Origin of the Foveal Granular Pattern in Entoptic Viewing

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Purpose. To investigate the controversial origin of the foveal granular pattern at the center of the entoptic Purkinje vessel shadows. Both phenomena may be vividly elicited by oscillating a focused spot of light across the scleral surface of the eye in a circumferential direction.

Methods. The site and pattern of oscillation of the light spot were varied and were correlated with the appearance of the foveal granular pattern. Movement of the granular pattern relative to a foveal afterimage was also observed.

Results. Oscillation of the light in a meridional direction abolishes the granular pattern. Oscillating illumination through the central pupil can elicit Purkinje vessel shadows but not the characteristic foveal granular pattern. With transscleral illumination, the granular pattern oscillates with an "against" motion with respect to the motion of the Purkinje vessel shadows and with a "with" motion with respect to apparent motion of an afterimage serving as a fixed anatomic reference, and it is displaced from the center of the foveal avascular zone in the visual direction away from the source of illumination.

Conclusions. These observations strongly suggest that the foveal granular pattern is a random moiré pattern produced by spatial aliasing as the striated light pattern cast by the parafoveal nerve fiber elements sweeps over the photoreceptors in the form of a faint, high-spatial-frequency, irregular grating. An anatomic section of the fovea reveals the necessary geometry for production of such striated patterns, and the Nyquist frequency for the foveal photoreceptor mosaic supports the spatial aliasing effect. Also, a grating moving over a stationary random dot background demonstrates the origin of the "against" motion that is characteristic of the foveal granular pattern. Invest Ophthalmol Vis Sci. 1994;35:3319-3324.

The entoptic phenomena of the Purkinje vessel shadows and the foveal granular pattern have been recognized for more than a hundred years. Steinbuch observed the vessel shadows originally in 1813, and Purkinje described them in greater detail in 1815. Some years later, the origin of this entoptic phenomenon was clearly explained by Helmholtz in his classic treatise on physiologic optics. He determined that with a small, moving source of light achieved either by transscleral illumination or by projecting a narrow beam through the pupil, the shadows of the retinal vessels could be made to sweep across the underlying photoreceptors more rapidly than adaptation could occur, giving rise to perception of the shadows. Constant motion of the light beam is therefore required to perceive a continuous image of the Purkinje vessel tree.

In contrast, the origin of the foveal granular pattern entoptic phenomenon has remained unclear since Müller described it for the first time in 1842 as a pulsating granular shagreen in an area free of vessels at the center of Purkinje's vascular pattern. Through the years, investigators have usually considered the foveal granularity as originating from the mosaic of cones (Wolffberg [1886], Czermak [1860 and 1861], Bole [1877], Ayres [1884], Hölzke [1885], Hess [1904], Langenhan [1911], and ten Doesschate [1953], as cited in Ehrich's comprehensive review of the literature). The experimental methods used to elicit granular entoptic phenomena in the fovea have varied considerably. Müller was able to elicit a granular pattern by looking up to the gray sky for half a second and then closing his eyes. Junes (1949) reported such a pattern after contemplating the clear night sky when he looked intently to a bright light afterward. Czermak (1860) elicited the granularity in
the center of the Purkinje vessel shadows by looking at a bright light while interposing a stenopeic diaphragm in front of his pupil and moving it back and forth. Brückner (1909) saw a clear image of the foveal granular pattern by shining a Sechsschen lamp on his sclera. Other foveal entoptic patterns have been described, but these are dark areas, not granules, and are clearly different from the foveal granular pattern considered here.

Ehrich, in 1956, described for the first time a standardized method to elicit the foveal granular pattern for clinical application. By focusing a Cüppers Euthoscope (Oculus, Dutenhofen, Germany) on the sclera and moving it from side to side, he was able to observe a clear foveal granularity at the center of the branching vascular pattern on a red-orange background. Furthermore, he noted that when moving the light beam over the sclera in a strictly meridional direction, the foveal granularity disappeared whereas the vascular background survived. Ehrich explained the origin of this entoptic phenomenon as the result of “intensity variations that are characteristic of the pigment in the foveal cones.”

We have experimented with different modes of illumination to maximize perception of the Purkinje vessel shadows and the foveal granular pattern. Based on our observations, as well as on several experimental results reported in the literature, we propose a new explanation for the origin of the foveal granular pattern, accounting for its psychophysical characteristics.

**METHODS**

To elicit both entoptic phenomena consistently, we focused a 2-mm spot of light from a slit lamp biomicroscope onto the sclera approximately 5 mm behind the limbus. By replacing the 45° mirror on the slit lamp with a rotating tilted mirror (Fig. 1), we scanned the spot of light in a circular path 3 to 4 mm in diameter with a frequency of approximately 2.0 to 4.0 Hz. This same circular scanning arrangement was used through the pupil, but in this case best results were obtained with a 1-mm spot of light, a red-free filter dialed into the slit lamp’s beam, and a single layer of translucent plastic film placed between the lamp and the pinhole aperture within the slit lamp, resulting in a uniformly luminous field of optimum brightness.

We used another experimental arrangement to compare the different entoptic images elicited by radial versus circumferential movement of the light spot on the sclera. A 2-mm aperture was mounted within the slit lamp adjacent to the standard selectable apertures and was moved in various linear or circular fashions using linkages to an eccentric cam on a small electric motor.

To determine the absolute direction of motion of the foveal granular pattern with respect to the photoreceptors, we viewed the entoptic images superimposed upon a horizontal, linear afterimage in the fovea. A linear flash tube subtending 0.1° vertically and 5.5° horizontally served to create the afterimage.

A minimum of six observers, including the authors, with minimal refractive errors and normal visual acuities viewed the various entoptic phenomena produced. All observers except one (DLG) were previously inexperienced in entoptic viewing. No observation contrary to those reported here was reported by any observer; there was unanimity of observation for each phenomenon. The rotating-mirror attachment to the slit lamp was demonstrated at a conference of approximately 50 ophthalmologists, each with normal visual acuity. All ophthalmologists appreciated the Purkinje vessel shadows; all but two perceived the foveal granular pattern.

**RESULTS**

**Radial Versus Circumferential Scanning**

As Ehrich observed previously, we found that when the spot of light was scanned back and forth in a circumferential direction on the sclera, parallel to a line tangent to the corneal limbus (Fig. 2), both entoptic images were clearly seen. However, if the spot of light on the sclera was scanned along a meridian of the eye (Fig. 3), the granular pattern disappeared, and only the Purkinje vessel shadows could be elicited.
Perception of the Purkinje Vessel Shadows

A circular scan for the illuminating spot on the sclera yielded the most complete Purkinje vessel shadows, whereas a linear scan produced no shadows of those vessels parallel to the direction of scanning. Scanning the beam of light through the pupil yielded respectable vessel shadows, but over a much smaller field of view than with transscleral illumination. The limited field size was clearly due to the fixed cone size of the light bundle passing through the pupil, whereas with transscleral illumination the light was scattered over a much wider angle.

When the spot of light was scanned over the sclera, the perceived vessel shadows moved in the same direction as the beam of light, moving linearly when the spot was scanned linearly and moving in a circular pattern when the beam was scanned in a circle. For example, when the spot of light moved upward on the temporal sclera, the shadows of the vessels moved downward on the retina and thus were perceived as moving upward in the visual field, a "with" movement with respect to the movement of the spot of light on the sclera.

Perception of the Foveal Granular Pattern

Even though both the vessel shadows and the foveal granular pattern could be elicited by scanning the spot across the sclera, we were able to perceive only the vessel shadows when scanning was performed through the central pupil. With this transpupillary mode of illumination, the foveal avascular zone and the parafoveal capillary network were both clearly recognizable, but the foveal region was an empty area with the same texture as the background; the granular pattern was not seen. Only swirling shadows of occasional vitreous floaters were seen in the vessel-free zone. When the pupil was dilated to approximately 8 mm, however, and the scanning path was displaced eccentrically to the edge of the pupil, the characteristic foveal granular pattern began to appear, but only intermittently, synchronized with the light beam's passing just within the very edge of the pupil. Three of the six observers could appreciate the granular pattern only when the scanning path was displaced to the temporal edge of the pupil. The other three appreciated the pattern with displacement of the scanning path up, down, right, or left.

When the foveal granular pattern was elicited transsclerally, it always oscillated in a linear fashion, parallel to the circumferential component of the moving spot of light on the sclera. This movement was always an "against" movement with respect to the circumferential component of the vessel shadow movement. In other words, when the spot of light was moving upward on the temporal sclera, the perceived vessel shadows also moved upward, but the granular pattern appeared to move downward.

The absolute movement of the perceived vessel shadows with respect to the visual field was readily apparent by superimposition of the vessel shadows upon the dimly seen details of the examining room. The absolute movement of the foveal granular pattern, on the other hand, was difficult to judge with respect to externally viewed details. The linear foveal afterimage from the flashtube, however, provided an excellent reference for judging relative movement. With the spot of light moving in a circle on the temporal sclera, the horizontal flashtube afterimage appeared to move up and down, opposite to the movement of the vessel shadows. This apparent up-and-down movement of the afterimage was much more striking than the apparent movement of the vessel shadows themselves. The translation of the afterimage
actually followed a circular path with respect to the vessel shadows, but only the vertical movement was readily apparent because of the horizontal disposition of the linear afterimage. The key observation was that the granular pattern oscillated up and down in the same direction, and roughly twice as far, as the afterimage. This proved conclusively that the perceived granular pattern moves with an "against" movement with respect to the circumferential component of the moving spot of light on the sclera.

Finally, the granular pattern was always displaced from the exact center of the foveal avascular zone, with its projection overlapping the perifoveal capillary ring in the visual direction away from the incoming beam of light (Fig. 4).

DISCUSSION
It is clear that the Purkinje vessel shadows and the foveal granular pattern are generated by different psychophysical mechanisms. They share some characteristics, however, in that they both can be elicited by a spot of light moving circumferentially across the sclera.

Purkinje Vessel Shadows
Our observations support Helmholtz's original explanation of the Purkinje vessel shadows. When a narrow beam of light is projected either through the sclera or through the pupil, the retinal blood vessels cast shadows on the photoreceptor layer, diminishing the excitation of those photoreceptors immediately underlying the vessels. If the beam of light remains static, the retinal shadows are stabilized, and adaptation of the photoreceptors quickly extinguishes perception of the shadows. However, if the vessel shadows are swept across the photoreceptors more rapidly than adaptation can occur, the shadows will be perceived continuously. Sharpe studied the stability of the retinal vessel images by focusing a spot of light in the plane of the pupil and oscillating it to elicit the perceived vessel shadows. He reported that the slowest frequency of oscillation at which the capillaries become visible is 1.5 Hz and that the maximum frequency at which the arterioles are still visible is 18 Hz. Furthermore, he observed that the shadows oscillate in the same direction as the direction of scanning (a "with" movement), as confirmed by our observations.

The Foveal Granular Pattern
From our experimental results, it appears that the characteristic foveal granular pattern is appreciated if the light beam enters through the sclera, or through the very periphery of the dilated pupil, and only as long as the scanning movement has a circumferential component. Scanning the beam through the central pupil elicits no granular pattern at all.

These observations may be explained by considering the faint striated light pattern cast by the radially arranged retinal nerve fibers on the foveal photoreceptors. The radially arranged photoreceptor inner segments may also contribute to the striated light pattern. In the center of the fovea, the fibers belonging to Henle's nerve fiber layer are few and are oriented primarily perpendicular to the retinal surface. They curve radially outward from the fovea, becoming more parallel to the retinal surface in the parafoveal and perifoveal areas (Fig. 4). Light projected through the central pupil will pass to the foveal photoreceptors relatively parallel to the few central Henle's nerve fibers, resulting in an amorphous and indistinct pattern on the photoreceptors. Light projected obliquely (transscerally), on the other hand, will pass through the numerous parafoveal nerve fibers, coursing roughly parallel to the retina, and will cast onto the photoreceptors a faint striated pattern made up of irregular light and dark stripes with a spatial frequency related to the distance between the nerve fibers and the thickness of the nerve fiber layer. This helps to
explain the need for oblique illumination (accomplished transsclerally or through the periphery of the dilated pupil) to elicit the characteristic fine-grain foveal granular pattern.

The eccentric displacement of the granular pattern from the center of the foveal avascular zone, visually projected away from the incoming oblique beam of light, is consistent with a striated pattern cast by those parafoveal nerve fiber elements on the same side of the fovea as the incoming beam of light, that is, either Henle's nerve fibers or the inner segments of the photoreceptors themselves, as can be appreciated in Figure 4.

The observation that the granular pattern appears to oscillate with approximately twice the amplitude of a reference afterimage, with respect to the vessel shadows, suggests that the striated pattern is formed by fiber elements close to the vessel layer. This implicates Henle's nerve fibers more than the photoreceptor inner segments as the source of the striated pattern. On the other hand, because the granular pattern can be elicited by a light beam passing through the edge of an 8-mm pupil, inclined only 10° from the line connecting the fovea with the center of the pupil, the photoreceptor inner segments may also contribute to the striated pattern.

If the light beam is scanned meridionally, the irregular striated pattern cast by the nerve fiber elements onto the photoreceptor mosaic remains relatively stationary and does not elicit an entoptic perception. If the light beam is scanned circumferentially, however, the pattern cast onto the photoreceptor mosaic will be equivalent to an irregular grating oscillating transversely, constantly stimulating fresh photoreceptors and eliciting a sustained entoptic image.

The entoptic image appreciated in the fovea is not in the form of an oscillating grating but instead appears as a collection of fine boiling granules moving with an "against" motion with respect to the motion of the retinal vessel shadows, and with an "against" motion with respect to the moving spot of light on the sclera according to our afterimage experiments. Such an image can originate from projection of an irregular, high-spatial-frequency grating onto a uniform, finite-grain detection system, representing an example of spatial aliasing.

Spatial aliasing is the phenomenon of undersampling that occurs when the sampling rate provided by a regular array of point detectors is less than twice the highest spatial frequency imaged onto that array. Shannon's sampling theorem explains the concept of aliasing in one dimension, but aliasing also applies to sampling of two dimensional signals such as retinal images. Any detection system composed of a uniform array of discrete detectors, including the photoreceptor mosaic, is susceptible to this phenomenon. Williams has shown that the cones in the human fovea are arranged in a highly structured, hexagonally packed lattice mosaic, and that if the regular photoreceptor mosaic is exposed to high-contrast gratings having spatial frequencies higher than half the reciprocal of the spacing between rows of receptors, low-frequency moiré patterns will be perceived, distorting the original image. The critical spatial frequency in cycles per degree (c/deg) above which aliasing occurs is called the Nyquist frequency (fN). In the case of the hexagonally packed array of foveal cones, the Nyquist frequency is equal to:

\[ f_N = \frac{1}{(2)\sqrt[3]{S}} \]

where \( S \) = center-to-center spacing of the foveal cones in degrees.

Williams calculated the Nyquist frequency for a human fovea having a hexagonally packed photoreceptor mosaic with \( S = 0.62 \) minutes of arc, obtaining a value for \( f_N \) of 56 c/deg. He then projected interference fringes having spatial frequencies ranging from 60 c/deg to 200 c/deg on the retinas of normal observers. At 60 c/deg and retinal eccentricities beyond the central 3° of the fovea, some observers reported a faint granular appearance of the field. At frequencies of 90 to 100 c/deg, they reported in the fovea the appearance of a patch resembling a fingerprint or a pattern of zebra stripes. Between 150 and 160 c/deg, however, the zebra stripes disappeared abruptly, and at frequencies close to 200 c/deg, the stimulus pattern could only be detected by a faint, scintillating, granular appearance of the field within the central fovea.

Roughly assuming that Henle's nerve fibers are as closely packed as cones in the fovea and that 0.29 mm on the retina corresponds to 1° of visual angle, we calculated that the irregular grating resulting from the oblique passage of light through the parafoveal Henle's nerve fiber layer must have an average spatial frequency of at least 100 c/deg. Furthermore, because of overlapping of the parallel nerve fibers, the irregular grating pattern on the fovea probably has spatial frequency components substantially greater than 100 c/deg. Thus, we believe that by projecting an oscillating beam of light through the sclera, we are creating a stimulus on the photoreceptor mosaic similar to Williams' high-spatial-frequency interference fringes, and that the scintillating granular pattern he has reported is the same phenomenon as the pulsating granular shagreen that Müller described in 1842. Presumably, the granular pattern is seen only in the fovea because the pattern cast by the parafoveal nerve fiber elements is of a higher spatial frequency and is probably better.
defined than those patterns cast by the retinal nerve fiber elements present elsewhere, and the spatial frequency of the striated light pattern in the fovea appears to be optimally matched to the spacing of the foveal photoreceptors for production of the aliasing phenomenon.

Moiré patterns result from the overlapping of two periodic structures that have solid and open regions. The best-known moiré patterns result from slight misalignment of two superimposed identical gratings, but they can also be generated by superimposing two screens consisting of regular patterns of dots or by placing a grating over a periodic field of dots. In the latter, when the grating is moved transversely, a moiré pattern of dots moving “against” the movement of the grating is seen. An “against” motion of similar origin has been noted in the study of insect vision where it has been observed that a fly will follow the true direction of a moving grating as long as the grating’s spatial frequency is below the Nyquist frequency of its omnatidial array. On the other hand, if the grating’s spatial frequency is greater than the Nyquist frequency calculated for its omnatidial array, the fly will move in a direction opposite to the true movement of the grating. Coletta and coworkers have also observed the reversal of motion of an aliasing image on the human parafoveal retina by projecting drifting laser interference fringes of spatial frequencies between 1.0 and 2.0 times the Nyquist frequency calculated for this area of the retina.

The striated pattern generated by transillumination of nerve fiber elements will not be as regular as a parallel ruled grating or laser interference fringes. Thus, to demonstrate the moiré pattern generated by transscleral illumination, we constructed a model using an irregular grating transparency with irregular black-clear lines, roughly 1.25 mm apart, superimposed on a uniform array of 0.5-mm black dots spaced 0.5 to 1.0 mm apart on a white background. By moving the grating transversely, one could see the field of dots begin to boil with the same scintillating character and move with the same type of “against” motion as the foveal granular pattern.

To summarize the apparent directions of movement, if the light on the sclera moves up, the striated pattern cast by the nerve fiber elements moves down on the photoreceptor layer. If viewed anatomically, the moiré pattern formed would move up, but this is perceived as downward movement in the visual field, resulting in a “against” movement with respect to the movement of the light on the sclera and an “against” movement with respect to the perceived movement of the retinal vessel shadows.

We submit, therefore, that the foveal granular pattern is a random moiré pattern produced by spatial aliasing as the light pattern cast by the parafoveal nerve fiber elements sweeps over the photoreceptors in the form of a faint, high-spatial-frequency, irregular grating. As an indication of foveal integrity, perception of an optimized foveal granular pattern may prove useful as a measure of potential visual function behind dense cataracts.

Key Words
aliasing, entoptic image, foveal granular pattern, moiré pattern, Purkinje vessel shadows

References