from the convex margin of the canal, and, passing constantly in an oblique direction, empty into the veins of the plexus—sometimes with a true and proper anastomosis, at other times after having looped over in the form of a hook. According to several investigators, these collector trunks have a conical form, with the wide end corresponding to their origin, and the narrow end at the place of the outlet; their scarcity is also characteristic, their number varying between 20 and 30 around the globe. These collector trunks, which are very much flattened, open into the canal, forming a sort of narrow fissure; this fissure is so thin that, in order to distinguish it, considerable magnification is often necessary, since the two walls, superficial and deep, often appear to be coalesced. If under any particular circumstances red blood corpuscles are accumulated in the canal, this fissure becomes wide.

Schwalbe[16] and Waldeyer[17] assumed the existence of true valves in the lumen of the canal or some of the collecting channels which would prevent a back flow; but Heisrath,[18] Königstein,[19] and others denied the presence of valves between Schlemm's canal and the ends of the vessels. If valves existed, the true nature of Schlemm's canal might at once be admitted. In the absence of valves there must exist a condition that normally impedes the passage of blood corpuscles into the canal. Troncoso (1909) found that the intraocular pressure is higher than that in the intrascleral veins, and that aqueous humor which filters through the inner wall of the canal, while filling the cavity of the latter, preserves a certain pressure which is augmented by new liquid constantly flowing into it.

On the basis of physiologic researches Troncoso asserts that the collecting trunks are not continued in the veins but in the lymphatic perivenous spaces. Maggiore, however, has been able to establish perfect continuity between the collector trunks and the venous plexus, not finding any foundation for Troncoso's assertion. Maggiore states that the examination of serial sections excludes the presence of valves, but that occasionally anfractuosities appear in the wall which are suggestive of valves. Maggiore is of the opinion that the fissural formation of the flattened collector channels shows a mechanism of functional interruption between Schlemm's canal and the veins that substitutes for and renders unnecessary the existence of a valvular apparatus.

Maggiore found the form of the deep intrascleral plexus most characteristic: first, because of the tendency of the large channels to assume a quasi-varicose appearance; and, second, because of the small reticulae that interrupt the continuity of the plexus. The varicose aspect is still more evident in the channels which connect this plexus directly with the episcleral veins, or indirectly, by anastomosis with the venous trunks which come from the ciliary muscle and pass through the sclera. The most noticeable fact in connection with this is that none of these communicating veins follows the shortest course to meet the particular vein for which it is destined; all these veins pass in a tortuous way through a more or less long tract in the thickness of the sclera, and before leaving it they twist and bend in such a manner as to assume the shape of the letter "S" or the figure "8."

Brief mention must be made here in regard to embryology. Most authors, in referring to it, merely state that Schlemm's canal is found in the third, fourth, or fifth month of fetal life. Seefelder[20] (1910) concluded that a small circular vessel found anterior to the group of cells which formed the continuations of Descemet's membrane is the canal of Schlemm, and because it contained a few blood corpuscles, he believed that he had demonstrated its vascular nature.

Sondermann asserts that the development of the canal of Schlemm depends closely upon the processes which direct the development of intra-ocular pressure. At first the canal is developed not as a circular vessel, but from radial venous vessels which, in the last half of the third fetal month, convey blood from the tissue of the fold of the optic cup to the anterior ciliary vessels, which penetrate for a short distance into the edge of the sclera and are called iridoscleral veins.

After these veins originate in the pupillary membrane, they enter the marginal part of the sclera, pass through it for a certain distance, and then penetrate the sclera proper. At the beginning of the third fetal month there is considerable hardening of the sclera in its anterior portion, which causes a slowly increasing pressure upon the penetrating veins. This results in the development of a stasis pressure and in dilatation of the distal part of the veins. Due to the stasis pressure the dilatation is so great that anastomosis between the dilated vessels takes place, thus forming the iridoscleral sinus. As the sinus corresponds to the position of Schlemm's canal, it may be assumed that it is a precursor of this canal and the further development bears out this assumption. Ultimately, the iridoscleral veins become obliterated beyond Schlemm's canal, which anastomoses with the anterior ciliary veins by means of channels which Sondermann designates as external canals. Capillaries also proceed internally from the iridoscleral sinus and become the so-called inner canals. Although Schwalbe, Iwanoff and Rolett, Brucke,[21] Waldeyer, and others found open connections between the anterior chamber and the canal of Schlemm, the first definite description of communications between the canal and the trabeculae is made by Sondermann. He found that the inner canals are lined with endothelium. They branch off at right angles to the canal, and then run parallel to the course of the canal. The inner canals are narrower and usually more numerous than the external canals and they are in open connection with the fissures of the trabeculae. The same growth relationship is true for the inner canals as for the canal of Schlemm and the external canals, namely, they are narrow during the first years of life and wide in old agė. Sondermann found these internal canals in the eyes of persons between fifteen and seventy years of age.

A résumé of the general anatomic considerations of Schlemm's canal shows that Sondermann believes that there are open communications between Schlemm's canal and the fissures of the trabeculae, and thus with the anterior chamber. Leber, and subsequently Schwalbe and others, believed that there was no direct communication between the trabeculae and the canal. Maggiore expresses the view that, under normal conditions, the canal is not in direct communication with the trabeculae, and that its endothelial covering does not normally present any trace of discontinuity. A direct continuity is admitted between the anterior chamber and the spaces of the corneo-scleral trabeculae, and Leber and others are of the opinion that the aqueous enters the anterior ciliary veins by filtration.

II. Does Schlemm's Canal Normally Contain Blood?

Does blood circulate in Schlemm's canal normally? The literature on the subject does not settle the question of the presence or absence of red blood corpuscles normally in Schlemm's canal. Occasionally red corpuscles are found in fetuses in different stages of development, and in other instances the lumen is quite empty. In cadaver eyes Schlemm's canal almost always appears to be empty, whereas in eyes enucleated from living subjects the canal contains more or less blood.

When not due to inflammatory hyperemia, the presence of blood in the canal of enucleated eyes may be the result of imbalance between the blood-pressure of the vessels of the eye and intra-ocular pressure, or an inevitable effect of the operative traumatism. Since the full continuity between Schlemm's canal and the vascular plexus is established, it is not surprising that under such abnormal conditions some blood should pass from the veins into the canal. If blood circulated in Schlemm's canal normally, the almost constant absence of blood in the eyes of cadavers could not be explained. The deduction that Schlemm's canal is a venous vessel, this being based upon the occasional findings of blood in and extravasations through the canal, and traumatisms into the anterior chamber, seems to require further confirmation.

Weber[22] was the first investigator to observe that when Schlemm's canal was ruptured, blood could penetrate into the anterior chamber. In the literature several similar observations are reported. In the examination of globes with a ruptured limbus it is not always possible to exclude a concomitant rupture, caused by the traumatism, of those vessels that form the deep intrascleral plexus and that are in continuity with Schlemm's canal. Therefore, the blood in hyphemia may not come from Schlemm's canal alone. On the other hand, admitting the continuity of the canal with the vessels referred to, the traumatic imbalance of the intraocular pressure may cause an excessive passage of blood corpuscles.

In 1905 Fuchs[23] referred to the possibility of seeing Schlemm's canal in the living human eye. He believed that in persons with a thin sclera this was possible. He stated: "A not very sharp, dark, circular line can be seen concentric with the edge of the cornea. If this corresponds to the canal of Schlemm, as I believe it does, then this would furnish another proof that the canal conveys blood during life, as this color could be caused only by blood."

Trantas[24] could not see blood in Schlemm's canal, either in normal or in pathologically altered eyes, and he was satisfied that it was not a blood vessel but an annex of the anterior chamber.

Troncoso[25] was never able to discern a red blood color throughout the whole Schlemm zone, which he believes he would certainly have been able to do if it were a venous sinus.

Maggiore asserts that under normal conditions Schlemm's canal does not contain blood, but that, as Leber[26] declared, the slightest imbalançe of pressure is sufficient to allow blood from the venous plexus to pass into the lumen of the canal, and that, as a matter of fact, this does happen in traumatisms, such as contusions, enucleations, and the like. Maggiore states that in the normal physiologic state blood corpuscles cannot pass into Schlemm's canal, because the tortuosity and narrowing of the lumina of the collector channels allow only an extremely thin fissure, through which only lymph can pass from the canal into the venous plexus.

III. ELIMINATION OF INTRA-OCULAR FLUIDS THROUGH SCHLEMM'S CANAL

By far the most important problem in connection with the physiologic functions of Schlemm's canal is to determine the part it plays in the elimination of intra-ocular fluids. Ever since the discovery of the canal a remarkable physiologic significance has been attributed to it—it being considered as the most important, if not the only, pathway for the elimination of intra-ocular fluids. Many investigators, by injecting various substances into the anterior chamber in experimental animals, have affirmed the existence of open communications between the anterior chamber and Schlemm's canal. Schwalbe (1870), believing the canal to be a lymphatic vessel, although normally empty, affirmed the existence of these connections. Waldeyer (1875), who was of the opinion that the canal was a blood vessel, agreed with Schwalbe.

In 1895 Leber stated that what Schwalbe and his followers considered an open communication was in reality an osmosis due to differences in pressure between the anterior chamber and the anterior ciliary veins. Later Schwalbe was inclined to adopt Leber's theory.

Leber, who believed in the venous nature of Schlemm's canal and often found blood in it normally, was of the opinion that the aqueous would flow very easily into the canal of

Schlemm, and that the canal was especially adapted anatomically and topographically for this purpose.

Hamburger and Weiss considered the pressure in Schlemm's canal and in the veins of the iris higher than the intra-ocular pressure, and therefore they believed that filtration from the anterior chamber into Schlemm's canal and into the iris veins in the way Leber describes was impossible. They believed that the aqueous humor was stagnant.

Thompson[27] and Fortin[28] found that the movements of the iris and the ciliary body exert an influence on the interchange of fluid between the anterior chamber and the canal of Schlemm. Contraction of the ciliary muscle tends to open the canal, and is the principal function of this muscle.

Sondermann,[29] in an article published in 1933, takes an entirely different view. He asserts that in the angle of the anterior chamber the pressure is normally in equilibrium, and is modified only under the influence of systolic and diastolic variations. This change in pressure produces the phenomenon of filtration. Sondermann is of the opinion that Schlemm's canal contains aqueous humor, and that the pressure in it is less than that of the ciliary veins at the point of their departure from the sclera. The aqueous humor is drawn into Schlemm's canal by filtration and not by osmosis.

To solve the question of the elimination of the fluid of the anterior chamber, Sondermann injected red blood corpuscles into an ape's eye, and was convinced that the contents of the chamber passed into Schlemm's canal. Unlike India ink and similar fluids, blood has the advantage that it is not a foreign body and does not cause irritation or create unphysiologic conditions. Sondermann believes that the canal of Schlemm, with its inner and outer canals, is the chief means of absorption, while only secondary importance must be ascribed to the iris.

Nuel and Benoit,[30] at a much earlier date, had reached the conclusion that the iris shares in the absorption of intra-ocular fluids, and in this respect may be even more important than Schlemm's canal.

In 1909 Troncoso, on examining blood from the vascular network of the limbus, found that it contained a quantity of lymph that could have come only from the anterior chamber through Schlemm's canal. Troncoso, therefore, maintains that Schlemm's canal is lymphatic in nature, and that the afferent vessels of the canal which course through the sclera must be considered as lymphatics, as they are simply endothelial tubes through which the lymph is flowing. The presence of other branches connecting the canal with the anterior ciliary veins is only a precautionary measure taken by nature to make possible an outflow of lymph at a sudden rise of intra-ocular pressure. In the absorption of intra-ocular fluids Troncoso attributes more importance to Schlemm's canal than to the iris vessels. According to Troncoso, all observations support the theory of the existence of a continuous current of excretion through the iris and Schlemm's canal, which, with its collector channels, must be regarded as a lymphatic system.

Friedenwald and Pierce,[31] in a more recent investigation, point out the direct communication of Schlemm's canal with the ciliary veins, on the one hand, and with the episcleral veins, on the other. These investigators believe that unless these two venous beds constantly maintain an equal pressure, a flow of plasma into the canal must occur.

Reviewing the whole question of the elimination of intraocular fluids by way of Schlemm's canal, up to the present time the numerous experimental investigations, made by similar methods in the hands of different observers, show contradictions.

These experiments, especially the earlier ones, have been carried out, for the most part, under artificial conditions which cannot find a counterpart in the physiologic state of the normal globe. Under such circumstances it is difficult to arrive at definite satisfactory conclusions. From a review of these experiments, it would seem plausible to consider that, in the eyes of human beings, the entire region of the iris angle and Schlemm's canal participate in the excretion of intra-ocular fluids. It seems reasonable to conclude that Schlemm's canal is an independent organ, lymphatic in nature, whose direct communication with the anterior chamber is still in doubt. A direct continuity between the anterior chamber and the spaces of the corneo-scleral trabeculae appears to exist. The trabeculae are so constructed that pressure from within will narrow the spaces of Fontana and even obliterate them so that no fluid, and especially no foreign particles, can pass through them.

Schwalbe and his followers, by exerting gentle pressure, succeeded in injecting the canal and anterior ciliary veins with dye solution introduced into the anterior chamber. Leber and his associates found this difficult to accomplish without causing lacerations—"no matter how great the pressure." I may mention here that it was the privilege of many who attended the meeting of the American Medical Association in Milwaukee in 1933 to examine the excellent injection preparations exhibited by Dr. P. F. Swindle, of Marquette University. Dr. Swindle injected diluted India ink into the anterior chamber of an enucleated human eye, and succeeded in having it reach the anterior ciliary veins through what he termed "opened mouths." On examination of the cleared specimen with a binocular microscope the ink could be traced through the trabeculae, into the canal of Schlemm, through the collector channels, and into the anterior ciliary veins, which gathered into nine large veins leading to the recti muscles; three to the external rectus and two to each of the other recti muscles. No lacerations were visible between the trabeculae and the canal. The investigations of Sondermann and of Swindle point conclusively to open connections between the trabeculae and Schlemm's canal.

IV. Personal Researches on Schlemm's Canal

The renewed interest in the function of the canal of Schlemm, as a constantly called upon outlet for the discharge of intra-ocular fluid, demands added anatomic study from the viewpoint of the ophthalmologist. Since anatomic variations have an important bearing upon clinical pathology, further studies of individual eyes are needed so that a clearer understanding of the anatomy in the vicinity of the canal of Schlemm may be had by the clinician.

The eye used for this work was sent to my laboratory at the Illinois Eye and Ear Infirmary by Dr. George F. Suker. It was the right eye of a woman, aged fifty-two years, who for five months had complained of progressively blurring vision. She had suffered no pain, there had been no increase in tension, and clinically the anterior part of the eyeball presented no pathologic change. Viewed with the ophthalmoscope a bulging was seen in the posterior temporal side of the eyeball, and there were several vitreous opacities. A tentative diagnosis of sarcoma of the choroid was substantiated by microscopic examination. Dr. Suker removed the eye carefully with the least possible amount of trauma, so that there were no ruptures or hemorrhages into the tissues. The eyeball was fixed in formalin. We must assume that the amount of shrinkage was the same in all directions, so that even though the lumen of the vessels is smaller than in the living eye, the shape remains about the same. Eight hundred and ten serial sections, each 15 microns thick, 66½ to the millimeter, were cut horizontally, the first and the last section being within the inner margins of Schlemm's canal. The 810 microscopic sections represent 12,150 microns; on the nasal side the collector channels occupy 750 microns, and on the temporal side they represent 1,140 microns. I was convinced that it would not be enough to study every tenth or twentieth section, as is usually done. Unless every section was studied, anatomic detail would be lost and the collector channels might be overlooked.

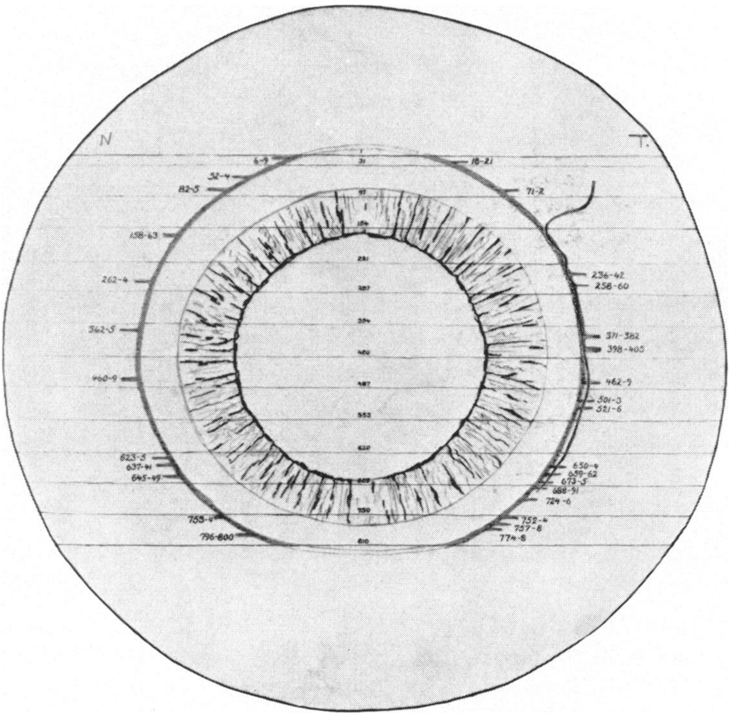


Plate I

Reconstructed from 810 serial sections. The space between the horizontal lines represents 1 mm. No. 420 is the center section.

Shows: 1. Twenty-nine collector channels leaving the canal of Schlemm at irregular intervals. They are most numerous in the lower temporal quadrant, where there are as many as 4 to 1 mm. At No. 469 to 623, and T. 72 to 236, the space between is more than 2 mm.

2. A large artery is shown joining the canal of Schlemm at Section 159, and running along intimately with it for more than 8 mm.

The center sections were at right angles to the surface and showed excellent detail. Off center, the sections were more oblique and blurring was proportionate to the distance from the center. Henderson, who made a large number of serial sections and whose work is referred to in the first part of this article, called attention to the fact that the greater the distance from a truly meridional section, the more obscure become the minute details, owing to the obliquity with which the fibers are sectioned.

Most of the sections were stained with hematoxylin and eosin, and for the others van Gieson's stain was used.

The sections were studied serially; drawings and two wax models were made. The drawings consisted, first, in constructing a chart locating the external collector channels (Plate I); and, second, in reconstructions, with a camera lucida, of interesting details around Schlemm's canal, each drawing representing from 45 to 75 sections (Plate II, A and B).

The wax models were made according to the method of Dr. Otto F. Kampmeier, Professor of Anatomy, and head of his department at the University of Illinois College of Medicine. This method is as follows: The slides were projected, 320 magnification, and the lumen of the vessels was outlined, using a different sheet of paper for each section. These drawings were traced on sheets of vari-colored wax composition, 4.5 mm. in thickness. Green was used for Schlemm's canal, blue for the veins, red for the arteries, and yellow for the nerves. The small outlined discs were cut out, placed in position on the original paper, and held together with wires. The discs from consecutive sections were then placed one on the other in rotation, and fused and smoothed by means of a heated instrument. In this manner a cast of Schlemm's canal and the adjacent vessels was reproduced.

Each model represents approximately 1 mm. of the canal of Schlemm, and shows the connections of the collector channels and also the disposition of the surrounding vessels.

From a study of the sections and from Model 1, four vessel plexuses were distinguished (Plate V, Model 1-A):

1. The conjunctival plexus.
2. The episcleral plexus.
3. The intrascleral plexus.
4. The deep scleral plexus.

It will be observed that this classification differs from that of Maggiore, referred to in Part I. I could not distinguish the Tenon's capsule plexus described by Maggiore; otherwise, the arteries and veins were tortuous and varicose, as described by him, and thus far my work confirms his.

The lumina of the vessels of the different plexuses have various degrees of roundness, depending on their proximity to the surface and the amount of pressure exerted on them during the process of development and during life.

As Maggiore demonstrated, the vessels of the conjunctival plexus form large loops, and the lumen of the vessels is round.

The episcleral plexus is situated in the outermost scleral layers. It is an extremely dense plexus and the vessel walls touch one another. The lumen of the veins is slightly elliptic. The veins anastomose frequently, and form short small loops; they are much more numerous than the arteries. It is this layer which gives the purple color to the sclera when ciliary injection is present (Plate V, Model 1-B).

The vessels of the intrascleral plexus are small in caliber, 10 by 24 microns, and they are found in various depths of the sclera. Both the arteries and the veins are flattened, but the arteries are rounder, and because of their thicker walls they are more easily distinguished. They form large loops and anastomose very infrequently. Model 1-B shows an "H" anastomosis and also a direct anastomosis between an artery and a vein (Plate V, Model 1-B). The arteries and veins travel in various ways: (1) They may bear no relation to each other; (2) an artery and a vein may travel

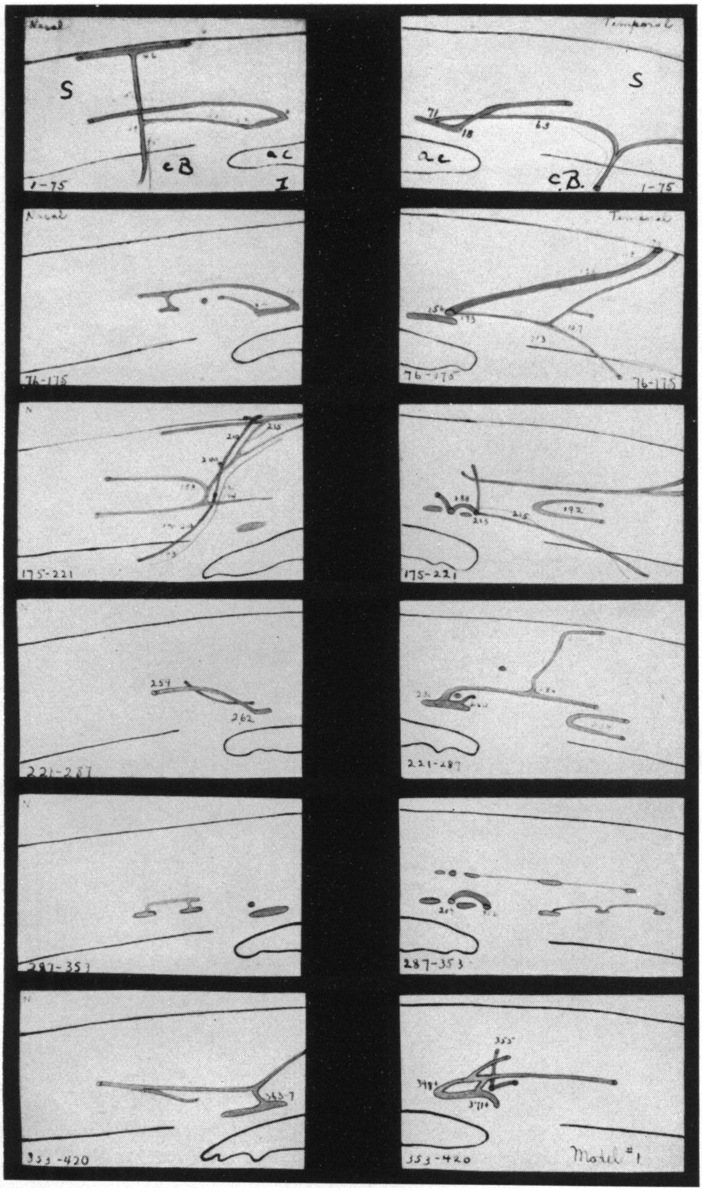


Plate II A

Plate II

Reconstruction of details about the canal of Schlemm, made with the aid of the camera lucida.

Shows: 1. Manner of junction of canal of Schlemm with the deep scleral plexus.

2. Anastomoses between vessels of sclera and ciliary body.

3. Relation of the larger arteries to the canal of Schlemm, and especially of the large one on the temporal side.

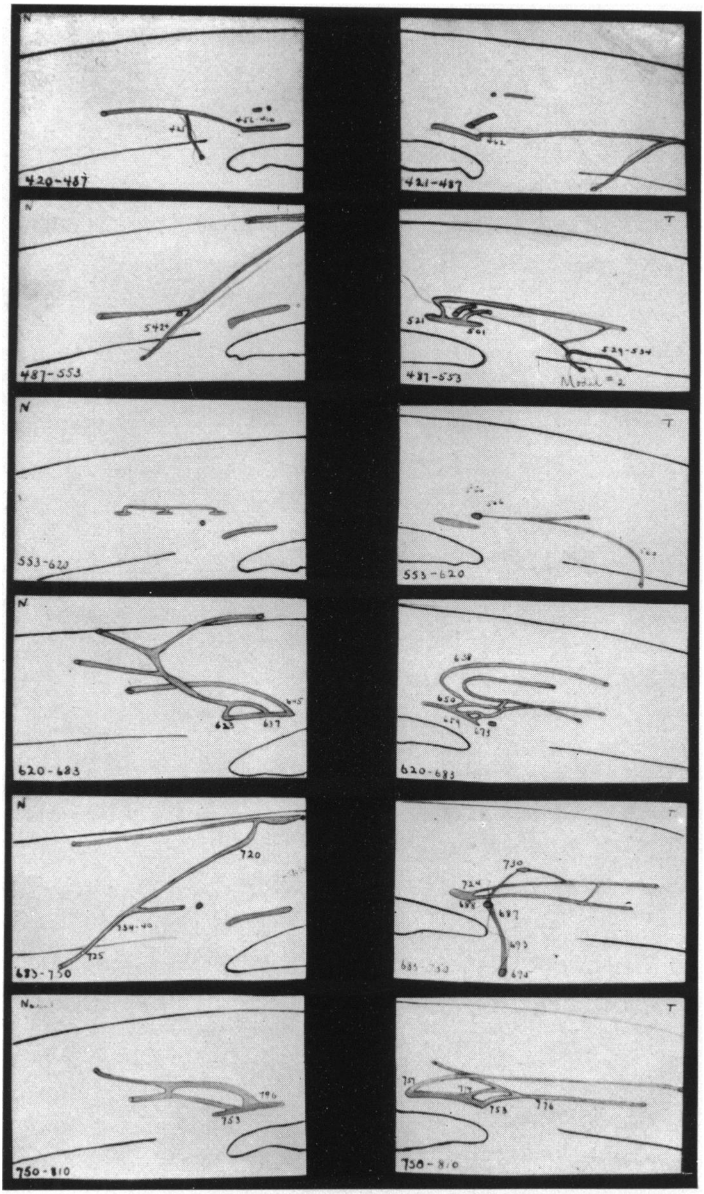


Plate II B

Plate II

Reconstruction of details about the canal of Schlemm, made with the aid of the camera lucida.

Shows: 1. Manner of junction of canal of Schlemm with the deep scleral plexus.

2. Anastomoses between vessels of sclera and ciliary body.

3. Relation of the larger arteries to the canal of Schlemm, and especially of the large one on the temporal side.

together; and (3) an artery may be accompanied by two veins.

The deep scleral plexus, which, for the most part, lies parallel to the scleral fibers, is composed of flat, wide veins which are extremely tortuous and anastomose very freely with one another. The size of the lumina varies greatly—from 315 by 99 microns to 10 by 6 microns—the greatest diameter being parallel to the scleral fibers (Plate V, Models 1 and 2). The canal of Schlemm is connected with this plexus by means of the collector channels, as described in Part I.

Anastomoses between the four plexuses are not numerous, and are effected by loops which may be almost straight or which may make large sweeping curves toward or away from the cornea.

Vessels coming from the ciliary body and anastomosing with branches of the anterior ciliary vessels usually accompany the nerves and course obliquely through the sclera toward its surface. Very frequently an artery and a vein accompany the nerve. This is the rule when the nerve and the vessels enter the sclera at the flat portion of the ciliary body. (In these sections there were eight vessels on the nasal side and seven on the temporal side.)

When a nerve enters from the muscular part of the ciliary body, either an artery or a vein traverses the same course. In the eye under examination nine veins and three arteries were found between the sclera and the ciliary body. Most of the veins anastomose with the deep ciliary plexus. Some are continuations of arteriolar branches of the large artery which accompanies the canal of Schlemm. The three arteries take the following course:

1. On the nasal side (Plate II, Sections 175 to 221) an artery from the ciliary body anastomoses with an artery of the intrascleral plexus.

2. On the temporal side (Plate II, Sections 487 to 553; also Plate V, Model 1-B) a small artery loops into the sclera

and gives off an arteriole, which anastomoses with a venule going to the deep scleral plexus.

3. On the temporal side (Plate II, Sections 683 to 750) a branch from the circulus iridis major courses in front of the scleral spur to anastomose with the large artery at the canal of Schlemm.

Section 159 shows that on the temporal side of this eye a large artery (33.3 by 49.5 microns) joins Schlemm's canal. It comes from the episcleral plexus, and is in intimate relationship with the canal for a distance of more than 8 mm., bisecting it or coursing above or to the temporal side of it. It will be remembered that Maggiore reported arteries at Schlemm's canal. An artery as large as this one may have been responsible for the reports of Fuchs and of others, who believed that they saw blood in Schlemm's canal in the living eye. This artery gives off small branches which anastomose with other arteries in the intrascleral plexus. It also gives off arterioles which almost immediately become venules and join with the deep scleral plexus, or send branches into the ciliary body (Plate II, Sections T. 76 to 175, 175 to 221, 487 to 553). As mentioned previously, in Sections 683 to 750 this artery receives a branch from the circulus iridis major; this branch travels anteriorly to the scleral spur.

In Plate V, Model 2-B, an arteriole is seen leaving this artery and almost immediately becoming a venule. An external collector channel from Schlemm's canal empties into this venule. From such a vessel blood could easily flow into the canal when the intra-ocular pressure is low.

In this eye the 29 collector channels which connect Schlemm's canal with the deep ciliary plexus are placed at irregular intervals (Plate I). In some portions there are as many as four collector channels in 1 mm.; in other parts the collector channels are more than 2 mm. apart. On the nasal side there are 12 collector channels, 6 of which are in the upper and 6 in the lower half. On the temporal side there

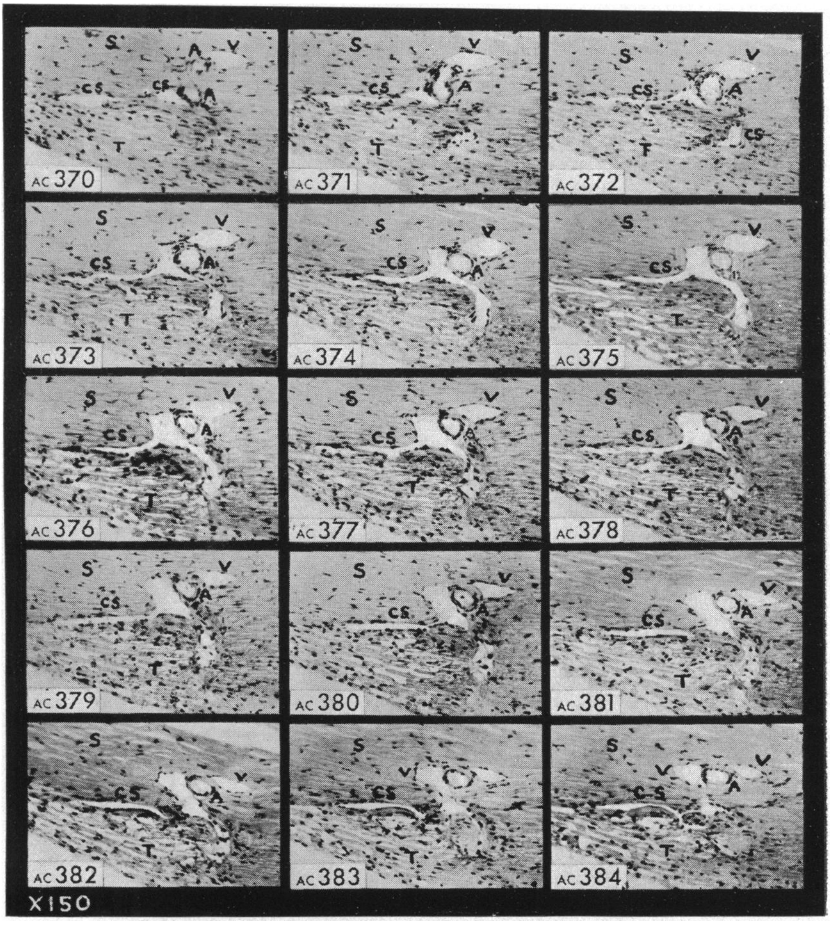


Plate III

Serial Sections T. 370 to 384 of large collector channel leaving the medial surface of the canal of Schlemm. (Upper collector in Model 1.)

Note: 1. Marked change in detail from section to section, especially in the contour of the canal of Schlemm.

2. Irregular inner wall of the canal of Schlemm.

3. The size of the large artery at the canal, which may be responsible for the dark line seen clinically in the vicinity of the canal of Schlemm.

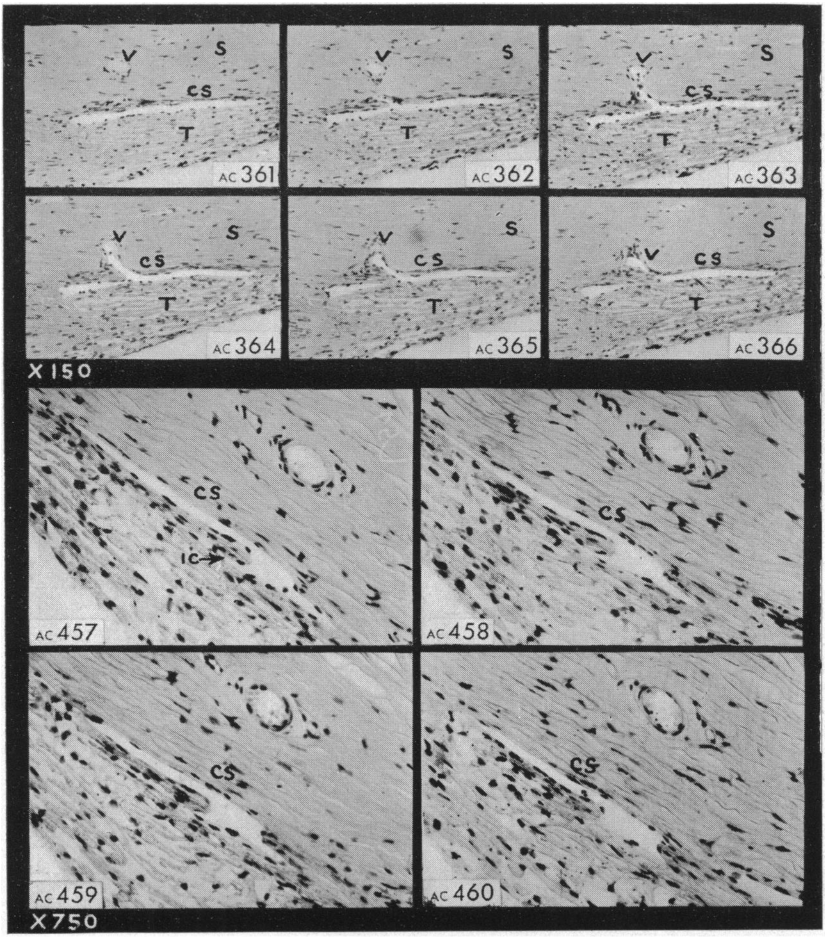


Plate IV A

Plate IV B

Plate IV

A. Serial sections of a small collector channel leaving the medial surface of the canal of Schlemm.

Note: The shape of the canal in these sections is such as we see in textbook illustrations, and is representative of the greater part of the canal of Schlemm in this eye.

B. Serial sections of a Sondermann "inner canal." An opening can be traced into the inner spaces.

are 17 collector channels—6 in the upper and 11 in the lower half. There is no set rule by which these collector channels leave Schlemm's canal. There are 17 channels at the ends of the canal—11 at the outer and 6 at the inner end—and there are 12 in the medial part of the canal (Part II). These collector channels are of various sizes and diameters. They run through from 2 to 11 sections, making the diameter parallel to the canal from 30 to 165 microns. The cross-diameter varies from 5 to 50 microns. Plate III shows serial sections of a large collector channel leaving the medial portion of Schlemm's canal almost at right angles. The change from section to section is marked, not only in the collector channel, but in the shape of Schlemm's canal. Plate IV shows serial sections (A) of a small collector channel leaving the medial portion of Schlemm's canal diagonally. The collector channels are not always funnel shaped or inverted cone-shaped, as described in the literature. They are funnel shaped, cylindric, or elliptic. Maggiore terms it "flute mouth." In several places, after the collector channel anastomoses with the vein, the vein makes a wide curve toward the cornea, resembling the curves in a river caused by a strong current (Plate V, Model 2, lower collector channel; also Plate II, Sections 487 to 553, same as Model 2, and Sections 620 to 683).

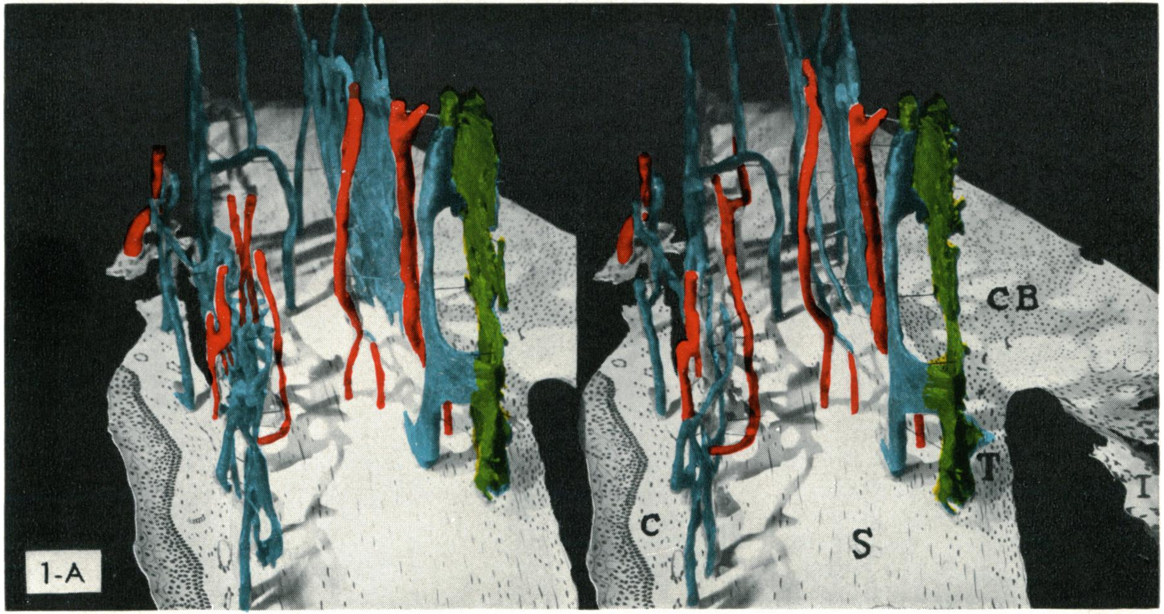
There are no afferent vessels to the canal. Efferent collector channels from the canal unite with efferent vessels from the corneo-scleral border, and unless these are studied in series, they may appear to be going to the canal instead of coming from it (Plate II, Sections 1 to 75, 353 to 420, 620 to 683). We should not, therefore, speak of the connection of the anterior ciliary veins with Schlemm's canal, but rather of the connection of Schlemm's canal with the anterior ciliary veins.

The two models (Plate V, especially Model 1-C) show well the irregular plexiform nature of the canal of Schlemm. It is composed of from one to three lumina of varying thickness and varicosity, which anastomose freely. These models show the canal, not as the usual formation with a sharp inner margin which one is accustomed to see in textbook illustrations (Plate IV, A), but with a very irregular surface toward the trabeculae. In some places the canal is "L"-shaped, in others it is double, with the inner portion continuous with an inner canal. At some points the canal was so small that it could not be distinguished from the "sponge pore" spaces between the trabeculae. Few blood corpuscles were found, and these were present only in the vicinity of collector channels, or where the large artery and the canal shared a wall. The widest radial diameter was 462 microns; the anteroposterior diameter width averaged 49.5 microns.

The inner canals of Sondermann are extremely interesting. As described by this observer, they are small canals lined with endothelium; they leave Schlemm's canal at right angles, only to bend shortly and run parallel to the canal. They can be traced down through the trabeculae (Plate IV, B). It was not possible to count them. Sondermann believed that there might be five or six to each external canal. These inner canals are as irregularly placed as the external canals, and they are most numerous in the vicinity of the latter. They run through from 1 to 3 sections (15 to 45 microns), and are from 3 to 12 microns in width. Because of their minuteness, it can readily be seen that they could be overlooked in oblique sections, especially in sections that are from 20 to 25 microns in thickness. Sections thinner than 15 microns would be more desirable for the study of these canals and we should endeavor to secure such sections.

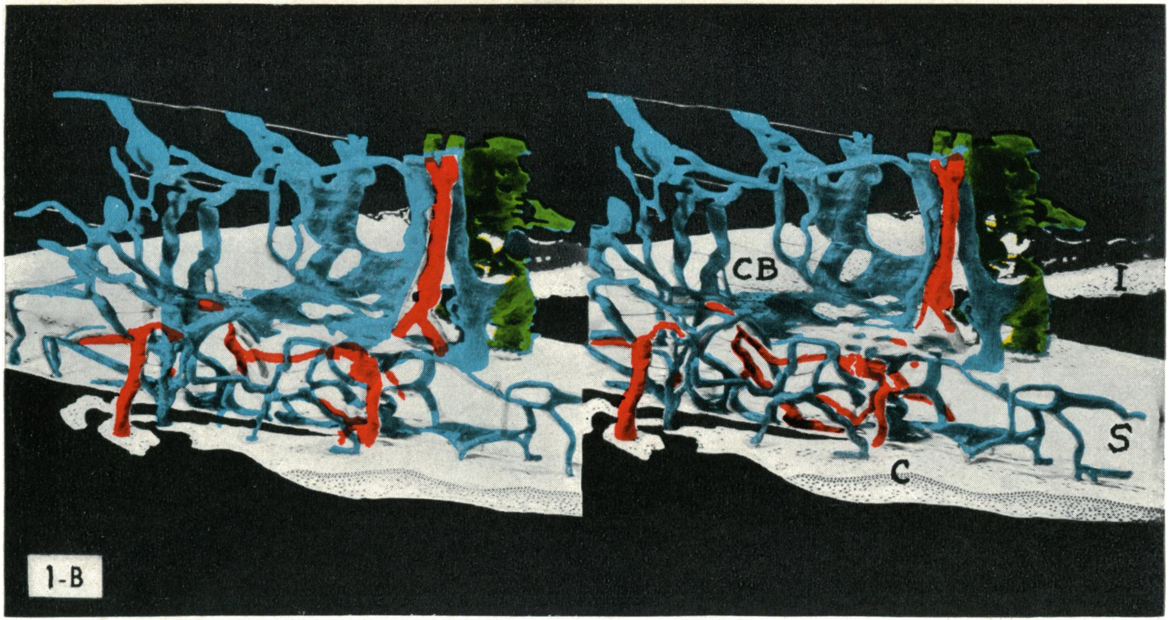
Although these inner canals could be traced down through the trabeculae, it was impossible to make a model of them. There were two reasons for this: the complex form of the minute spaces, and the unequal shrinkage of the different sections during the staining process. At the magnification (× 750) attempted for this reproduction, this unequal shrinkage becomes very apparent.

Plate V



Model 1-A shows: (*Theobald*)

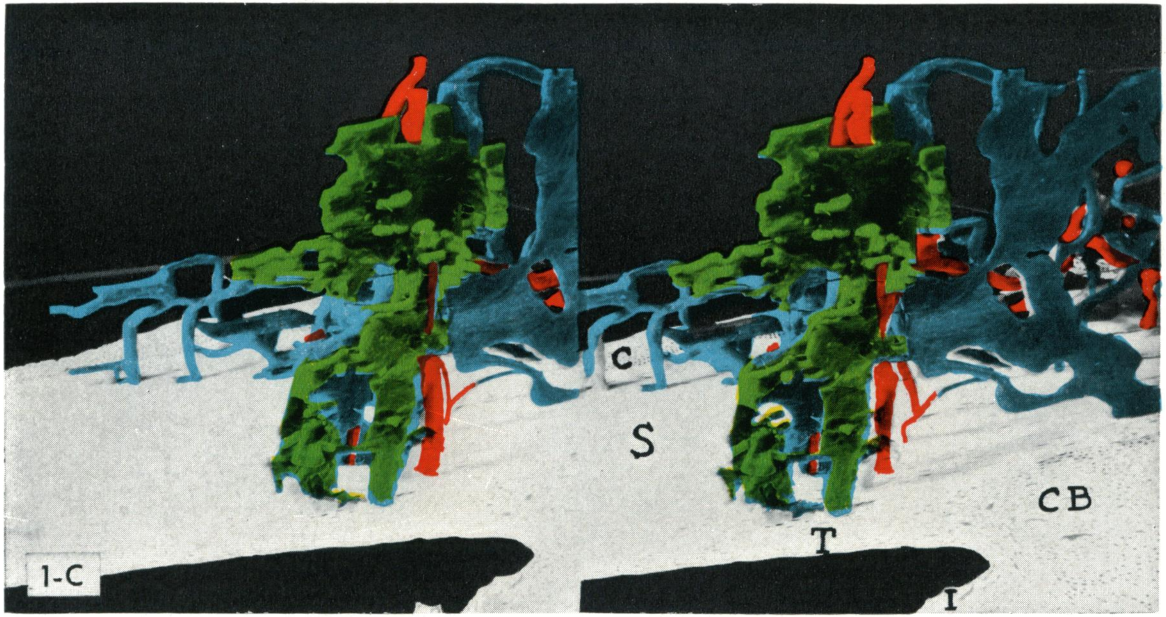
1. The four plexi of vessels belonging to the anterior part of the eyeball.
   1. Conjunctival *2. Episcleral* *3. Intrascleral* *4. Deep scleral*
2. Two collector channels leaving the canal of Schlemm. The lower one leaves from the inner end of the canal; the upper one (see Plate III) leaves from the medial part of the canal.



Model 1-B shows: (*Theobald*)

The dense episcleral plexus. In the intrascleral plexus there are:

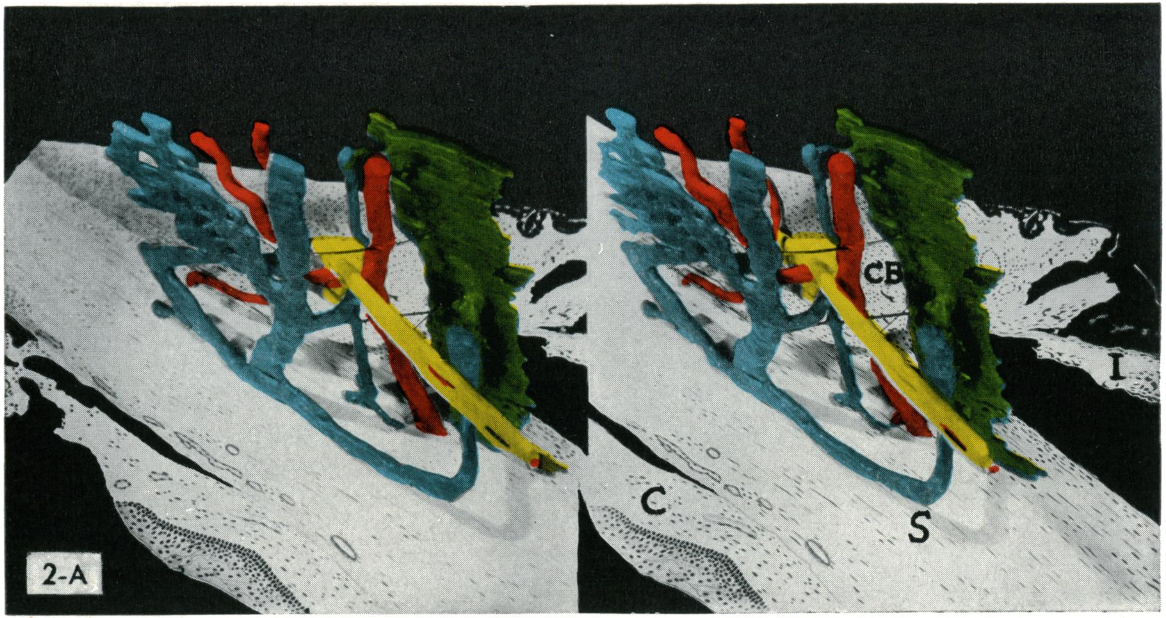
1. *An H anastomosis.*
2. *A direct anastomosis between arteriole and venuole.*



Model 1-C shows: (*Theobald*)

The plexiform irregularity of the canal of Schlemm with its irregular inner surface.

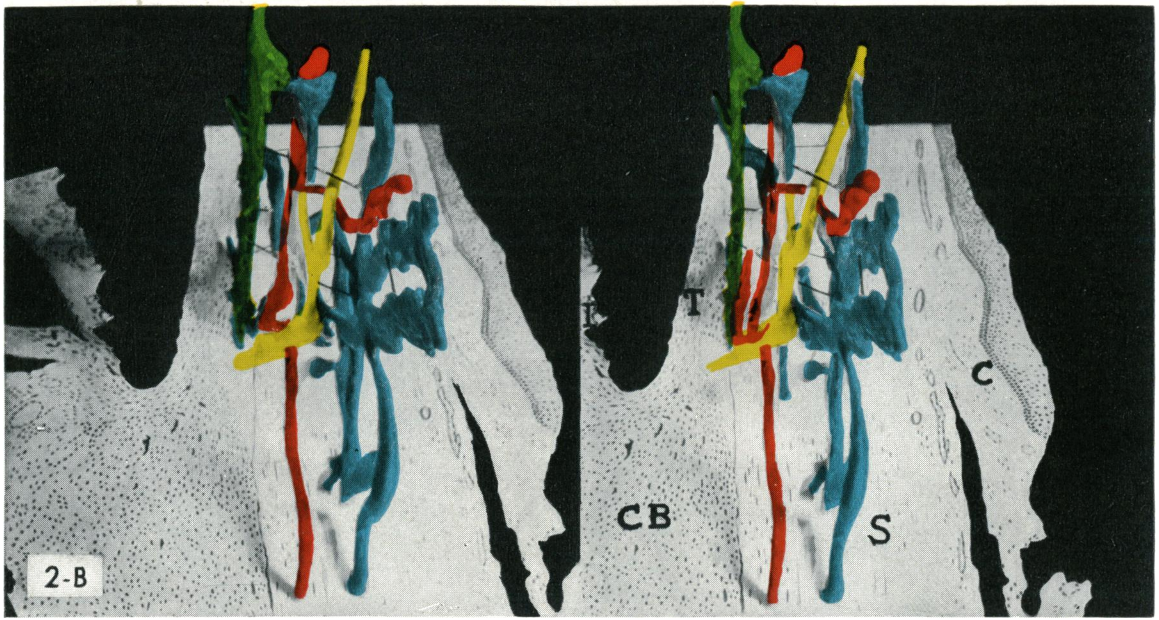
Note: In all three pictures the flat, tortuous, deep scleral plexus.



Model 2-A shows: (*Theobald*)

Two collector channels leaving the canal of Schlemm, from its medial portion. The lower collector channel and the vein resemble the head of a cobra.

Note: The curve toward the cornea in the lower vein before it courses backward.



Model 2-B shows: (*Theobald*)

A nerve from the ciliary body entering the sclera and going toward the cornea. (See Model 2-A.)

Note: The arteriole becoming a venuole, and later receiving the upper collector channel from the canal of Schlemm.

From the foregoing demonstrations it will be seen that my work has been mainly confirmatory of that done by Maggiore, Sondermann, and other observers. I have contributed some knowledge as to the exact number and disposition of the collector channels, and have found them to be more numerous than is ordinarily believed. The models show the arrangement of the plexuses in relation to the canal of Schlemm.

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