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# Functional Anatomy of the Choroidal Circulation: Methyl Methacrylate Casting of Human Choroid

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**Summary**
**The functional anatomy of the normal choroidal circulation in man is described from scanning electron microscopic examination of methyl methacrylate microvascular casts. Distal and para-optic short posterior ciliary arteries supply wedge-shaped areas of choroid. Regional variations in choriocapillary morphology are well recognised; the lobules are densely packed at the posterior pole with a high capillary to inter-capillary ratio. Choroidal capillaries are flattened providing a large surface area for metabolic exchange with the retinal pigment epithelium. In acute choroidal ischaemia (from a variety of systemic disease), wedge shaped choroidal lesions may correspond to occlusion of short posterior ciliary arteries and geographic or focal lesions to occlusion of choroidal arterioles or choriocapillary lobules.**

Several techniques have been employed to define the anatomy of the choroidal circulation and its supply in man, including dissection,[1-3] histology,[4] indian ink injections,[5] flat preparations,[6-9] and neoprene latex casts.[5,10-13] From examination of earlier casts using neoprene latex[11],[12] the choroid was regarded as highly anastomotic with little potential for ischaemia occurring. This was contrary to both early and more recent interpretation of findings based on clinical[14-26] and experimental[27-35] evidence. Techniques including clearing,[36] Roentgen ray imaging[37] and methylmethacrylate vascular casting[38-41] have since added to our understanding of the functional anatomy of the choroid. The purpose of this paper is to elaborate on the arrangement of the vasculature and identify its relevance to acute choroidal ischaemia.

## Methods

The anatomy of the choroidal circulation was examined from methyl methacrylate microvascular casts prepared according to standard methods.[42] The entire orbital contents and intracavernous part of the internal carotid artery were exenterated at autopsy 36–48 hours post mortem (preserving the lids *in situ*). The ophthalmic artery was canulated. Primary infusion of phosphate buffered saline (PBS) was followed by gluteraldehyde 0.5% in PBS, at infusion pressures of 120–175 mmHg at physiological temperatures. Casting was achieved by secondary perfusation with 25–50 mls thinned methyl methacrylate resin (using a base of Batson's no.17, Polysciences) injected under manometric control until the resin hardened (7–10 minutes). The surrounding tissue was corroded in six Molar potassium hydroxide which was changed regularly and the casts washed in distilled water and air dried. The casts were gold sputter coated (50 nm) and dissected appropriately to include examination of the choroid. Ocular casts were examined by the scanning electron microscope (Hitachi S-520, Tokyo, Japan) either whole or as dissected fragments mounted on an aluminium stub, at 20 kv and magnifications of ×22 to ×1.3k.

## Results

The main findings are illustrated in Figures

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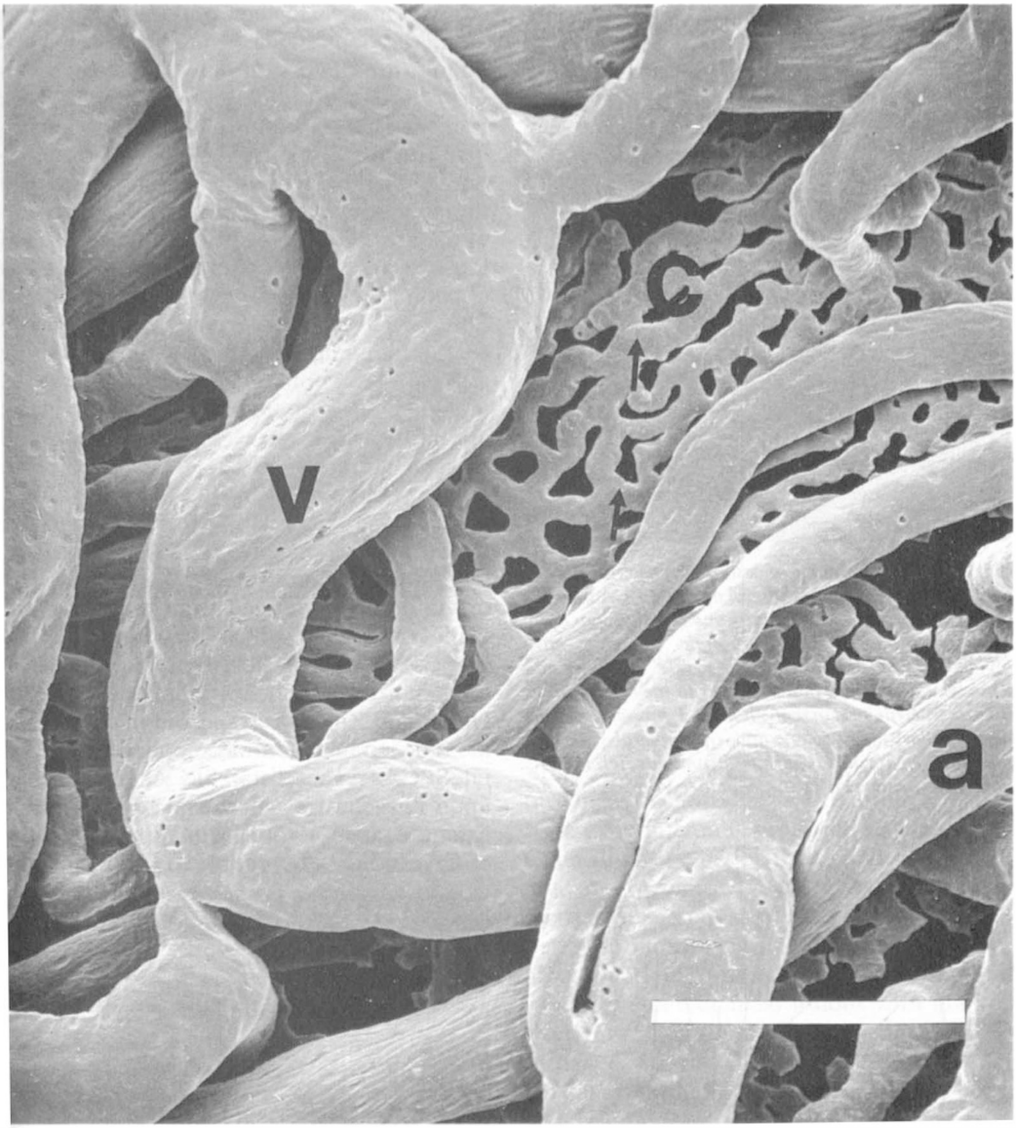


**Fig. 1.** *Scanning electron photomicrograph of cast of choroidal vasculature viewed from the sclerad side showing venules (v) (with oval endothelial nuclear impressions) draining choriocapillary lobules, arterioles (a) (with elongated endothelial nuclear impressions) and choriocapillaris (c) (with small oval endothelial nuclear impressions, arrows). Bar=231 μm.*

1–5, based on compilations from 21 ocular vacular casts. Arteries and veins were differentiated by the appearance of the endothelial nuclear impressions on the surface of the intra-lumenal vascular casts (Fig. 1). Endothelial nuclear impressions were noted on the outer surface of the choriocapillaries cast (sclerad surface) but not the inner surface (retinal aspect) towards the retinal pigment epithelium.

The short posterior ciliary arteries (SPCAs) were formed by second and third order divisions of the posterior ciliary arteries (PCAs) originating from the ophthalmic artery. The SPCAs were grouped usually in two bundles (temporal and medial) close to the posterior

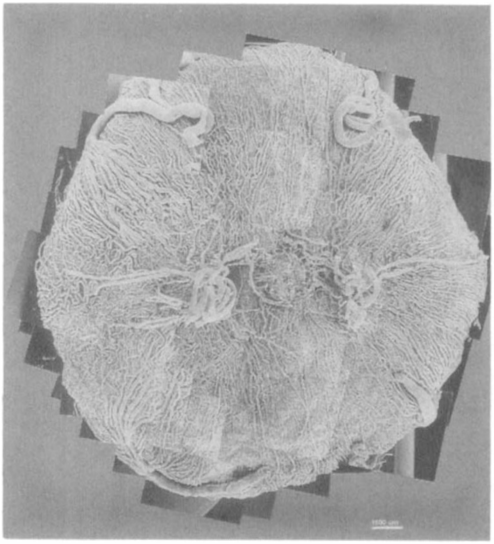

**Fig. 2a.** *Photomontage of cast of the posterior pole of a left eye showing temporal and medial SPCA bundles supplying choroidal vasculature and retrolaminar optic nerve vasculature. The para-optic branches have divided on each side to form the 'circle' of Haller and Zinn which provides pial branches to the retrolaminar optic nerve and recurrent choroidal branches to the peri-papillary choroid and peripheral vertical meridional choroid. The lateral and medial LPCAs have been truncated at the equator. Vortex veins are clearly seen.*

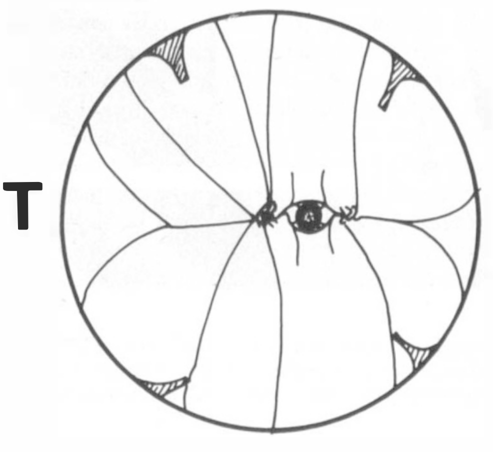


**Fig. 2b.** *Diagrammatic representation of above montage of left eye showing gross division of the choroid into triangular and trapezoid areas supplied by the SPCAs. T=temporal.*

aspect of the globe at a short distance from the optic nerve (Fig. 2).

The distance from the edge of the posterior scleral foramen to the temporal bundle was greater than to the nasal bundle. Within each bundle the SPCAs sub-divided further into distal branches and a smaller para-optic branch. This division occurred more posteriorly (further away from globe) in the temporal bundle than in the nasal bundle and therefore was more readily identifiable in the temporal bundle. The more numerous and larger distal SPCAs supplied triangular areas of choroid temporally and nasally. The distal SPCAs entered the sclera at right angles close to their bundle of origin before radiating towards the periphery. The triangular shaped areas of choroid supplied by the distal SPCAs are illustrated in Figure 2. The apices of the triangular areas were posterior close to the point of entry of each SPCA from the temporal and nasal bundles. The smaller and less numerous para-optic SPCAs supplied the vertical and peripapillary choroid, either directly or via branches derived from the 'Circle' of Haller and Zinn which they formed. The shape of the area of choroid supplied by recurrent choroidal branches from the circle of Haller and Zinn was trapezoid in contrast to the more triangular areas supplied by the distal SPCAs. The distal SPCAs encroached upon the vertical meridian to a variable extent. Branches from the undersurface of the SPCAs in the outer choroidal layer (Haller's

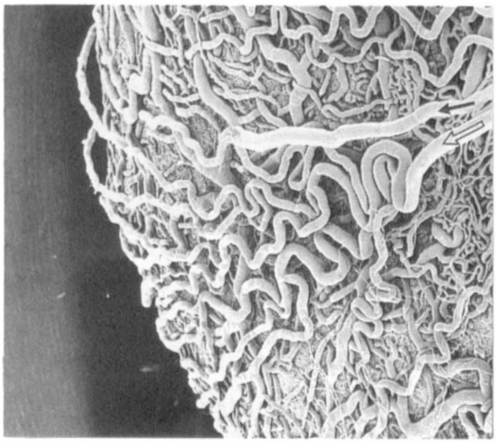

**Fig. 2c.** *Detail from temporal part of montage showing recurrent choroidal branch (empty arrow) of lateral LPCA radiating out to supply a triangular shaped area of choroid. Lateral LPCA (black arrow) continues around the globe but has been truncated in this specimen. Note dense vasculature at macular on right.*

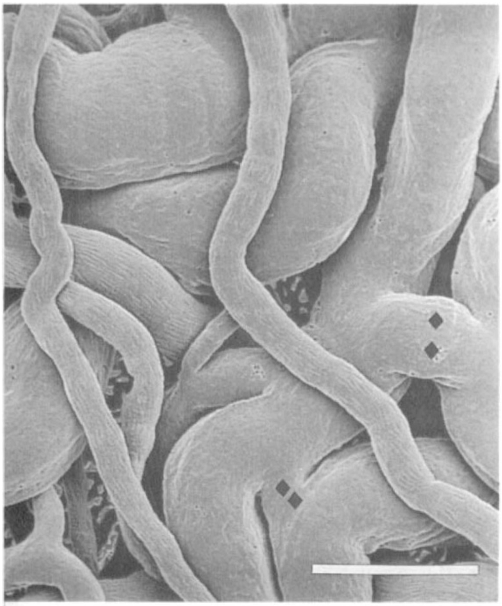

**Fig. 3.** *Dense choroidal vasculature at posterior pole close to fovea. Inter-venous anastomoses demonstrated (black diamonds). Sclerad surface of choriocapillaris just visible. Bar=270 μm.*

layer) gave rise to choroidal arterioles in the intermediate layer (Sattler's layer).

The long posterior ciliary arteries (LPCAs) arose directly from distal SPCAs. The distal SPCA forming the lateral LPCA consistently supplied a recurrent branch towards the posterior pole whereas the medial LPCA continued directly around the globe, without a branch to the posterior pole. Recurrent choroidal arteries from the anterior segment (branches of the LPCAs, of intra-muscular arteries and from vertical anterior ciliary arteries) contributed to the supply of the anterior choroid. Inter-capillary and inter-arteriolar anastomoses were noted rarely, predominantly in the vertical meridian, between the anterior and posterior uvea. Small inter-arteriolar anastomoses and inter-venular anastomoses were encountered at the posterior pole (Fig. 3) but not arteriolar-venular anastomoses.

Terminal choroidal arterioles supplied the choriocapillaris. At the posterior pole the lobular appearance of the choroid was only readily apparent on closer inspection (Fig. 4a); lobules were small, densely packed and several small choroidal arterioles could supply a single lobule entering at right angles to the plane of the choriocapillaris. The lobular pattern of the choriocapillaris became more evident towards the equator (Fig. 4b) and periphery (Fig. 4c) where the lobules were progressively larger, radially elongated and with arteriolar and venular components found in the same plane as the choriocapillaris. In addition, the diameters of the capillary casts increased towards the periphery, with corresponding wider and progressively more elongated intercapillary spaces (see Table I). The choroidal capillaries were flattened antero-posteriorly having an elliptical cross section (Figs. 5a, b) and although the diameters of choroidal capillary lumens varied, their antero-posterior thickness remained between 8–20 μm.

## Discussion

### *Present Clinical Concepts*

The extent to which the choroidal circulation is segmentally supplied[2,8,9,14,15,27,34] or richly anastomotic[4,11,12,28] has been the subject of much debate. Our main understanding of the functional anatomy of the choroid has come from examination of patients with acute disturbances of choroidal vasculature[14,15,19-26] and from experimentally produced ischaemia.[29-35] Clinically two types of acute choroidal ischaemia are recognised with systemic disease: (i) triangular-shaped areas of choroidal filling delay on fluorescein angiography with variable overlying retinal dysfunction, and (ii) geographic or focal lesions with marked overlying retinal and pigment epithelial disturbance. The first is attributed to complete or partial occlusion of PCAs or SPCAs from systemic diseases such as temporal arteritis. The second is attributed to occlusion of choroidal arterioles or choriocapillary lobules in, for instance, toxaemia of pregnancy or DIC. (See aetiologies, Table II). Both forms usually resolve spontaneously or may leave characteristic lesions (triangular shaped scars or small Elschnig spots). The tendency for rapid spontaneous resolution over several days implies that although the choroidal circulation functionally has a segmental supply, it is not truly endarterial. The potential for resolution of ischaemia is supported by modern vascular casting and experimental fluores-

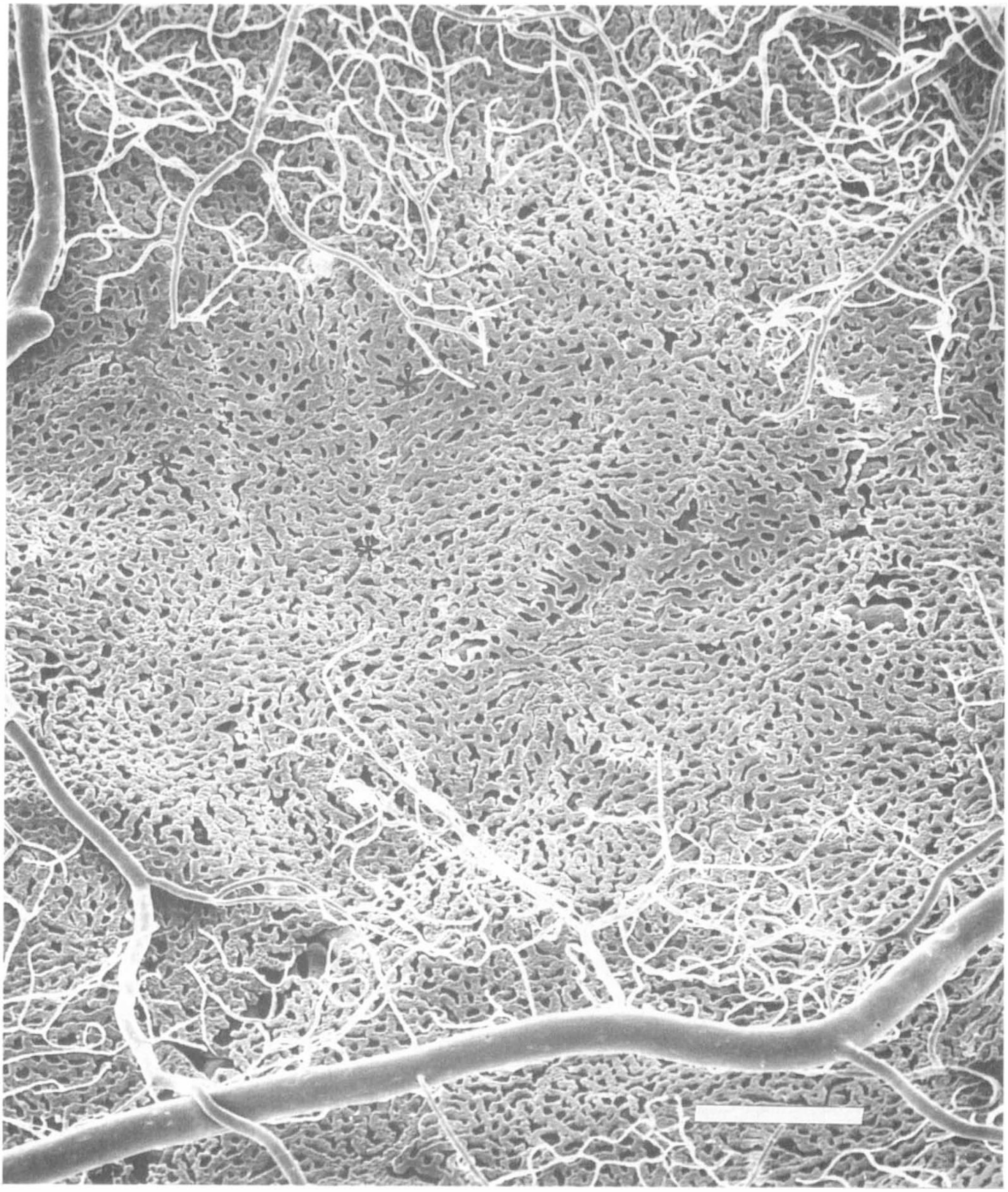

**Fig. 4a.** *Posterior pole choriocapillaris viewed from retinal aspect. Remnants of the inferior retinal vessel arcade and retinal capillaries are visible. Lobular appearance is difficult to distinguish but can be identified. *=choroidal arteriole opening. Bar=250 μm.*

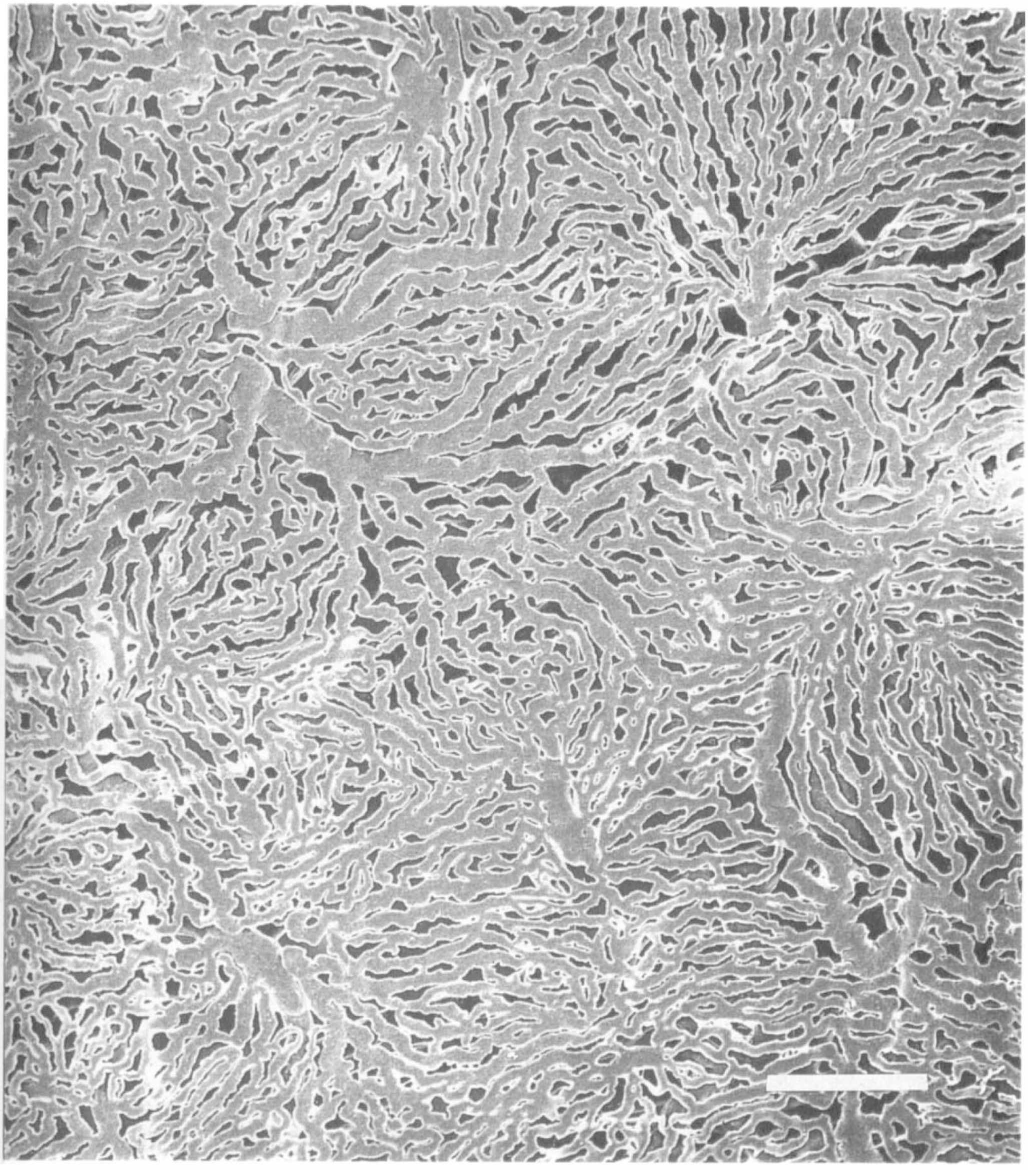

**Fig. 4b.** *Equatorial choriocapillaris viewed from retinal aspect. Lobular pattern is more apparent. Terminal parts of arterioles and venules are visible. Bar=250 μm.*

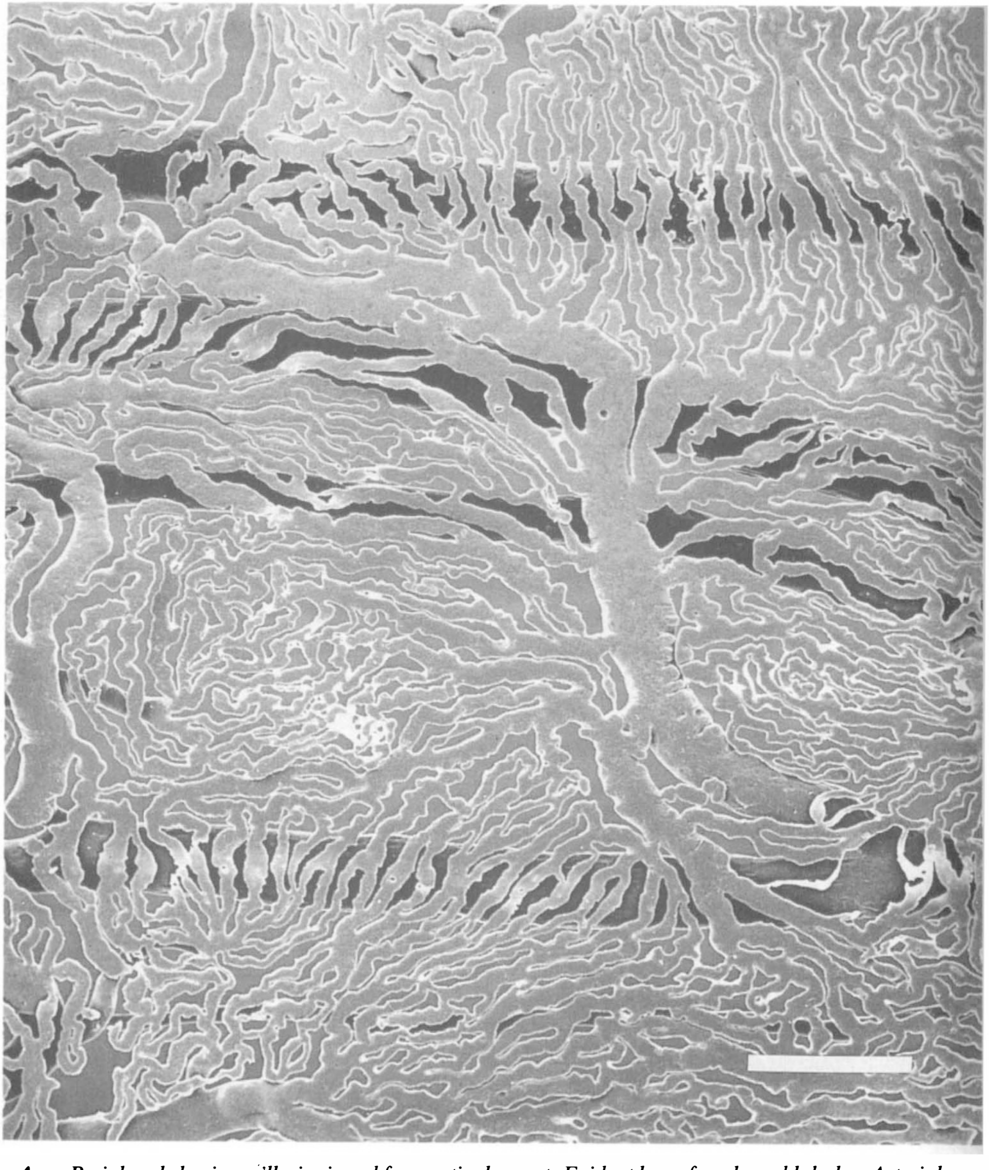

**Fig. 4c.** *Peripheral choriocapillaris viewed from retinal aspect. Evident large fan-shaped lobules. Arterioles and venules lie in the same plane as the capillaries. Bar=250 μm.*

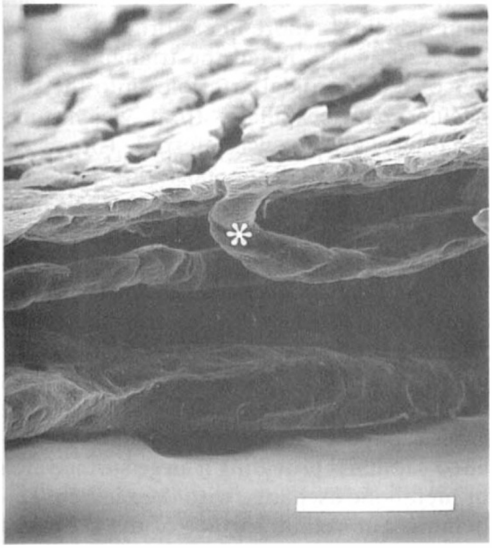

**Fig. 5a.** *Cross section of equatorial choroid showing flattened wide diametered capillaries and a draining venule (star). Bar=60 μm.*

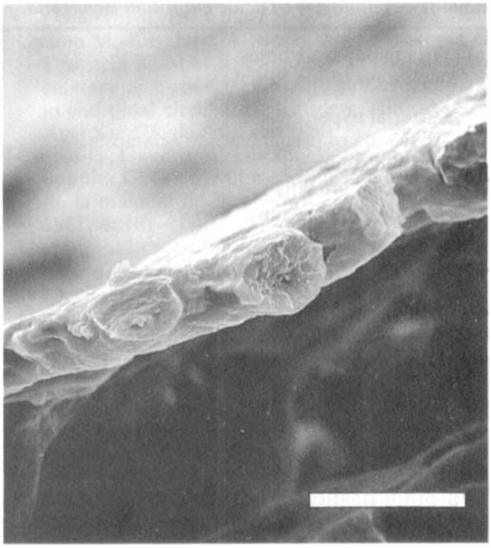

**Fig. 5b.** *High magnification of cross section of choriocapillaris at posterior pole. Bar=23.1 μm.*

cein angiographic studies. Yoneya and Tso[40] demonstrated arterial-arterial anastomoses in the posterior choroid from methyl methacrylate vascular casts of human eyes, as had Ring and Fujino,[13] Weiter and Ernest[5] from neoprene latex casts. Similarly, in experimentally induced large vessel disease fluorescein angiographic resolution is often rapid.[30,31,43,44] The potential for ischaemia was first demonstrated from early experimental SPCA division[27] and clinical observations of large triangular cicatricial choroidal lesions in association with systemic disease.[14],[15] It was suggested from these early studies that the SPCAs supplied the choroid segmentally, although Nicholls[28] found experimentally that sufficient numbers of SPCAs had to be divided to produce evident ischaemia. More recent experimental evidence from injection of microspheres[32,35] and division of PCAs and SPCAs[30,31,33-35] also supported the concept that the choroid was supplied segmentally. The potential for acute choroidal ischaemia exists in man contrary to conclusions based on neoprene latex casting[11,12] and limited experimental[28] and histological[4] evidence.

### *Vascular Anatomy*

Although the main morphological features of the choroidal circulation are well known, our knowledge is incomplete. Rigid methyl methacrylate microvascular casting has provided several advantages over other techniques of morphological examination. It allows three dimensional examination of the choroid with sequential micro-dissection and accurate identification of arteries and veins. Better quality polymers with lower viscosities have largely overcome problems of fragility and poor capillary filling.[45,46] Vascular casting, however does not provide dynamic and physiological information on the function of the choroid, but can be interpreted in the light of clinical and experimental data.

**Table I** *Choriocapillary regional variations. Dimensions μm.*

| | *Lobule size* | *Capillary diameter* | *Intercapillary distance* |
|---|---|---|---|
| Posterior pole | 200–350 | 16–20 | 5–20 |
| Equator | 300–400 | 20–50 | 20–200 |
| Periphery | 500–1000 | 20 + | 20–300 |

**Table II** *Aetiologies of acute choroidal ischaemia.*

| | |
|---|---|
| (a) | Triangular syndromes<br>Acute occlusion SPCAs |
| | Arterial hypertension<br>Toxaemia of pregnancy and eclampsia<br>Carotid stenosis<br>Temporal arteritis<br>Ocular compression |
| (b) | Focal or geographic<br>Multiple arteriolar/capillary occlusion |
| | Accelerated hypertension<br>AMPPE<br>DIC<br>ITP<br>Eosinophilia |

The division of the SPCAs into distal and para-optic branches is an important morphological feature in the supply of the choroidal vasculature. From neoprene casts, Weiter and Ernest[5] first described the temporal short posterior ciliary arteries sub-dividing into a sub-macular group and a separate unnamed group closer to the optic nerve. The sub-macular group was so named because of its site of entry but the supply was not solely sub-macular. The sub-division of the SPCAs into constant distal and para-optic branches was later confirmed by Ducournou[37] and provides the key to understanding the sectoral supply of the SPCAs and the altitudinal supply of the retrolaminar optic nerve.[47]

The small para-optic branches are significant in forming the circle of Haller and Zinn, an intrascleral anastomosis in man between temporal and nasal paraoptic branches having superior and inferior parts. Pial and recurrent choroidal branches originate from this anastomosis and supply the retro-laminar optic nerve and the peripapillary and vertical meridional choroid.

The triangular nature of acute choroidal ischaemia is well recorded and corresponds to the triangular areas supplied by the distal SPCSs in which the apices are close to the entry points of the temporal and medial SPCA bundles into the eye. The more rectangular nature of choroidal ischaemia affecting the vertical meridional choroidal is less well known but was recognised by Amalric[16,21] and corresponds to the area supplied by recurrent choroidal branches from the superior and inferior parts of the 'circle' of Haller and Zinn, which is a more linear origin.

Fryczskowski[41] noted the triangular openings of the choroidal arterioles into the sub-macular choriocapillaris from which functional specialisation was inferred. These were found routinely at the posterior pole and helped to identify lobular pattern; their morphology reflects the right angled entry of the choroidal arterioles into the choriocapillaris and functional inferences cannot be made. The dense packing of the choriocapillaris at the posterior pole in man[2,5,9,40] and monkey[46-49] has been well recognised by several authors using different methods of examination. The choriocapillaries have wide diametered flattened capillaris providing a large surface area for metabolic exchange with the pigment epithelium. The retinal surface of the choroidal capillaris is further adapted anatomically for unimpeded metabolic exchange by location of their endothelial nuclei on the sclerad surface. This feature (of endothelial cells in the capillary wall away from Bruch's membrane) was noted by Hogan[4] from microscopic examination of the choroid but is more readily observable from rigid methacrylate casts.

Vascular casting supports concepts, based on clinical and experimental evidence, that the choroidal vasculature has a distinct segmental arrangement, both at the level of the larger vessels and at the level of the smaller vessels (choroidal arterioles and choriocapillary lobules) and potential for acute choroidal ischaemia. The triangular shaped infarcts of acute choroidal ischaemia correspond to larger vessel occlusion and focal or geographic infarcts corresponding to smaller vessel and choriocapillary occlusion. However, the choroidal circulation is not truly end-arterial since there are potential collaterals from inter-arteriolar and inter-venular anastomoses and recovery of acute choroidal ischaemia may be rapid and spontaneous. Vascular casting also demonstrates the anatomical adaptation of the capillaries for metabolic exchange with the retinal pigment epithelium, particularly at the posterior pole. It is a useful tool to demonstrate the functional anatomy of the choroidal circulation, considered in conjunction with dynamic and physiological aspects.

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