Entoptic Visualization of the Retinal Vasculature Near Fixation

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The authors review (1) the range of techniques used to study the retinal vasculature near the fovea, (2) describe the need and rationale for noninvasive in vivo monitoring of the retinal vasculature, (3) present theoretic and practical considerations which show that entoptic visualization of the smallest capillaries near the fovea is optimized by a small short-wavelength source (1 mm or less) rotating at 3.5 hertz in a circular path (radius 2 mm) imaged in the plane of the eye's entrance pupil, and (4) discuss the feasibility of using these techniques as a research and clinical tool. Invest Ophthalmol Vis Sci 31:2088-2098, 1990

In foveated primates, the presence of a foveal avascular zone (FAZ, Fig. 1) has been generally accepted since it was first reported over 130 years ago.1 Teleologically, it is argued that the presence of a FAZ and the thinning of the inner retinal layers at the fovea (Fig. 2) increases the optical quality of the image presented to the foveolar cones.2

Techniques to study the FAZ can be classified into three categories: anatomic, angiographic, and psychophysical. Anatomic studies in humans and other primates include whole mount3 and flat mount after trypsin digestion,4-6 and injection with India ink,7 neoprene latex,8 and derivatives of methacrylic esters9 (Fig. 1). While anatomic studies often provide eloquent detail of the vasculature surrounding the foveal area (Fig. 1), they do not allow in vivo monitoring of changes in the vasculature and may be misleading. For example, latex injection under pressure may open anatomic connections which are not operative under normal physiologic conditions.

Fluorescein angiography, as well as angiography with other dyes have been used to study the retinal vasculature and FAZ in both healthy and diseased eyes in vivo. Laatikainen and Larinkari10 reported FAZ diameters around 0.57 mm for 167 eyes of 158 healthy patients (mean, 0.572; range, 0.23-0.83 mm). Bresnick et al,11 in a study of the FAZ in diabetics, reported FAZ diameters between 0.58-1.00 mm with a mean of 0.73 mm for the normal control group (nondiabetic). Together these findings are consistent with the anatomic findings of Bligard et al,6 where postmortem human-eye FAZ diameters were reported to range from 0.12-1.2 mm (mean, 0.65 mm) using trypsin digestion. In diseased eyes, the FAZ has been reported to be smaller than normal in patients with cicatrical retinopathy of prematurity12 and larger than normal in vascular occlusive diseases such as diabetes,11 sickle cell retinopathy,13 talc embolic retinopathy,14 and retinal branch vein occlusion.15

Although fluorescein angiography is generally accepted as the standard procedure for in vivo study of the human retinal vasculature, it is an invasive procedure not generally repeated daily or even weekly. Furthermore, using fluorescein angiography to obtain the capillary detail necessary to study the FAZ and the vasculature near the fovea requires clear optical media and skilled photographic personnel. Even if photographic conditions are ideal, the angiographic detail of the foveal area vasculature may be variable in quality depending on the density of the macular pigment and variations in normal fundus pigmentation. These limitations have led investigators to explore the use of noninvasive psychophysical techniques.

There are two different psychophysical procedures for entoptically evaluating the foveal area vasculature. First, even in the presence of cloudy ocular media,16 viewing a bright uniform blue field (430 nm) allows the entoptic visualization of leukocytes ("flying corpuscles") in the retinal capillaries surrounding the foveal area.17,18 Careful observation of the phe-
nomens reveals an area apparently centered on fixation (the FAZ) where no leukocytes are seen. Yap et al.\textsuperscript{19} capitalized on this phenomenon to measure, in one eye of 22 normal subjects, FAZ diameters ranging between 1.92–2.86° (0.59–0.83 mm on the retina assuming a secondary nodal point-to-retina distance of 16.67 mm). Earlier estimates using the same entoptic phenomena found the diameter of the FAZ to be approximately 1.5° as measured in object space or 0.44 mm on the retina\textsuperscript{20} (Weale quoted by Dartnall and Thomson\textsuperscript{21}). Although entoptic visualization of leukocytes provides a noninvasive method for making inferences about the FAZ and the vasculature of the foveal area, it does not provide a view of the retinal vessels themselves.

Direct entoptic visualization of the retinal vasculature can be achieved by allowing light to enter the eye from unusual or constantly varying angles. This effect, first noted by Purkinje\textsuperscript{22} in 1819, is strikingly distinct and often spontaneously reported by patients during routine ophthalmoscopy. Bird and Weale,\textsuperscript{23} using both fluorescein angiography and entoptic visualization of the retinal vasculature by scleral transillumination, noted that not all normal individuals with excellent visual acuity have FAZs which are truly avascular. They found that, unless extreme care is taken during the entire photographic process, vascular details in the FAZ may not be imaged (or seen) with fluorescein angiography but are visible entopically. These findings corroborate the earlier fluorescein angiographic work of Yeung et al.\textsuperscript{24,25} and emphasize the potential sensitivity of entoptic viewing of the central retinal vasculature.

Clinically, entoptic visualization has been used to help evaluate the functional status of the retina behind obstructed media.\textsuperscript{26} More recently it has been used as a guide to train eccentric fixators to improve fixation\textsuperscript{27} and to study the normal variation in the size and shape of the FAZ.\textsuperscript{28} To the best of our knowledge, only one study has used entoptic visualization to monitor an active disease state. Kluxen and Wilden\textsuperscript{29} taught 136 insulin-dependent diabetics how to observe their retinal vasculature entoptically. In patients with one to five microaneurysms, as revealed by fluorescein angiography, 55% could entoptically detect their own pathology. In patients with six to 20 microaneurysms, the percentage increased to 77%. In patients with greater than 20 microaneurysms with severe background and proliferative retinopathy, 90% could reliably detect their own pathology, and many could document the appearance of new and disappearance of old microaneurysms over time.

Although entoptic visualization of the retinal vas-
culature is impressive in its apparent detail, capturing this detail in a quantifiable manner is difficult. First, entoptic visualization is subjective by nature. Second, foveation of various intricacies of the vascular detail is impossible because the entoptic image remains fixed with respect to the retina (i.e., the location of the retinal vasculature is fixed with respect to the photoreceptors; therefore, eye movements cannot foveate the vessel of interest). Together these effects have limited the usefulness of this phenomenon. To minimize these problems, we attempted to enhance stimulus effectiveness by presenting the test stimulus in Maxwellian view and optimizing stimulus movement.30,31

The use of Maxwellian view for entoptic visualization of the retinal vasculature was first alluded to by Helmholtz32 in his Treatise on Physiological Optics where, in discussing entoptic visualization of the retinal vasculature, he said:

“The...vascular figure may be seen also by looking through a compound microscope with nothing upon the stage, the background being the uniformly bright circular aperture of the diaphragm. When the eye moves to and fro a little at the ocular, the slender retinal blood vessels appear sharply delineated in the field, particularly those running at right angles to the direction of the motion; whereas the others vanish that are parallel to this direction.”

Helmholtz32 considered the importance of the size of the Maxwellian view exit pupil on shadow formation by stating:

“If the pupil is perfectly free, and the eye is turned towards the bright sky, every point of the pupillary plane may be considered as a source of light sending rays in all directions to the fundus of the eye, just as if the pupil itself were a luminous surface. The result is that the blood vessels of the retina project broad hazy shadows on the parts of the retina immediately behind them, the length of the umbra being only about four or five times the diameter of the blood vessel...Hence it may be assumed that the umbra of the vascular shadow does not reach the posterior surface of the retina at all. But when the light enters the eye through a narrow aperture in front of the pupil, the shadow of the blood vessel is necessarily smaller and more sharply defined, and since the umbra is longer, parts of the retina that were formerly partially shaded are now completely shaded, while other adjacent parts are not shaded at all.”

We expand these principles by presenting a detailed discussion of the theoretic and practical considerations for optimizing the entoptic visualization of the smallest capillaries in the macular area using the principles of Maxwellian view and discuss the feasibility of using these techniques as a research and clinical tool.

Theoretic Considerations for Optimizing the Entoptic Visualization of the Central Retinal Vasculature

Since the retinal vasculature lies anterior to the photoreceptors, shadows of the vasculature are cast in the plane of the photoreceptors. Under normal viewing and lighting conditions the vascular shadows of all but the largest vessels have low contrast, and all are effectively stabilized with respect to the photoreceptors. Since patterns which are stabilized in the plane of the receptors fade and become invisible, vascular shadows are not perceived under normal lighting and viewing conditions.

Entoptic visualization of the vascular shadows can be achieved by increasing shadow contrast and breaking shadow stabilization. Contrast can be increased by placing a small light source in the eye's entrance pupil, and shadow stabilization can be broken by changing the retinal angle of incident light by constantly moving the light source.34,35

There are at least four parameters of the vessel shadow pattern in the plane of the entrance aperture of the photoreceptors which will affect shadow visibility: (1) the width of the shadows, (2) the contrast of the shadows, (3) the spacing of the shadows, and (4) the speed and path of shadow movement. Our first goal was to design an illumination procedure that optimizes these parameters and renders the vascular bed surrounding the fovea easily visible.

Modeling Assumptions

Although a full treatment of the optical properties of the retinal blood vessels would deal with absorption, focusing, and scattering by the blood vessel walls, the blood plasma, and the individual red and white blood cells, as well as diffraction effects, we found we could provide an excellent description of the entoptic perception of the retinal vessels near fixation using a model based on absorption and the geometric optics of shadow formation. Therefore, for this model we ignored the optical consequences of focusing, scattering, and diffraction in favor of a model based on absorption and geometric optics.

Shadow Width

Using geometric optics, we can see that shadow width at the photoreceptor entrance aperture, here defined to be the outer limiting membrane (Fig. 3), depends on four key elements: (1) the width of the vessel, c; (2) the distance from the vessel to the entrance aperture of the photoreceptor, s; (3) the distance from the illumination source to the vessel, d; and (4) the size of the source illuminating the vessel, P.

Vessel width: Detailed histologic data from human eyes provide estimates of diameter for arteries (100 μm), veins (180 μm), arterioles (21 μm), venules (23 μm), and capillaries (7 μm). Shimizu and Ujiie contend that capillaries may be slightly larger at the border of the foveal avascular zone (10–15 μm).
Distance from the vessel to photoreceptors: In general, the major arteries, veins, arterioles, and venules lie in the nerve fiber layer, and the capillaries are distributed from the inner limiting membrane (ILM) down into the inner nuclear layer (INL). However, the precise distribution of the capillaries is controversial. It has been suggested that they are either evenly distributed\textsuperscript{36,37} or that they are concentrated in two laminae.\textsuperscript{38,39} Despite the disagreement over the precise distribution of the capillaries, collectively, these reports set the range of the distribution of vessel location as the INL and outer plexiform layer border (Fig. 4). Therefore, around the foveal region, we will consider the retinal vessels to lie between 80–300 \( \mu \text{m} \) from the entrance aperture of the photoreceptors.\textsuperscript{36,40} Hereafter, for readability the entrance aperture of the photoreceptors will be referred to simply as the photoreceptors.

Source distance: The exact distance from the illuminating source to the vessels (\( d \) in Fig. 3) is not important in determining shadow size in cases where the distance, \( d \), is considerably larger than the distance \( s \) from the vessels to the photoreceptors (a \( \pm 3\)-mm axial length change [approximately equal to \( \pm 10\)-diopter refractive error change] alters the shadow configuration approximately \( \pm 0.5\mu\text{m} \)). Nevertheless, to calculate accurately the width of the vascular shadows for various capillary locations the distance, \( d \), needs to be defined for each capillary location. This can be done by defining the location of the source (or source image) and adopting the optical parameters of a schematic eye. If we assume the eye to be Gullstrand's simplified schematic eye\textsuperscript{41} and place the eye's iris (the aperture stop of the eye) on the anterior surface of the crystalline lens, then the distance from the eye's exit pupil to the photoreceptors is 20.49 mm (Fig. 5). Combining these assumptions with the knowledge that distance from the capillaries...
to the photoreceptors ranges from 80–300 \( \mu m \), the
distance, \( d \), varies from 20.410 mm for capillaries at
the INL to 20.190 mm for capillaries in the ILM.

Given these parameters, and assuming the source is a
point source in the plane of the entrance pupil, the
retinal shadows of the vessels will have a rectangular
illumination profile and, at the outer limiting mem-
brane, will be slightly wider (0.4%-1.5%) than the
vessels themselves. Alternatively, if we had placed the
point source at the anterior focal point of the eye,
then light after refraction by the eye would be colli-
mated, and the shadows cast would be the same width
as the vessels. By similar triangles in Figure 3, the
shadow width (\( w \)) in the point-source case is given by

\[
\text{width of shadow} = w = \frac{(s + d)c}{d} \quad (1)
\]

where \( c \) is vessel diameter. It is clear from this analysis
that the shadow from the smallest capillaries (7 \( \mu m \)) is
larger than the diameter of one photoreceptor (ap-
proximately 2 \( \mu m \)). Unfortunately, a point source
considerably smaller than 7 \( \mu m \) is difficult to create.

If the source is large compared with the size of the
vessel, which in any real apparatus it will be, then the
illumination profile of the shadow is no longer rectan-
gular.

Size of the source: When the light source has a
finite diameter \( P \), there is, in general, an umbra, a
region of total shadow (darkly shaded area in Fig. 6),
and a penumbra, a region in which the source is
partly eclipsed by the vessel (lightly shaded). The illu-
minance profile in the shadow may or may not con-
tain an area of total shadow (umbra) in the plane of
the photoreceptors (Fig. 6). When an umbra is pre-

dent in the plane of the photoreceptors (Figs. 6A–B),
illumiance is a minimum over a central uniform
area, then increases through the penumbral regions.

As \( P \) or \( s \) increases, or \( c \) or \( d \) decreases, the width of
the umbra in the plane of the photoreceptors can
decrease to zero (Fig. 6C). As a further change in this
direction is made, by further increasing the source
diameter \( P \), for instance, no photoreceptor will be
hidden from the entire source by the vessel. However,
a region of uniform illuminance will again appear
(Fig. 6D). This region is less darkened than the actual
umbra, and its illuminance will approach that of the
background as \( P \) continues to increase. Using similar
triangles (Fig. 7), the width of the umbra region \( w \)
in the extended source case is given by

\[
w/t = \frac{c}{s + t} = \frac{P}{d + s + t}
\]

and the width of the penumbra on each side of the
central uniform area \( a \) is given by

\[
a/s = \frac{P}{d}
\]

and \( a = (Ps)/d \quad (3) \]

Small changes in the diameter of the source image,
\( P \), in the plane of the pupil will have a marked influ-
ence on shadow width, shadow contrast, and mean
retinal illuminance. Figure 8 illustrates these three
points. Figure 8A displays the variation in the total
width of the shadow (squares) and the width of the
central uniform portion of the shadow (triangles) as a
function of source diameter for a 7-\( \mu m \) capillary loca-
ted either 300 (solid symbols) or 80 \( \mu m \) (open sym-
 bols) from the receptors. In Figure 8A, although the
total shadow width (squares) is always greater than
the width of a foveal cone (approximately 2 \( \mu m \)) and
increases monotonically with source diameter, the
width of the uniform portion of the illuminance pro-
file (triangles) first decreases and then increases with
source diameter. The initial decrease in the width of
the uniform portion of the illuminance profile corre-
sponds to the umbra portion of the shadow moving
anterior to the plane of the photoreceptors. At the
point where the uniform portion of the illuminance
profile goes to zero and starts to increase, maximum
contrast of the shadow begins to decay. These effects
of source size on image contrast are illustrated in
Figure 8B for a 7-\( \mu m \) capillary located either 300
(closed circles) or 80 (opened circles) \( \mu m \) in front of
the photoreceptors. Examination of Figure 8B reveals
that increasing the source size beyond 0.5 mm will
reduce shadow contrast for the smallest capillaries
near the ILM (300 \( \mu m \) distance); however, shadow
contrast will remain high for larger vessels or for
those capillaries located nearest to the photoreceptors
until the source diameter exceeds 1.75 mm. Figure
8C illustrates the typical limitation of most Maxwell-
ian view illumination systems. That is, for a constant
source luminance, reductions in source area (ie, a
decrease in the size of the exit pupil of the Maxwell-
ian view optical system) produces proportional re-
ductions in retinal illuminance. For a circular Max-
wellian view exit pupil, retinal illuminance will be
inversely proportional to \( r^2 \). Thus a trade-off exists.

Decreases in source size will increase shadow contrast
but decrease retinal illuminance. The former will in-
crease the contrast of the shadow, and the latter will
decrease the retinal sensitivity to contrast.

Given these three considerations, shadow width,
shadow contrast, and retinal illuminance, combined
with our desire to keep shadow contrast at least five
times the threshold, we set the source diameter \( P \) at 1
mm for modeling purposes.

Figure 9A illustrates the width of: (1) the uniform
portion (open squares), (2) the ramping portion (open
circles), and (3) the total width (solid squares) of the
illuminance profile in the plane of the photoreceptors
as a function of vessel distance from the photorecep-
tors. There are several important points illustrated by
this figure. First, notice the total shadow width (solid
Fig. 6. Interaction of source size and vessel location and size on the illuminance profile of the vessel shadow in the plane of the entrance aperture of the photoreceptors. \( P \) denotes the source diameter in the exit pupil of the eye, \( a \) illustrates the penumbra portion of the shadow (ramping illuminance profile) and \( w' \) represents the portion of the shadow with a uniform illuminance profile of less than maximal contrast. Parameters \( c, d, s, \) and \( w \) are defined in Figure 3. (A) Illustration of the effects of decreasing the size of the source \( P \) (B), increasing the distance \( s \) (C), and decreasing the vessel size \( c \) (D).

squares) of the 7-\( \mu \)m capillary increases as the distance of the vessel from the photoreceptor increases. Second, and more importantly, notice the width of the shadow with a uniform illuminance profile (open squares) at first decreases to zero and then increases. Like Figure 8A, the decreasing portion of this function reflects the gradual movement of the umbra to a position anterior to the photoreceptor. Further increases in vessel distances (greater than approximately 140 \( \mu \)m) produce increases in the width of the central uniform section of the illuminance profile. As the width of the uniform section of the illuminance profile increases, the illuminance of this section increases and lowers shadow contrast (Fig. 9B). The width of the ramping portion of the shadow (open circles; Fig. 9A) at first increases as the uniform portion decreases to zero and then remains essentially constant as the capillary-to-photoreceptor distance continues to increase. Although this analysis shows that total shadow width for the smallest capillary is always considerably bigger (> 10 \( \mu \)m) than a photoreceptor (2 \( \mu \)m), it does not indicate whether or not there is sufficient total contrast or if the spacing of shadows is adequate for perception.
Fig. 7. Schematic diagram purposely distorted to illustrate the geometric relationships of shadow formation that define shadow width and the nature of the illuminance profile. Parameters defined in Figures 3 and 6.

Contrast of the Shadows

As illustrated in Figure 9B, the relative shadow contrast is affected by vessel size and position. As can be seen, the use of a small 1-mm diameter source ensures a full-contrast shadow for all but the smallest vessels positioned near the ILM. Vessels larger than 15 \( \mu \text{m} \) will always have a portion of the umbra in the plane of the photoreceptors. The lowest contrast expected for 7-\( \mu \text{m} \) capillaries positioned 300 \( \mu \text{m} \) from the entrance aperture of the photoreceptors (worst-case situation) using a 1-mm source is approximately 50% of the maximum. Now the question becomes, is this contrast reduction sufficient to render the shadow of these small capillaries invisible? To answer this question the actual contrast of the shadow must be determined.

Bird and Weale\(^{23} \) discussed this issue and, using estimates of hemoglobin absorption for white light in small capillaries to be 40% (transmission 60%), they calculated \( \log \Delta I/I \) to be -1.6 (or a contrast of 2.5%). Using the same estimate of hemoglobin transmission, we calculate a maximum shadow contrast of 40% \([(1 - 0.6) \times 100]\). Thus a 7-\( \mu \text{m} \) capillary 300 \( \mu \text{m} \) in front of the photoreceptor entrance aperture experiencing a 50% reduction in contrast should have a contrast of approximately 20%. Larger sources (greater than 1 mm) will further decrease the shadow contrast of the small 7-\( \mu \text{m} \) vessels (Fig. 8B) and expand the range of vessel widths affected with a contrast loss. Smaller sources (less than 1 mm) will increase the contrast of the smaller vessels and decrease the range of vessels widths affected with a contrast loss. This analysis helps to explain why transscleral illumination with a
source such as a penlight or illuminator (which presumably becomes even larger due to scatter in the sclera) does not provide an easily visible entoptic view of the foveal capillaries.

The contrast of the vascular shadows can be increased further for any sized source by limiting the spectral output of the source to the absorption peak for blood and, in particular, hemoglobin. Given the wavelength of maximum optical density (absorption) for oxyhemoglobin is 415 and deoxyhemoglobin is 430, limiting the spectral output of the 1 mm diameter source imaged in the plane of the eye’s entrance pupil to a band between 415 and 430 nm will optimize the physical contrast of the capillaries. To estimate the increase in contrast possible, we followed the advice of Francois Delori and calculated the optical density of the red blood cell to 415 nm light, and, in turn, the resulting contrast of the shadow.

The calculation was performed as follows: optical density at 415 nm = 20.7 µmole/cm³ (concentration of 95% oxygen saturated hemoglobin within a blood cell) × 63.98 (the extinction coefficient of 95% oxygen saturated hemoglobin at 415 nm in cm²/µmole) × 0.00052 cm (thickness of hypothetical red blood cell passing through a 7 micron capillary) = 0.689; as a result transmission through the capillary will be 20.5% (1/100 × 100) of the incident light creating a contrast of (1 – 0.205) × 100 = 79.5% in the umbra (which lies in front of the photoreceptors in the case of the 7 micron capillary) and 39.75% in the plane of the photoreceptors.

Although a short-wavelength narrow-band source (415–430 nm) theoretically provides the best retinal contrast, practically, as a result of the lower sensitivity of the middle- and long-wavelength-sensitive cone mechanisms to short-wavelength light, the reduced spatial resolution of the short-wavelength-sensitive cone mechanism, the low output of tungsten light sources at short wavelengths, and the loss of contrast sensitivity with decreasing retinal illuminance, it is better to use a fairly broad-spectrum source of slightly longer wavelength. (We found that a 3M color filter part #47 with peak transmittance at 470 nm half-band pass ±60 nm worked well.)

**Shadow Spacing**

Periodic grating patterns with a contrast of 40% are easily visible at photopic light levels for spatial frequencies up to 30 cycles/degree. Detailed photographs of latex-filled retinal vessels around the fovea (macaques) show capillaries every 28 µm (or 5.7 minutes of arc) or approximately ten vessels per degree. Periodic grating patterns of 10 cycles/degree can be detected with contrasts of approximately 1% at the fovea, but they become invisible at 5° eccentric to the fovea. To the extent grating data can be generalized to the periodic but irregular shadow pattern of the retinal vasculature, the finest detail of the smallest macular capillaries should be easily visible. This is, of course, assuming that image stabilization is appropriately broken.

**Shadow Movement**

Sharpe carefully analyzed the parameters of shadow movement necessary for entoptic perception. He noted: (1) for perception of the fine capillaries, the shadows must move smoothly from one photoreceptor to the next; (2) since the maximum movement of any shadow is provided by source movement perpendicular to the orientation of the vessel of interest, perception of the whole vascular bed is best perceived by a random or circular motion of the source; and (3) despite optimization, the percept of the shadows fade in approximately 60 sec presumably due to adaptation of pattern detectors.

Previous evidence suggests that, for longest duration of the entoptic percept, the vascular shadows should drift at approximately 150 min of arc/sec and drift over a distance of approximately 40 min of arc. We verified this finding experimentally by changing the diameter of the circular path our source followed in 1-mm steps and adjusting the velocity of the rotation for each path diameter for optimal vessel perception. This verification process revealed that little, if any, improvement in perception was obtained with a source rotation diameter greater than 4 mm and an associated rotation frequency of 3.5 hertz (Hz). For vessels located 300 µm from the photoreceptor entrance aperture, this stimulus configuration caused each point of the vascular shadow to move in a circle over a distance of approximately 38 min of arc at a velocity of approximately 134 min of arc/sec, a finding consistent with Sharpe’s original work. However, the distance and velocity over which the vascular shadows move vary with vessel location.

Figure 10A illustrates the chief ray of the source as it travels its circular path at two different points in time (t₁ and t₂) 180° apart. Notice that a vessel at a distance, s, from the entrance aperture of the photoreceptors has a shadow which is displaced by a maximum distance of y when the source is traveling in a circle of diameter, T, in the entrance pupil of the eye. The geometry of this configuration is more clearly illustrated in Figure 10B.

Figure 11 illustrates the maximum shadow movement perpendicular to the vessel’s long axis as a function of the distance of the vessel from the photoreceptors. Figure 12 shows the variation in shadow velocity perpendicular to the long axis of the capillary...
Fig. 10. (A) Vessel shadow movement $y$ induced by movement $T$ of a small source in the plane of the eye's exit pupil. (B) Scale exaggerated to illustrate the effect.

as a function of source location during one complete rotation of the source in the eye's entrance pupil. Calculations for Figures 11 and 12 were made using a chief ray moving in a circular 4-mm diameter path in the plane of the eye's entrance pupil. As can be seen in these figures, the shadow of a vessel located in the ONL (outer nuclear layer) moves a distance perpendicular to the long axis of the capillary of approximately 59 $\mu$m with a velocity varying between 0–653 $\mu$m/sec (0–134 min of arc/sec) while a vessel located at the ILM moves approximately 16 $\mu$m at a velocity varying between 0–171 $\mu$m/sec (0–35 min of arc/sec). More importantly, this stimulus configuration moves any point on the shadow over approximately 35–134 photoreceptors per sec depending on vessel location. This experimentally determined rotation speed of the source and resulting shadow drift rate is consistent with data from image stabilization experiments that report optimal drift velocities of 15 min of arc/sec for detection of a 10 cycle/degree grating.48,49

Discussion

Under normal viewing conditions the shadows formed by the small capillaries of the macular area are low contrast and stabilized. To visualize entoptically the shadows formed by these small capillaries, shadow contrast must be increased, and image stabilization must be disrupted. Our analysis indicates that this is best accomplished by a small, short-wave-length source (1-mm diameter or less) rotating at 3.5 Hz in a circular path (radius, 2 mm) imaged in plane of the eye's entrance pupil.

We verified these predictions experimentally and reconfirmed the observation that some normal indi-
viduals do not have a FAZ. When present (most cases) the FAZ subtends approximately 1.75°. Furthermore, we gathered and presented evidence which suggests that the retinal area used to fixate (presumably the foveola in normal subjects) is often displaced from the center of the FAZ. To our knowledge, this latter finding has not been reported previously and has significant implications for photoacoagulation therapy protocols which advocate safe distances from the foveola for burns, based on distances measured from the center of the FAZ. The following paper in this issue of IOVS presents these findings in detail.

We have just begun to test patients with retinal vascular disease and verified the finding of Kluxen and Wilden that patients with diabetic retinopathy can easily “see” and locate their own microaneurysms.

Encouraged with these early successes and the simple nature of the test, it is our belief that entoptic viewing of the central retinal vasculature can provide the clinical researcher with fundamental information concerning the early natural history and pathogenesis of central retinal vascular disease and offer: (1) the potential for early detection and diagnosis; (2) a firm foundation on which to base a rationale for preventative therapy; and (3) a sensitive means of evaluating various therapies and treatments designed to alter the natural course of the disease.

Key words: retinal vasculature, foveal avascular zone, entoptic perception, noninvasive assessment of the visual system, Purkinje tree

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