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CERTAIN CLINICAL FEATURES OF THE NORMAL LIMBUS*

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THE following features were recorded by the writer many years ago. The controversial subject of "clinical value" is here eluded—in the absence of a consensus of opinion as to the meaning and scope of this elastic term. It may, however, be said that the observations to be mentioned were all made with Zeiss oculars No. 2, combined with objectives A2 (*i.e.*, $\times 24$ magnification) or A3 (*i.e.*, $\times 35$ magnification)[†]; they are quite easily seen by anyone with slight experience, save, perhaps, the double nature of the little sessile vascular stumps; but this, if not seen, is easily enough anticipated by anyone seeing the neighbouring vascular features of which they are seemingly a reduced counterpart. They serve to illustrate how "anticipation" automatically unfolds realities step by step provided only the empirical opportunity is available. The observations were all clinical and were not influenced by histological examination. I waited for years for an opportunity to supplement them thus, but none presented itself. This is not intended to

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[†] These values are not to be confused with the magnifications specified in reference to the actual size of many of the figures reproduced here on a scale which is purely arbitrary and varies, according to convenience or caprice, with the different figures.

be a full account of the normal limbus, *e.g.*, the common mild degenerative changes of the senior years of life are not touched on and the few subjects raised might be further elaborated. The figures reproduced are essentially diagrammatic. When I first started this work I had to take lessons in drawing. It is interesting now to look back on the repeated assertion that for this type of work it is essential to seek a draughtsman who "lacks imagination," and will record "only what he sees;" that visual acuity is to be regarded only in terms of the size of retinal images and that its stimulation by anticipatory conceptions is to be discouraged.

It may be convenient to note now that whenever the word "conjunctiva" is used in the following pages it refers only to the bulbar conjunctiva of the globe, and not to that lining the lids which does not enter into the discussion. The word "limbus" (Fig. 1), or more accurately "limbus region," will often be used to cover a slightly wider area than the actual junction of sclera and cornea; a neighbouring portion of episclera, on which lies the visible plexus of anterior ciliary vessels, is included with the limbus for the sake of descriptive convenience, as also is the neighbouring attached area of the bulbar conjunctiva.

On the vascularization of the normal limbus, writers are prone to repeat a diagram familiar to ophthalmologists, originally published by Vogt, which inevitably lacks many details owing to limitation of space in an initial publication covering a subject of such magnitude as that of the slit-lamp examination of all parts of the eye—more than a lifetime's work. Vogt's schematic drawing of the limbus circulation depicts a plexus of medium-sized capillaries. The corneal border of this plexus is prolonged; as may easily be seen in most persons, into some terminal capillary loops whose calibre is so fine that in ordinary circumstances many or most of them are empty. The scleral boundary of the limbal network merges with deep visible channels on the surface of the sclera, and coming to this network at varying intervals of separation are more or less radially arranged conjunctival vessels which are moderately superficial, some very fine ones often being the most superficial. These features are easily seen in most subjects. Vogt represents superficial centripetal vessels in his scheme and calls them "arteries of the palisades."

The "palisade system" is a term which Vogt has given to certain features consisting of radial striae in the marginal conjunctiva at the limbus. They are readily visible without the aid of the slit-lamp; ophthalmologists are familiar with their appearance. I have been accustomed to speak of these features under the title which I first heard applied to them by my early teacher, Mr. A. C. Hudson, *viz.*, the "trabeculae of the limbal conjunctiva," when I was interested in this subject some 11 years ago. For the sake of brevity

here I omit particulars of their various forms and of their prevalence in different persons. The common straight variety measures about 0.5 mm. to 0.9 mm., but they may reach 1.25 mm. in length. About seven to ten are distributed over a lateral width of one mm. They usually conform in the main to the diagrammatic patterns represented in Figs. 8, 9, 10, 11, and 12, but in many persons they are branched and subdivided so as to form a more intricate pattern, and their lower extremities are sometimes directed towards fainter extensions disposed in circular or mosaic patterns. They are found mainly at the lower and upper limbal arcs, but are absent in many persons. Under binocular magnification their level is stereoscopically seen quite easily to be only just beneath the surface of the conjunctiva; it is on the plane of union of the basal epithelial cells and the adjoining constituents of the substantia propria. Slit-lamp inspection readily reveals numerous fairly straight main conjunctival blood vessels running radially to and from the limbus in the bulbar conjunctiva, and some of these often bear a certain relationship to the trabeculae; many of the finer vessels often run under and in alignment with the axes of the trabeculae, but such a co-relationship is by no means constant even in those cases in which the trabeculae may be conspicuously well-developed.

The Conjunctival Circulation

Before the trabeculae are discussed further, it is desirable to recount certain features of the conjunctival circulation. Although the pictures of various individuals differ much from each other, the whole vascular system of the conjunctiva is built on a plan broadly common to all persons, as can be determined from observation of a number of cases. Clinical examples from two subjects are given in Figs. 2 and 3; these two records have been selected for description before others which will be given later because they were from persons having no trabecular structures. In many persons distinct conjunctival vessels can easily be seen running more or less radially and conveying blood centripetally towards the limbus (E and E1 in Fig. 2). Their level can be seen stereoscopically to be in the average person about a quarter to one-third the distance between the surface of the bulbar conjunctiva and the sclera; but sometimes and in parts of their course they lie deeper, while many, especially finer ones, are more superficial. At the limbus these main conjunctival vessels turn deep in an arched course and join the episcleral vessels (C) at the base of the limbus-net, or even the loops of the net itself. (The larger epilimbal vessels and also the vessels with which they communicate, lying deep under the conjunctiva on the surface of the sclera, are drawn in hatched lines. A large perforating vessel (M) is seen passing through the sclera).

If the vessels E, E1, whose centripetal blood circulation is very easily seen, are studied carefully, it will be seen that very close to them is a concomitant minute vessel A1, A2, which in such cases can very easily be overlooked; in these the blood runs centrifugally and effects a fine ramifying anastomosis with the radicles of E and E1 in the conjunctiva somewhere between the limbus and the fornix. The largest of these afferent-efferent loops meet branches connected with loops (*e.g.*, P) coming from the fornix, while many of the loops like A1, E, and others, that are shorter, merely run out into the conjunctiva without effecting a substantially obvious anastomosis with loops coming from the fornices. This remark needs qualification; very careful observation is necessary to detect that a fine capillary does not communicate with what at first sight appears to be a "self-contained" loop. Thus, in Fig. 5A, which represents a loop running down into the conjunctiva from the lower part of the limbus, only careful

FIG. 4.

inspection will reveal the fine capillary C coming up from the conjunctiva below. The arrangement of Fig. 2, though quite common, has its variations, *e.g.*, that shown in Fig. 3, from a different subject in which the centrifugal vessels (A3, A5, A6 and A8) are not so intimately associated with the centripetal and larger

FIG. 5.

vessels (E2, E3 and E4). (To economize space this figure has been drawn somewhat shortened vertically in its lower two-thirds. Some actual distances in the living subject were as follows: from the limbus vertically to the letter "A6" 2.2 mm.; from the limbus to the letter "Q," 4.4 mm.; from "Q" to "E5," 11.3 mm.). The efferent vessel E2 may be noted; together with the littletwig coming

from the limbus it affords an example of a short main conjunctival loop.

Reference to Fig. 6, U, shows a long afferent-efferent loop based on the limbus-region through connections which are both seen in this case; the arterial afferent component is seen to be derived from a branch of a vessel which springs direct from one of the perforating vessels shortly before this enters the tunnel in the sclera; the arterial twig arches upwards and forwards into the conjunctiva. The efferent component of the loop is seen to join one of the many components of the episcleral limbal anterior ciliary system.

The afferent vessels in Fig. 3 (A3, 4, 5 and 8 in particular) differ from those in Fig. 2 (A1, A2) in being of larger diameter and quite easily visible. These vessels A3, 4, 5 and 8, as also R1 and R2, are of a common and characteristic type. They are of a medium calibre which is almost uniform and unvarying throughout their course—often a long and straight one—in which they give off few, if any, branches on their way; they are of a uniform, pale pink colour; they lie stereoscopically at about one-third to one-half the distance from the conjunctival surface to the sclera; the circulation in them is not often visible because it is too rapid and is uninterrupted, and so the direction of the blood has to be inferred as often as not by inspection of one of the end branches. (Because an arrow is marked showing the direction of the blood this does not mean that the flow has been seen in all parts where arrows occur; but no arrow was inserted when the records were being made unless it was known that its indication was almost certainly correct from inference based on local interpretation and experience.) That the general purpose of these vessels is to bring blood to the conjunctiva whence it will return by larger bored vessels such as E3, E4 and E5 is quite evident by following the course of the vessels in Fig. 3. That it is a matter of indifference in the case of some connecting vessels as to which way the blood flows in them is also revealed by this figure; the blood in many of them exists in a state of hydrostatic equipoise, liable to be swayed one way or the other at any moment. Thus, the blood usually flowed south in YY; but in either C or Y it was often stationary or in a state of oscillating hesitation; it might be going south-west in C and at the same time east in Y in which case the flow must be south in YY. But YY comes up from the arterial vessel R3 so that blood going south in YY can find its way ultimately into the venous system E5, either by going round the loop Z, or by going up RR, whence it can go north *via* B (if it does not go south *via* BR) and eventually south to E5 *via* the thick concomitant of YY. But the flow in TU is in a state of equipoise, being sometimes north and sometimes south, hence it is possible for the blood ascending in B to go in part up TU. It was not possible to determine whether the vessel

L joined the tributary to E4 or (more likely) sprang from either N or A6, but this does not much matter, because on such occasions as the blood was going north in TU it was going east in S.

Returning to the consideration of the region of Y, the flow usually ran east in D owing to the dominant delivery in the arterial branch NKOD; when, therefore, the flow was west in Y—as it occasionally was—the outlet for it was *via* X, and thus mainly to E5 (except for what could enter a negligible little branch given off by X). On such occasions the flow was also west in C. At other times the flow would be east in both Y and C. It is easy to conceive other effects should the blood flow north in YY, which would be in conformity with what primarily was probably intended of it as a straight arterial channel running up from R3 below. In the region of V and W the blood hesitated and varied in its direction—sometimes going southward, sometimes northward.

At first sight there appeared to be no functioning connection between the blood flowing north in the arterial route R1R and that flowing south in the arterial route NKO, but careful observation revealed a very minute cross-connection in which the direction was from R to NKO on the one occasion when the flow across was seen. This delicate contact anastomosis, influenced by the selective domination of subtle local influences at the time of embryonic development, could at any time in adult life be enlarged in response to some local pathological demand whose purpose could be suited by the altered balance that might induce or follow such a modification; but probably in the every-day normal life of this part of this particular eye, the very small cross-connection plays a rôle which, if it varies, does not do so within wide limits.

These examples suffice to suggest that the major circulation in the bulbar conjunctiva can be reduced in simplified form to a meeting of afferent-efferent loops in various potential zones of approximate equipoise somewhere between the limbus and the fornix, from the vessels of both of which they spring.

So delicate may be the bias which at times sways a hesitating column of blood in a given length of vessel in a "region of equipoise" that, for a time, the blood may very slowly advance by a series of regular and similar impulses, corresponding with the heart-beats, each of which consists of an oscillation in which the excursion in the forward direction exceeds the length of that which immediately ensues in the backward direction; so that the column of fluid with its corpuscles slowly progresses forward as might a man who, walking up an ice slope, takes regular steps forward measuring one yard at the end of each of which he slips back twelve inches. This slow rhythmic progression may then suddenly be succeeded by a rapid continuous flow "backwards," *i.e.*, in the opposite direction, under some transient mechanical and doubtless even emotional vaso-motor influence on the neighbouring vessels.

All sorts of grotesque pulsation-phenomena are often found in these ocular vessels so accessible to view and might be worth observation under the influence of drugs and in cases of cardio-vascular disease. Thus, another example is shown in Fig. 4, R and S, in which X and Y are episcleral branches of the perforating vessel Z.

They are large and abundantly full, so, as is usually the case with such vessels unless their ultimate destination can be traced, no hint is discoverable to indicate which way the blood is flowing in them. The column of blood in Y is, as shown in R, usually in continuity with that in X and Z; but, in periodic relationship with the heart beat, the column in Y is rhythmically retracted and momentarily breaks continuity with that in XZ (as shown in S). During this short phase when the blood column in Y is retracted, it is linked with the unaltered column in XZ only by that which adheres by capillarity, as drawn in the figure, to the inner face of the vessel. The time-duration of the phase of S is shorter than that of R. Various phenomena often seen thus indicate the presence of "negative" suction-influences as well as those of positive pressure.

It would be convenient if we simply say that the territory of the ocular conjunctiva has an afferent supply from both its fornix and limbus boundaries, and an efferent drainage by way of each, and intermediately "neutral" zones—real or potential—in which there is some inevitable intermingling of the blood conveyed and returning across the two boundaries whence it arrived. It is easily conceivable that transient influences (pressure variations on either side, blinking, local vaso-motor disturbances, etc.) can result in the zone of equipoise in parts being displaced towards, and over, one or other boundary causing an increase of blood-flow across that boundary in excess of the amount which crosses it in the opposite direction. It is impossible to see the conjunctival circulation, even for the first time, without being attracted to the many possibilities which its ordered complexity suggests.

Nourishment at the limbus boundary which borders on the highly evolved cornea being presumably a matter of more specialized importance than at the fornix boundary, we may examine the conjunctival circulation for evidence indicating whether the amount of *arterial* blood which passes centripetally from the conjunctiva to the limbus-plexus is likely to exceed that of the arterial blood which flows in the opposite direction from the limbus-plexus to the conjunctiva. Difficulties are apparent from the outset; we can probably decide that a given vessel in the conjunctiva is "arterial" as it comes up from the fornix, but it is by no means always easy to conjecture how much of its blood is "arterial" when it has traversed—and, in doing so, established anastomoses with—a territory where such ramifying interminglings can have taken place and which, incidentally, is so very close beneath an exposed moist portion of the body-surface. If the quest is pursued further, and we attempt to decide as to the arterial character of a centripetal vessel according to its functional destination at the limbus, the difficulty is that the morphology of the limbus-plexus itself is not at first sight a guide to its function, while many of the centripetal vessels merge with dependencies of the net (*e.g.*, the trabecular and paratrabecular loops to be described later) whose functions are not too clearly apparent. I will, therefore, not for the moment stress in detail this question from the point of view of the destination of the centripetal vessels at the limbus, but will

FIG. 1.

THE NORMAL LIMBUS.

Linear magnification : approximately $\times 35$.

Fig. 3.

CONJUNCTIVAL CIRCULATION.

Fig. 2.

Fig. 6.

FIG. 16.

Portion of the vascular system at the limbus, left eye, 8 o'clock, in a child. The linear magnification is $\times 55$, the distance between the letters U and Z, which here measures 82.5 mm. being, in the living subject, 1.5 mm. Similarly, the distance from the letter W to the peripheral tip of the loop HH is here 71 mm. and, in the original, 1.3 mm. A slight error in proportion occurs in that the terminal capillary loops at Z, and the "open ring" plexus-loop just peripheral to them, have been drawn a little too large in relation to the rest of the figure. Elsewhere, all proportions are correct, *e.g.*, the ring s'-sd-d' measured 0.1 mm. at its longest diameter and it will be found to measure 5.5 mm. in this reproduction.

review the vessels in their conjunctival course to find what evidence there may be to throw light on this from their mere individual character. For this purpose we may refer in more detail to points already alluded to under Figs. 2 and 3.

A record from a normal case of the type represented by Fig. 2, but in fuller detail, is given in Fig. 4. This figure is from the class of case displaying—as mentioned under Fig. 2—an exceedingly fine inconspicuous arterial concomitant vessel (A, Fig. 4) radiating from the limbus in close association with the relatively conspicuous “venous” channel (C). This record, incidentally, shows how a relatively large single vessel may maintain a copious flow—even to the extent of providing fully for an ample flow through four branches (at T), none of which is of smaller diameter—when fed by the slenderest of tributaries, in this case A, O, P, H and L.* As a drain partially offsetting this supply there is a fine exit *via* G; NM has no connection here with the system. The very fine concomitant vessel A, coming from the limbus region, is clearly arterial, as is possibly also H; but if we started to trace O, P and L to a functional origin, in seeking to know if they were essentially arterial or venous, we should probably get lost in conjecture over the intricacies of potential zones of equipoise. A caution may here be mentioned; it must not be assumed, because four minute vessels, A, O, P and K of more or less equal size, are delivering blood to such a relatively big vessel as C, that they have difficulty in meeting the demand and that they must all conjointly deliver blood at a maximum, and therefore “arterial,” rate. One of the most enlightening features revealed by a study of capillaries is the possible degree of disproportion, which is sometimes very great, displayed in the minute size of an arterial afferent vessel which may be the only source of supply to a much larger capillary loop transmitting an abundant and full flow of blood. It would be quite possible, in the case of Fig. 4, for no blood to be contributed to the vessel C by the channels O, P and K, and yet for C to display a copious flow derived from the single remaining fine arterial channel A. Indeed, A probably does provide the bulk of the blood returning in C for the reason that at no time was its movement visible—an indication of either no speed or great speed—whereas the flow was sufficiently leisurely and “dilute” in O, P and K to admit of its being easily seen. (The only way that the direction of the flow in A could be determined was by interpretation of the conditions in the region of the loops C, D, E, etc.) Hence the conditions in Fig. 4 are more or less of the simplified type described under Fig. 2, the large

* An error has occurred in this figure in the region of L. The reader should reverse the direction of each of the five arrows near L, M, J, and also of that actually on the vessel N.

vessel C, joining the base of the limbus-net, being morphologically "venous" in character when considered in relation to its conjunctival course independently of its functional destiny on arriving at the limbus.

Fig. 5B is drawn to show diagrammatically how an extremely fine arterial vessel can provide enough blood to flow quite fast in opposite directions from its point of union with a relatively large vessel. In Fig. 5A, an even smaller vessel, C, affords an example of a very minute centripetal vessel bringing blood towards the limbus but, again, I would not be prepared to conjecture to what extent the blood in this may be arterial.

Reference may now be made again to Fig. 3; R2 and R1 are of the typical direct even straight arterial type already referred to. R2 is simple; most of its blood will come back to the fornix, save that possibly when the circulation chances to go north in W and V (as it sometimes did) some will find its way up to E3; but E3 would appear to be a "vein" not concerned with the transfer of arterial blood to the limbus. But of R1 there is something suggestive in its projected linear continuity (across the constriction K) with the vessel NK—a branch of the afferent vessel A5 which is identically of the same type as R1. If we were presented with the frequent sight of one continuous vessel of this sort (R1RKNA5) in which the blood ran all the way direct from the fornix and into the limbus, then the arterial supply *via* the conjunctiva to the limbus could in some measure be discussed on a simple basis. The difficulty is that even when we find a major characteristic straight conjunctival arterial channel of this type proceeding from the fornix centripetally to the limbus region, something all too often occurs in its course to upset the estimation. Thus, following it up, we first notice that R has escaped the embryological possibility that it might have established (or retained) connection with HH, as it passes beneath this vessel. Next, what, at K, was for a time in the embryo possibly a free communication between R and N has resolved itself into a negligible little anastomosis scarcely functioning, and for that matter, even if it did and if the dominance of pressure directed the upward flow of R still on up through KN, for the blood to succeed in reaching the limbus-system *via* A5 it would have to be delivered at sufficient pressure to cope not only with any opposing influence from A5 but also with whatever influences might arise from the presence of the branch NN.

Fig. 6, F, is worth quoting as a case in which it might be inferred at first glance that the long even-calibred conjunctival vessel FMZ is an example of an arterial vessel proceeding straight from the fornix to the limbus through the onward continuity of AA, especially as AA is of much the same diameter

as FMZ which is a typical direct channel having the "arterial" characteristics already described in the discussion of the afferent channels of Fig. 3. (At first observation, and until noted carefully, it appeared so; in drawing the figure it has been necessary for the sake of clearness to exaggerate considerably the horizontal scale in proportion to the vertical, with the result that the departures from straight linear continuity of the vessel FMZAA are much more apparent here than they were in the original subject). In the original subject* the vessels FMZ and AA were fairly easily seen, but with the possible exception of DG, the vessels closely associated with them were only visible with difficulty, so that FMZAA could be mistaken for a straight arterial channel from the fornix to the limbus which on its way across gives off one arterial branch DG to the conjunctiva. The asymmetrical bifurcation of FN, at M, would scarcely be detectable if attention were not drawn to the presence of the very fine vessel X from the fact that it becomes rather thicker near where it joins A. (The reader may find it convenient to bear this fact in mind because reference will be made to it later.) Z, the larger and undiminished continuation of FNM, turns abruptly round at D and is destined mainly for GJL and H. Thus FNZ brings arterial blood from the fornix to return, *via* the regions of YY', to conjunctival efferent venous channels at the fornix. Where it turns round at D it is also joined by a very fine arterial channel BB coming from the limbus region. (If BB is not at first seen, its presence, in concomitant association with the vessel AA, is to be suspected, by anyone familiar with conjunctival vascular architecture, from the existence of the "side-stepping" of AA in at any rate one part of its course; probably in the initial stages of their development the vessels, BB, AA, formed an arterio-venous loop based on the limbus region even though, morphologically, their destination now deprives them of this simple classification in the strictest sense.) Before the remaining branch of D, *viz.* K', is considered, attention should be paid to the small afferent-efferent loop TOW.† Arterial blood from D could ascend *via* K'K to the loop O, whence it might in part enter the efferent route of TOW to the limbus, or in part descend

* It is very difficult or hardly possible, in reproduced diagrams so reduced as these, to represent all the vessels in their true relative proportions, in spite of skilful reproducing by the publishers. There is an unavoidable tendency for the thinnest lines to undergo slight relative thickening in reproduction, as *e.g.*, in Fig. 5 and particularly in Fig. 4; also Figs. 11, 12, 13, 20, 21, etc.

† These figures were made long ago. I had forgotten the existence of notes, stored away rather inaccessibly, in which I had recorded, in formerly checking the figures, errors which should be corrected in them; unfortunately, where this has occurred the blocks have been made before I remembered this. Thus, concerning Fig. 6, I have come upon a note to the effect that in the case of the loop TOW, W should be its thin afferent channel, and should have its arrow pointing south, and T should be the thicker efferent channel and should have its arrow pointing north.

again in P, admixed with some arterial blood from TOW, to enter the main "venous" channel AA. Into this "venous" channel, AA, passes the arterial blood from the very fine vessel MX.

It may be remarked in passing that apical connections like P and K—though commonly there is not more than one—with afferent-efferent loops such as TOW, are a common feature in vascular architecture. If they are not at first seen their possible presence should be anticipated; thus, a more subtle example is seen at R. An arterial vessel, coming from the limbus, such as F, which was all but invisible, might easily escape notice; the direction of the blood flow in the stretch of vessel QR was not visible, but it was visible (*viz.*, southward) in the onward continuation RSV, from which it might be not unnaturally inferred that the direction is also southward in QR. But the abrupt diminution in calibre of the channel QR at the level of the letter R should give rise to suspicion, whereupon search reveals the tiny and, what was usually almost empty, arterial vessel F which, for a distance F'R, contributes to form a minute superficial close conjunctival afferent-efferent loop of which the afferent component, continuous with F, is invisible; from this, it can be inferred that the invisible direction of the blood in RQ is northward, and not southward as might be inferred if only the evidence of RSV is accepted.*

Returning for a moment to K/K, the direction of whose flow was not visible (it might have been stationary), K could equally well serve to conduct a southward flow, from the loop TOW, to the vessel E, in which case the blood in K' could be in a state of equipoise.

Hence, it is by no means easy to be clear on the question of the extent to which there may be a supply of truly primary arterial blood to the limbus-region by way of an essentially conjunctival route. There are many centripetal vessels going from the conjunctiva to the limbus-plexus region on the nature of whose blood it is very difficult to conjecture, partly because of the complex anastomoses which they effect on their way across in the territory of the conjunctiva and partly, in many cases, because of their terminal communication with afferent-efferent loops (*e.g.*, Figs. 4, 5 and 6) emerging from the limbus-region into the neighbouring conjunctiva. However, not infrequently fine channels, seemingly

* The minute vessel F should spring from the afferent component of TOW where it is represented as crossing this loop, so that the dotted continuation of F on the east side of this loop should be deleted. I find I have a note to the effect that at times the direction of the circulation was visible in QF'R and that occasionally it was north but that at other times it was south; in the latter instance the loop F'R would convey a dual southward flow (*i.e.*, from both QF' and FF') into the minute vessel RS.

arterial, can be found traversing the conjunctiva to reach the limbus-region and of these there is one class not easily seen in normal eyes, but sometimes detectable in cases of engorged conjunctival circulation. It is a very fine, round, even, pink superficial vessel. Its diameter and character rather resembles that of the fine arterial vessels of the limbus plexus. If the course of such a vessel is followed in the conjunctiva it may often be seen here and there to give off fine efferent return branches in accordance with an architectural principle which will be discussed later. It might be vessels such as these to which Vogt refers when he speaks of the "superficial arterial way to the rim-loop net."

Conjunctival vessels connected with the limbus, such as those described in Figs. 2, 3, 5A, and 6, are prone to have a radial disposition and to pass under trabeculae when these structures exist, but they by no means constantly have a subtrabecular course. Of these, more will be said later in the discussion of the vessels of the limbus, but before proceeding to this an opportunity will be taken, now that figures of the conjunctival circulation have been reproduced, to discuss, conjecturally, one or two features of interest from the hypothetical point of view of development.

The Conjunctival Vascular Architecture in Relation to its Development

In the short time when I was able to do this work I attempted to watch clinically the changes displayed by pathological vascular invasions of the cornea in the course of their creation. They are based on an initial ingressive scaffolding formed by simple endothelial intubation. It is presumably permissible to assume that on mechanical principles, up to a certain point, the different phases displayed by a pathological vascular invasion beneath the epithelium of the avascular cornea may be imitative of the stages traversed in the course of the embryonic development of the normal vascular system in the homologous plane of a neighbouring tissue. Whether or not this is so, inspection of the fully formed normal vascular system of the conjunctiva often reveals certain fundamental features which, like archaeological remains, suggest something of the hidden embryological history of the part which might escape the notice of anyone not knowing something of the steps revealed by pathological vascular invasions of the living human cornea during their formation. Viewed from this standpoint the architecture of the vessels of the bulbar conjunctiva is suggestive of their embryonic development from two opposite "camps," the fornix and limbus, much as tunnels may be developed through a mountain from starting points at opposite sides. The "zones of equipoise" are probably formed partly as the result of unions

between these constituents invading from the regions of the fornix and the limbus respectively.

There is a characteristic of capillary loops which will be referred to elsewhere in this article; where an afferent (arterial) capillary turns back on its efferent (so-called "venous") course, usually its diameter is seen to be thereafter materially increased. When these two components run concomitantly side by side in a "close" loop this change in diameter is often relatively abrupt and occurs usually at the apex of the loop (*e.g.*, Fig. 5, L, and also the end capillaries of the limbus-net of Figs. 20 and 21). In cases in which the vascular loop is more open, *i.e.*, less acute, the transition from smaller to larger diameter is, though definite, commonly somewhat less abrupt, as in Fig. 5, S. In the very early stage of the formation of a small terminal capillary loop in a pathological vascular invasion, the afferent and efferent components are rather alike, and in respect of their diameter they are usually alike; but at a variable period after the loop has settled down to uninterrupted and full functional activity the characteristic difference in diameter usually establishes itself unequivocally.

Another feature, which it is helpful to know in interpreting the architecture of normal vascular systems, concerns one of the evolutions which may be seen in pathological vascular invasions advancing to a distant outpost far from the initial base of supply; it is illustrated purely schematically in Fig. 7, from which I have omitted certain characteristics which will not be discussed here.

The invading intubation, be it simple or complicated, initially builds itself up on a plan suggestive of the provision with certainty of ample efferent channels of return during the various successive stages of its infiltrating course, reminiscent of a pioneer cautiously establishing multiple paths of retreat from different stages of his advance. But as an offset to the apical insufficiency which would ensue were this principle to hold unchecked ascendancy, these primary channels partly cease to function when they have become merely short-circuits which would deprive the active advance-zone of the blood which it apparently requires.

In the case of a formed pathological loop AE, when a later stage of advance, B, is reached, adequate flow of blood to the apex S is often associated coincidently with a functional diminution of calibre in the return part of the parent loop XE. If, in spite of this, XE is destined still to function (particularly in the "metabolic" capacity, conjecturally dependent on slowness of speed, to which I shall refer later) this "constriction" in the parent efferent path (XE) may perhaps be seen to exist only for a short distance (say XY) along it from the point (X) at which the afferent path (XS) continues its onward course from the parent loop. (In making this statement I avoid the use of terms which would imply cause and

effect; a discussion of these is outside the scope of this article; the word "constriction" is possibly not an appropriate one: it is used here in a relative sense only.) Thus, the destiny of the efferent component (XE) of a parent loop AXE may be (a) that it remain unaltered; or (b) that it develop a relative constriction which is present for a short distance (XY) from its apex

FIG. 7.

and therefrom gradually becomes less marked until further back, say beyond Y, the vessel is found gradually attaining its original unaltered diameter (E); or (c) that functional obliteration occur by an extension of this retrograde "constriction" throughout its length. It may be added (C) that if the apex of a primary parent-loop (A'X'E') later establishes continuity with an *efferent* channel (PX') from a more advanced (*i.e.*, more distal) active region in circumstances which impose an increased demand on the effluent capacity of the efferent portion (X'E') of the parent-loop, a functional change by way of "constriction" of the primary *afferent* portion (A'X') may then ensue. A long time after this last possibility has occurred in pathological systems in the cornea—I know it can amount to months, and I believe possibly years—the site of the same channel may suddenly be seen to be in full function again under the influence, apparently, of no greater inducement than an increased and prolonged local affluent activity.

Another pattern of developing pathological capillary loop is shown in Fig. 7, F—J, in which the portion of the narrow parent-loop which undergoes disuse, coincidentally with adequate delivery of blood to the new apex, is the short cross-piece S which formed the original transitional apical portion of the parent-loop. A modification of this is shown in K—N, in which the final super-added loops have a transposed disposition resulting in a formation whereby each component of the parent-loop is extended in functional continuity with a tangent to some part of its pre-existing curve at the apex.

Reference to loops like F—J and K—N will suggest the natural conclusion, when they are seen in the cornea, that their disposition must to some extent be governed by the pressure of the pre-existing anatomical tissue-planes between which they develop. By analogy, the presence of architectural vascular features similarly disposed, as they so commonly are, in the normal conjunctiva suggests a like "pressure" influence in the course of embryonic development and it may well be that this is aided by the adaptation of the eye-lids to the contour of the firm sclerotic coat. The word "pressure" used loosely in this connection probably does apply to one of the limiting factors of a pathological vascular invasion within a normal tissue like that of the cornea whose structure is so essentially a lamellated one; but, if the embryological vascularization of the conjunctiva takes place by invasion in the manner suggested, the commonplace word "pressure" is inadequate to explain why the invasion should confine itself so strictly to this predestined thin anatomical plane when no apparent mechanical cellular barrier exists to obstruct anastomosis of the conjunctival with the underlying episcleral vessels.

between the limbus and the fornix. Such selective discrimination implies the existence of forces and factors presumably beyond present conception. I have seen something reminiscent of this in pathological invasion in the cornea; great vascular activity may be evinced at some region towards which vessels may creep across long distances in a chosen plane by means of complicated and tortuous evolutions; yet other near-by vascular loops—which are apparently in a favourable position in the same plane to link themselves on, across seemingly unobstructed distances that are shorter in comparison—will remain for weeks, or months, or for all time, without contributing their assistance; and this, even though their apices display unmistakable signs of a dormant initial activity, as if enticed in anticipation of an apparently simple task which they are destined never to fulfil.

Soon after capillaries are formed in the cornea they may, in certain instances, be seen to undergo a slight degree of change in position chiefly by way of a partial straightening out of some of their curves, apparently in obedience to their own intrinsic hydrostatic stresses, much as an aneurysm may erode a bone. So that the endothelial tubes, whose evolutionary pathological wanderings have been influenced in their disposition to some extent by the structural solidity of an adult tissue in which they have developed, can, when approaching maturity of function and in the height of their formative activity, turn the scales against their host. On this ground it might be supposed that nothing further is wanted to bring about, in turn, ultimate disfunction of the intruders than sustained assertion of the tissue-tension which they initially overcame, so that they should finally succumb to the antecedent forces whose priority holds sway. The ultimate emptiness of the smaller components of pathological vascular invasions of the cornea bears witness to this sequel. It is tempting to conjecture than an explanation of the origin of the difference between the diameters of the afferent and efferent components of primitive vascular loops might lie in some such simple direction. However, it is borne in on anyone watching such simple vital processes that, from immaturity right through to senescence, they are not the simple self-existent actualities which they appear to be, but, rather, are a mean between constantly opposed inordinates whose poise is sustained throughout the period of maturity with a delicacy beyond interpretation; and that even though their component steps, at present not understood, will sooner or later be explained, they must always lead with compelling sequence to others in the mist of obscurity, so that in the long run man is appropriately fated never finally to elucidate his own vital phenomena in terms of the philosophical comprehensions which he himself has evolved.

In normal conjunctival vascular architecture a long afferent-efferent loop may show as many as six or more crossings such as those in N, Fig. 7, and sometimes these will follow each other in uninterrupted succession in the same relative rotatory direction, so that the afferent vessel will cross superficial to the efferent at one point, deep to it at the next, superficial at the next, and so on in alternating sequence to the last. In cases in which the sequence is broken an associated variation in the symmetrical axial relationship of the two vessels to each other may sometimes be found. Not until an observer—having learnt from experience to anticipate what needs recording—depicts these features for himself, is he likely to note accurately as to which vessel crosses superficial to the other in a series of such crossings which, not always easy to unravel at a rapid glance, takes even longer to depict. I did not years ago pay full attention to accuracy as regards this point in the normal* until I had watched it occur in the process of a pathological invasion, when I came upon some evidence which I think is tentatively suggestive of possible factors contributing to this entwined formation. The crossing of paired afferent and efferent components seems to occur where a reactivation in the process of advance follows upon a transient lull of the ingressive activity. It seems possible, if not probable, that a determining factor in the direction of the "twist" at these crossings lies in a delicate bias of the simple mechanical balance between the two opposed factors of intravascular centrifugal force on the one hand and the enveloping "tissue-tension" on the other. Scope for sway of this bias in the positive or negative direction can exist alone in the mere factor of variation of the local intravascular affluent activity. As with many of the other suggestions here made, the evidence on which I surmise this—consisting of consecutive records far too extensive to publish—was insufficient to justify any definite conclusion being drawn and I allude to it now only because, having ceased to pursue the subject, I feel it will be solved by anyone who can elect to follow it up.

Nearly all such "normal" structural conjunctival features as I am describing were among the earliest clinical records I made, many of them being with the Czapski binocular magnifier before I knew of the existence of the slit-lamp; but it was not until later, when I had closely watched one or two available cases of vascular invasion in disease of the eye, that apparent meaning was revealed in many of the architectural features previously recorded in the normal vessels. An example of this seemingly justifiable application may be quoted from Fig. 3; at some time in their life history some modification has probably taken place affecting the dichotomously linked loops FJ and GH (Fig. 3); in these the afferent components fed by the vessel A8, are anomalously of greater diameter than the respective efferent components which unite in a common trunk (BB) that does not assume the customarily proportional diameter of an efferent trunk until shortly before it unites with E4. Something happened, it may be suggested, to bring about this reversal in this way:—FJ and GH had developed as end-loops of a system, originating at the limbus, based on the parent vessels A8 and E4; between the points BB and BG some disposition probably existed whereby the afferent blood from A8 continued on down the *thin* components of FJ and GH whence the *thick* components delivered their blood to the tributary BB going to E4. (This condition could have existed through the medium of various simple possibilities, e.g., a delicately established intercommunication at BB; or an anastomotic tubular endothelial loop—like the channel Z in the lower part of the figure—which has subsequently ceased to function and has disappeared: it is significant that the efferent vessel BB, which passes under but does not communicate with A8, does not begin to increase in diameter until it has just passed this point.) Conditions had settled down for an appreciable time when the established order was upset, quite possibly by the arrival of the forerunners of a vascular invasion from the fornix below, and by the mutual anastomotic contact thereby initiated, such as, possibly, the union between the apex of the loop GH and the vessel HH. The sudden establishment of

* I had written this article and selected its figures before I decided to insert this section on "development." In these figures not all the crossings are correctly drawn as to which vessel in a loop passes superficial to the other. In this respect only, the accuracy is to be doubted of Figs. 2, 3, 4, 5, 8, 20 and 21. In the case of Fig. 6 a note records that the crossing of A and B just above the level of the letter Q is correct, but in the crossing just above the letters XZ the thin vessel should be superficial to the thick (G), and this same vessel S also should cross the branch L superficially. The two crossings in rotatory sequence, just above and below the letters VJ, are correct. The loop PA is correctly drawn except that, even though it passes deep to G and also RS, it should cross superficial to DH and DK'. These errors do not affect the bearing which in other respects these figures have upon the text, but I mention them in case they should mislead anyone investigating the question of entwining of paired vessels.

even a slight anastomosis like this might upset the local balance so as to bring about a reversal of the direction of flow in neighbouring vessels.

Hence, in the process of embryonic vascular invasion of the conjunctiva, purposeful and prescribed though the successive events initially may be, it is understandable by analogy how their subsequent course might become vicarious when suddenly thwarted by the influences arising from apical union between separate invasions developing from two opposite bases.

I came upon evidence suggestive of a probability that pathological capillaries can in part adapt their configuration to a functional change occurring during their initial development, or at a reasonable time after their apparent stabilization. The anomalous reversal of flow in the loops FJ and GH possibly occurred some time after the primary function in the opposite direction was established. In the case of Fig. 3, features along an approximate line JHKS were hypothetically suggestive of a past cessation, here, in the creeping advance of a complex invasion coming from the limbus as a base. It has already been pointed out that the distance from the limbus to the letter "Q" was actually one-third that from "Q" to "E5" which was not quite at the full periphery of the lower fornix.

It is interesting to review also certain points of Fig. 6 (F) from this conjectural standpoint. It has already been stated that the flow in both MX and MZ is northward. Now at first sight the architecture of these portions considered as a conjoined loop XMZ—neglecting the onward continuation MNF—is suggestive of XM originally having had a southward arterial function and of MZ having had a northward "venous" one; in this case the possibility could be considered of XM having originally come from BB and of MZ having originally passed up straight into the "venous" channel AA. In this way BBX—M—ZZAA could be assumed to have been an independent arterio-"venous" loop based on the limbus region at some stage in the embryonic development prior to establishment of a connection of its apex with the channel NF. But this is not the only possibility. It will be noted that the very fine vessel MX, followed northward, increases slightly in diameter before it joins A. This gives rise to a suggestion that, for a period during the embryonic development, the channel MXAA might have been an efferent northward return route (from the southwardly advancing afferent channel BBZZMN) which for a distance, MX, has undergone functional constriction in the manner described under Fig. 7. In other words, MX might correspond to XY of Fig. 7, allowance being made for the fact that this figure is "upside-down" in relation to the loop ZMX, Fig. 6. But if this is so, the abnormally greater diameter of the portion ZZM of the hypothetical embryonic afferent channel BBZZM might need explanation on the basis of its union, quite soon afterwards during embryonic development, with a dominant northward arterial delivery *via* FNM which, thereafter being in continuity with D, *via* ZZ, subsequently brought about a greater, and reversed, northward arterial flow through ZZ; this might have caused permanent dilatation of this portion which originally started by being no greater than that of the primarily established afferent channel BB. This last consideration brings to mind an interesting clinical side-issue which I endeavoured to watch, but in so far as I was able to pursue it I came to no conclusive decision. Some evidence was forthcoming suggestive of the possibility that components primarily belonging functionally to the afferent type more readily submit to a subsequent developmental modification of permanent form, in relation to adventitious changes of function, than do those initially evolved in relation to an efferent function and, in particular, those which early play a rôle in harmony with the essentially "metabolic" type of vessels to be referred to later.

The main value of the slit-lamp when it first became available lay, not so much in the entertainment afforded by its pictorial details—lucidly accessible to view and only a matter of opportunity of access—as that nearly every ocular condition appropriate for inspection by its means suggested fields for clinical investigation, each successive step of which displayed fresh aspects pregnant with possibilities. The making of detailed records of this nature discloses new information in three main ways: at the time, it reveals self-evident processes, and it confirms others primarily less obvious but suggested in imagination by what is already unfolding itself and becoming so apparent; and finally, the subsequent reviewing of the records reveals links between early and late events not noticed or anticipated during the contemporary making of the records. It is often said that the "laboratory mind" cavils at the "clinical;" the distinction is falsely founded. The late Mr. Treacher Collins,* when the slit-lamp was first demonstrated to him, shortly after he had retired

* His Zeiss instrument was recently acquired through Gayer Morgan for use in the ophthalmic department of Guy's Hospital.

from active clinical work in hospital, promptly acquired one to use in his private practice, remarking that von Graefe, on first being shown the ophthalmoscope years after it had been initially rejected, said of it that it "opened up a new world." The artistic appeal of the pictorial dissections of the slit-lamp is clearly a matter of personal discretion; and the contention that they did not reveal anything more than was already detectable may be disregarded. But the explicit subject of the slit-lamp—even just recently referred to as the "much maligned" instrument—should in retrospect help to show that empirical and optional exploration, so commonly deprecated, can often be more fruitful of conjecture than can investigations subordinated to the coercive limitation that is often cloaked under the import of educative "scientific" rationalism. Not mere cynicism alone suggests that imposing "scientific discoveries" are fundamentally the outcome of cumulative empiricism to a far greater extent than human nature is willing to admit. At this apparently late stage there is yet scope for more work on this subject, even to the extent of recording some ocular affections aetiologically as yet unclassified, if not unsuspected—unless probably by a few—and almost certainly unrecorded in the detail which without doubt will be accorded them gradually in due course.

In final reference to embryological possibilities, attention may be drawn to the vessels DGJ (with L) and SV, Fig. 6, with a conjecture that a southward flow common to both of these probably did not exist in their early embryonic period. The mutual crossing of these vessels here and there (just below the letter "G," and both above and below the letters "VJ"), together with their difference in calibre, is suggestive of the original southward advance of a vascular loop of which SV was the arterial afferent component and JG the efferent component; for analogy with a pathological invasion compare Fig. 7, K—O. Some later development has probably brought about the establishment of a southward flow in GJ, and, among the multiple factors possibly associated with this, probably one was the linking up of GJ, in the region of Y, with outgrown venous channels originating from, and functionally leading southward to, the fornix.

It may reasonably be proposed that whilst most of the embryonic evolutions, when matured, are established for good, some of them (as at K in Fig. 3) might leave partially unobliterated features which could possibly play a material rôle in permitting a local return, in at any rate some measure, to an embryonic balance of the flow in the event of some change demanding it later. It might be an interesting speculation as to how far such considerations might bear relation to the general clinical pathology of bodily tissues in which a complex vascular structure plays a dominant part. Also worth consideration might be the general question of the ontogenetic significance—if any—of the embryonic meeting and interdigitation of vascular invasions from opposite bases, and whether the response of the primitive asymmetrical vascular loop to influences thus imposed upon it might bear any relationship to the evolutionary specialization of particular tissues.

The Trabeculae

In the cases so far illustrated there were no trabecular structures. Returning now to the consideration of these, when they exist many of the radial conjunctival vessels, such as I have described, pass beneath them on their way to and from the limbus.

The coarser of these vessels quite clearly pass stereoscopically deep to the trabeculae, but often a false appearance is conveyed suggesting that the vessel is going longitudinally exactly through the trabecula in cases in which the vessel lies in alignment with and deep to it. It was, however, at once apparent when the trabeculae were studied that many of them have a small and even more superficial blood vessel in intimate relation with them and often actually in them. A feature that was striking when I first saw these intrabecular vessels was that the blood could be seen

circulating nearly always in a centripetal direction towards the limbus-plexus, to the vessels of which most of them had an attachment at their limbal end. At first sight this looked odd because the distal (*i.e.*, more peripheral, more "conjunctival") end appeared free and "blind." It was, however, soon apparent (Fig. 8, V) that the distal end was a bend of a little loop of which the centrifugal afferent component is, in accordance with the common custom, so fine as often to be visible only with difficulty. (In Fig. 8, the hatched lines represent the conjunctival trabeculae and are not to be confused with the hatched lines in Figs. 2 and 3, which represent episcleral vessels.) Thus these intratrabeular loops display

FIG. 8.

Trabeculae, one having an intratrabeular loop.

in miniature a system built on the plan of the grosser conjunctival vessels already drawn in Fig. 2, *viz.*, a centrifugal afferent vessel—which is of very minute calibre—and a larger concomitant easily visible centripetal efferent in which the flow is more leisurely and is easily seen.

The matter, however, cannot quite be left with this simple description. All intratrabeular loops have by no means free ends unconnected with the conjunctival circulation. Fig. 9 is an example of a few types of which there are many. Loops D, F and J have no other connections than those of their limbal attachments. In D and F conjunctival vessels, conveying blood centripetally, pass beneath the trabeculae on their course to the

basal vessels of the limbus-net; these particular vessels at this site lay stereoscopically at about one-third of the depth from the surface of the epithelium to the surface of the fibrous coat. It will readily be seen that casual inspection of F by anyone unaccustomed to this work might lead to the supposition that the main conjunctival vessel is dividing and sending a centripetal branch by way of the trabecula. In B the afferent vessel comes centrifugally along one limb of a Y-shaped trabecula, and emerges at the lower end of the stem of the Y; the returning component of the loop accompanies the other up the stem of the Y, but thereafter takes a course, as drawn, not beneath the trabecula. In G the end of a long intratrabecular loop receives a small afferent conjunctival vessel. In Fig. 10, K explains itself; in M two trabeculae having no vessels are placed between two other trabeculae containing loops between which there is a paratrabecular cross-anastomosis by way of a small vessel lying superficially in the conjunctiva.

(The matter of nomenclature is not simple; the terms "centrifugal" and "centripetal" are used here for convenience of description; obviously they can only be applied to directions radial to the limbus and they could not be used, *e.g.*, in speaking of the loop C in Fig. 17. With a two-way trabecular loop, whose afferent and efferent components are both connected only with the limbus-plexus, it may be convenient to emphasize this fact by speaking of the loop, as a whole, as running "centrifugally" or radially from the limbus out into the conjunctiva, *e.g.*, Fig. 9, D, F and J, and Fig. 16, R and T. But in speaking of either component of the loop these words may be required in reference to the blood-flow in either, *i.e.*, centrifugal for the minute afferent component of the loop and centripetal for the thicker efferent component. It hence may be suggested that these terms "centrifugal" and "centripetal" might be avoided. The use of the two synonymous terms "arterial" and "afferent" has no difficulty, but the use of "venous" and "efferent," for *e.g.*, the thicker centripetal component of these trabecular loops, is not easy if accepting the conception of a "metabolic" system for normal and pathological capillaries which I shall suggest below and of which these centripetal components might reasonably be regarded as being a part. The whole question of these clinically visible circulatory features opens up suggestions for speculative investigation bearing on both the physiological and pathological, but in the absence of prosecution of this it is not possible to be dogmatic about suggested terms. I therefore simply use these different terms according to whichever at the moment happens to be the more convenient for anatomical identity without implied reference to physiological function.)

FIG. 9.

FIG. 10.

Trabeculae and intratrabecular loops. Also (in Fig. 9) basal crypts and sessile loops.

Whilst the course, from the free (more peripheral) end to the attached (limbal) end of the thicker ("centripetal") component of a trabecular loop can usually be traced with ease, it is often difficult to trace the minute afferent centrifugal component. Fig. 11

FIG. 11.

shows a group of four trabeculae. In the first, S, a true intratrabecular loop, C, will be seen pointing in the usual radial direction, and the connection of its thicker efferent component with the limbus-plexus above is very apparent. Near where it runs to this connection a minute accessory loop, D, presents the rather uncommon spectacle of its free end being directed towards, instead of away from, the limbus. R is not vascularized. In B is a typical intratrabecular loop whose central ("efferent") connection with

the limbus-plexus is very apparent. The vascular loop M is a not uncommon feature—in type, not necessarily in actual form. Its two limbs, apparently in trabeculae S and P, respectively, are really applied to the deep part of the trabeculae. The main circulation is conspicuously downward (centrifugal) in the limb beneath the trabecula S, but its connection near C and D is obscured. Careful inspection reveals, near the letter "S" and along the inferior parts, a concomitant minute vessel, too small to allow the direction of its blood-flow to be determined. (It would be more correct to say that its circulation was too rapid and "compact" to be visible.) At U this very fine concomitant vessel takes a loop-like departure for a short distance away from the main loop.

Anastomotic loops of this type which are apparently in, but actually under, trabeculae, and others which are between or otherwise near trabeculae, might be named subtrabecular and paratrabecular loops respectively to distinguish them from the true intratrabecular loops.

Fig. 12 shows a number of trabeculae in the same subject as that of Fig. 11. The distance from G to Q was about 2.5 mm.; most of the trabeculae were about 0.75 to 0.8 mm. in vertical length. The trabeculae labelled E had no vessels; G, K, N and S contained

FIG. 12.

Linear magnification: approximately $\times 36$.

single vessel, but is accompanied by a minute concomitant vessel. A and B are deep episcleral vessels of the anterior ciliary system connected above with the base of the limbus-plexus. The radial vessel M is deep to and not in a trabecula (which is not drawn). The type of loop in P and Q is sometimes seen, but is a little uncommon. A superficial conjunctival connection is established with the apex of the loop in U.

Fig. 13 is from a pigmented subject; the trabeculae were very evident owing to pigment in certain of the basal epithelial cells. (The patient was the subject of many basal epithelial crypts to be referred to later.) The centripetal direction of U is not very common, as compared with the more ordinary pattern; the loops apparently in the trabeculae B and C are not quite in them but

are applied to their deep surfaces. Their connections with deeper radial conjunctival vessels are apparent.

Fig. 14 is from another case. The vascular loop as seen from a point in A, descending from the trabecular region, appears to come down in one of the trabeculae; actually it is under and not

FIG. 14.

in it and it will be noted that its course is not in alignment with the axis of the trabecula. By taking an oblique stereoscopic view it was easily apparent that the vascular loop (V) bore the relationship to the trabecula (T) diagrammatically represented in Fig. 14B which is a sectional plan, E being the surface of the epithelium.

Fig. 15A represents another subtrabecular (not truly intratrabecular) loop, TT. It is in a plane just beneath the trabeculae but it is not very deep in the areolar tissue, being applied to the back of the trabeculae. The portion of the loop X, drawn as though

FIG. 15.

passing sideways, is actually not so much directed thus as backwards towards the limbus-plexus, to which it runs deep down on the face of the fibrous coat. This recession of the portion X, from the more superficial plane of the loop on the back of the trabeculae, is quite easily seen with binocular stereoscopic vision, but cannot be represented satisfactorily in a diagram. This case displayed (Fig. 15B) what is moderately conspicuous in some people, *viz.*, radial tenuous relucant striations (S, S, S, S) deep in the conjunctiva near the limbus and practically lying on the sclera. In this case one such striation corresponded to each trabecula but the figure, as drawn, is purely schematic. One of these striations bifurcated above just beyond the apical point of the trabecula which dips down to its level. They probably represent tissue condensations in the plane of the loose subepithelial conjunctival tissue. This patient acquired chemosis and, as can sometimes be seen in such circumstances, an almost septal, optical and textural condensation (P) of this areolar tissue runs from each trabecula to the deeper tissue in the plane of the radial striation. In this connection, it is interesting to note the relationship, already referred to, of many of the vessels normally radiating from the limbus-plexus into the conjunctiva, *viz.*, that they often follow a subtrabecular course which is in alignment with the trabeculae. V, V, represent portions of faintly evident superficial vascular trabecular loops.

When chemosis elevates the surface of the limbal conjunctiva, it primarily is limited by an attachment on the front of the superficial limbal spur (described later) near the level of the apices of trabeculae when these exist. Should swollen conjunctiva overlap the cornea it does so merely by its gross redundancy overlapping the unaltered limit of this attachment.

The Conjunctival Limbal Vessels

To pursue the matter of the limbus circulation in fuller detail resource may be had to a clinical record (Fig. 16) of a small region of the limbus of a child. I have here omitted some details of the original record in order to clarify the points under discussion at the moment. The portion reproduced is taken from about "8 o'clock" in the left eye. The distance from U to Z was 1.5 mm. The area shown is beyond (above) the region of "7 o'clock" at which well-marked conjunctival trabeculae are seen, but there are two mildly evident trabeculae (not drawn) in each of which the loops R and T respectively run; R runs truly in a trabecula, and T runs not in the superficial part of a trabecula, but is applied to its under surface. The afferent and efferent connections of T are very clearly revealed, the centrifugal afferent being a branch from

the minute deep arterial anterior ciliary vessel a4. The trabeculae become better marked outside the limits of this figure in a downward direction, *i.e.*, towards the lower part of the limbus which is not drawn here. Loops P and H are under faintly marked trabeculae. Loops F and E are by no means quite superficial in the conjunctiva.

To summarize: vessels, commonly very fine, conveying blood from the limbus region, and vessels, usually coarser, conveying blood towards the limbus region, run in the conjunctiva at a variable stereoscopic depth within, say, the superficial half of the distance from the conjunctival surface to the sclera. They may run in concomitant association, in which case the finer component is very easily overlooked; this particularly applies to the minute short loops making very superficial excursions centrifugally into or concomitantly beneath the conjunctival trabeculae.

It may be added that short close afferent-efferent loops connected with the limbus may be found in the absence of trabecular structures. Fig. 17 is an example in a woman, aged 48 years in 1923; the vessels had not altered in 1933. The loop C is 0.3 mm. long and the loop E nearly 0.5 mm. The fine afferent deep arterial vessel "a" supplies blood to the loop C and also to a terminal

FIG. 17.

Linear magnification: approximately $\times 100$.

loop at the corneal border of the limbus-network. The similar type of deep fine arterial vessel "b" supplies a small loop F, then sends a branch which finally supplies the loop E; this branch, on its way, pursues a concomitant course with the vessel D yet has no apparent connection with it.

Thus far an adequate conception is afforded of the vascularization of the ocular conjunctiva, in which it may be that conditions can favour a balance of arterial blood entering the limbus-plexus from the conjunctiva in excess of that given to the conjunctiva by vessels of the limbus-plexus; though this is a point which probably cannot be proved from mere clinical inspection, detailed though it may be, of the complicated architecture of the conjunctival vessels. Thus, probably many vessels follow potential tenuous septal condensations of the loose areolar tissue and many have a truly arterial function. Many of the finest, also taking a subtrabecular course, have come from conjunctival regions in which such free anastomosis has occurred that it is difficult on the sole basis of their morphology to speculate as to the likely character of the blood which they convey to the limbus. Certain relatively straight conjunctival vessels do pass to the limbus, many of them taking a course which passes beneath trabeculae; in some the flow is centripetal, in others centrifugal. Vogt, in describing the "palisade system" as he names it, says that a "palisade (trabecula) as a rule contains a thin blood vessel . . . representing the superficial arterial vessel-way to the rim loop-net (the limbus-plexus)." (I am relying on what has been picked out for me from Vogt's "Atlas" by a translator who tells me that nowhere does Vogt either illustrate or refer to the double character of the small intratrabecular loops.* My own observations were all made years ago without reference to anything that had been previously written and they were then, and are now, approached from an unbiased standpoint.) Anyone not used to this work, seeing Vogt's schematic diagram and its appended description, might interpret his "A: Arteries of the Palisades" as being essentially the arterial supply to the limbus-plexus coming by way of the bulbar conjunctival vessels. The depicting of all intratrabecular vessels as being simple single conjunctival arterial routes to the limbus-net is not in keeping with the double (afferent-efferent) character of these radial looped excursions from the limbus-plexus region towards the conjunctiva; unless some such conception as will be suggested later is accepted in explanation of their morphology. I have purposely selected Fig. 16, among others, for reproduction as an illustration of the

* It should be added that Vogt dealt with the limbus, but practically not at all with the conjunctiva, in his first edition. In his second edition, he deals with the limbus in Volume I, already published, but Volume III, in which the conjunctiva will be dealt with, is not yet published.

limbus-plexus because of the way in which it shows fine afferent conjunctival vessels running up to its conjunctival limbal loops (this figure is from a girl whose limbus I recorded when she was 6 years old; she is now aged 16 years). Fairly well marked trabeculae are found in the inferior region of her limbus and this figure is taken from a portion (at about "7.30 o'clock") just above this area so that there are only inconspicuous trabeculae in the lower half of the figure, from the loop H downward, while none exist above the level of the loop H. The connections of the loop T have already been described. As regards the loop P, its bifurcated end Q, PP, has no apparent accessory conjunctival vascular connection. As we go to the loops higher up we find evidence of an afferent conjunctival connection with them. Thus it would look as if the very fine centripetal conjunctival vessel L might, at the limbus, join an afferent (centrifugal) component of the loop K; the possibility cannot be denied that L might, at the limbus, even turn centrifugally back in its course to constitute the only afferent vessel to the loop K. In the case of the loop H it appeared at first sight very much as though its afferent supply were solely from the centripetal conjunctival vessel J, but it was ascertained definitely that J joins a fine normal afferent anterior ciliary component of the loop HH, on the deep side of this loop, which, therefore, has a double source of afferent supply, *viz.*, conjunctival (from J) and limbal episcleral; I have not drawn the origin of the latter in this figure as it is immediately beneath and parallel with the portion of the efferent component adjoining the upper letter "H." It will be noted that the afferent channel J springs from the apex of a conjunctival loop b—bj, on the developmental principle illustrated in Fig. 7, and this type of architecture is strongly indicative of a centripetal arterial circulation in J. If reference is made again to Fig. 6 it will be recalled that a loop TOW, at the limbus, is seen to establish conjunctival connections at its free end; one of these, P, conveys blood centrifugally from the loop, and the other, K, the direction of whose blood-flow is not recorded, can be regarded as capable of transmitting a flow in either direction. In the region of vessel E, Fig. 16, there was a complication of minute conjunctival connections which was not easy to unravel because they were so fine; lying beneath vessel E is a very minute afferent-efferent loop EB coming radially from the limbus, and giving off a terminal fine continuation branch. Blood from a superficial conjunctival vessel CC may enter the loop C, by way of CE, unless the blood in CE, whose direction was not visible, flowed in the opposite direction. In either event it will be noted that CE is of the same diameter as, and joins, the thick centripetal component of the loop C.

In the example of Fig. 9, G, the small centripetal vessel going

to the trabecular loop might have been an instance of a dominating direct flow from the fornix below, or of a capillary from a complex intermediate conjunctival anastomosis, or of an arterial twig which, having taken origin from the limbus-plexus and passed down into the conjunctiva beneath some neighbouring trabecula has then turned round in its course back towards the limbus to join the end of the loop G. The notes from which I have taken this example do not record the origin of this small vessel.

So, of these adventitious small vessels joining some of the trabecular and paratrabecular loops some (*e.g.*, J, Fig. 16) may apparently be "arterial," while others (*e.g.*, CE, Fig. 16) may apparently be "venous," if they are considered merely from the morphological point of view of relative diameters.

It might be said that from what is revealed by Fig. 16, the connections apparently established by such loops as K, L, and H, J, and possibly also F, E and C, do indicate that, in this instance, these loops are drawing an appreciable blood-supply from conjunctival blood going towards the limbus. Such connections as these seem more prone to be established with these loops in the regions above the inferior area ("4.30 to 7.30 o'clock") in which well-marked trabeculae and intratrabecular loops occur. Even so, *Fig. 18, from another subject, may be considered; it is at about "4.30 or 5 o'clock" on the limbus, and shows a complete close conjunctival loop, T, following a faint trabecula and, nearly parallel with it, the efferent return channel, O, of a rather complicated conjunctival loop. (The double nature of the end t' of the loop T, is formed by the combination of the arterial and efferent components; but the "ring" M is merely a two-way splitting of the path of the vessel.) In this figure the loop B comes from one of the episcleral arteries, as also does the loop U by bifurcation of an episcleral artery at V; the fine superficial conjunctival artery W is also from one of the finer arterial anterior-ciliary elements of the limbus-plexus region. The dotted line indicates an area of the conjunctiva omitted from the drawing to economise space; the vessels BC and U in particular, also W, run nearly down to the fornix, BC and U being essentially the "arterial" direct purposeful type of vessel just beneath the surface of the conjunctiva already described in Fig. 3, R1, N, and particularly in Fig. 6, F. The flow in all the three arterial vessels BC, W and U, of Fig. 18, is from the limbus towards the fornix. In the region C, not far from the fornix, the artery B divides into two vessels supplying arterial blood to the conjunctiva and it will be noted how these are joined by the vessels D', D'', of the same type, but finer, bringing arterial blood from the fornix-region. In this case we have a clear example of the derivation of the arterial supply to two limbal conjunctival loops, Tt' and JKLMNO, from the vessels of the limbal episcleral system, and, in addition, of a dominating afferent-

* Fig. 18 will appear with the second portion of the paper, in the next issue.

effluent flow in the conjunctiva, right down to near the fornix, also derived from the episcleral vessels of the limbal region (compare also Fig. 5U).

As a further instance of the difficulty, in the case of many of the vessels of the bulbar conjunctiva, of distinguishing physiologically between "artery" and "vein" on the ordinary functional and morphological bases, reference may be made to RR, Fig. 18. This vessel springs from a fine artery W, already described as originating from an episcleral anterior ciliary artery of the limbus-plexus; it runs centripetally towards the limbus and, though receiving no tributaries, its diameter increases to that of a "vein" well before it joins SS', but where it joins SS' it gives off a constricted onward continuation Q which in turn again soon dilates more to the size of a "vein" by the time it receives the effluent channel, N, coming back from a loop already referred to. It would seem permissible to look upon RR as equivalent to a "loop" whose two constituents are opened out instead of being folded into mutual apposition; but the vessel Q, though similar morphologically to the vessel R, derives its blood from a source which has already become "venous" if this word is to be related essentially to calibre of the vessel. Similar gradual dilatation in the course of a fine conjunctival vessel joining the limbus-plexus will be seen at EE—E, near the top of Fig. 16. I think that questions of this nature are better comprehended if the conception of a "metabolic" system (referred to below) is accepted.

I suggest that the loops of the trabeculae—and similar short loops existing near the limbus in the absence of trabeculae—can be regarded as afferent-effluent looped out-shoots fundamentally from the vessels of the limbus-region in the form of reduced counterparts of the larger arterio-"venous" conjunctival loops of the type illustrated in Figs. 2 and 3.

Basal Crypts and Sessile Loops at the Limbus

A further feature of interest soon became apparent in the clinical study of the limbus, *viz.*, in some persons there are few, or many, little spherical crypts stereoscopically deep to the surface of the epithelium and on a plane superficial to the limbal network in front of which they lie. They are easily seen. They have the same optical properties as the trabeculae and are usually situated just on the corneal side of the apices of the trabeculae and sometimes between their corneal ends. Some of these contain, exactly in their centre, a little red stem springing from the limbus-network clearly pointing towards the observer much as a finger might appear were it dipped in red paint and stuck into the middle of a jelly contained in a round glass cup through the bottom of which the observer was looking. At first sight it appeared odd to see these little red vascular

stumps sticking forward with stereoscopic clarity from the flat limbus-plexus, like cut off stumpy twigs seen on end and having no apparent superficial terminal connection; but it was soon clear that each is a compact loop whose afferent (arterial) component can be seen only on careful scrutiny and often not at all because it is very fine and is too closely associated with the efferent component which is much thicker and mainly contributes to the visibility of these stump-like sessile loops. I have suggested naming these spherical structures, many of which are thus axially vascularized, the "*basal epithelial crypts of the limbus*" as they clearly are a contour-formation of the basal layer of the epithelial cells. A diagrammatic example of them is shown in Fig. 9, C and E. Their average diameter is about 1/40th to 1/15th millimetre. (Sometimes, as with the trabeculae also, pigment in the cells may make these features conspicuous). I occasionally saw a few measuring up to 1/7th millimetre in coloured patients in my classes in Philadelphia and New York in 1925.

These little sessile forwardly directed loops may exist in many people who have no visible crypts, just as (*e.g.*, Fig. 17) tangential loops not so short may repose beneath the epithelium of the limbal conjunctiva in persons who have no visible trabeculae. Sometimes in elderly plethoric people with "irritable" red eyes these little sessile stumps are engorged so as to form numerous fairly conspicuous small red spots. In connection with the clinical finding of these sessile loops, it is interesting to recall the histological characteristics of the epithelium of this region, *viz.*, that, instead of consisting of three layers of cells as over the bulbar conjunctiva, it here comprises some 10 layers and whilst its aerial surface is smooth, the deep face of the limbal epithelium is indented and contoured in a manner somewhat reminiscent, as I have ascertained from Dr. S. Watson Smith, of the basal-papillary zone of the skin.

As has been considered so far, there is thus a main aggregation of vessels at the limbus-region from which two-way loops, open or closed, radiate into the system of the bulbar conjunctiva, the shorter and finer running within, or intimately close under, the conjunctival trabeculae when these structures exist. The shortest loops, running flat beneath the surface, may enter very short trabeculae of the type illustrated in Fig. 9, A and J. Finally, these two-way loops may become so short as to form little sessile "stumps" perpendicular to the surface under the irregularly contoured deep face of the limbal epithelium.

Sufficient evidence has now been given to justify a full simplified classification, in principle, of the vessels of the bulbar conjunctiva: (a) Afferent-efferent loops of varying length and complexity and having basal connection with either the fornix-region or the limbus-region, those in the latter region attaining a somewhat

FIG. 19.

specialized morphology. (b) Mainly conducting channels—especially from the fornix towards the limbus, but also from the limbus towards the fornix—of blood which is fundamentally arterial; these, in their course, usually effect anastomoses with the “metabolic” vessels of the bulbar conjunctiva. A third group (c) for certain of the conjunctival vessels may here be considered, *viz.*, some of those of medium or major size may be looked upon as anastomotic loops or “bonds” connecting, *e.g.*, the vascular system of the fornix region with that of the episcleral (anterior ciliary) limbal region, their function on their way across the conjunctiva being to give branches to, or receive tributaries from, the conjunctival circulation, if not also to provide channels through which adjustments and variations in the mutual vascular pressure relationships of these parts may be facilitated in various circumstances.

To illustrate this, I give one more figure (19) at the risk of being tedious. (I have, in error, had the block of this figure made from a diagram which is incomplete before realizing that, stored away, I had, from the same subject, another which is more accurate and includes fuller details. The reader might with advantage pencil in a line to represent a coarse *episcleral* vessel, starting in the top left corner below the limbal episcleral tributaries at about 8 or 9 o'clock and running concentrically with the limbus to, say, the letter U (which is drawn a little too near the limbus)—so that the vessel TU joins it here—shortly after which it turns abruptly south and, gradually increasing in diameter, goes to the fornix, still as a big, deep (episcleral) vessel, passing deep to the vessels F, O and G; the blood in the part of this omitted vessel concentric with the limbus flowed east and it can, therefore, be presumed that it continued south in its stouter vertical continuation (not depicted) running south to the limbus). Let the thin vessel MNOR be considered, with its branch P (which has been drawn carelessly at its origin, just where it leaves the main thin vessel MN; it passed under, and was not connected with, the branch H of the thick vessel ABC, whereas in the drawing it appears to make a connection with H; moreover at its first crossing with the thick vessel B, just after it passes under H, it should cross superficial and not deep to B—with which it has no connection). Clearly, MA is suggestive of a primary long afferent-efferent loop dividing into two loops NHJK and CPDQ, of which the former, *via* LOGR, establishes a major anastomosis in the fornix region. A rather insignificant arterial branch is given off to the conjunctiva just above the letter “M.” The arterial branch, P, has an insignificant anastomotic destination down at QQ', except that there is, again, an omission from this drawing in that the small branch leading south-west from the crossing Q' should be a thin single vessel springing from the afferent (thin) component just below this crossing and running across, with diameter gradually increasing slightly, to join the main “vein” at the letter F (the reader should correct the figure in this respect). In the arterial branch P, leading to the arterial component of the loops Q, Q', and thence, *via* the branch (omitted) from Q' to F and into the “vein” FG, the flow was always south. When the direction of flow in the arterial component of the sector “M” was actively south, then the flow in N—O was also south whence it presumably passed west in OR; but when, as was often the case, the flow was copiously north in O—N, then it would turn abruptly south into P, while in the sector M it would either be stationary or would go only feebly south. Thus, RONM constitutes an arterial “bond” which, on its way across, gives off mainly the branch P whose blood is destined for tributaries passing mainly south into the venous channel G.

The vessel VRSTU was interesting. It was not observed to give off a single branch from R to U; its destination at or near U has been described above as joining a large main episcleral vessel going south. The portion VR was almost certainly arterial. But although this eye was frequently examined (during the course of treatment) the blood in RSTU was usually in a state of oscillatory (cardio-vascular) equipoise, the northward constituent of each oscillation having the “kick” or “punch” in it.

Reference to Fig. 3 will show that the vascular line R1RKN5 is an arterial

"bond" in so far as there is an anastomotic cross-communication at K, fine though this be.

The vessel ABCDEFG, Fig. 19, looks "venous" in character, especially at G in the fornix. This "bond" receives the conjunctival tributaries, X, Y, Z, as well as the efferent component of the loop QQ'. Now up to a point the portion ACDQQ', being accompanied by a thin concomitant M, and its branch P, may be considered as an afferent-efferent loop based on the limbus region, and such it would functionally be if the direction of the blood flow in A were always northward, as it often was. But it so happened that on other occasions the flow was noted to be southward in A. Now the direction was never noted to be other than southward in H, no matter which way—north or south—the blood flowed in the sector AB. If the blood flowed south in AB, it also flowed south in C, D and E, and presumably also in F and G—though down here the vessel was too thick for the direction of its compact flow to be visible. When, however, the flow was northward in BA, it was south in CDE (to F), the point of disjunction of the two directions being that where the tributary X ran in. (It is a very common functional feature of conjunctival vascular architecture that the flow in a vessel takes place in two opposite directions from the point of union of a small tributary with it: see Fig. 5B). At other times the flow would be north not only in B and A, but—the southward direction in the tributary X still being unchanged—also north in C; in this case the point at which the coincident main southward flow began was that of union of the tributary Y. Hence, this channel, ABCDEFG, from limbus to fornix, though in some respects functioning as part of a potential loop system, can also be regarded as merely a "bond" joining the circulation of the limbus region with that of the fornix region and receiving, on its way across, venous conjunctival tributaries, such as X and Y. If the lower, i.e., more peripheral part of the limbus-plexus which it joins is to be regarded as purely "venous," then the whole vessel ABCDEFG is a venous "bond" between the limbus and the fornix; but if this part of the limbus-plexus conveys, as will be suggested later, blood which is not purely venous, then the upper portion of this long "bond" vessel can, when it is conveying blood northward, perhaps, be regarded as being specialized for the oxygenating function which will be suggested presently.

It will thus be seen, from both Figs. 6 and 19, that both features—afferent-efferent loops based on the fornix or limbus, and "bonds" joining corresponding systems at the limbus and fornix with one another—are functionally related and often may, in fact, be practically synonymous one with the other.

(To be continued)

ALL-INDIA OPHTHALMOLOGICAL SOCIETY, ANNUAL CONGRESS, 1933

THE third conference of the All-India Ophthalmological Society was held in Calcutta, from the 19th to the 21st December, 1933. The attendance was the largest on record and was well supported by delegates from all parts of India. Dr. A. Fuchs from Vienna and other visitors attended the Conference.

The Conference was formally opened by Sir HASSAN SUHRAWARDY, M.D., F.R.C.S.I., Vice-Chancellor of Calcutta University. He spoke of the absence of facilities for ophthalmological work in India and regretted that this vast country was still very backward