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OUTFLOW

I

The Retinal Circulation

If it is to serve its function as the organ of vision, the eye must have sufficient rigidity to maintain a clearly focused image, sufficient strength to survive significant trauma and a sufficiently low rotational inertia to facilitate rapid and accurately controlled movements. These specifications are met with a tough, inelastic fluid filled sphere. Since the tissues within the eye are metabolically active, they require nourishment, hence the inflow of fluid. The fluid that enters the eye must also drain from it, and into a tissue environment whose pressure is lower than that of the eye. This circumstance defines an important problem in ocular biophysics: how fluid may escape from the eye in so controlled a fashion that the reservoirs essential to the integrity of the eye should not be emptied in the process. Glaucoma, both in its genesis as an impairment of aqueous outflow and in its consequence of optic excavation and atrophy, is a disease that reflects the imperfect solution to this problem. A control mechanism for outflow is not unique to the aqueous circulation. Drainage of blood from the retina and the choroid is similarly controlled. Perhaps if we can gain some understanding of these latter, more readily observable circulations, we will have a better idea of the nature of outflow obstruction in glaucoma.

The three circulations all have the same origin and the same destination. They all arise from the arterial blood stream in the ophthalmic artery, and they all drain into the venous bed of the ophthalmic vein. The central retinal artery branches from the ophthalmic artery within the substance of the optic nerve, but the choroidal and aqueous circulations share the ciliary arteries as a common pathway to the capillaries of the ciliary body, at which point the aqueous is discharged into the vitreous cavity. Since the similarities between the outflow mechanisms of these three circulations are inapparent, we shall review them in greater detail.

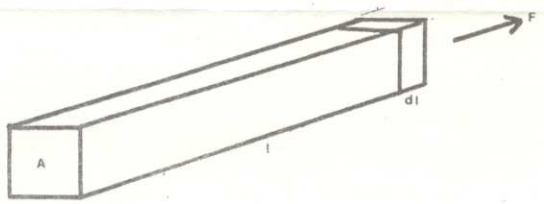

FIGURE 1 - When a force F is applied to a solid, such as a rubber band, of length l and cross-section A, which is tethered at one end, there is induced in the solid a stress equal to F/A. As a result of this stress, the solid expands by some small amount dl. The stress F/A divided by the fractional increase of deformation dl/l is called Young's modulus, and the fact that for small amounts of deformation it is a constant is a rule known as Hooke's law. At the same time that the solid expands in the direction in which the force is applied, it contracts laterally. The ratio of these two deformations is called Poisson's ratio. For example, Young's moduli for rubber, aluminum and steel are .0001, 7 and 22 all as 10e+11 dynes/sq. cm. respectively, and the corresponding Poisson's ratios are .49, .13 and .28. (Handbook of Physics, Condon and Odishaw, N.Y. 1958)

It is the retinal circulation which is most easily studied. One needs only an ophthalmoscope to observe the pattern of arteries and veins on the disc and in the retina. Fluorescein angiography provides additional insight, but in the decade that it has been in use, it has received no systematic fluid dynamic interpretation, a circumstance which is not surprising, if one considers that through more than a century of ophthalmoscopic observations their implications in terms of fluid mechanics have been largely ignored.

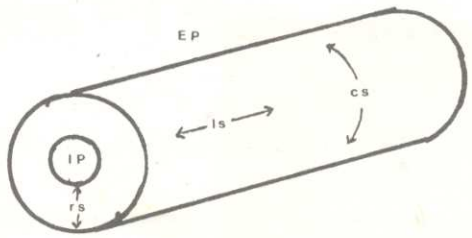

FIGURE 2 - This cylinder serves as a model for a blood vessel. IP, the intravascular pressure is equal to the arterial, capillary or venous pressure as the case might be. EP is the external pressure and, if the blood vessel is within the globe, is equal to the intraocular pressure. A pressure is a force acting in a fluid and is transmitted equally in all directions. A stress is a force within a solid and its effect depends upon the shape of the solid. The pressure differential EP - IP induces stresses in the cylinder which are conveniently described as radial stress rs, circumferential cs, and longitudinal ls. If IP is greater than EP, the radial stress will be compressive and the wall of the cylinder will become thinner as IP increases, while the circumferential and longitudinal stresses will be tensile, tending to expand and to lengthen the cylinder.

Let us in our imagination accompany a small quantity of blood as it courses from the ophthalmic artery into the eye. The relative thinness of the arterial wall reflects the circumstance that it is supported externally by the intraocular pressure. The stresses that arise in the vessel wall are induced by the difference between the extravascular and the intravascular pressures, a fact from which one might infer that the glaucomatous eye with poorly controlled intraocular pressure might be less susceptible to the ravages of arterial hypertension. This surmise from the armchair, to my knowledge, is still awaiting clinical investigation. An increase in intraocular pressure has little if any effect on the pressure gradient across the walls of capillaries or veins because as intraocular pressure rises or falls so does the pressure in the veins, and to a lesser extent in the capillaries, so that the difference between intravascular and extravascular pressure of these vessels remains approximately unchanged. Palpation of the carotid arteries in the neck demonstrates how pulsatile flow rhythmically distends the elastic media of the arterial wall. It is easily confirmed with ophthalmodynamometry that at least in the large arteries within the globe this pulsatile flow persists. If pulsation is not visible, this fact must mean that the elastic modulus of the arterial wall is sufficiently great that the stresses which the arterial pulse induces in the arterial wall lead to no visible displacement of tissue.

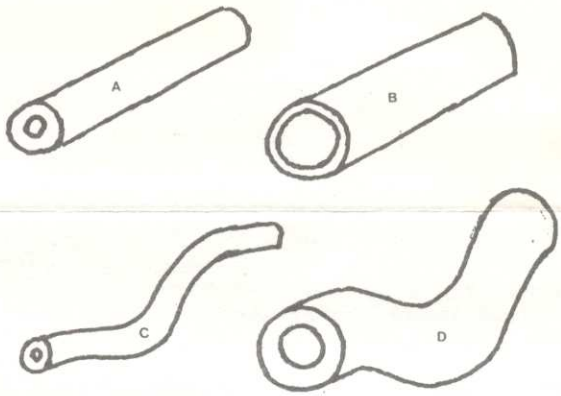

FIGURE 3 - The deformation sustained by an elastic cylinder under increased internal pressure IP will depend not only on Young's modulus and Poisson's ratio but also on whether it is isotropic or anisotropic. Isotropia and anisotropia are terms used to designate respectively equality and inequality of coefficients of elasticity in the three spatial dimensions. An elastic cylinder A) which is tethered at both ends and subjected to increased internal pressure may, depending on the relative values of its elastic moduli in the radial, circumferential and longitudinal dimensions sustain B) dilation only, C) elongation with narrowing of the lumen, or D) dilation and elongation combined. Because its ends are tethered, elongation makes the cylinder tortuous.

An increase in intravascular pressure also brings about increased stresses in the vessel wall parallel to the direction of flow. The effect of these stresses depends upon the relative value of the circumferential and longitudinal elastic moduli. Whereas the metallic vessels considered in engineering are isotropic, their circumferential and longitudinal elastic moduli being equal, isotropy is hardly to be expected in blood vessels, each of whose multiple layers is composed of different cells with different geometric orientations. If the elastic modulus of the vessel wall parallel to the axis of flow is relatively low as compared with that at right angles, then with an increase in intravascular pressure, one

might expect not a dilation but a constriction of the lumen. This physical fact should be considered as a partial explanation for the progressive nature of vascular hypertension. Thus when increased pressure in the retinal arteries is the result of systemic hypertension, one observes constriction of the vessel rather than dilation to accompany its tortuous lengthening. A different set of circumstances obtains, however, if there is an occlusion of the central retinal vein or one of its branches. The blockage of flow will bring about an increase of the intravenous and intracapillary pressures to approach the value of the arterial pressure as a limit. The consequence of this fluid dynamic change is dramatic and is easily observed with the ophthalmoscope. The increased stress that is perpendicular to the axis of flow leads to dilation of the vessels. The veins become engorged, while the capillaries assume an irregularly contoured dilatation to which the adjective telangiectatic is sometimes applied. There is often lengthening of retinal veins upstream from the site of partial occlusion. Such veins, being tethered at intervals and therefore unable to expand longitudinally, become tortuous. The veins thus elongated do not become narrow because the circumferential stresses induced by lengthening, which tend to constrict the vessel lumen, are more than offset by opposing stresses that tend to cause dilation of the vessel.

The pressure in the retinal veins, as is well understood, is transmitted from the arterial tree through the capillaries. Upstream from the disc, the venous pressure is slightly higher than intraocular pressure. Downstream from the disc, it is low, approximating the negligible venous pressure of the other cephalic veins. It is on the disc itself that there occurs, visible to the ophthalmoscope as a collapse in the vessel wall, a precipitous drop in the venous pressure. This biologic pressure-reducing valve is able to compensate not only for fluctuations in the intraocular pressure, but also to a large extent for variations in the flow rate. If, however, as a result of partial arterial or arteriolar obstruction, the flow rate diminishes beneath a critical point, then the discharge from the capillaries will no longer be able to distend the veins, the large veins of the entire fundus collapse, and as they do so, their cross-section changes. They become more and more elliptical until, just before flow ceases entirely, they take the shape of a broad thin ribbon. The orientation of this ribbon determines how the collapsed vein appears through the ophthalmoscope. If the edge of the ribbon faces the observer, it looks like a narrow thread. If its breadth faces him, it appears as a broad band, which is often misinterpreted as congestion whereas just the opposite is the case.

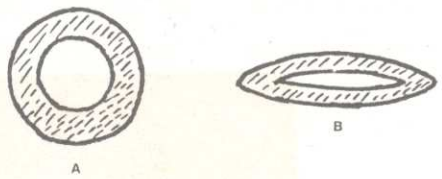

FIGURE 4 - The vein at A is normally distended with blood forced into it from the capillary bed. The vein at B is partially collapsed because the rate of flow is insufficient to keep it distended. Such partial collapse occurs when there is arteriosclerotic narrowing of the carotid, ophthalmic or retinal arteries and in hypertensive small vessel disease. As the vein collapses the area of its cross-section decreases but the circumference remains unchanged. If as is usually the case, the long axis of the collapsed vein is parallel to the surface of the globe, the vein, although it in fact contains less blood, will appear wider. A totally collapsed vein is 1.57 times as wide as a fully distended vein. An increased ratio of the width of the vein to that of the accompanying artery has long been recognized as a sign of arteriosclerotic disease but the explanation that such widened veins are not distended but flattened, and that the widening reflects a decrease in the flow rate, has not, to my knowledge, appeared in the literature. Infrequently the vein collapses with its long axis radial to the globe. It then appears narrow to the point of being thread-like.

In general, when the vein collapses from intraocular pressure in the face of insufficient filling, it forms a ribbon whose breadth is tangential to the globe. This circumstance is the primary cause of the increased V/A ratio long recognized as a stigma of arteriosclerotic and hypertensive vascular disease. In that condition, not enough blood is transmitted through the capillary bed to keep the cross-section of the vein circular. Instead, it becomes elliptical, and the major axis of the ellipse is seen as a broadening of the vein. It represents not, as one might assume, an increase, but a decrease in volume.

At A-V crossings, however, the vein is bound to the artery by a common sheath of adventitia. A collapse of the vein in a plane tangential to the globe would entail a sharp outward deflection of the overlying artery. Perhaps the artery is too stiff to permit such a deflection. In

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any event, it is the failure of the vein to flatten in the tangential plane that creates the appearance of relative constriction at the A-V crossing. Sometimes radially oriented collapse occurs at the A-V crossing. Then the narrow side of the band only is visible to the observer, giving the vein the appearance of having been choked off by the artery. Paradoxically, flattening of the vein is not likely to be associated with permanent occlusion. So long as only a small fraction of the total flow resistance is attributable to the collapsed vein, the velocity of flow will be approximately inversely proportional to its cross-section. The smaller the vessel lumen, the greater the velocity of flow at any given point. Thus, so long as flow is not entirely stopped, one would not expect vein collapse to predispose to thrombus formation. On the contrary, if the vein were held open by a rigid frame that prevented it from collapsing, as is probably the case at some A-V crossings, then with decreasing flow, there would develop in the vein just under the artery a pool of stagnant blood to serve as a nidus for thrombus formation. And it seems indeed to be the case that the occlusive thrombus of branch vein occlusion often propagates from just this point.

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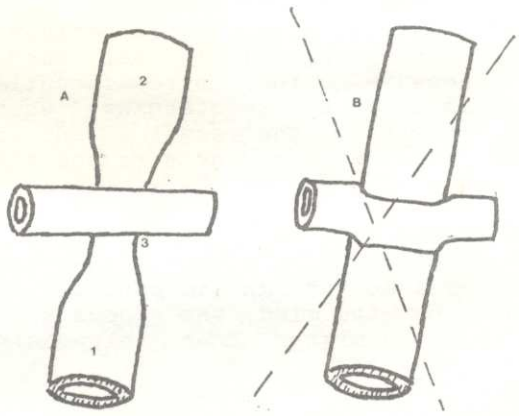

FIGURE 5 - At points 1 and 2 the vein A is collapsed from lack of flow. As it passes under the artery at 3, the vein seems to be constricted, a phenomenon referred to as A-V nicking. It occurs because the anatomic relationships at the point where the artery crosses the vein prevent the tangentially oriented collapse of the vein. Such collapse, if it occurred, would require a sharp deflection of the artery, as in B. Instead, radially oriented collapse may occur. Alternatively, stiffness of the artery combined with stiffness of the enveloping fibrous tissue may so impede the collapse of the vein at the crossing as to create a dead space of relatively stagnant blood. Such stagnation explains the branch vein occlusions that begin at A-V crossings. A vein crossing over rather than under the artery will not exhibit A-V nicking because in that location collapse of the vein can and does occur without deflection of the artery.