Extraction of Choriocapillaris Hemodynamic Data From ICG Fluorescence Angiograms

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Purpose. There are conflicting views about the organization of the posterior pole choriocapillaris, particularly concerning blood flow through it, and there are difficulties associated with attempting to obtain such information using histologic techniques, sodium fluorescein angiography, or both. The present study uses a method of analysis based on high-speed angiograms to investigate posterior pole choroidal blood flow.

Method. The analysis method employed is based on the premises that dye filling of the choriocapillaris is more rapid (because it is pulsatile) than dye filling of the underlying larger diameter vessels, and that fluorescence from these two overlapping layers is additive. The described analysis algorithm was applied to high-speed ICG fluorescence angiograms to emphasize information about choriocapillaris hemodynamics.

Results. The analysis method was demonstrated in rhesus monkeys, and results indicate that the posterior pole choriocapillaris does not behave as a homogeneous structure, consisting of discrete lobular segments. In general, the cycle of dye filling of the choriocapillaris begins in the macular area and progresses radially toward the periphery in a wavelike manner, the filling cycle beginning with and being completed during one cycle of the intraocular pressure pulse.

Conclusions. It is possible to extract information related to choriocapillaris blood flow from high-speed ICG angiograms when a fairly well-defined dye bolus wavefront is present. Interpretation of the results suggests that the choriocapillaris lobules fill in a pulsatile manner, out of phase with each other, and may act thereby to dissipate the blood volume entering the choroid during each cardiac cycle in such a way that the retinal macular is not significantly displaced by expansion of the choroidal vascular volume. Depending upon the distribution of pressure gradients across a group of lobules, blood may flow from one to another of the adjacent one. Invest Ophthalmol Vis Sci 1993:18:2720-2729.

Numerous investigators have used a variety of histologic techniques and angiography to collect the current body of information about the choroidal circulation. Although the gross aspects of choroidal angioarchitecture and blood flow have been amply revealed by their efforts, controversy remains regarding regional differences in morphology, and more controversy has arisen regarding details of blood flow through this highly complicated vascular network. Of particular interest is blood flow through the choriocapillaris because it is in this vascular layer that the nutritive function of the choroidal circulation takes place. Even though the state of the larger choroidal blood vessels must certainly influence choriocapillaris blood flow, ultimately it is a precise understanding of the choriocapillaris blood flow itself that is fundamental to understanding the choroid’s role in the pathophysiology of retinal disease.

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Based on histologic studies, currently there are two major differing views regarding the architecture of the posterior pole choriocapillaris. The first of these, which appears to be the majority view, is well represented by Torczynski and Tso’s description of the choriocapillaris based on their studies of flat preparations of pieces of normal human choroid. They used the term lobule to denote a mosaic of three- to six-sided vascular units, each consisting of “a cluster of narrow, tightly meshed capillaries that appeared to radiate from a central focus in which a round opening was present in the posterior wall of the capillaries. At an average distance of 300 to 400 μm from the central focus, the direction of the capillaries changed from radial to circumferential.” By examining serial oblique and transverse tissue sections for “appearance of vessels, the manner in which these vessels joined the choriocapillaris, the features of the surrounding capillaries, and the thickness of the sub-capillary collagen,” they determined that the vessels joining the centers of the lobules are arterial in nature, whereas those joining the circumferentially oriented capillaries surrounding each lobule are venous. They concluded that such a center-filling lobular organization dominates the posterior pole region.

The second—and differing—view of posterior pole choriocapillaris organization is most recently represented by the findings of Fryczkowski et al., who studied plastic corrosion casts of normal human vasculatures. They consistently found a discrete region in the posterior pole beneath the central macula and around the disk where the choriocapillaris does not have a distinct lobular structure. Within that region, the choriocapillaris “appears to be a freely interconnected monolayer with no lobular demarcation between the arterial and venular channels.” In the posterior pole, they noted “lobuli often have feeding arterioles in the center and collecting venules located on the periphery of each lobule,” but they also “were able to see lobuli that had a central venule and feeding arterioles in the side.” The criterion they used for differentiation of arterioles from venules was the characteristic endothelial cell nuclear indentations left in the vascular casts, those in arterioles being elongated and parallel to the vessel axes and those in venules being rounded, randomly placed, and of larger diameter. Moreover, because the casts were of whole choroidal vasculatures, they also were able to trace specific pre-capillary lobule vessels to their main vessel origins, thereby providing additional confirmation as to the arterial or venous nature of vessels filling and draining lobules. For these authors, the major point was that in terms of lobular organization, the posterior pole choriocapillaris should not be considered to be a homogeneous structure.

Angiographic data generated to date largely support the view represented by the work of Torczynski and Tso. For example, Hayreh performed sodium fluorescein angiography on rhesus monkeys with choroidal vascular occlusions or whose intraocular pressures were artificially elevated to slow down the choroidal circulation enough to permit photographing various dye filling phases. Even then, apparently it was not possible to capture a continuous sequence of angiograms in a single animal such that all the discrete filling stages of individual lobules could be demonstrated, because it is stated in Hayreh’s paper that the example sequence is from two different monkeys. He concluded that the posterior pole choriocapillaris lobules are center filling. Moreover, he concluded that “the choriocapillaris has a segmental distribution and the choroidal arteries behave as end-arteries” and that “because of hemodynamic factors in each segment, the blood does not flow from one segment to the other.” This conclusion supported Torczynski and Tso’s speculation that “cross flow from lobule to lobule does not normally occur”; additional support came from observations by other investigators who noted that in lightly pigmented patients, there occur constant, well-demarcated, multisided patches of choriocapillaris fluorescein dye filling. However, fluorescein angiographic data about the normally fast flow of blood through the choriocapillaris must be viewed with suspicion—especially if it is derived under physiologic conditions like artificially elevated intraocular pressure.

High-speed indocyanine green (ICG) dye fluorescence angiography was developed to overcome the major problems encountered when attempting to visualize the rapid choroidal blood flow encountered in fluorescein angiography. ICG angiography uses near-infrared wavelengths, which penetrate the retinal pigment epithelium and choroidal pigment with relative ease. Although choriocapillaris fluorescence resulting from intravenously injected fluorescein appears to arise mainly from extravasated dye molecules or those adhering to the vessel walls, ICG fluorescence arises from dye molecules in the moving blood volume. No doubt, scanning laser ophthalmoscope fluorescein angiography and the experimental technique of injecting fluorescein encapsulated in lipid vesicles eventually will produce additional information about choroidal blood flow, but with respect to conventional fluorescein angiography, ICG angiography provides much greater temporal resolution, making visualization of dye passage through the choroid possible without having to slow blood flow artificially. For example, after intracarotid injection of a small ICG dye bolus, ICG angiograms have been produced that clearly show the complete cycle of dye passage through an individu-
When making intravenous dye injections, however, it is difficult to observe the choriocapillaris in individual ICG angiogram images because of the much higher levels of fluorescence arising from the large diameter underlying vessels. Nevertheless, an analysis algorithm has been developed that makes it possible to extract information about choriocapillaris filling from venous-injection ICG dye angiograms, and this algorithm has been used to investigate choriocapillaris blood flow in a group of young rhesus monkeys.

MATERIALS AND METHODS

The Algorithm

The algorithm was suggested by the repeated real-time observation that during ICG dye transit, after the large choroidal arteries fill, there is a rapidly pulsating faint and diffuse fluorescence superimposed over the steady fluorescence of the large vessels at the posterior pole. These pulsations appeared to occur at a greater frequency than the heart rate, and they appeared to cease by the time the large choroidal veins completely filled. Subsequent frame-by-frame analysis of the angiograms, however, indicated that the greater-than-heart-rate frequency was a perceptual phenomenon resulting from the out-of-phase pulsatile filling of individual lobules, all at heart-rate frequency. Unfortunately, not enough is known yet about details of choriocapillaris hemodynamics to account with certainty for the observed, more rapid fluorescence intensity changes in the choriocapillaris than in the larger underlying vessels. Two possible reasons, however, are that choriocapillaris blood flow velocity is greater than that through the underlying choroidal vessels, and, despite its small vessel diameters (compared to those of the underlying vessels), choriocapillaris fluorescence is disproportionately bright. The algorithm is based on the premises that the fluorescence intensities of ICG-filled choriocapillaries and underlying vessels are additive and that there are detectable differences in the rates of change of fluorescence intensities emanating from the choriocapillaries and the underlying choroidal vessels as they fill with dye.

Although the average cross-sectional diameter of the choriocapillaries is much smaller than that of the underlying arterial and venous vessels that feed and drain them, it appears that fluorescence from the two vascular layers is additive. ICG fluorescence additivity was demonstrated by creating a stair-step wedge of overlapping thin layers of heparinized blood containing ICG dye (0.03 mg/ml); each step was formed by a thin layer of the blood sandwiched between two microscope slide coverglasses. Figure 1 shows an ICG fluorescence image of the stair steps. The horizontal white line through the center of the image indicates where brightness (i.e., gray level) was determined to produce the graph at the bottom of the figure.

The greater rate of change in dye fluorescence intensity in choriocapillaries than in the larger underlying vessels is shown schematically in Figure 2. On the left, the brightness of a large diameter vessel and an overlying choriocapillaris vessel (both in cross-section) are indicated as vectors $I_A$ and $I_C$, respectively; the fluorescent light emitted by both is detected at time $t_1$ by a light sensor, $S$. On the right, the status of the same two vessels and sensor is shown at later time $t_2$, where $\Delta I_A$ and $\Delta I_C$ are the incremental increases in bright-
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FIGURE 2. On the left, the brightnesses of a large diameter vessel and an overlying choriocapillaris vessel (both in cross-section) are schematically indicated as vectors $I_A$ and $I_C$, respectively; the fluorescent light emitted by both are detected at time $t_1$ by a light sensor, $S$. On the right, the status of the same two vessels and sensor is shown at later time $t_2$, where $\Delta I_A$ and $\Delta I_C$ are, respectively, the incremental increases in brightnesses of the two vessels.

Therefore, the total brightness detected by the sensor at $t_1$ is:

$$S_{t_1} = I_A + I_C$$

At time $t_2$, the total brightness detected is:

$$S_{t_2} = I_A + I_C + \Delta I_A + \Delta I_C$$

The change in total detected brightness occurred between $t_1$ and $t_2$, $\Delta S$, then is:

$$\Delta S = S_{t_2} - S_{t_1} = \Delta I_A + \Delta I_C$$

But since

$$\Delta I_A \ll \Delta I_C$$

In other words, the small change in the combined brightness of the overlapping capillary and large vessel that occurs during a short time interval is virtually attributable entirely to the choriocapillaris vessel. This phenomenon can be demonstrated simply by subtracting, pixel for pixel, two successive images from a high-speed ICG fluorescence angiogram sequence, as demonstrated in Figure 3. Figures 3A and 3B are angiographic images made one-thirtieth of a second apart. Figure 3C is the result of subtracting those two images, and Figure 3D is simply an enlargement of 3C. Note that in the resultant image lobular structures are seen that were not apparent in either of the original images. Also, instead of the dye-filled retinal arteries seen in the original images, only a dye wavefront representing the movement of additional dye into the retinal arteries near the disc is seen in the resultant image. Of course, the more spatially well defined the dye bolus, the more dramatic is the effect of this algorithm; not all intravenously injected dye boluses produce the dramatic results achieved in this example, but in each case there is enhancement of the choriocapillaris component of fluorescence.

Five normal rhesus monkeys between 2 and 3 years of age were used in this study. All animals involved in this research experienced minimum distress or discomfort. They were cared for in accordance with the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research. For each observation, a monkey was immobilized by intramuscular injection of ketamine hydrochloride (5 to 10 mg/kg), intubated, and then maintained lightly anesthetized with halothane; mydriasis was induced by topical application of 1% tropicamide. Small boluses (about 0.05 ml) of ICG dye (12.5 mg/ml) were injected through a catheter inserted in the greater saphenous vein and immediately followed by a 2.0 ml saline flush. Passage of dye through the choroidal vasculature was detected using a modified Zeiss fundus camera (Oberkochen, Germany) and directly digitally recorded by PC-based video framegrabbers. At least three angiographic studies of the same eye were performed on different days for each monkey.

The usual fundus camera xenon flash tube light source was replaced by an 805 nm wavelength laser diode (Spectra Diode Labs, San Jose, CA) coupled to the fundus camera’s illumination optics via a small integrating sphere whose exit port was located at the position normally occupied by the flash tube arc. The fundus camera’s photographic film camera was replaced with an infrared-sensitive vidicon tube (model 4532URI Ultracon, Burle Industries, Lancaster, PA), in front of which an 807 nm wavelength cut-on filter was placed to exclude the excitation laser light while admitting ICG dye fluorescence light. Choroidal dye transit was recorded in 32 consecutive video angiographic images at a rate of 30 or 15 frames per second by two digital frame grabbers (model 2861-60, Data Translation [Marlboro, MA]) installed in a personal computer (Compaq, model 386/25e [Houston, TX]).

RESULTS

Figure 4 summarizes the angiographic findings obtained in this study by applying the image subtraction
FIGURE 3. A and B are ICG fluorescence images showing a 50-degree field of view centered on the macula of a right eye; the images were made one-thirtieth of a second apart. C is the result of subtracting image A from image B, and D is simply an enlargement of C. Note that in the resultant image C, lobular structures are seen that were not apparent in either of the original images. Also, instead of the dye-filled retinal arteries seen in the original images, only a dye wavefront representing the movement of additional dye into the retinal arteries near the disc is seen in the resultant image.

Algorithm. In this example case, each image in a 15 frames per second ICG angiographic sequence was subtracted from the image immediately following it; the images in the figure were selected from the resulting sequence of subtracted images. Dye first enters the macular area of choriocapillaris, which lies temporal to and above the points at which the short posterior ciliary arteries enter the eye (Fig. 4A). A lobular pattern can be seen in the center of the angiogram, particularly just nasal to the center; here a cluster of unfilled lobules is shown. The entire central area is completely filled 0.133 seconds later (Fig. 4B), although two smaller clusters of late-filling lobules may be seen superior to the center. Choriocapillaris filling progresses almost radially from the macular region. By close inspection of this image, faint loss of fluorescence around lobules can be seen; these likely correspond to choriocapillaris drainage channels.

Figure 4C, 0.200 seconds later, indicates that the radially oriented wave of choriocapillaris dye filling has been completed, and dye distribution at the posterior pole region appears fairly uniform. This image indicates that the first wave of dye filling is complete within the center of the macular region, as indicated by the appearance of relatively hypofluorescent areas that were hyperfluorescent in Figure 4A. In Figure 4D, 0.133 seconds later, it appears that the first wavefront of dye filling has reached the peripheral region; at this stage, Figure 4D is nearly a complete reverse contrast image of Figure 4A. The wavefront of dye filling traveled radially from the macular region to the periphery of the 30-degree field of view in approximately 0.466 seconds. This overall filling pattern was present in each eye observed, and details of the filling patterns were remarkably consistent from observation to observation for each subject eye.
FIGURE 4. Four images of a left eye selected from a sequence of images produced by subtracting each image in a 15 frames per second ICG angiographic sequence from the image immediately following it. Each image shows a 30-degree field of view, centered just below this macular region. (A) Dye first enters the macular area of choriocapillaris, which lies temporal to and above the insertion points of the short posterior ciliary arteries. Arrows indicate unfilled lobules. (B) 0.133 seconds later, the entire central area is completely filled. Arrows indicate late filling lobules. (C) 0.200 seconds later than B. Indicates that the radially oriented wave of dye movement through the choriocapillaris has been completed. (D) 0.133 seconds later, it appears that the first wavefront of dye movement has entered the peripheral regions. The wavefront of dye traveled radially from the macular region to the periphery of the 30-degree field of view in approximately 0.466 seconds.

Using a previously described method, each sequence of angiogram images was also analyzed to generate an intraocular pressure pulse profile and to determine the instantaneous distributions of full-choroidal-thickness relative blood flow rates at various intervals during one cycle of the intraocular pressure pulse. These distributions are shown in Figure 5 for the same angiographic study from which the data in Figure 4 were derived. The x-y plane of each three-dimensional surface corresponds exactly to the 30-degree field of view shown in the Figure 4 images; the height of any point on a surface above the x-y plane is proportional to the instantaneous relative choroidal blood flow rate at that location on the fundus.

During the systolic phase of the intraocular pressure pulse, blood flow rates increase throughout the choroid, but they are especially high at the center of the field of view, corresponding approximately to the location where the short posterior ciliary arteries enter the vasculature (Fig. 5, surfaces 4 to 6). The location of greatest blood flow rates at the end of systole (surface 6) corresponds to the macular area, where in Figure 4A the choriocapillaris lobular structures are most evident. During the early part of the
Image number 16 18 20

arily into the submacular choroidal vasculature during systole is radically dissipated toward the periphery during diastole. This is consistent with the radial progression of choriocapillaris dye filling shown in Figures 4B and 4C. Starting at the dicrotic notch and throughout the late part of the diastolic phase of the intraocular pressure pulse, the distribution of relative blood flow rates changes such that the submacular rates become increasingly lower with respect to the peripheral rates (surfaces 11 to 13). Interestingly, surface 13 approximates a cast of surface 6, just as Figure 4D is approximately a reverse of Figure 4A.

In the peripapillary region where a large number of short posterior ciliary arteries enter the globe, the dye filling pattern is consistent with a freely communicating vascular network. Elsewhere, especially in the macular area, it appears that a finite number of lobules are discretely filled by individual arterioles. This filling pattern is easily seen in Figure 3 and is strongly suggested in Figure 4, in which choriocapillaris filling begins with a finite number of lobuli concentrated most heavily in the region above which insertion of the short posterior ciliary arteries occurs. Thereafter, filling with dye-tagged blood appears for the most part to progress as a wave radially expanding from this epicenter toward the periphery.

**FIGURE 5.** (Top) Intraocular pressure pulse curve derived from the same angiographic data used to generate the images in Figure 4. (Bottom) Three-dimensional surfaces indicating the distribution of instantaneous relative choroidal blood flow rates at various intervals of the pressure pulse curve, as indicated by the surface numbers corresponding to image numbers on the abscissa of the pressure pulse curve. The x-y plane of each three-dimensional surface corresponds exactly to the 30-degree field of view shown in the Figure 4 images; the height of any point on a surface above the x-y plane is proportional to the instantaneous relative choroidal blood flow rate at that location on the fundus. The letters A to D indicate the intervals and surfaces to which the images in Figure 4 correspond.

Instantaneous distributions of choroidal filling rates

**DISCUSSION**

The differing views of choroidal angioarchitecture focus only on the pattern of available blood flow pathways through the choriocapillaris; they address only one factor important in determining choriocapillaris blood flow. However, connections between the choriocapillaris and choroidal arterioles are interspersed among those between choriocapillaris and choroidal venules in such a way that it is not always clear whether certain arterioles are surrounded by venules or visa versa. Consequently, only a direct observation of the blood flow pattern can suffice to determine which vessel type is central and which is peripheral.

The existence or nonexistence of a homogeneous lobular pattern notwithstanding, it is clear that the choriocapillaris is a continuous labyrinth of vascular channels through which it is possible to pass from one location to another without leaving the capillary vessels layer. Although numerous arteriolar and venular vessels are connected to the choriocapillaris vascular network, it has been demonstrated that the entire network can be filled with a substance injected through any single choroidal artery. What then determines the blood flow patterns in the choriocapillaris—lobules, in particular—is not only the distribution of arterioles and venules connected to it, but also the relative distri-
The distribution of blood pressure gradients extant between those arterioles and venules at any given instant. Given the complex geometry of the vessel network connected to the choriocapillaris, it is conceivable that pressure in one arteriole feeding one lobule could be slightly higher than that in another arteriole filling an adjacent lobule, such that blood from the first lobule might flow into or even through the adjacent one. Flow may not even necessarily exist through every arteriole or venule during each cardiac cycle. Such hemodynamic possibilities, however, cannot be determined with certainty by studying only the static component (the architecture and geometry of the chorioidal vasculature); angiographic studies are needed to determine these dynamic relationships.

Because of the multilayered organization of the choroidal vasculature, observation of the choriocapillaris with fluorescent dye angiography is best accomplished when a very small volume dye bolus with a sharply defined wavefront passes through. Obviously, progression of a sharply defined wavefront is more easily tracked through the capillary network than an ill-defined one, and if the bolus volume is small enough essentially to clear the underlying vascular layers by the time it enters the choriocapillaris, images of the dye-filled capillaries will be of higher contrast than when significant fluorescence from beneath is simultaneously present. Unfortunately, neither of these conditions is readily produced by intravenous injection, even though passage of a dye bolus through the choroid can be optimized by appropriate injection technique. As a consequence, it is extremely difficult to isolate choriocapillaris dye filling in raw ICG fluorescence angiograms even when they are recorded at high speed, but as an alternative, the subtraction enhancement algorithm demonstrated here makes it possible to extract information about choriocapillaris dye filling by taking advantage of the differences in large vessel and choriocapillaris blood flows that naturally exist. Instead of distinguishing choroidal layers by dye bolus appearance, dye filling rates can be used to separate them.

The premise that blood velocity through the choriocapillaris is greater than that in the underlying larger diameter choroidal vessels is contrary to what is ordinarily observed in vascular beds. The choroidal vasculature, however, is not an ordinary one, especially with respect to its capillary vessels. Whereas capillary diameters in most vascular beds range between 10 to 15 μm, widths of the relative flat choriocapillaris vessels range between 20 to 30 μm. These large vessels freely interconnect, especially beneath the macular area, in such a way that the ratio of vessel segment length (i.e., distance between bifurcations) to vessel diameter (i.e., width, in the case of the choriocapillaris) is nearly 1. In most other vascular beds, where that ratio is much larger and the smaller capillary diameters force blood cells to move through them one-by-one instead of side-by-side as in the choriocapillaris, capillary bed resistance to blood flow is significant, contributing to low blood velocity. Moreover, unlike other vascular beds in which there is a gradual transition from large vessels to capillaries through arterioles and venules, the transition from large choroidal vessels to the thin, wide choriocapillaris vessels is sudden, and the choroidal arteries enter the choriocapillaris nearly perpendicularly.

In addition to vascular geometry, blood flow through choroidal arteries and the choriocapillaris is a complex function of many other parameters, including blood viscosity and hematocrit, and not enough is known about that function to describe the blood flow rigorously, but it is clear that choroidal angioarchitecture is sufficiently atypical that atypical blood flow might be expected. For example, it appears that the abrupt perpendicular interfacial between arterioles and the wide, flat choriocapillaris may behave somewhat like a relief valve, closing until the elastic compliance of the artery is exceeded as blood fills and expands it, and then opening to release a high-velocity microbolus of blood into the low resistance choriocapillaris. Such a mechanism would account for the fluorescence pulsations observed and is consistent with the 1 to 2 sec. lobule dye transit time observed in image sequences, as in Figure 4. Because the lengths of the many arterioles entering the choriocapillaris differ, their compliance volumes and, hence, the operating frequencies of the "relief valves" with which they terminate would vary. An array of such relief valves throughout the choriocapillaris would act effectively to prevent the entire choriocapillaris surface from moving in phase, thereby suppressing uniform displacement of the retina; this would be comparable to having soldiers marching across a bridge break step to avoid establishing resonance in the structure.

Another phenomenon that may contribute to the ability to differentiate between blood flow in large choroidal vessels and in choriocapillaries by use of the subtraction algorithm is the fact that fluorescence of ICG-stained plasma is significantly greater than fluorescence of ICG-stained whole blood. The explanation for this phenomenon is that scattering of light by small particles in plasma can result in increased excitation of available dye molecules, whereas scattering by large erythrocytes in whole blood can result in reduced excitation of dye molecules present in deeper layers of the blood volume. Using venous blood and plasma from human ICG angiography subjects, Scheider et
al14 determined that plasma fluorescence is about six times greater than that of whole blood; they speculated that because “the hematocrit is significantly reduced in capillaries,” the persistent macular fluorescence typically seen in late phase ICG angiograms “must be caused by retinal and choroidal capillaries with a significantly reduced hematocrit.” Reduced choroidal hematocrit presumably is meant to describe the microbubbles of plasma that separate individual erythrocytes as they move one-by-one through capillary vessels. And although erythrocytes are not constrained to move single file through the choriocapillaries, the flat, wide profile of these vessels probably constrains them to move through in a single layer, thereby exposing a margin of plasma around each cell. Thus, during transit of an ICG dye bolus, the choriocapillaris’ thin cross-section might be compensated for by plasma fluorescence brightness that is on par with that of the underlying larger vessels, making detection of choriocapillaris fluorescence easier than might otherwise be expected.

Because the choroidal vascular network consists of many interconnected vessels of varying diameters and compliances, it may be expected to respond non-uniformly and nonlinearly to changes in those parameters that influence blood flow through it. Nevertheless, in some previous fluorescein angiographic studies, to overcome the relatively poor temporal resolution of fluorescein angiograms (three to four images per second), choroidal blood flow velocity was reduced by artificial elevation of intraocular pressure in an attempt to discriminate various phases of choriocapillaris dye filling in the angiograms. Reduction of transmural pressures throughout the choroidal vascular network by stepwise elevation of intraocular pressure will not, however, result in uniformly proportional reduction in blood movement throughout that network. For example, according to the law of Laplace, the closing transmural pressure of a blood vessel is inversely related to its unstretched radius; hence, for any subset of all choroidal vessels having the same wall thicknesses (i.e., in which the wall tensions are assumed to be equal), those with smaller luminal radii will tend to close at a lower level of applied intraocular pressure than those with larger luminal radii, thereby producing an unrealistic configuration of the choroidal vascular network and unrealistic blood flow patterns. To avoid such situations, it is necessary to use a method for blood flow observation, such as the one described in the present study, that minimally disturbs normal physiologic conditions.

For the most part, results obtained by application of the subtraction enhancement algorithm to ICG angiographic studies are consistent with the choriocapillaris organization described by Fryczkowski et al as opposed to that described earlier by Toranczski et al (and supported by the angiographic studies of Hayreh) in that they suggest that the posterior pole choriocapillaris does not behave as a homogeneous structure and that it appears, in fact, that blood may flow from one choriocapillaris segment (i.e., lobule) to another. An explanation for differences in the conclusions of the two earlier histologic studies may be attributed to the fact that the first study was based on observations made of pieces of the choroidal vasculature, whereas the second had the advantage of observations made on essentially intact whole choroidal vascular casts, making possible both anterior and posterior views of specific structures and their relationships with the rest of the vascular network.

ICG fluorescence angiography gradually is being used more frequently by both researchers and clinicians to investigate the choroidal circulation. Clearly, as such new tools are applied in a variety of new ways to study the choroid, old concepts about it and its physiology will be revisited, and some will change or give way to entirely new concepts. Fortunately, some approaches to analyzing choroidal angiograms, such as the one discussed here, may be applied both in animal and in human clinical research with complete safety, perhaps hastening a better understanding of choroidal blood flow in health and disease.

Key words
choroidal blood flow, ICG angiography, image analysis

References