ANATOMY OF THE PCAS

There is much confusion in the literature about the anatomy of the PCAs. For a proper understanding of the subject, it is essential to clarify their nomenclature, origin, number, and distribution.

Nomenclature, Origin, and Number of PCAs

Most investigators use the term “PCA” loosely, as a generic term, for the PCAs, short PCAs (SPCAs) and long PCAs. This is misleading. My anatomic studies on the PCAs in humans showed the following.

PCAs. There are one to five PCAs arising from the ophthalmic artery, one in 3%, two in 48%, three in 39%, four in 8%, and five in 2% of eyes studied. They run forward along the optic nerve, and each divides into multiple branches before reaching the eyeball. The branches of a PCA pierce the sclera lateral, medial, or, infrequently, superior to the optic nerve. Accordingly, I have named them lateral, medial, and superior PCAs, respectively.

Lateral PCAs. They were present in 97% of the eyes: one in 75%, two in 20%, and three in 2%.

Medial PCAs. They were present in 100% of the eyes: one in 71% and two in 29%.

Superior PCAs. They were small and present in only 9% of the eyes: one in 7% and two in 2%.

Branches of the PCAs

Short PCAs. They may be 10 to 20 in number, depending on the intraorbital subdivisions of the PCA before it reaches the sclera (Fig. 1).1–5 The SPCAs are of two types.2–5

Paraoptic SPCAs. These are only a few small SPCAs that enter the sclera close to the optic nerve.

Distal SPCAs. These constitute most of the SPCAs. They enter the sclera a short distance away from the optic nerve on the medial and lateral sides and run radially toward the equator. The temporal distal SPCAs pierce the sclera to enter the eyeball in the macular region.

Long PCAs. There are two of these: one medial and one lateral (Fig. 1). They enter the eyeball in the horizontal plane on the medial and lateral sides, some distance away from the distal SPCAs, and run radially in the horizontal meridian forward to the iris.1,6

VASCULAR PATTERN OF THE PCAS AND THEIR BRANCHES

Knowledge of the vascular pattern of the PCAs and their branches was originally drawn entirely from postmortem cast studies, since the first description by Frederick Ruysch in approximately 1700. All the postmortem cast studies appeared to show that (1) PCAs have no segmental distribution, (2) they anastomose freely with one another as well as with the anterior ciliary arteries, (3) there are interarterial and arteriovenous anastomoses in the choroid, and (4) choriocapillaris form a freely communicating and an uninterrupted vascular bed in the entire choroid.6,8,9 However, clinically, inflammatory, ischemic, metastatic, and degenerative choroidal lesions are usually localized. This puzzling discrepancy was well summarized by Duke-Elder:10 “The tendency for inflammatory and degenerative diseases of the choroid to show a considerable degree of selective localization, despite the fact that anatomically the vessels would appear to form a continuous network, has given rise to speculations regarding the anatomic isolation of specific choroidal areas.”

To investigate this discrepancy between the postmortem cast studies and the clinically seen lesions, I started to research the subject in vivo experimentally as well as clinically in 1967.

In Vivo Vascular Pattern of the PCAs

Experimentally in rhesus monkeys, I have cut one or another or all the PCAs and evaluated the area of their distribution in...
the choroid and ONH and anastomoses by fluorescein fundus angiography.\textsuperscript{11–14} PCA occlusion caused by thrombosis has been well documented in patients with giant-cell arteritis, by various histopathologic studies.\textsuperscript{15–20} That provided a model of PCA occlusion in humans, to evaluate the in vivo distribution and anastomoses of the PCA in the choroid and ONH by fluorescein fundus angiography.\textsuperscript{21–26} These experimental and clinical studies showed that each PCA had a segmental distribution in the choroid and ONH, and they anastomosed neither with the adjacent PCAs nor with the anterior ciliary arteries.\textsuperscript{2,3,11–14,21–29} Similarly, when we produced anterior ciliary artery occlusion by recession and resection of the various recti in rhesus monkeys as well as in patients with strabismus, the PCAs did not fill the area of the anterior uvea supplied by the occluded anterior ciliary artery.\textsuperscript{30,31}

\textbf{In Vivo Vascular Pattern of the SPCA and Long PCA}

Likewise, experimental occlusion of one or the other—SPCA\textsuperscript{32} or long PCA\textsuperscript{6}—in rhesus monkeys resulted in a segmental choroidal filling defect in the area of distribution of the occluded artery. The area did not fill from adjacent normally filling choroid.

\textbf{In Vivo Vascular Pattern of the Peripapillary Choroid}

Experimental and clinical studies similarly have revealed that the peripapillary choroid has a segmental pattern\textsuperscript{3,11,25,27} that in turn is responsible for the segmental pattern of blood supply in the ONH and consequently for the well-known sectorial nature of ischemic lesions seen in anterior ischemic optic neuropathy (AION) and other ischemic disorders of the ONH.

\textbf{In Vivo Vascular Pattern of the Choriocapillaris Bed}

My fluorescein fundus angiographic studies revealed that the entire choriocapillaris bed is composed of independent small lobules.\textsuperscript{27,33,34} Each lobule is supplied by a terminal choroidal arteriole in the center, and its venous drainage is by venous channels situated in the periphery of the lobule (Fig. 2). These in vivo studies further revealed that various choriocapillaris lobules normally do not anastomose with their neighbors. The various lobules are arranged like a mosaic. The shape and size of the various choriocapillaris lobules vary in different regions of the choroid (e.g., polygonal in the posterior part and elongated in the peripheral part). The choriocapillaris is arranged more compactly at the posterior pole than in the periphery, so that it gradually becomes less dense toward the periphery. Ernest et al.,\textsuperscript{35} Torczynski and Tso\textsuperscript{36} and many other investigators since have confirmed the lobular pattern of choriocapillaris in humans.

Thus, my studies clearly demonstrated for the first time that the in vivo vascular pattern of the PCAs and their branches in the choroid and ONH vascular bed is strictly segmental, with no anastomoses between the adjacent segments, which indicates that the PCAs and their branches in the choroid and ONH behave as end arteries in vivo. This helps to explain the localized nature of choroidal and ONH lesions.

In conclusion, the findings of my in vivo studies clearly show that postmortem cast studies had misled us for almost
As has been described, the SPCAs are of two types.\textsuperscript{2,4} Areas Supplied by the SPCAs and Their Branches

When there are two PCAs, the importance of the blood supply of the ONH.\textsuperscript{2,3,20,23,25,29,39,40} These arteries not only supply the choroid but also play an important role in the blood supply of the ONH.\textsuperscript{2,3,20,23,25,29,39,40} Thus, in vivo studies with fluorescein angiography reveal the actual physiologic circulatory pattern. In the postmortem studies, by contrast, when the cast material is injected under pressure, the vessels without any neural control fill from all sources, irrespective of the normal blood flow pattern, and therefore they give information about the morphologic conduits only and not physiologic function. What matters clinically in explaining different vascular disorders is the in vivo circulatory pattern and not the anatomic pattern revealed by the postmortem casts. The in vivo studies explain why inflammatory, ischemic, metastatic, and degenerative choroidal lesions are usually localized. This reminds me of the lifelong feud between Camillo Golgi and Ramón y Cajal about the discrepancy between the microscopic anatomy and functional anatomy of the neuronal network. Cajal finally stated: “Who does not know that every scientific accomplishment dislodges some deeply rooted error and that behind it is usually concealed injured pride, if not enraged interest?”\textsuperscript{3,40}

**Areas Supplied by the Various PCAs and Their Branches In Vivo**

Our in vivo clinical and experimental studies of the various PCAs and their branches in health and disease provided essential information on the areas supplied by each.

**Areas Supplied by the PCAs**

These arteries not only supply the choroid but also play an important role in the blood supply of the ONH.\textsuperscript{2,5,20,25,29,59,40} When there are two PCAs—one lateral and one medial—there is a marked interindividual variation in the area supplied by each PCA in humans.\textsuperscript{2,3,25,40} The medial PCA may supply the entire nasal choroid up to the level of the fovea, including the entire ONH; or its supply may stop short, nasal to the nasal peripapillary choroid, so that it may take no part in the blood supply of the ONH; or there may be any variation between these two extremes (Figs. 3, 4). The lateral PCA supplies the area of the choroid and ONH not supplied by the medial PCA. When there is more than one medial or lateral PCA, the area supplied by each of them may be one quadrant or only a sector (Fig. 5). When the superior PCA is present, it accordingly supplies a superior sector of varying size. Given the marked interindividual variation in number and distribution by the various PCAs, we can get an extremely variable pattern of distribution by them in the choroid and ONH.

**Areas Supplied by the SPCAs and Their Branches**

As has been described, the SPCAs are of two types.\textsuperscript{2,4} Paraoptic SPCAs. Branches from these go to the corresponding parts of the ONH, peripapillary choroid, the circle of Zinn and Haller (when present), and recurrent branches to the retrolaminar ONH pial vascular plexus. Thus, available evidence indicates that all these branches of the paraoptic SPCAs constitute the main source of blood supply to the ONH. The circle of Zinn and Haller is discussed at length elsewhere.\textsuperscript{5}

**Distal SPCAs.** Each of these arteries supplies a sector of the choroid, usually extending from the posterior pole to the equator (Fig. 6).\textsuperscript{34} Each sector varies markedly in shape, size, and location and has irregular margins. The various sectors fit together like pieces of a jigsaw puzzle. Further subdivisions of the SPCAs supply correspondingly smaller segments of irregular shape and size, so that the blood supply by the various choroidal arteries has a geographic pattern: the smaller the artery, the smaller the size of the geographic area. Finally, each terminal choroidal arteriole supplies a lobule of the choriocapillaris (Fig. 2).\textsuperscript{27,32–34}

**Areas Supplied by the Long PCAs**

Each artery runs radially in the horizontal meridian: one on the medial and the other on the lateral side (Fig. 1). On the temporal side, the long PCA supplies a sector of the choroid temporal to the macular region, with its apex oriented posteriorly (Fig. 6).\textsuperscript{5} In addition to supplying a sector of the peripheral choroid, each artery also supplies a small sector of the ciliary body and iris on the medial and lateral sides.

**Watershed Zones in PCA Vascular Bed**

A watershed zone is the border between the territories of distribution of any two end arteries. The significance of the watershed zones is that in the event of a decrease in the perfusion pressure in the vascular bed of one or more of the end arteries, the watershed zone, being an area of comparatively poor vascularity, is most vulnerable to ischemia. In the brain, for example, development of watershed zone infarcts along the borders of areas of supply by the cerebral arteries is a well-known phenomenon.\textsuperscript{41–45} As shown earlier, PCAs and their branches, right down to the terminal arterioles, have a segmental distribution in vivo. Thus, I discovered that there are
watershed zones between the distribution of the various PCAs, between the SPCAs, and between the anterior and posterior ciliary arterial circulations. The subject is discussed at length elsewhere; the following is a brief summary.

**Watershed Zones between the PCAs**

My fluorescein fundus angiographic studies in humans have clearly shown the watershed zones between the various PCAs (Fig. 3). When there are two (medial and lateral) PCAs, the area of the choroid and ONH supplied by the two shows marked interindividual variation (Figs. 3, 4), and that results in wide variation in the location of the watershed zone between them. Figures 3 and 4 illustrate some of the locations of the watershed zone between the medial and lateral PCAs in humans. They show that the watershed zone may (1) be located temporal to the peripapillary choroid (Fig. 4A); (2) pass through the temporal peripapillary choroid (Figs. 3A, 4B); (3) pass through one or the other part of the optic disc (Figs. 3B, 3D, 4B, 4D), or the entire optic disc may lie in the watershed zone (Figs. 3C, 4C); (4) pass through the medial peripapillary choroid (Fig. 4E); or (5) various combinations of these. When there are three or more PCAs supplying an eye, the locations of the watershed zones vary accordingly, as shown diagrammatically in Figure 5. Thus, the PCA-watershed zone may involve any part of the ONH, or may cover the entire ONH, or may pass temporal or nasal to the ONH. The watershed zone may extend vertically along the entire length (Figs. 3, 4), may be only in the lower or upper vertical half, or may show other variations (Fig. 5). The watershed zones between the various PCAs play a very important role in ONH ischemic disorders, because the part of the ONH that is located in the watershed zone is most vulnerable to ischemia.

**Watershed Zones between the SPCAs**

My experimental study has shown that each SPCA supplies a well-defined sector of the choroid. Figure 6 is a diagrammatic representation of the various sectors of the choroid supplied by the temporal SPCAs and their watershed zones between the adjacent sectors. Because all the temporal SPCAs enter the eyeball in the macular region and spread out radially to the periphery of the fundus to supply the temporal half of the choroid (Fig. 7), it is natural that most of the segments of the choroid supplied by the temporal SPCAs and their watershed zones meet in the macular region, and that must make the macular region most vulnerable to ischemia in the event of vascular insufficiency (discussed later).

**Watershed Zones between SPCAs and Long PCAs**

Figure 6 shows the area of the choroid supplied by the temporal long PCA. My experimental and clinical studies have revealed that there are no anastomoses between the long PCA and the adjacent short PCAs. Thus, there is a watershed zone between the long PCA and its adjacent SPCAs.

**Watershed Zones between the PCAs and the Anterior Ciliary Arteries**

Experimental and clinical studies dealing with occlusion of a PCA or an anterior ciliary artery clearly show...
that there are no anastomoses in vivo between the PCAs and anterior ciliary arteries. Also, Takahashi et al. on wide-angle indocyanine green angiography in humans, found an absence of functional anastomoses between terminal branches of the anterior and posterior ciliary arteries. Thus, there is a watershed zone between the anterior and posterior ciliary arteries that is situated in the equatorial region of the choroid.

The PCA circulation is the main source of blood supply to the ONH and choroid in glaucoma. My studies in AION and glaucoma indicate that the distribution pattern of the blood supply by the various PCAs and the location of their watershed zones in relation to the ONH (Figs. 3, 4, 5) determine the extent of ONH involvement by ischemia. For example, as described earlier, the medial PCA may supply the entire ONH, a variable amount of it, or none at all. Therefore, medial PCA occlusion can result in a variable amount of visual loss or none at all. The same holds true for lateral PCA occlusion. The end-arterial nature of the PCA circulation and its segmental distribution also explain the development of only a sectoral ischemia in the ONH, typically seen in AION and other ischemic disorders of the ONH. Similarly, the watershed zone may involve a variable amount of the ONH, the entire ONH, or none of it (Figs. 3, 4, 5). The part of the ONH that lies in the watershed zone is more vulnerable to ischemia than the rest. Clearly, when the entire optic disc lies in the center of a watershed zone, it is most vulnerable to ischemia.

Anterior Ischemic Optic Neuropathy. AION has come to be recognized as a common, severe, visually disabling disease, particularly in the middle-aged and elderly. In my experimental and clinical studies, I discovered that AION is due to interference with the PCA circulation to the ONH (Fig. 3). Arteritic AION, seen in giant-cell arteritis, is due to thrombotic occlusion of any one of the PCAs. Nonarteritic AION, by contrast, is essentially due to transient hypoperfusion or nonperfusion of the PCA circulation in the ONH (and usually not to occlusion of the PCA), with nocturnal arterial hypotension playing an important role. Therefore, the visual loss is usually much worse in arteritic than in nonarteritic AION.

Glaucomatous Optic Neuropathy. Glaucoma is a major blinding disease. My experimental and clinical studies since 1964 have shown evidence of vascular insufficiency in the ONH in glaucoma. Based on those studies up to 1970, and on evidence from other studies in the literature, I postulated that glaucomatous optic neuropathy is vasogenic in origin—a view now widely accepted, despite the initial skepticism. Evidence has progressively accumulated during the past three decades suggesting that vascular insufficiency in the ONH plays an important role in its pathogenesis. My studies in eyes with glaucoma and normal-tension glaucoma show that 60% of the watershed zones are located as shown in Figure 4B, 16% as in Figure 4C, and 10% as in Figure 4D. Other factors that influence the blood flow in the ONH also play a role in development of ONH ischemic disorders for example, our studies showed a significantly (P = 0.0028) lower nighttime mean diastolic blood pressure and a significantly (P = 0.0044) greater mean percentage decrease in diastolic blood pressure in normal-tension glaucoma than even in AION.

Choroidal Ischemic Disorders

These lesions have been seen in a number of systemic diseases. They may also be due to local vascular occlusive disorders. I have produced many of these lesions experimentally in rhesus monkeys by PCA occlusion or by malignant arterial hypertension.

Acute Choroidal Ischemic Lesions. Their appearance and types depend on (1) the stage of evolution of the lesions, (2) the size of the artery or arteriole involved, and (3) the severity of ischemia.
Stage of Evolution of the Lesions. Fresh lesions are white, due to infarction of the RPE and the adjacent outer retina. After one week they begin to change gradually, so that over a 2- to 3-week period they become grayish-white, granular, depigmented areas, ultimately changing into choriotinal pigmented degenerative lesions. Histopathologically, initially there is coagulation necrosis of the RPE and of the posterior part of the outer retinal layers, and the blood-retinal barrier in the RPE is broken, but we found that 3 months later, it re-forms, even in eyes with severe ischemic damage.

On fluorescein angiography, therefore, typically during the acute stage of fresh white lesions, the involved choroid initially shows filling defects, and the ischemic lesions show late staining, but later on the choriotinal degenerative lesions show window defects without any staining.

Size of the Occluded Artery or Arteriole. The size and shape of choroidal ischemic lesions depend on the size of the artery involved. These lesions can be divided into the following separate clinical entities for descriptive purposes, although they represent a continuous spectrum of the disease.

Occlusion of the large choroidal artery produces localized wedge-shaped or segmental lesions.

Occlusion of the medium-sized choroidal artery produces lesions of various shapes and sizes. There are often triangular sector-shaped lesions located in the peripheral part of the fundus, with their bases toward the equator and apices toward the equatorial watershed zone of the posterior pole.

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Example 1. In our experimental studies on malignant arterial hypertension in rhesus monkeys, the submacular choroid showed a marked, selective delayed filling, particularly of its central part, on fluorescein angiography. Consequently, hypertensive choroidopathy was almost invariably seen in the macular region, and the choroidal ischemic lesions were most prominent there. I have seen that clinically as well.

Example 2. In my experimental studies in rhesus monkeys, when I reduced the perfusion pressure in the ocular vessels, fluorescein angiography revealed delayed filling of the watershed zones in the macular choroid and of the central macular choriocapillaris.

Example 3. In eyes with age-related macular degeneration, several histopathologic studies have reported degenerative changes in the submacular choriocapillaris, and fundus angiographic and other blood flow studies have also shown evidence of impaired macular choroidal circulation. These would suggest that vascular impairment may play a role in the pathogenesis of age-related macular degeneration in some patients.

Thus, all the evidence collectively seems to point to the conclusion that the submacular choroid is more vulnerable to chronic ischemia than any other part of the posterior choroid. Similarly, in eyes of patients with marked atherosclerosis and arteriosclerosis, a reticular pigmentary degeneration is frequently seen in the equatorial region (in the region of the equatorial watershed zone between the anterior and posterior ciliary circulation).

Hypertensive Choroidopathy. The physiologic properties of the choroidal vascular bed influence its response to malignant arterial hypertension. The choroidal vascular bed has no blood-retinal barrier, because of large fenestrations in the walls of the choriocapillaris, and readily leaks plasma. The choroidal vascular bed has a rich autonomic nerve supply. Bill and Sperber have concluded in their reviews that the choroidal circulation is not autoregulated. Our study also showed absence of autoregulation in the choroidal vascular bed in primates and humans. In our experimental studies on malignant arterial hypertension in rhesus monkeys, we found that the development of hypertensive choroidopathy is a prominent feature. Following is a brief description of the pathogenesis of development of hypertensive choroidopathy: Absence of the blood-retinal barrier in the choriocapillaris → marked leakage of plasma (with angiotensin II and all other vasoconstrictors found in malignant arterial hypertension) into choroidal fluid → vasocostriction of choroidal vessels → choroidal ischemia → RPE ischemia → breakdown of the blood-retinal barrier in RPE → serous retinal detachment. Thus, in hypertensive choroidopathy we found the following lesions:

Choroidal Vascular Bed Abnormalities. Initially, on fluorescein angiography there was delayed choroidal filling, particularly marked in the central part of the macular region. Later on, histopathology showed occlusion of the choroidal arteries.

RPE Lesions. These are focal ischemic lesions and consist of two stages.

Acute focal ischemic lesions are punctate, pale or white, pinhead-size lesions, situated at the level of RPE, mostly in macular region and less often elsewhere. They are associated...
with overlying focal serous retinal detachment. On fluorescein angiography the lesions stain during the late phase.70

In 2 to 3 weeks the acute lesions change into focal RPE degenerative lesions. Later on, these RPE lesions become confluent and are progressive (mostly in macular and peripheral regions), to become polymorphous RPE atrophic areas or diffuse pigmentary changes. There may be choroidal sclerosis.72

Fluorescein angiography shows window defects and no staining, because by this time the RPE blood-retinal barrier has re-formed.69,70

Serous Retinal Detachment. This may be focal (blister-like), flat, bullous, or total (with shifting subretinal fluid). It is located in the macular, peripapillary and/or peripheral regions, with subretinal fluid initially clear, later on becoming turbid, and occasionally proteinaceous. Later on, subretinal fibrosis may develop. The macular retina over the detachment may show microcystic change, separation of nerve fibers, and foveal cysts.

Choroidal Vascular Changes in Glaucoma. In our experimental studies in monkeys, evaluation of choroidal circulation with fluorescein angiography showed that a decrease in perfusion pressure, caused by either an acute increase in intracocular pressure or a decrease in systemic arterial blood pressure, resulted in delay in filling of the choroid, and the transit time of the dye in the choroid was prolonged: the lower the perfusion pressure, the more marked the changes in the choroid.58 In this study, the peripapillary choroid was found to be more susceptible to the changes than the rest of the choroid; this was later confirmed by other experimental studies.61

Laatikainen,88 in her fluorescein angiographic studies of patients with glaucoma and normal-tension glaucoma, also found choroidal filling defects in most glaucomatous eyes; 60% of the eyes with moderately controlled intraocular pressure showed delayed or deficient filling of the peripapillary choroid. The peripapillary choroid is an important source of blood supply to the ONH.

In our experimental chronic high pressure glaucoma study in rhesus monkeys,89 our most striking finding was a significant reduction of choroidal thickness and loss of choroidal ganglion cells, especially in the central portion of the choroid. Corrosion casts of the choroidal vascular bed in these glaucomatous eyes showed a slight decrease in capillary density and a decrease in length of the choroidal arterioles.

RETNAL ISCHEMIC LESIONS SECONDARY TO OCCLUSION OF PCA

In eyes with PCA occlusion, in addition to AION and choroidal ischemic lesions, the following types of retinal ischemic lesions may also develop: (1) Ischemia occurs in the RPE and outer 130 µm of the retina;12,68 (2) because the cilioretinal artery is supplied by the PCA circulation, PCA occlusion results in occlusion of the cilioretinal artery.20,22,24,26, (3) in some cases, the PCA and central retinal artery arise by a common trunk from the ophthalmic artery.1 The occlusion of the common trunk results in occlusion of both arteries, which can be demonstrated by fluorescein angiography.20,22,26

In my studies, the most common cause of PCA occlusion associated with either cilioretinal or central retinal artery occlusion has been giant-cell arteritis, because of the special predilection of giant-cell arteritis to involve one or the other PCA.20,22,24,26,40

In conclusion, my studies have shown that the PCA circulation is the most important element in the ocular and ONH circulation, because various subdivisions of the PCAs supply the ONH, choroid, the outer retina, and medial and lateral segments of the ciliary body and iris. The areas of the choroid and ONH supplied by the PCAs and their branches show marked interindividual variation. In vivo, the vascular pattern of the PCAs and their branches down to the terminal arterioles is strictly segmental, with no anastomoses between the adjacent vascular segments. The choriocapillaris bed has a lobular pattern. Because the PCAs and their branches in the choroid and ONH behave as end arteries in vivo, they have watershed zones between them. That explains why various vascular lesions in the ONH and choroid are usually localized and why those parts of the ONH and choroid lying in the watershed zones are more vulnerable to ischemic disorders than the rest. The end-arterial nature of the PCA vascular bed and location of the watershed zones are the major determinants of the extent and pattern of ischemic disorders of the ONH and choroid. Disturbances in the PCA circulation can result in a variety of ocular and ONH disorders, causing varying degrees of visual loss. Herein, I have summarized the major disorders of the PCA circulation involving the ONH, choroid, and retina and have described briefly the role of PCA circulation in their pathogenesis, as revealed by my studies.

Acknowledgments

Modern research relies on teamwork. Over the years, I have had a series of excellent collaborators and coworkers, too many to name. I am happy to have this opportunity to acknowledge their invaluable help. I am also grateful to Georgiana Perrett and Patricia Duffel for their help with the literature, and to my wife for translating the Latin manuscript by Frederick Ruysch.7

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