Synopsis of “METHOD AND APPARATUS FOR IMPROVING VISION AND THE RESOLUTION OF RETINAL IMAGES” by David R. Williams and Junzhong Liang from the US Patent Number: 5,777,719 issued in July 7, 1998

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The art in the present literature involves a method and an apparatus for improving vision system using a combination of laser based retinal imaging system, Hartmann-Shack wavefront sensor, wavefront compensation device such as deformable mirrors, and advanced user feedback and imaging processing algorithm. Together, they enable precise measurement of higher order aberrations beyond defocus and astigmatism limited by existing ophthalmic metrology. The resulting output correction signal from the sensor may be used to fabricate contact or intraocular lenses, or to guide a surgical procedure to correct for the aberrations of the eye.

The method described in the literature includes a low power laser beam producing a point source on the retina. The scattering energy is reflected from the retina and received by an array of lenslets in a Hartmann-Shack wavefront sensor such that each of the lenslets in the array form an aerial image of the retinal point source on a CCD camera located adjacent to the lenslet array. The output signal is acquired and processed by a computer which then produces a correctional signal that can be used to control a compensating optical or wavefront compensation device, such as a deformable mirror. The proper adjustment is made to the deformable mirror with a goal to null the aberration in the measured point spread function of the eye. The process can be iterative until a best correction is achieved, allowing improved vision and imaging of the inside of the eye.

The novelty behind this patent is that it provides a method and apparatus for improving vision and the resolution of retinal images by measuring and compensating for the high order wavefront aberrations beyond defocus and astigmatism that have never been achieved before. Furthermore, the measured data can be used to develop corrective means to improve optical quality of the eye achieving supernormal vision; something that is not possible with existing ophthalmic techniques.

There are a number of existing systems and techniques described in the invention as prior arts that are insufficient in delivering a comprehensive measurement of aberrations in the eye. The current ophthalmic lenses can only correct defocus and astigmatism in spite of the recent advances in the optical design of spectacle and contact lenses. The remaining uncorrected aberrations such as spherical, coma and other irregular aberrations not only blur images formed on the retina but also blur images taken of the living human retina. The obstacles that limited the further corrections of visual system beyond defocus and astigmatism have been the non-existence of quantitative technique to measure and correct for the residual aberrations in the eye.

Optometrists have long used subjective refractive methods and objective autorefractors to measure aberrations of the eye but such techniques cannot measure complete wave aberration and are typically limited to defocus and astigmatism. Walsh et al. in 1984 disclosed a method using objective aberroscope to simultaneously measure wave aberration of the entire pupil; however, such technique cannot provide pupil sampling resolution better than 0.9mm which is not accurate enough

Recently, in a report published by one of the co-inventors herein, a method of objective measurement of wave aberrations of the eye using a Hartmann wavefront sensor was disclosed. However, using the disclosed system, the authors were only able to measure up to fourth order polynomial functions. Furthermore, the wavefront fitting with polynomials up to fourth order does not provide complete description of the aberrations in the eye and with that it is generally insufficient to determine the exact optical performance of the eye. In addition, the instrument was not adequate in removing stray light, such as unwanted light reflections from lens and the corneal surfaces of the eye.

There have been other attempts to correct for aberrations beyond defocus and astigmatism using a confocal scanning laser ophthalmoscope. In this technique, a fundus contact lens was used to null light refraction at the first surface of the cornea. However, this approach to increase the axial resolution of a confocal scanning laser ophthalmoscope only showed modest improvement because it neglects the interaction of wave aberration of the eye with different index media throughout the optics of the eye.

Finally, another approach that was proposed by Bille in a U.S. patent is to use a deformable mirror in a confocal laser scanning ophthalmoscope in conjunction with the human eye; however, no method to measure the wave aberration of the eye was disclosed. Then Dreher, Bille, and Weinreb demonstrated the usage of a deformable mirror for the eye to correct for astigmatism in Applied Optics. However, this proposal is no better than the correction provided by the conventional ophthalmic techniques. The use of such optical device to correct for aberrations beyond second order has never been achieved.

The proposed method and apparatus for providing improved visual acuity and resolution retinal images have few main objectives to meet to overcome what were not possible or inadequate with prior arts. The main objective of the present invention is to enable accurate measurement of higher order aberrations of the eye and for using the data thus measured to compensate for those aberrations with a customized optical element. A second objective is to provide an improved wavefront sensor that suppresses stray light by rejecting light reflected from structures other than the retina and which is capable of providing a complete measurement of eye’s aberrations. Another objective is to utilize the improved wavefront sensor in combination with a deformable mirror to correct for the wave aberration in an iterative feedback manner such that the subject achieves better than normal visual acuity. Finally, an equally important objective is to be able to produce a high optical quality and resolution retinal images which will make the imaging of microscopic structures of a single cell in a retina possible.

The objectives mentioned above are achieved by providing a system with a laser beam creating a point source on the retina of an eye. The reflected light from the retina and the aberrated wavefront emerged from pupil are received by a lenslet array in a Hartmann-Shack wavefront sensor. Each lenslet in the array is used to form aerial image of the retinal point source on an adjacent CCD camera. The wave aberration is decomposed by the array of lenslets which individually forms a focus spot on the sensor. Each lenslet displaces its focus spot by an amount proportional to the local slope of the aberrated wavefront. The output from the digital CCD camera is sent to a computer which then computes the centroid of each of the spot formed by the lenslets and compares the actual location of the focus spot versus the ideal case with an unaberrated reference. The offsets of the spots in x and y directions are then calculated and used as the slope data to fit with the sum of the first derivatives of 65 Zernike polynomials using a least square procedure to determine the weight for each polynomial. The Zernike polynomials are then weighted with the calculated coefficients and added together to create a reconstructed wave aberration. The wave aberration is then evaluated at the planes wavefront compensation device or the actuators of a deformable mirror in order to produce the correction signal which is then sent by the computer to the device. The feedback loop continues to receive the reconstructed wave aberration results, feeding back an appropriate correction signal, and the process iterates according the steps shown in **Fig. 1** until the root mean square of the reconstructed wave aberration signal reaches an convergence criteria, at which point, the deformable mirror has been acquire a shape that is identical to the wave aberration measured at the outset but with half the amplitude. The amount of mirror deformation flattens the distorted wavefront into a plane wave by compensating for all detected aberrations in the eye and thus improving image quality of the visual system.

As a result, the final aberration correction signal can be used either to produce contact or spectacle lenses to correct for all of the monochromatic aberrations of the eye, or to provide detail prescription for surgical procedures. In addition, the proposed system can also be used to provide high resolution images of the retina through a secondary imaging path. The system uses a krypton flash lamp to illuminate the retinal disk and then an image of the retina is relayed through a series of optics and reflected by the deformable mirror onto a lens and through an aperture such that the reflected retinal image is focused onto a second CCD camera. Because the deformable mirror has already acquired the appropriate shape to compensate for all aberrations found in the eye, it is possible to acquire high optical quality and aberration-free images of a retina with its resolution limited to only the diffraction spot size of the imaging optics.

In the preferred embodiment of the patented system, shown as **Fig. 2**, a collimated laser beam passes through a spatial filter (104) and is recollimated by an achromatic doublet lens (106). The then collimated laser beam will have a state of polarization reflected by a polarizing beamsplitter (110) and passes through a set of afocal relay lenses (112, 116) to reach the deformable mirror (118). The laser beam reflected from the deformable mirror is then relayed by a set of similar afocal lenses (120, 122) and passes

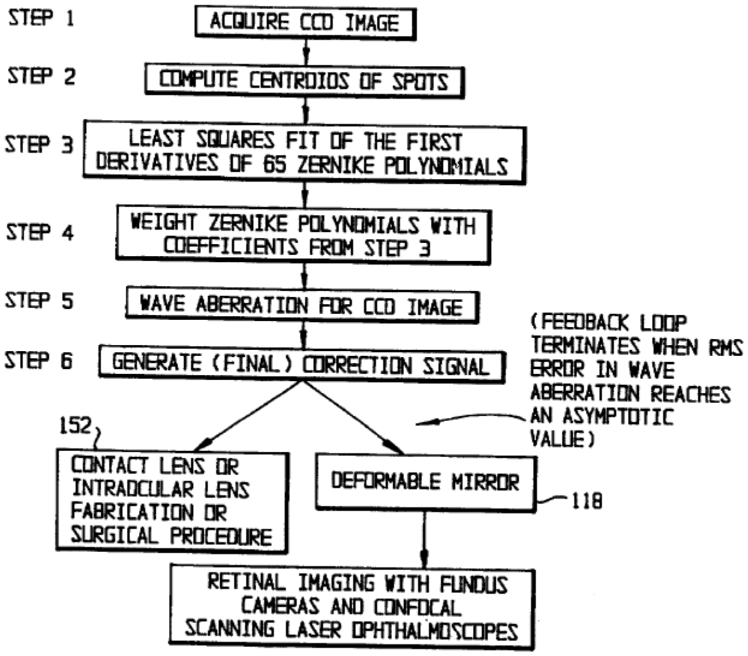

Fig. 1: Steps in the adaptive optics feedback loop using a wavefront sensor and a deformable mirror

through a second beamsplitter (124) to reach the eye at a diameter of about 1.5mm at the pupil. The optics in the eye (100) focuses the laser beam onto its retina creating a localized point source. In the event that the subject under test has myopic or hyperopic vision, accommodation is achieved through the movement of the tested eye (100) and the lens (122).

The light reflected from the retina forms a distorted wavefront at the pupil. The aberrated wavefront is relayed by the lenses to the deformable mirror (118) then reflected and passes through the polarizing beam splitter onto the plane of the lenslet array (148) of a Hartmann-Shack wavefront sensor. By this preferred layout, the pupil of the eye is conjugated to the deformable mirror which is also conjugated to the lenslets such that each lenslet in the array forms an aerial image of the retinal point source on the adjacent CCD camera (146). The deformable mirror has actuators behinds them that can control the phase of light at different conjugate points in the pupil. A computer (150) then analyzes the digital image and calculates the slopes of the incident wavefront by determining the displacement of focus spot relative to an unaberrated reference simultaneously in both x and y directions across the entire pupil. From synthesizing the array of slopes, the wave aberration is measured. The computer then evaluates the wave aberration at the plane of the deformable mirror and feed back an appropriate correction signal to compensate for the wave aberration of the eye. The process is repeated with the computer generating signals to cause the deformable mirror to continue deforming until the root-mean-square error in the measured wave aberration reaches certain convergence criteria, at which point the deformable mirror should have acquired an appropriate shape to provide compensation for aberrations in the eye.

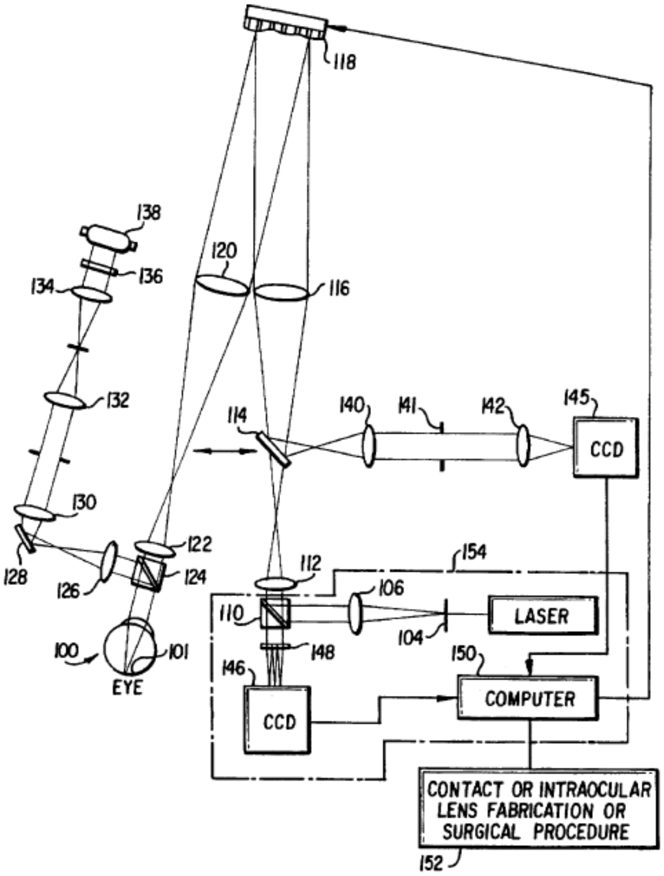

Fig. 2: Optical layout of the adaptive optics feedback looping using a Hartmann-Shack wavefront sensor and deformable mirror

In addition, the system presented can be used to acquire high resolution images of the retina (101). A krypton flash lamp (138) passing through a narrow band pass filter (136) is imaged onto the pupil of the eye by a series of lenses (134, 132, 130, 126) after reflected off a beam splitter (124) to illuminate a retinal disk on the retina that is about a degree in diameter. Next, the image of the retina is relayed by the lenses (122, 120) to the deformable mirror, which has already been deformed to compensate for the aberrations in the eye, then reflected and passes through a set of similar relay lenses (116, 140) and the aperture (141) and eventually focused onto a CCD camera (145) by a focusing lens (142). Since the deformable mirror has compensated for all the aberrations in the eye, the resulting retinal image is aberration free and with high optical quality with its resolution only limited to the diffraction spot size of the imaging optics.

FIG. 3a-3d shows the results of measured data from a human subject with and without adaptive optical compensation. In particular, **FIG. 3a** shows the wavefront error of all detected aberrations in the eye while **FIG. 3b** shows the corrected wavefront error after compensated by the deformable mirror. Moreover, **FIG. 3c-3d** shows the point spread function of the eye without and without adaptive compensation using a deformable mirror. It is important to realize that after compensation, the strehl ratio is significantly increased from 0.09 (uncorrected) to 0.47 (compensated), close to the value expected simply from the diffraction of the aperture in the eye. The present invention is believed to have achieved the best optical quality ever for a human eye.

FIG. 3a

WITHOUT COMPENSATION

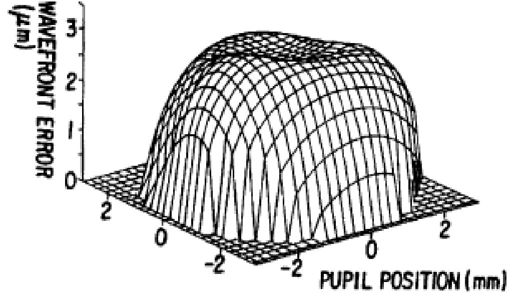

FIG. 3b

WITH COMPENSATION

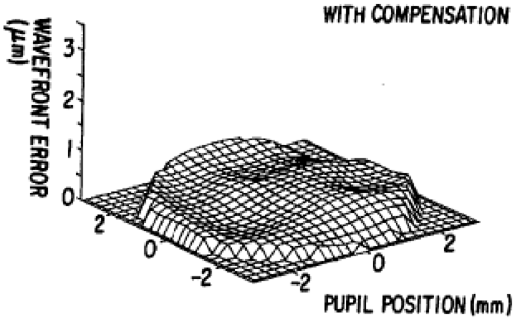

FIG. 3c

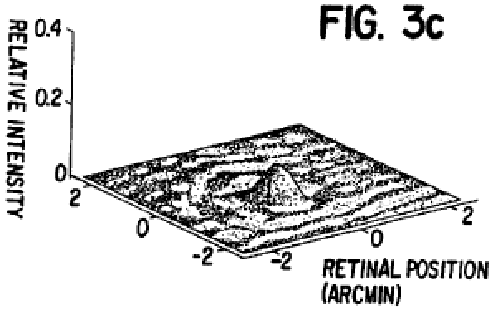

FIG. 3d