Principles of Hartmann-Shack Aberrometry

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The operating principle of the Hartmann-Shack aberrometer is extremely simple. It is so simple, in fact, that the only real barrier to understanding the technique is the language we use to describe it. For this reason, it is worthwhile describing the technique twice, first using the language of ray optics and then again using the language of wave optics.

RAY OPTICS DESCRIPTION

Nearly 400 years ago, the celebrated Jesuit philosopher-astronomer, Christopher Scheiner, professor at the University of Ingolstadt, demonstrated the focusing ability of the human eye using a simple device known as the Scheiner Disk.[1] Scheiner's experiments showed that if an optically imperfect eye views through an opaque disk perforated with two pinholes, a single distant point of light such as a star will form two retinal images as illustrated in Figure 1. If the eye's optical imperfection is a simple case of defocus, then the double retinal images can be brought into register by viewing through a spectacle lens of the appropriate power. For optical aberrations other than defocus, however, a simple lens won't bring the two retinal images into coincidence. In such cases a more general method is needed for quantifying the refractive imperfections of the eye at each pupil location. This is achieved by using a fixed light source for the central, reference pinhole and a moveable light source for the outer pinhole as illustrated in Figure 2. By adjusting the moveable source horizontally and vertically, the isolated ray of light is redirected until it intersects the fixed ray at the retina and the patient now reports seeing a single point of light. Having made this adjustment, the displacement distances Δx and Δy are measures of the ray aberration of the eye at the given pupil point. This subjective aberrometer was first described by Smirnov[2] and has been used extensively in visual optics research the past 40 years.

To convert the Scheiner-Smirnov subjective technique into an objective aberrometer, we reverse the direction of light propagation by placing a spot of light on the retina. This spot then becomes a point source which radiates light back out of the eye as illustrated in Figure 3. Additional holes are drilled in Scheiner's disk, which astronomers and optical designers call a Hartmann screen.[3] Each aperture in the Hartmann screen isolates a narrow pencil of rays emerging from the eye through a different part of the pupil. These emerging rays intersect a video

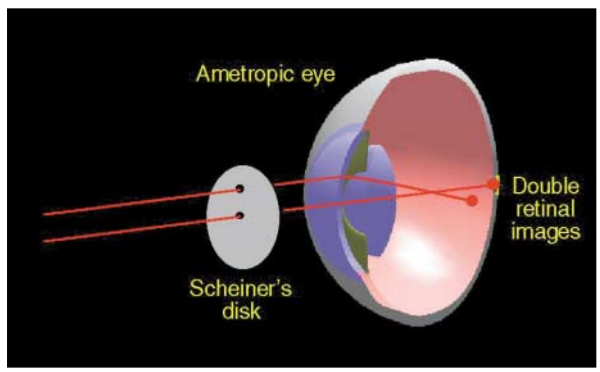

Figure 1. Scheiner's disk produces double retinal images of a single object if the eye is ametropic.

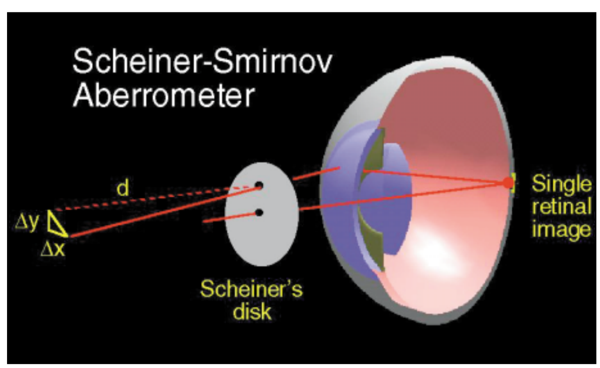

Figure 2. Scheiner's disk was used by Smirnov to create a subjective aberrometer.

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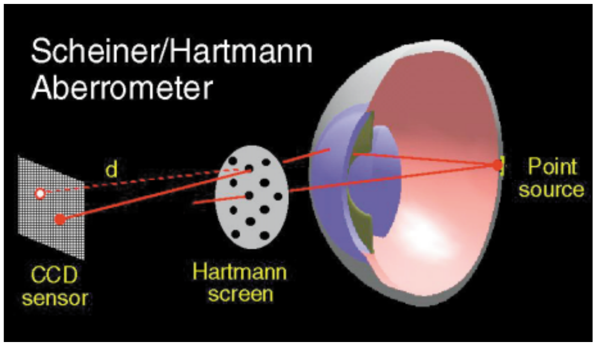

Figure 3. A Scheiner's disk with multiple holes is called a Hartmann screen and may be used to construct an objective aberrometer.

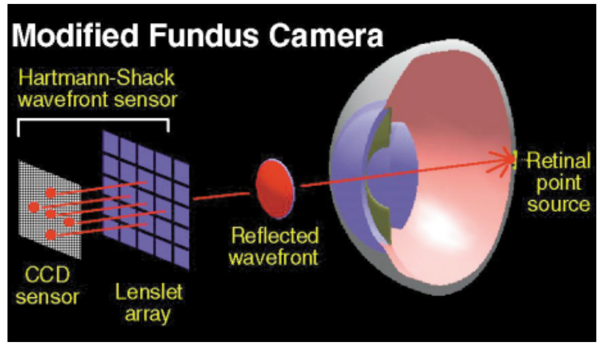

Figure 4. The Hartmann-Shack aberrometer is a modifed fundus camera that has an array of objective lenses which subdivides the wavefront into smaller beams of light, thereby forming multiple images of the same retinal point source.

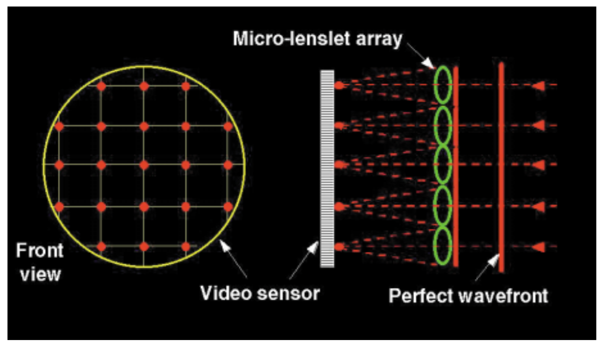

Figure 5. A micro-lenslet array subdivides the wavefront into multiple beams. Local slope of the wavefront over each lenslet's aperture determines location of spot on video sensor.

sensor to register the horizontal and vertical displacement of each ray from the corresponding, non-aberrated, reference position. The result is a Hartmann aberrometer for objectively measuring the ray aberrations of the eye. Now fill each individual aperture of the Hartmann screen with a tiny lens as described by Shack and Platt[4] and the result is a Hartmann-Shack aberrometer, or to be historically correct, a Scheiner-Hartmann-Shack aberrometer.

To summarize this ray-optics description, the purpose of the Scheiner-Hartmann-Shack aberrometer is to simultaneously measure the ray aberrations of the eye at multiple pupil locations. This is accomplished with a modified, objective form of the classic Scheiner's Disk in which there are now multiple apertures, as in the Hartmann screen, and each aperture consists of the face of a tiny lenslet in an array of such lenslets, in the manner described by Shack and Platt.

WAVE OPTICS DESCRIPTION

To repeat the above description using the language of wave optics, the purpose of the Scheiner-Hartmann-Shack aberrometer is to measure the wave aberration function of the eye's optical system, which is the same as saying the purpose is to measure the shape of the wavefront of light that is reflected out of the eye from a point source on the fundus. For example, the wavefront of light reflected out of a perfect eye would be a circular piece of a plane wave with the same diameter as the pupil. If this wavefront were to be captured by a conventional fundus camera, all of the reflected light would be focused into a single image of the retinal spot. However, a Shack-Hartmann aberrometer has an objective lens which is actually an array of tiny lenses, rather like the compound eye of an insect. With this kind of lens, shown in Figure 4, the reflected light is broken into many individual beams, thereby producing multiple images of the same retinal spot of light.

To see how the array of spot images can be used to determine the shape of the wavefront, consider the wavefront in cross-section as shown in Figure 5. For a perfect eye, the reflected plane wave will be focused into a perfect lattice of point images, each image falling on the optical axis of the corresponding lenslet. By contrast, the aberrated eye reflects a distorted wavefront as illustrated in Figure 6. The local slope of the wavefront is now different for each lenslet and therefore the wavefront will be focused into a disordered collection of spot images. By measuring the displacement of each spot from its corresponding lenslet axis, we can deduce the slope of the aberrated wavefront when it entered the corresponding lenslet. Mathematical integration of this slope information yields the shape of the aberrated wavefront.

The shape of the aberrated wavefront is a fundamental description of the optical quality of the eye

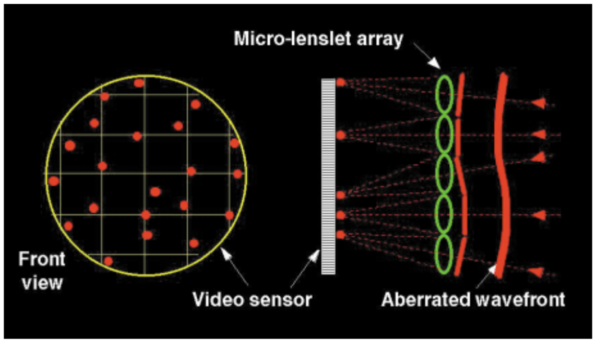

Figure 6. An aberrated wavefront produces an irregular pattern of spots on the video sensor. Displacement of each spot from the corresponding lenslet axis is a measure of the slope of the wavefront.

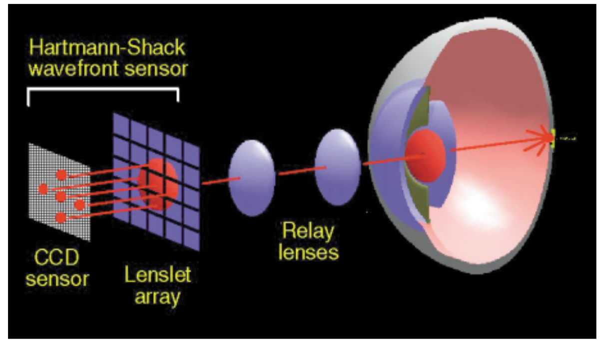

Figure 7. The lenslet array is focused into the plane of the pupil by relay lenses in order to measure the shape of the wavefront as it leaves the eye's pupil.

called the "wavefront aberration function." This function lies at the heart of a rich optical theory that allows us to calculate the retinal image of any object, to assess the quality of that retinal image quantitatively, and ultimately to predict human performance on visual tasks. However, to apply this wonderful optical theory we need to analyze the wavefront as soon as it passes through the eye's pupil. To do this we use a pair of relay lenses which focus the lenslet array onto the pupil of the eye as shown in Figure 7. Optically, then, the lenslet array appears to reside in the plane of the eye's pupil where it can subdivide the reflected wavefront immediately as it emerges from the eye's pupil. This final configuration is the basic form of the modern Hartmann-Shack aberrometer used in studies of optical aberrations in the normal eye[5] and for clinical populations of optically abnormal eyes.[6]

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