History of the Shack Hartmann wavefront sensor and its impact in ophthalmic optics

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ABSTRACT

The Shack Hartmann wavefront sensor is a technology that was developed at the Optical Sciences Center at the University of Arizona in the late 1960s. It is a robust technique for measuring wavefront error that was originally developed for large telescopes to measure errors induced by atmospheric turbulence. The Shack Hartmann sensor has evolved to become a relatively common non-interferometric metrology tool in a variety of fields. Its broadest impact has been in the area of ophthalmic optics where it is used to measure ocular aberrations. The data the Shack Hartmann sensor provides enables custom LASIK treatments, often enhancing visual acuity beyond normal levels. In addition, the Shack Hartmann data coupled with adaptive optics systems enables unprecedented views of the retina. This paper traces the evolution of the technology from the early use of screen-type tests, to the incorporation of lenslet arrays and finally to one of its modern applications, measuring the human eye.
Keywords: Shack Hartmann, wavefront sensing, adaptive optics, LASIK, retinal imaging

1. INTRODUCTION

The Shack-Hartmann wavefront sensor is a simple and elegant means for measuring the shape of an aberrated wavefront. This technique has advantages over traditional interferometry in that is can be performed with an incoherent source. The Shack Hartmann technique also does not require vibration isolation and can be designed to measure highly aberrated wavefronts where traditional interferometric tests often fail. The Shack Hartmann technique has found application to a wide variety of applications from enhancing astronomical images to improving human vision. This technique has become widespread throughout the world with hundreds of millions of astronomical images benefiting from the information provided by the sensor. Furthermore, millions of corrective refractive surgeries have employed this technology to enhance vision. It is rare for a technology to have such a dramatic impact on a single field, let alone multiple fields as the Shack-Hartmann sensor. This paper describes the history and evolution of the technology and describes many of the ophthalmic applications found today. Additional details regarding applications to both the astronomy and ophthalmology can be found in previous reviews of the technology.[1-2]

2. EVOLUTION OF SCREEN TESTS

2.1 Scheiner's Disk

The history of the Shack-Hartmann wavefront sensor can be traced back about 400 years to the Bavarian city of Ingolstadt. There, a Jesuit priest named Christoph Scheiner (Figure 1) developed a simple device for measuring eyesight now known as Scheiner's disk.[3] The disk, which has two small holes, is placed before a subject's eye. A distant light source such as a candle is viewed through the holes. If the subject sees a single candle, then their retina is conjugate to the distant candle and they have good eyesight. If the subject sees two candles, then defocus (or in the parlance of the ophthalmic world, refractive error) is present. If the subject approaches the candle and the dual images of the candle fuse into a single image, then the subject is near-sighted (positive defocus). Failure of the dual images to fuse means the subject is far-sighted (negative defocus). In effect, the Scheiner disk is creating a spot diagram on the subject's retina, albeit with only two spots. However, this information is sufficient to gain insight into the refractive state of the eye. The distance between the subject and the candle when the image is fused tells the location of the object plane that is conjugate to the retina. The failure of the image to fuse in the far-sighted case tells that only a virtual object can be conjugate to the retina. This simple concept has evolved over the past several hundred years to enable not only the measurement of defocus, but also the higher order aberrations of optical systems.

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Figure 1. Christoph Scheiner was a Jesuit priest who taught at the University of Ingolstadt in the early 1600s. He lectured on optics, astronomy and telescopes. *Image: Wikipedia*

2.2 Tscherning aberroscope

The next step in the evolution of screen tests comes from the Danish ophthalmologist, Marius Tscherning. He developed a technique for measuring the aberrations of the eye that dates back to the late 1800s.[4] Tscherning placed a grid of equally spaced lines over a +5.00 diopter lens. Subjects viewing a distant point source through the lens perceived a distorted shadow of the grid on their retinas, as shown in Figure 2. The introduction of the lens introduces additional defocus into the eye which spreads out the grid pattern enabling the subject to more easily perceive the pattern. This technique, like Scheiner's disk, is creating a spot diagram on the subject's retina. The spots are formed by the light passing through the gaps in the grid, and each spot is displaced by the transverse ray error associated with the auxiliary lens and the aberrations of the eye. Tscherning had the subjects draw the distorted grid, and the drawings were then analyzed to determine the individual wavefront aberrations. Howland and Howland[5] later modified this subjective technique using a crossed-cylinder lens in place of the positive-powered lens to facilitate viewing and analysis. While the early version of the Tscherning technique was subjective, Walsh and colleagues[6] further improved on the technique by photographing the distorted grid pattern on the subject's retina, thus making the test objective. Finally, the modern version of this technology was described by Mierdel and coworkers[7] and Mrochen and colleagues.[8]

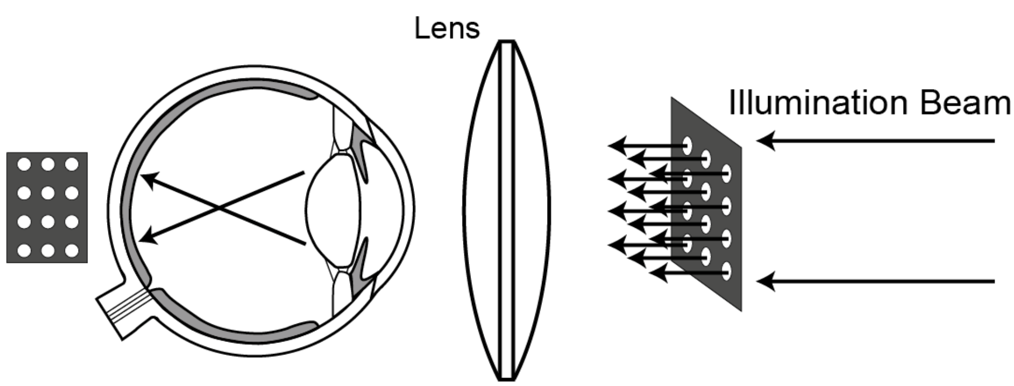

Figure 2. In the Tscherning aberroscope, a grid pattern is combined with a positive powered lens to create a spot pattern on the retina. The distorted retinal pattern encodes the transverse ray aberrations of the eye.

2.3 Hartmann screen test

Johannes Hartmann, a respected German astrophysicist, spent his career in Germany and Austria.[9] It was during his tenure as a Professor in Potsdam at the beginning of the 20th century that Hartmann developed the screen test associated with his name. Hartmann worked on the "Great Refractor," an 80 cm refracting telescope primary, which was meant to continue Potsdam's leadership in the field of astronomical spectroscopy. However, upon first light, the optics of the telescope were of inadequate quality to capture usable photographic images. Hartmann developed a testing technique to identify the source the problem. He constructed a mask containing an array of holes, and placed the mask over the aperture of the telescope. Photographic plates were then inserted and exposed on either side of focus as shown in Figure 3. The mask on the telescope effectively creates a discrete set of ray bundles that pass through different entrance pupil locations. The exposed plates, as with the previous examples, represent a spot diagram of the telescope for positions on either side of focus. If the photographic plates are outside of the caustic region, the spot on one plate can be uniquely connected to its corresponding spot on the other plate. This information can be used to draw rays between the two plates and determine the location where the rays cross the optical axis. High quality optics would have the rays crossing the optical axis at the same point, while poor optics would result in a variation in location of the ray crossings. Using this technique, Hartmann was able to determine that the problem in the Great Refractor resided in the primary lens. After this lens was refigured, the 80 cm telescope became usable and Hartmann went on to spectrographically identify calcium clouds with the system. The Hartmann Screen test is still used to this day, a testament to its simplicity and value. The technology remained unchanged for nearly 70 years. However, a need to perform wavefront measurements with extremely low illumination would force the technology to evolve into what is known as the Shack-Hartmann sensor. This evolutionary process required new sophisticated optical elements. However, the simplicity of implementation remained.

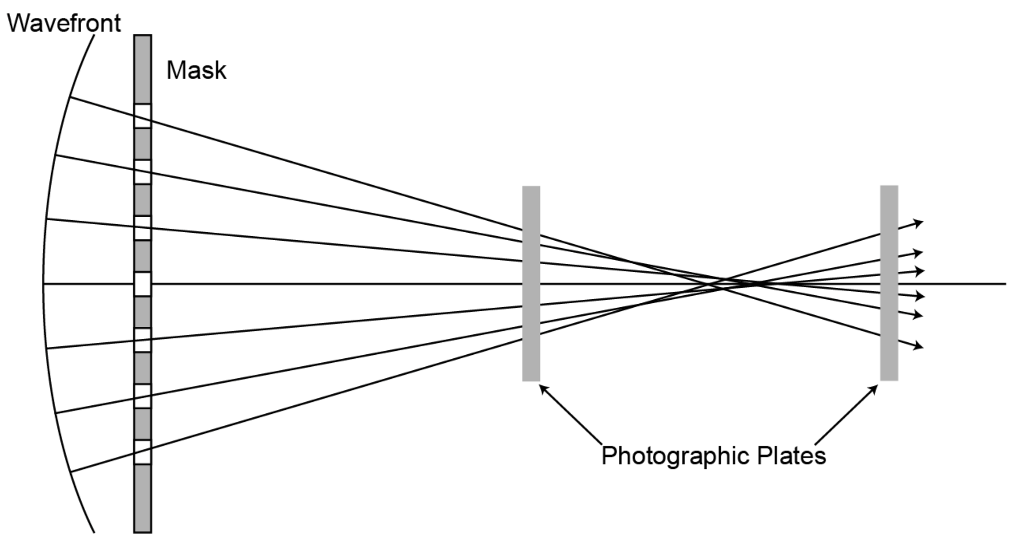

Figure 3. Light passing through the holes in the Hartmann screen create discrete ray bundles which converge towards the focus. Photographic plates were used to record the spot pattern formed on either side of focus.

3. SHACK HARTMANN WAVEFRONT SENSOR

The development of the Shack-Hartmann wavefront sensor is a direct result of the Cold War between the United States and the Soviet Union. The US Air Force had a desire to image Soviet satellites from ground-based telescopes. Atmospheric turbulence distorted the quality of the images formed and extremely low light levels reflecting from the satellites made this task challenging at best. The military approached Aden Meinel and the Optical Sciences Center (OSC) at the University of Arizona to help resolve the imaging problem. Meinel suggested siphoning off a portion of the incident light and using a Hartmann test to determine atmospheric aberrations at the time the image of the satellite was captured. The concept was to deconvolve the captured image using the point spread function calculated from the measured wavefront information. Roland Shack, who Meinel had recruited to OSC several years earlier, was given the task to determining if this technique was feasible. Several severe limitations of the proposed technique became immediately obvious. Satellites themselves send little light to the ground-based telescopes, and most of this light is needed to record the image of the satellite. Consequently, only a small fraction of the available light can be sent to the Hartmann screen. The Hartmann screen, furthermore, has poor light efficiency since it blocks all the photons except for those passing through its holes. Shack's first innovation was to place lenses within each of the holes in the Hartmann Screen. By adding lenses, the light passing through the apertures would be concentrated to a focal spot. This concentration would aid in boosting the photon density and allow the spot to be more easily recorded. Shack's second insight was that the screen itself was no longer needed. If the diameters of the lenses expanded until their edges met, then all of the photons incident on the screen would find their way to a focal spot. Consequently, this setup creates the most efficient use of the incident light possible, an ideal situation for a system that is photon starved. The next step in the implementation of the technique was to obtain a suitable array of lenses.

3.1 Lenslet fabrication

Lenslet arrays were commercially available. However, their dimensions and focal lengths were not suitable for the satellite-imaging problem. Fabrication of custom lenslet arrays by the manufacturers was expensive, so in-house lenslet fabrication was undertaken at the OSC. Ben Platt, a graduate student, was assigned to Shack to work on the development of the lenslet arrays. They devised a fabrication technique involved grinding and polishing a series of concave cylindrical grooves into glass plates.[10] A 120mm diameter nylon rod was mounted on a steel rod so that the nylon rod would slide back and forth along the steel rod. A glass plate was placed under the nylon rod with some polishing compound. By stroking the nylon rod repeatedly over the glass plate, a polished cylindrical groove was created in the glass plate. Once the groove reached a width of 1 mm, the nylon rod was lifted, the glass plate translated 1 mm and the polishing process repeated. In this manner, an array of concave grooves was formed in the glass. The glass plate was then split into two pieces and used as a master to mold the lenslet arrays. Plexiglass with a thickness of 1 mm was heated and molded between the two orthogonally oriented pieces of the glass master. The molded part consequently had an array of cylinder lenses along one side and a second array of cylinder lenses rotated by 90 degrees on its other side. The combined cylindrical lenses are indistinguishable from a spherical lens over the small aperture and dimensions of the array. The wavefront sensor was completed and delivered to the Air Force satellite-tracking telescope in Cloudcroft, New Mexico. Unfortunately, the system was never used, and it is unknown what became of this original wavefront sensor.

4. OPHTHALMIC APPLICATIONS OF THE SHACK HARTMANN SYSTEM

In the mid-1980s, Shack visited Josef Bille at the University of Heidelberg. Bille was the first to apply the Shack-Hartmann technique to the eye. The technique was first applied to measuring corneal topography by analyzing the wavefront reflected from the anterior cornea.[11] Later, the Shack-Hartmann system was modified to measure the aberrations of the entire eye.[12-13] This initial work by Bille and his students opened a new era in ophthalmology and vision science in which the aberrations of the eye could be measured by the Shack Hartmann and ultimately corrected with adaptive optics systems, laser surgery or ophthalmic lenses. Figure 4 shows the conceptual arrangement for measuring ocular aberrations with a Shack Hartmann system. A source beam (not shown) is focused onto the retina to serve as a "guide star" for the wavefront sensor. Light scattered from the retina emerges out of the eye forming a wavefront containing the ocular aberrations. This wavefront is relayed onto a lenslet array. The individual lenslets form

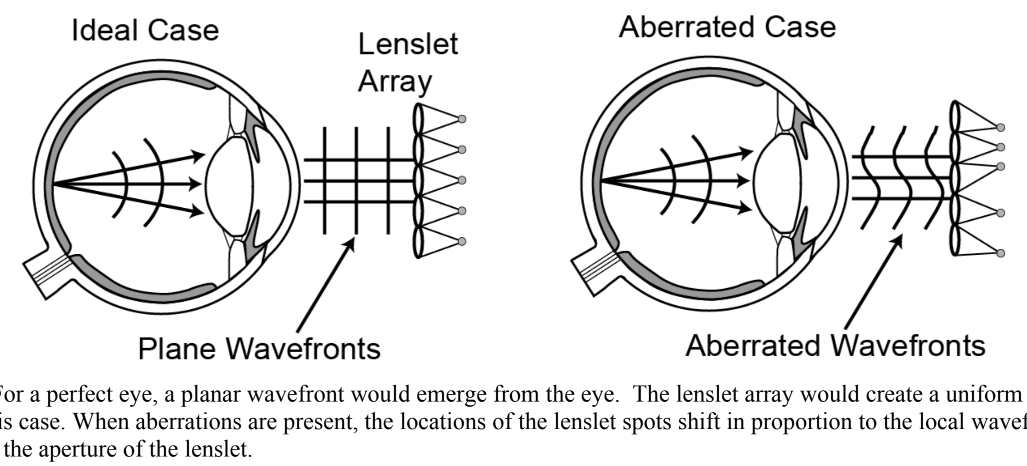

Figure 4. For a perfect eye, a planar wavefront would emerge from the eye. The lenslet array would create a uniform grid of spots in this case. When aberrations are present, the locations of the lenslet spots shift in proportion to the local wavefront slope over the aperture of the lenslet.

a grid of spots at their rear focal points. Since the aperture of the lenslets is small, the incident wavefront is essentially planar over the lenslets aperture. However, this planar portion of the wavefront can be tilted due to the local wavefront slope. The tilt in the incident wavefront still creates a spot in the rear focal plane of the lenslet, but the spot location is laterally shifted. By comparing the spot positions in the aberrated case with the ideal case, the wavefront gradient can be determined at each lenslet position. These gradients are then integrated to recover the original wavefront error.

4.1 Supervision

Supervision is the somewhat unfortunate name that has been applied to the vision feasible when the ocular aberrations are corrected. The optical quality of the eye tends to be the limiting factor in the performance of visual instruments. Liang *et al* demonstrated that the resolution limit of the eye can be dramatically improved by coupling a Shack Hartmann wavefront sensor with a deformable mirror.[14] The wavefront sensor measures the ocular aberrations and the deformable mirror compensates, in closed-loop fashion, for these aberrations. An observer viewing a target in reflection from the deformable mirror can now perceive the target limited only by diffraction and the limitations imposed by the sampling of their photoreceptors. As shown in Figure 5, subjects with “normal” visual acuity of 20/20 (1 arcmin resolution) were able to routinely achieve a visual acuity of 20/10 (0.5 arcmin resolution) with the correction of their ocular aberrations. This demonstration of the potential vision improvements stimulated rapid development of modalities for the practical implementation of aberration correction in the human eye. Conceptually, the wavefront error defines the required shape of a custom lens that compensates for the aberrations of the eye. This custom lens, as shown in Figure 6, pre-distorts incident plane waves such that the eye’s aberrations are canceled. This custom lens can be surgically placed in or on the eye or embedded into corrective lenses.

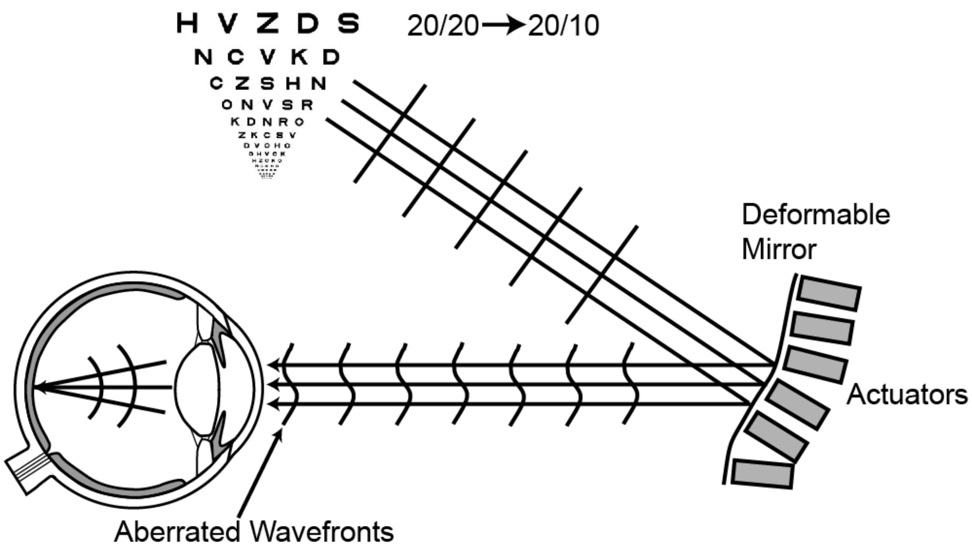

Figure 5. A wavefront sensor measuring ocular aberrations is used to drive the shape of a deformable mirror to null the effects of the aberrations. A viewer looking at a target in reflection from the mirror will only be limited by diffraction and retinal sampling effects.

4.2 LASIK and PRK

The advent of the excimer laser operating at a wavelength of 193 nm has enabled precise sculpting of the cornea. By reshaping the curvature of the cornea, myopia, hyperopia and astigmatism can be corrected. Photorefractive keratectomy (PRK) and Laser in situ Keratomileusis (LASIK) are excimer laser surgical procedures for creating these corrections. Millions of people have been treated with this technology to dramatically reduce their defocus and astigmatism. Molebny and colleagues[15] suggested that wavefront measurements could be used to increase the accuracy of excimer laser refractive surgery and reduce the individual ocular aberrations. The custom lens shown in Figure 6 is ablated directly into the corneal surface in this case. Registration of the ablation pattern, as well as compensation for small eye motions during the procedure is critical. To overcome these issues, video registration with iris features and fast eye trackers are commonly used to appropriately impart the pattern into the cornea.

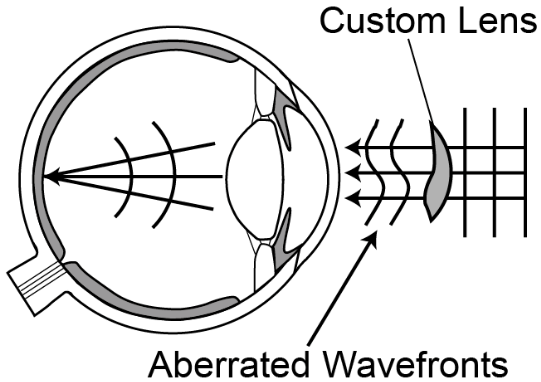

Figure 6. A custom lens creates the complementary wavefront to that created by the eye's aberrations, resulting in a near diffraction limited spot on the retina.

Correction of individual aberrations is a natural endpoint for this technology and the Shack-Hartmann technique has played a pivotal role in enabling the customization of refractive surgery. Other wavefront sensing techniques have been implemented, but the Shack-Hartmann sensor is the most widespread and well known technology for performing customized correction. By treating aberrations in the eye, the normal 20/20 acuity is often improved upon, and even the poor outcomes are nearly always achieving "normal" 20/20 vision. Custom refractive surgery based on measurement and correction of ocular wavefront errors is readily available. Studies using the technology have demonstrated a major impact on the results of refractive surgery.[16] Much of this impact from wavefront-guided refractive surgery has been from the bottom up. The number of patients achieving 20/20 vision following refractive procedures is dramatically higher than with conventional surgery, whereas a smaller but significant number of patients gain lines of acuity. This result suggests that the patients with larger degrees of aberration have the most to gain from customized technology.

4.3 Custom ophthalmic lenses

A less permanent method for correcting ocular aberrations is to impart the compensating pattern into an ophthalmic lens. Smirnov suggested that contact lenses could be manufactured that would correct for these errors.[17] For custom contact lenses, the compensating aberration pattern is imparted to one or both surfaces of a contact lens. Custom contact lenses have become much more feasible with recent developments in lathe technology. Modern lathes can now employ a rapidly oscillating tool that allows non-rotationally symmetric surfaces to be cut into contact lens surfaces. One issue that arises with this technology, however, is the stability of the correction on the eye. Unlike the laser ablated pattern, the contact lens translates across the surface of the cornea, especially following a blink. There exists only one location and orientation of the lens where the ocular aberrations are corrected. Efforts to desensitize the aberration correction to translation of the contact lens have been examined.[18] Furthermore, large scleral lenses with excellent positional stability on the eye are being used to correct ocular aberrations.[19]

Intraocular lenses (IOLs) are routinely used to replace the natural crystalline lens following cataract surgery. These lenses may also benefit from wavefront correction. Currently, aspheric IOLs are commercially available that correct for spherical aberration in the average human eye. Since the natural lens is removed in surgery and replaced with an artificial lens, the ocular wavefront aberrations will change during the procedure and their post-operative values cannot be predicted. Light-adjustable intraocular lenses may offer a solution for customized intraocular lenses.[20] The shape of these lenses can be modified through ultraviolet light exposure and then permanently fixed following implantation. Therefore, the lens can be implanted and the eye allowed to heal and stabilize following surgery. Then, residual aberrations can be measured with the implant in place and the lens modified to correct them.

4.4 Retinal imaging

The modalities above are designed to provide improved visual performance by reducing the aberrations in the image falling on the retina. However, the direction of light can be reversed leading to the ability resolved unprecedented detail in the retina. Conceptually, the target in Figure 5 is replaced with a fundus camera. The diffraction limited image of the retina is then recorded by the camera sensor. Liang and colleagues first used wavefront technology to improve the optical quality of fundus imaging.[14] This work led to the first *in vivo* imaging of photoreceptors[21] and *in vivo* classification of cone types.[22] These studies further resulted in the development of a scanning laser ophthalmoscope that can image individual photoreceptors and overlying structures, such a capillaries and the nerve fiber layer.[23] Wavefront technology has also enabled adaptive optics correction of Optical Coherence Tomography (OCT) systems.[24] These technologies provide unprecedented lateral and axial resolution in imaging the living retina, and provides further understanding about the architecture, function, and diseases of the retina, which until recently, were impossible to image in the living eye.

5. SUMMARY

The Shack-Hartmann sensor because of its simplicity and versatility in measuring complex wavefronts has become a wide used metrology tool. In addition to other areas of optics, the Shack Hartmann sensor has become the primary tool for measuring ocular aberrations in ophthalmic applications. Commercial devices for assessing the eye are available throughout the world. These devices are typically linked to a refractive surgery laser to enable the correction of the aberrations and enhancement of visual performance. Other corrective lenses such as custom contact lenses and intraocular lenses have been explored, but they have yet to reach commercial viability. Finally, the Shack Hartmann sensor has also been linked to adaptive optics systems to enable unprecedented views of the retina. The expense of the combined wavefront sensor and deformable mirror system has limited the commercial implementation of these fundus imaging systems, but a variety of research laboratories have systems. These devices are enabling vision scientists to better understand the architecture of the retina and the differences between a healthy retina and various disease states. The Shack-Hartmann sensor has had a direct impact on the vision of millions of people worldwide.

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