Measuring aberration of the eye with wavefront technology

Giuseppe Colicchia and Hartmut Wiesner

Research group of Physics Education, Ludwig Maximilian University, Schellingstr. 4, 80799 Munich, Germany

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Abstract
A simple device is used to show both the wave aberration emerging from an eye model and the basic principles of measuring wavefront aberration with a Hartmann-Shack aberrometer.

Introduction

One way to motivate students’ interest in physics is to teach it in the context of medicine[1]. Optics, for example, can be taught with examples of recent methods for ophthalmologic (ocular) examinations.
Conventional techniques are routinely used for the measurement of the spherical and cylindrical refractive errors of the eye. However, the eye has more complicated refractive errors, known as higher-order aberrations (e.g. coma, spherical aberration), that can decrease the visual performance. Because the correction of higher order aberrations requires a precise knowledge of its relevance, aberrometers which allow to measure wavefront aberrations become essential [1] [2].
Aberrometers measure all of the eye’s monochromatic aberrations and show the result in the form of an aberration map that describes the variation in optical path length from source to retinal image through each point in the pupil. Knowing the aberration map, the corneal surface can be ablated by an excimer laser in a customized way to minimize the wavefront aberration of the eye and hence to improve the quality of vision.
In this paper, by a simple experimental device simulating a Hartmann-Shack (HS) aberrometer, we show the basic principles of the measurement of wave aberration emerging from an eye model.

Hartmann-shack aberrometer

Light with a flat wave front passing through a perfect eye coincides exactly in one point on the retina (the second focal point of the eye). Conversely, light from a point on the retina leaves the eye with a perfect flat wave front. All deviations from the ideal wave front are due to imperfection in the dioptric components of the eye. This concept is the basis for many devices to measure aberrations.
The principle of a HS aberrometer is both simple and ingenious (figure 1) [3]. A narrow laser beam (around 1 mm wide) is sent via a beam splitter BS into the eye and forms a spot on the retina. Some of the light is scattered and propagates back through the lens and pupil, as if coming from a point-source on the retina. This light bundle then falls upon a regular planar array of identical converging micro-lenses (typically of the order of 0.5 mm diameter). Each micro-lens focuses its part of the light on a charge-coupled device (CCD) camera placed on the focal plane of the lenslet array.

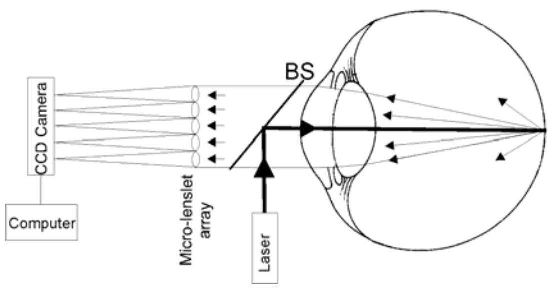

Figure 1. Simplified design of a Hartmann–Shack aberrometer.

If the eye is emmetropic (normal sighted), relaxed and free of aberration, the overall wavefronts leaving the eye are plane (parallel rays); each lens will focus the light on the focal point of its optical axis. Therefore, the overall set of point images (spots) on the CCD camera, duplicates the regular grid pattern of the lenses (figure 2 left).

If, however, the wavefronts leaving the eye are not plane, the parts of wavefront entering each micro lens will, in general, be tilted with respect to the lens' axis, so that the point image in its focal plane is not on its optical axis, but is displaced (by an amount and direction) depending on the local tilt of the wavefront (figure 2 right).

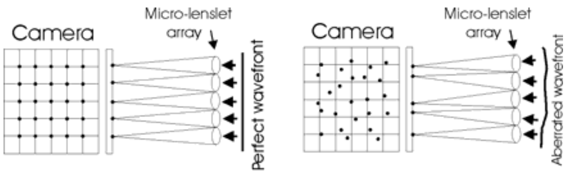

Figure 2. Flat (left) and aberrated wavefront (right).

The analyzing of the displacement of each spot of light from its corresponding lenslet axis allows the deduction of the path of each ray and the optical wavefront formed by the eye. All of its refractive errors, including sphere, astigmatism, and higher-order aberrations can be completely identified.

The underlying assumption of the technique is that the lenslets are small in diameter compared to the distortions present in the optical wavefront. In other words, the wavefront is locally flat over the finite diameter of the lenslet (figure 3a). This assumption begins to break down when the magnitude of the aberrations is large (figure 3b). In this case, the wavefront is significantly curved over the lenslet aperture and the result is a blurry spot. If the aberrations are large enough, the spots can even overlap, which complicates the analysis considerably. One other limitation concerns aberrations which are on a very fine spatial scale (figure 3c). These "micro-aberrations" scatter light and blur the spots. Although these blurry spots are problematic, they nevertheless contain useful information about the degree and location of scattering sources inside the eye.

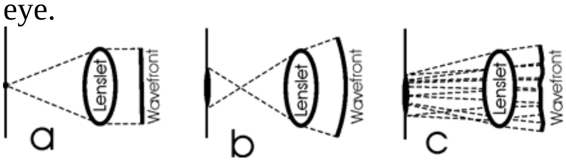

Figure 3. A flat wavefront produces a small spot (a), while large (b) or micro-distortions (c) produce a blurred spot of light.

Experimental device

For the experimental device we use a large eye model. The model consists of a hollow Styropor sphere which represents the ocular globe (figure 4). A light source R (for example LED of high intensity) placed on the internal surface of the sphere represents a light spot on the retina. On the opposite surface, a hole in the sphere is covered with a large lens C (for example, Ø 6 cm) which simulates the optical refractive power of both cornea and crystalline lens. The focal length of the lens must equal the axis length of the model eye, so it represents a model of an emmetropic eye.

Figure 4. Eye model from the front and from behind.

Figure 5 shows the set up simulating a Hartmann-Shack aberrometer.

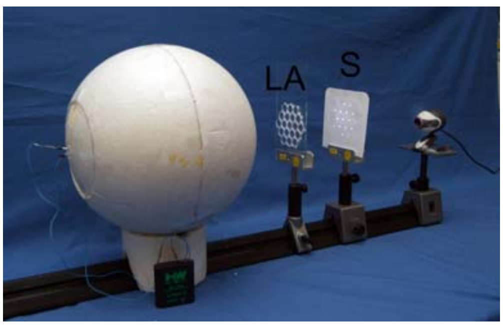

Figure 5. Optical configuration analysing wave front aberrations. The light source is placed on the "retina" of the model.

The light bundle emerging from the eye model is directed to a lens array LA (figure 6) that images the light into an array of spots on a screen (sheet of paper) S. The screen should be on the focal plane of the lens array.

Figure 6. Lens array formed of a matrix of 16 lenses (Ø about 1.6 cm, f = 120mm).

By observing the screen from behind with a camera connected to a video monitor, many students could observe simultaneously what happens.
With a perfect eye model the wavefront is plane. The images formed by the lens array consist of small light spots on the screen, regular located along the optical axis of its respective lens let (figure 7 left).

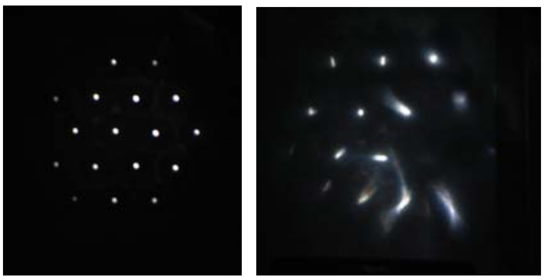

Figure 7. Light on the screen from the perfect eye model (left) and the aberrated (right).

With an aberrated eye model some or all of the focused spots do not get imaged on the optical axis of the respective lens let, but are offset (figure 7 right).
An aberrated eye model is obtained for example by the use of a plastic lens C of deformed profile as a cornea of irregular shape. However, a water-filled lens simulates both ametropia and irregular cornea shape [4]. The lens (s. fig. 8) consists of a transparent plastic Petri dish (Ø 6 cm) and a transparent elastic film (e.g. condom). A small hole is drilled into the side of the disk and a flexible tube is inserted. The elastic film is stretched on the open side of the Petri disk and fixed by a rubber band. When the lens was filled by a syringe (s. fig. 9) with water, the elastic film was deformed in a convex shape. By varying the water volume of the lens, the shape of the elastic film changes, the focal length will vary, and therefore the "ametropia" of the eye model. By touching the film, the shape of the lens will be deformed as an irregular cornea shape. (When the liquid-filled lens is placed vertically for the normal use, his shape will be deformed by the effect of gravity. However this effect is negligible).

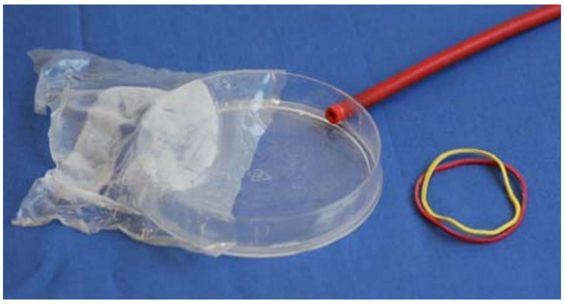

Figure 8. Elements of the water-filled lens

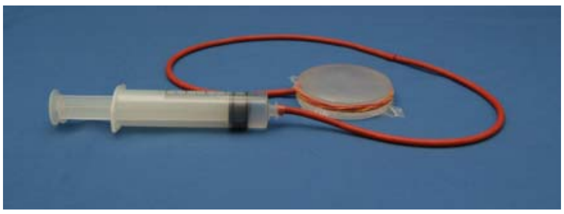

Figure 9. The water-filled lens

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[1] We developed and evaluated many materials for teaching physics in medical context. The teaching material both in human physiology and diagnostic methods is available in German: http://www.physik.uni-muenchen.de/didaktik

Giuseppe Colicchia has been teaching physics in secondary school for 20 years. He received his Ph. D. in physics education from the University of Munich in 2002. His research interests include science education and history of sciences.

Hartmut Wiesner is professor in physics education. His fields of interest are misconceptions, conceptual change, physics in elementary school, teaching of quantum physics.

List of key words: eye model, eye aberrations, wavefront measurement.