The History and Methods of Ophthalmic Wavefront Sensing

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It was once observed that the Russo-Japanese war of 1904-1905—with the introduction of high-speed bullets that made discrete lesions in the brains of the persons they intersected—did more for the understanding of brain function than any number of research efforts before that time.

In the same vein, I submit that refractive surgery has done more for the once neglected and esoteric field of monochromatic aberrations of the eye than any of the practitioners in that field had reason to hope for, by extending all of our aberration plots upward and to the right by several orders of magnitude. If we can put that genie back in the bottle and restore those plots to their original dimensions, our work will be truly and appropriately rewarded.

METHODS OF DETECTION OF WAVE ABERRATION

The primary methods of wave aberration detection and reconstruction have been based either on interferometry or ray tracing. The Twyman-Green interometer described in almost every book on physical optics, works by first dividing and then recombining a collimated beam of light after its divided beams have been reflected from a test and a reference surface. Only if the surfaces are identical and correctly aligned will no interference fringes be visible in the final, recombined beam. Otherwise, the resulting interference fringe pattern will provide a topographic map (in steps of one wavelength) of the wave aberration difference surface.

The interferometric method has not found much application in physiological optics, primarily due to difficulties in stabilizing the eye and constructing appropriate reference surfaces with which to compare, for example, corneal shape.

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All of the other methods have been based on ray tracing and reconstruction of the wave aberration surface by integrating the slopes of an array of beams intersecting the eye's entrance pupil. In physical optics, these methods were first realized by Hartmann[1] at the turn of the last century. About 5 years earlier, Tscherning[2] had constructed and described an appartus, which he named an "aberroscope," from a grid superimposed on a 5-diopter (D) spherical lens. Viewing a distant point source of light through the aberroscope, a subject could see a shadow image of the grid on his retina. From the distortions of the grid, one could infer the aberrations of the eye.

Tscherning's aberroscope was attacked and dismissed by Gullstrand, and possibly due to this, its use was temporarily abandoned. Sixty years later, Bradford Howland invented the crossed cylinder aberroscope[3] to investigate the aberrations of camera lenses. Instead of using a spherical lens to shadow the grid on the retina, he used a crossed cylinder lens of 5 D with the negative cylinder axis at 45°. The advantages of this over the Tscherning aberroscope are: A) diffraction blurs the grid lines along their axes, producing a sharper grid, B) the point of zero defocus of the eye is clearly indicated by the horizontal and vertical orientation of the central grid lines, and C) the distorted grid lines represent the ray intercept plots of classical optics.

Another 20 years passed before a subjective aberroscope was used to investigate and characterize the monochromatic aberrations of 55 subjects.[4] The principal result of that study was that third order coma-like aberrations dominate the aberration structure of the eye at all physiological pupil sizes. This was the first time that comatic aberrations had been measured—as opposed to estimated—in any eye. This study also introduced the use of Zernike polynomials to describe the wave aberration of the human eye.

The crossed cylinder aberroscope was improved by introducing an ophthalmic track and photographing grid patterns on the retina[5], making it an objective technique. More recently, an objective Tscherning aberroscope method has been adapted for clinical use.[6]

Another subjective method used to find the wave aberration of the human eye is that of Smirnov[7] wherein a grid is viewed by the entire aperture of the eye, minus a single central intersection, which is veiwed through a small aperture made to scan the entire pupil sequentially. Smirnov measured the topographies of 7 eyes and commented on them.

More recently, Webb and colleagues[8] made a modern implementation of Smirnov's method that computes the wave aberration and reduces it to Zernike polynomials. It shows remarkable repeatability.

Lastly, the Hartmann Schack wavefront sensor, a method initiated in astronomy to analyze the aberrations of the atmosphere above a telescope in real time, was adapted by J. Bille and J. Liang in Heidelberg and developed by Liang, Williams, and colleagues in Rochester to image the human fundus by removing the aberrations of the eye with a deformable mirror.[9] The measurement is made by focusing a bright spot of light on the retina and projecting the quasi-planar wave onto a matrix of lenslets that focus spots of light on a CCD video array. Just as in the Tscherning aberroscope, the displacement of the spots from their unaberrated positions yields the average slopes of the wavefront at each lenslet's position.

In conclusion, there exist today a variety of subjective and objective methods for assaying the wave aberration of human eyes, which span a wide range in cost, complexity, and accuracy. Due to the unique advantages of each method, we may expect to see their continued use in the near future.

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