Quantitative studies of choroidal blood flow by reflective densitometry

Stephen Trokel

Because of the small blood flow and unusual vascular distribution patterns, it is difficult to measure blood flow directly through the arteries and veins of the eye. The ophthalmoscopic technique of reflective densitometry avoids these problems by measuring blood flow through the pupil in a known portion of the eye. Normal values of flow and volume have been determined as have changes with different experimental conditions. The advantages of the method may be summarized. First, it does not require surgical intervention anywhere near the eye. The eye is left in a relatively undisturbed state during the measurements. Second, continuous monitoring of the choroidal blood volume is made. Then, multiple measurements of blood flow can be made which require very short sampling times. Finally, the exact area being studied is known. The chief limitation of the method is the maximum of about five serial measurements of blood flow that are possible for each experiment. Other problems arise from the necessity for rigidly supporting the animal and his eye to align the optical bench properly. In these experiments we have extended ophthalmoscopic studies of the posterior pole of the eye to obtain quantitative information about its vascular layers. The usefulness of this approach has been demonstrated by the experiments performed which investigate the reactivity of the choroid.

The purpose of the vascular system is the creation of a flow of blood and the movement of this blood to and from the tissues. The vascular physiology of the eye can be understood only when quantitative measurements of its blood flow have been made. Our understanding of the ocular blood flow has been impeded by the difficulties involved in making these measurements.

The characteristics of an ideal technique to study ocular blood flow are similar to those required at any small, metabolically active region of the body. The ideal technique would permit continuous sampling of the ocular blood flow and would allow continuous measurement of the ocular blood volume and the intraocular pressure. It should not disturb the eye nor require local surgical intervention. Direct catheterization, ligation, or cutting of vessels should be avoided. The accuracy and precision of the ideal method should be high.

The problems that must be overcome to study the ocular circulation are inherent in the small size of the eye and, in absolute terms, the small amounts of blood that flow through it. The weight of a human globe is about 7.5 grams with a volume of about 6.5 c.c., and a rabbit globe weighs about 2 to 3 grams. The rabbit eye has a total blood volume of about 40 μl and a total blood flow of about 2 ml per minute or 30 μl per second.
The small size of the eye and the small amounts of blood that are present introduce difficulties that are compounded by the inaccessibility of the globe in its bony orbit. The vessels which supply the eye with blood all arise from the posterior, most inaccessible portion of the globe. These vessels have multiple anastomotic sources and multiple sites of entry into and exit from the eye.

The major direct blood flow paths in the eye are outlined in Fig. 1. This chart excludes contralateral contributions to the ophthalmic artery and blood flow paths via the circle of Willis. The eye, the cerebrospinal fluid space, and the orbit are three separate local compartments whose pressures should be considered in flow analysis. Three distinct portions of the intraocular circulation must be appreciated. First is the retinal circulation which usually has no anastomoses with the uveal circulation. Then, there are the anterior and posterior uvea or choroid which have sufficient anatomical and functional differences to be considered two separate circulations.

The measurement of blood flow through single afferent or efferent vessels is highly unreliable due to the unknown distribution of blood in the many channels of flow diagrammed in Fig. 1. This suggests that measurement of blood flow should best be undertaken in the eye itself. This paper shows how this can be accomplished for the choroid by measuring changes in the intensity of light reflected from the eye's posterior pole when light absorbing dyes are injected into the bloodstream. When the posterior pole is illuminated in Maxwellian view, the light can be placed so that the vascular space of the choroid will be the only vascular tissue in the illuminated area.

In both man and rabbit the choroid has a trilamellar pattern. The outer layer of large vessels is known as Haller's layer and the inner small vessel layer is the choriocapillaris. The intermediate vascular layer, or Sattler's layer, occupies the plane between Haller's layer and the choriocapillaris. This intermediate layer contains arteries and some capillaries which seem to pass directly to the choriocapillaris, which functions as a capillary system. The chorioidal arteries and veins lie side by side in the large external layer.

There is an unusual flow pattern in this trilamellar structure. The over-all direction of flow is from the posterior short ciliary arteries to the vortex veins, which are anteriorly located. The blood in Haller's layer
must therefore be flowing in the same direction in both the arteries and the veins. Between these large arteries and the veins the blood will flow perpendicular to the main flow to reach the choriocapillaris. After blood reaches the choriocapillaris, it is drained by the efferent venules which run obliquely into Sattler’s layer. This oblique direction persists and the veins anastomose into the large veins of Haller’s layer, where they run to the vortex veins to leave the globe. This unusual flow pattern will be referred to later in the analysis of changes in reflected light when dye circulates through the eye.

General considerations

The technique of measuring light reflected from the posterior pole of the in vivo eye was developed and widely used by retinal physiologists. The basis of their experiments was that the image of the posterior pole of the eye arises from light that has been diffusely reflected from the sclera. Because this returning light must have passed through the vascular tissues, any changes in light absorption by the vascular compartment will change the total amount of returning light. It is the analysis of this returning light that allows qualitative and quantitative estimation of the blood volume and flow in the choroid.

Changes in light absorption by the vascular tissue of the choroid may be obtained by the injection of light-absorbing dyes, such as T-1824 (Evans blue), into the bloodstream. These dyes will increase the optical density of the vascular coat and reduce the amount of light returning from the eye.

Before the entering light reaches the sclera, some light will return by the process of light scattering. Corneal, lenticular, vitreal, and retinal elements will all contribute to the returning light rays. In order to analyze the light that returns from the eye, we must make several assumptions. First, the ocular media are optically inactive and isotropic. Second, the amount of light scattered back by the preretinal media and the retinal layers is a small constant fraction. We know the vascular coat is not uniform but has an irregular spatial distribution of large and small vessels. However, if the fraction of light absorbed is small, then dye in the vascular space will absorb light as if it were uniformly distributed.

Let us now consider the reflected light from an eye in detail. Let \( L_i \) be the light entering the eye. \( L_a \) can represent the light scattered back by the preretinal media, and \( L_r \) that light reflected from the sclera which leaves the eye. The total light leaving the eye can be called \( L_t \). If \( D \) represents the optical density of the vascular space of the eye, then the light reaching the sclera will be reduced so that:

\[
\text{Light reaching sclera} = (L_i - L_s)10^{-D},
\]

and the light reflected back through the eye will be:

\[
\text{Light reflected} = (L_i - L_s)R10^{-2D},
\]

where \( R \) is a reflectivity coefficient.

Therefore, the total light leaving the eye can be expressed as:

\[
L_t = L_r + L_s = (L_i - L_s)R10^{-2D} + L_s
\]

where \( S \) equals a scattering coefficient.

Since we know that the intensity of scattered light is much less than the incident intensity, we can write:

\[
L_i > > L_s
\]

and therefore,

\[
L_t = L_i R10^{-2D} + L_s S.
\]

Consider the three cases of reflected light when the optical density of dye in the vascular choroid has a value of 0, \( \infty \) and \( x \) units. By substituting in the above equation, we find:

\[
L_a = L_i S
\]

\[
L_s = L_s R + L_i S
\]

\[
L_r = L_r R10^{-2x} + L_i S
\]

Therefore:

\[
\frac{L_s - L_a}{L_s - L_a} = 10^{-x}
\]

*A similar analysis has been previously presented.*
and

\[ x = \frac{1}{2} \log_{10} \frac{L_x - L_{oo}}{L_x - L_{oo}} \]

This calculation gives us the optical density of the vascular tissue in terms of measurable values. By comparing the plasma optical density with this reflectively measured optical density, the average plasma thickness in the area of the measuring beam can be calculated. If the local hematocrit is assumed equal to a centrally measured venous hematocrit, then this can be converted to blood thickness and blood volume per unit area of choroid.

\[ \text{blood volume} = \frac{\text{plasma volume}}{100 - \text{hematocrit}} \]

It is emphasized that the measured data will apply only to the choroid in the area of the illuminating beam.

Making certain assumptions will allow an estimate to be made of the blood flow in this region. The unusual flow pattern that was described causes the choroid to act as a time delay system. The perpendicular flow is from the largest arterioles to the choriocapillaris and back to the largest venules. The blood, as it passes through the choroid, spends most of its time in the smaller vessels of the intermediate layer of Sattler and the choriocapillaris. This time represents the longest portion of the filling time required for normal blood in the choroid to be replaced with dye-carrying blood. Therefore, within certain limits, the filling time will be relatively independent of the area of the illuminated fundus. Because this area is a constant, this allows comparison of flow rates with precision. The assumption of an independent filling time introduces a possible source of error whose tendency to produce high results must be investigated further.

This filling time may be estimated from the record of inflowing dye. The dye inflow has a curved portion which arises from the spread of the dye bolus due to laminar flow and the pass through the pulmonary circulation. If the dye bolus had an infinitely steep concentration gradient as it entered the eye, then the filling curve of the choroid would be a straight line. The linear portion of the measured dye filling curve is extrapolated over the inflow portion of the dye curve to minimum and maximum values of reflected light. The time for the extrapolation to go from the maximum to the minimum value represents the filling time of the choroid. This extrapolation serves to compensate for the dye spread that has occurred.

**Methods**

*Experimental.* The experimental methods that allow us to obtain the data which are necessary to measure blood flow and blood volume are based on simple ophthalmoscopic principles. The optical bench used is a device which transmits the light reflected from the fundus onto the photocathode of a photomultiplier tube. We can see the necessary elements represented in Fig. 2. The coiled filament of a lamp, S, is at the focus.

![Fig. 2. The optical bench used to measure the light intensity reflected from an albino rabbit's eye. S is the light source. L1, L2, L3 are lenses. F is an interference filter with peak transmission at 620 mw. GP is a glass microscope slide, P is a Polaroid filter, and PM is an RCA 1P21 photomultiplier tube. (From Trokel, S.: Arch. Ophth. 71: 88, 1964.)](https://iovs.arvojournals.org/pdfaccess.ashx?url=data/journals/iovs/932955/)
of $L_r$. A glass plate, $GP$, is placed at the polarizing angle in the path of the beam. The light reflected by this glass slide is focused by $L_r$ into a Maxwellian view of the eye. This forms a retinal image of $L_r$ about 5 mm. in diameter on the fundus. An attempt is made to place this image on the choroid just superior to the optic disc. A plastic scleral contact lens contains the limiting aperture for the system and helps position the eye.

The light reflected by the eye is brought on to the cathode of a 1P21 photomultiplier tube, PM. An interference filter, $F$, with maximum transmission at 620 $\mu$m, is placed in front of the light source to select incident light complementary to the absorbing dye T-1824. A polaroid filter, $P$, is in front of the photomultiplier tube with its polarizing axis crossed with the polarized light reflected by $GP$. This reduces the intensity of the specularly reflected light that reaches the photocathode.

**Procedures.** Albino rabbits weighing more than 2.0 kilograms are anesthetized with Urethane for these experiments. Tracheotomies are performed on all animals to assure free respiratory exchange. In most experiments the animal's pupil is atropinized preceding the experiment. The minimum preparation for normal animals requires placement of a No. 50 polyethylene catheter into the inferior vena cava via the femoral vein. Additional catheters are placed into the aorta and posterior auricular artery homolateral to the eye being studied.

After preparation the animal is placed in a head holder attached to a movable board. The animal's position is then adjusted so that the eye to be studied is in alignment with the optical bench. The room is darkened and the base line of reflected light, $L_0$, is the corrected estimate of reflected light that reaches the photocathode.

A typical record is shown in Fig. 3. $P_e$ is the pressure recorded in the posterior auricular artery and $P_a$ is the pressure in the aorta. $Sig$ is a one-second signal marker. This represents the light reflected from an albino fundus when 10 mg. of T-1824 dye is injected. $L_e$ represents the base line of reflected light, and $L_r$ is the light reflected when the dye reaches circulating equilibrium; $L_{on}$ is the light reflected when the retina is covered with an infinite dye concentration; $t$ is the corrected estimate of the choroidal filling time.

A sample calculation for this record will clarify the principles involved here:

$\Delta L_e = 45.8$

$\Delta L_r = 36.8$

Therefore, according to equation derived for $x$, the choroid's vascular optical density can be calculated as:

$x = 0.0475$.

The serum optical density equals 5.18. Therefore, the average serum depth is 0.0917 mm., and the average serum volume is 9.17 $\mu$l per square centimeter of choroid. Since the central hematocrit is 37.1, the
Fig. 3. Change in intensity of reflected light when 10 mg. of T-1824 dye is injected into the inferior vena cava of an albino rabbit. $L_0$ is the light reflected when there is no dye in the circulating blood. $L_x$ is the light reflected when the injected dye reaches circulatory equilibrium and $L_\infty$ is the light intensity when there is essentially an infinite dye concentration in the blood. $t$ is the corrected filling time. $P_e$ is the pressure in the posterior auricular artery, and $P_a$ is the pressure in the aorta. Sig is a one second signal. Reflected Light indicates the intensity of light measured by PM. inj marks the injection of the T-1824 dye.

### Table I. Normal values

<table>
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<tr>
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<th>Blood flow (µl/sec./cm²)</th>
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</thead>
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<td>4.2</td>
</tr>
<tr>
<td>18</td>
<td>10.3</td>
<td>7.1</td>
</tr>
</tbody>
</table>

Mean 11.2; sd 2.5. Blood flow, 8.0; sd 2.6.

average blood volume is 14.6 µl per square centimeter of choroid.

$t$ is measured equal to 1.65 sec.

Therefore,

\[
\text{Blood flow} = \frac{\text{blood volume}}{\text{filling time}} = 8.9 \, \mu\text{l/sec./cm.}^2 \text{ choroid.}
\]

### Experimental results

The results of experimental determination of blood flow and blood volume in normal animals are listed in Table I. The average blood volume in these 18 animals is 11.2 µl of blood per square centimeter of choroid. The average blood flow rate is 8.0 µl of blood per second per square centimeter of choroid.

To compare these values to those found by other methods, it is necessary to convert blood flow per unit area to blood flow per unit mass of tissue nourished. This can be done by estimating the weight per unit area of the tissues supplied by the choroid in the area of the measuring light beam. In this region, the choroid supplies the entire uvea and the overlying retina because of the absence of a separate retinal blood supply.

To make the conversion, a 7.0 mm. diameter punch was used to make circles of
The conversion factor was calculated:

\[ \text{Weight per unit area} = 29 \text{ mg. per cm.}^2 \text{ choroid.} \]

This factor is of low accuracy because of the difficulty in separating the vitreous body from the face of the retina. The blood flow per 100 Gm. of tissue can be calculated:

\[ \text{Blood flow} = 1,680 \text{ ml./min./100 Gm. tissue.} \]

We can at this point compare the quantitative data with results obtained by other workers. Friedman, Kopald, and Smith reported the use of the $^{85}$Kr washout technique in albino rabbits to find a single rapid component with a half time of 2½ to 5 seconds. This calculates to a blood flow of 830 to 1,700 ml. per minute per 100 Gm. of tissue and compares to the mean blood flow of 1,680 ml. per minute per 100 Gm. of tissue reported from these experiments. Even though the value obtained by reflective densitometry is at the high end of this range, the agreement between the methods is reassuring.

The possibility exists that this high flow rate is based on a true difference of blood flow. Reflective densitometry studies the choroid at the posterior pole of the eye. The GM tube used to measure $^{85}$Kr washout is of necessity more anterior than the measuring beam of light used in reflective densitometry. The choroid is thickest at the posterior pole and it thins anteriorly. This anatomic difference may result in larger blood flows in these experiments.

It is possible to compare the choroid blood volume as determined in these experiments with the volumes determined by Vilstrup in her injection studies of the rabbit choroid. In seven rabbits, she measured an average weight of 15 mg. of plastic as necessary to fill the choroid. In these experiments, the mean blood volume is equal to 11.2 $\mu$l per square centimeter of choroid. As indicated before, this measurement is made in the posterior choroid in its region of highest blood flow and volume. The rabbit choroid is roughly 2 cm.$^2$. This would represent a blood volume of 22 $\mu$l, if the choroid were uniformly thick. This is somewhat larger than the 15 $\mu$l measured by Vilstrup. The disparity probably arises from the nonuniformity of the choroidal vasculature. A second possible source of error may arise from the underestimation of the blood volume by the injection technique due to incomplete filling.

The general agreement among the results suggests the validity of the many assumptions made in the three methods. It supports the usefulness of these different methods for studying the choroidal blood volume and flow.

Studies of the reactivity of the choroidal vasculature

We will now review three groups of experiments that have been performed using this technique. The first group studied the effect upon the choroid of breathing different gas mixtures: (1) 100 per cent oxygen; (2) 10 per cent carbon dioxide, 69 per cent nitrogen, and 21 per cent oxygen; and (3) 10 per cent carbon dioxide and 90 per cent oxygen. The resultant vascular changes are summarized graphically in Fig. 4. After the albino rabbits breathed 100 per cent oxygen for a 10 minute period, there was a 14.2 per cent decrease in choroidal blood volume. This was accompanied by a 32 per cent decrease in blood flow and a 69 per cent increase in vasomotor tone. Breathing the gas mixtures containing carbon dioxide gas had the opposite effect upon the choroid. A mixture of 10 per cent carbon dioxide, 21 per cent oxygen, and 69 per cent nitrogen produced a 55 per cent increase in blood volume, a 60 per cent increase in blood flow, and a 32 per cent decrease in vasomotor tone. Using a test gas with the same percentage of carbon dioxide but a higher percentage of oxygen produced a similar but smaller effect. A mixture of 10 per cent carbon dioxide and 90 per cent oxygen produced a 22 per cent increase in blood volume, a 15 per cent increase in blood flow, and a 13 per cent decrease in peripheral resistance.

Elevation of the blood carbon dioxide
has been shown to serve as a potent stimulus to decrease the resistance of the cerebral circulation, and elevated inspiratory oxygen concentrations have been shown to increase resistance of the cerebral vessels. The retinal circulation has been shown to behave in a similar manner. The experiments reported here show the remarkable similarity of the response of the choroid to the response of the brain and the retina when the inspiratory gas contains elevated carbon dioxide or oxygen concentrations.

In the second group of experiments, homolateral and bilateral carotid ligations were performed to study the effect upon the blood flow in the eye. The orbital arterial pressure was deduced from measured changes in the ear artery pressure. In Table II, we see the salient finding of the experiment was that the drop in the arterial pressure following carotid closure was not accompanied by a corresponding drop in choroidal blood flow. This is best accounted for by postulating a reduction in vasomotor tone which results after the drop in arterial pressure. The measurement of blood flow was made as soon as the regional pressure restabilized, which occurred within several minutes of vessel closure. The drop in vasomotor tone must, therefore, occur quite rapidly following local hypotension.

The findings of a compensatory drop in vasomotor tone with ligation of the carotid arteries are in agreement with those found by Linner. He measured vortex vein output 24 hours after carotid ligation. This contrasts with Cohan and Cohan, who believed the uvea acted as a system of rigid tubes when they found that blood flow was linear with the pressure gradient in the eye. Their results may be associated with the local effects of the large doses of barbiturates that were used to lower the blood pressure. The carotid ligation experiments of Linner and those reported here would seem to refute the idea that the choroid is a passive nonreactive struc-

Fig. 4. Vascular changes in the choroid when the albino rabbit's respiratory gas is changed from air to the indicated gas mixture. The base line of 100 per cent represents the blood volume, blood flow, and peripheral resistance when the animal is breathing air. The bars represent the percentage of change in these values after the animal has breathed the test gas mixture for a 10 minute period. The 10 per cent carbon dioxide and 90 per cent oxygen group represents the average of 5 animals. The other two groups each represent 6 animals. (From Trokel, S.: Arch. Ophth. 71:88, 1964.)
ture but suggest the opposite. The choroid appears to be a responsive vascular structure that has homeostatic mechanisms which serve to maintain its blood flow rate in the presence of arterial hypotension.

The third group of experiments are studies of the effects of norepinephrine and isoproterenol upon the choroid's blood volume. The change in volume with an increasing perfusion rate of norepinephrine is shown in Fig. 5. An increase in reflected light intensity means there is less blood in the choroid. At the perfusion rate of 4 mcg. per minute, a choroidal vasoconstriction is demonstrated with no change in the aortic pressure. At higher perfusion rates of 10 mcg. per minute, an effect of slightly greater magnitude is seen associated with a systemic hypertension. Increasing the drug dose to 20 mcg. per minute does not increase the local effect. A large systemic pressor response is seen at these higher dosages. Saline perfusion at high rates of flow causes some hemodilution with a small amount of increased light reflection.

Isoproterenol is a sympathetic amine known to produce vasodilatation. We are, therefore, surprised to demonstrate in Fig. 6 an increased light intensity indicating a local vasoconstrictive effect on the choroidal blood volume. This constriction occurs in the face of systemic hypotension due to vasodilatation at other sites.

The studies of the effect of norepinephrine have been extended to include simultaneous measurement of the intraocular pressure during the period of drug perfusion. In Fig. 7 we see the results of perfusing the eye with 8 mcg. per minute of

![Fig. 5. Record of changes in reflected light intensity when the animal's homolateral lingual artery is perfused with norepinephrine (20 mcg. per milliliter) and saline. \( P_a \) is the pressure in the aorta and \( \text{Light} \) represents the measured intensity of reflected light. The upper line is a one-second signal mark. There are 25 seconds between the heavy vertical lines. The perfusion at 4 gamma per minute is seen to constrict the choroid with little change in the systemic pressure. Increased rates of perfusion increase the response and a maximum effect is seen associated with a systemic pressor effect. The details of the response curve cannot be explained. Saline perfusion shows that hemodilution by the perfusate is a small factor only at rates greater than 1 ml. per minute. This is equivalent to 20 mcg. per minute of norepinephrine.](image-url)
Fig. 6. Perfusion of homolateral lingual artery with isoproterenol (10 mcg. per milliliter) and saline. Sig is the one second signal, Pa is the aorta pressure and Light is the intensity of reflected light. A vasoconstriction at 20 mcg. per milliliter was demonstrated.

Table II. Effects of carotid ligation on the choroid

<table>
<thead>
<tr>
<th>Animal</th>
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<th>Control values</th>
<th>Homolateral ligation</th>
<th>Bilateral ligation</th>
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<tr>
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*BV is blood volume in microliters per square centimeter of choroid; BF is blood flow in ml/sec./cm.² of choroid; Pe is the pressure in the posterior auricular artery, and PRU is the peripheral resistance, equal to Pe divided by BF.
Fig. 7. Perfusion of homolateral lingual artery with norepinephrine. In this record IOP represents the intraocular pressure measured with a No. 27 needle in the anterior chamber. Sig is a one-second signal. $P_a$ is the aorta pressure, and Light represents the intensity of reflected light. A marked simultaneous vasoconstriction and ocular hypotension is seen to accompany the perfusion of norepinephrine at 8 mcg. per minute.

Fig. 8. Perfusion of homolateral lingual artery with norepinephrine and Dibenzyline block. This records the response of the choroid to 8 mcg. per minute of norepinephrine before and after the slow intravenous injection of 10 mg. of Dibenzyline. The labels are the same as those employed in the preceding records. We see an initial vasoconstriction that does not occur after the intravenous Dibenzyline. This reaction characterizes the presence of alpha sympathetic receptors in the choroid.
norepinephrine. The expected vasoconstriction occurs and is synchronous with a large drop in the intraocular pressure from 18 to 10 mm. Hg. Both of these effects are reversed by stopping the drug perfusion.

The nature of this vasoconstriction is further elaborated in the experiment summarized in Fig. 8. Here, the norepinephrine vasoconstriction is antagonized by treating the animal with a slow intravenous injection of 10 mg. of Dibenzyline, a well-known sympathetic alpha receptor blocking agent.

These experiments with catechol amine perfusion have demonstrated sites of active vasoconstriction in the choroid. These sites are blocked by exposure to Dibenzyline. This pattern of reactivity is characteristic of alpha sympathetic receptors and proves their presence in the choroid. The large drop in intraocular pressure is temporally coincident with the drug-induced vasoconstriction. This is an expected finding because this vasoconstriction reduces the intraocular volume and hence the pressure.

I would like to thank Dr. William Hagins for suggesting the use of reflective densitometry to study ocular blood flow.

REFERENCES


