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Authors

Balderas-Mata, SE
Jones, SM
Zawadzki, RJ
et al.

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Application of a new hi-speed magnetic deformable mirror for *in-vivo* retinal imaging

Sandra E. Balderas Mata¹, Steven M. Jones², Robert J. Zawadzki¹, John S. Werner¹

¹*Vision Science and Advanced Retinal Imaging Laboratory, UC Davis Eye Center,
University of California Davis, Sacramento, California 95817, USA;*

²*Lawrence Livermore National Laboratory, 6000 East Avenue, Livermore, California, USA*

ABSTRACT

Nowadays in ophthalmologic practice several commercial instruments are available to image patient retinas *in vivo*. Many modern fundus cameras and confocal scanning laser ophthalmoscopes allow acquisition of two dimensional *en face* images of the retina with both back reflected as well as fluorescent light. Additionally, optical coherence tomography systems allow non-invasive probing of three-dimensional retinal morphology. For all of these instruments the available lateral resolution is limited by optical quality of the human eye used as the imaging objective. To improve lateral resolution and achieve diffraction-limited imaging, adaptive optics (AO) can be implemented with any of these imaging systems to correct both static and dynamic aberrations inherent in human eyes. Most of the wavefront correctors used previously in AO systems have limited dynamic range and an insufficient number of actuators to achieve diffraction-limited correction of most human eyes. Thus, additional corrections were necessary, either by trial lenses or additional deformable mirrors (DMs). The UC Davis AO flood-illuminated fundus camera system described in this paper has been previously used to acquire *in vivo* images of the photoreceptor mosaic and for psychophysical studies on normal and diseased retinas. These results were acquired using a DM manufactured by Litton ITEK (DM109), which has 109 actuators arranged in a hexagonal array below a continuous front-surface mirror. It has an approximate surface actuator stroke of $\pm 2\mu\text{m}$. Here we present results with a new hi-speed magnetic DM manufactured by ALPAO (DM97, voice coil technology), which has 97 actuators and similar inter-actuator stroke ($>3\mu\text{m}$, mirror surface) but much higher low-order aberration correction (defocus stroke of at least $\pm 30\mu\text{m}$) than the previous one. In this paper we report results of testing performance of the ALPAO DM for the correction of human eye aberrations. Additionally changes made to our AO flood illuminated system are presented along with images of the model eye retina and *in-vivo* human retina acquired with this system.

Key words: Adaptive optics, Fundus camera, Photoreceptor mosaic.

1. INTRODUCTION

Adaptive optics (AO) is a relatively mature technology used in remote imaging, astronomy and free-space optical communication to compensate for the aberrations due to atmospheric turbulence. It is also used in microscopy to correct for aberrations in deep tissue imaging. In ophthalmology and vision science AO has been successfully implemented to compensate for ocular aberrations introduced by imperfections of the cornea and lens, as well as dynamic aberrations from tear film, eye movements, blood flow, and so forth. AO was first used in a conventional fundus camera by Liang et al.¹, and then subsequently applied to confocal laser scanning ophthalmoscopes²⁻⁴, and later to optical coherence tomography⁵⁻⁷. In flood illuminated fundus cameras, the AO technique has played an important role in acquiring first images of cone photoreceptors.

The flood illuminated fundus camera system consists of a light delivery unit that sends sufficient illumination to acquire an image of the human retina *in vivo*. This image is acquired by capturing the backscattered light from the retina (usually photoreceptor layer) using a science camera. AO fundus imaging can be used to quantify cone photoreceptor

mosaic density and therefore reliably monitor changes as retinal disease progresses, as described by Choi *et al.*⁸, and references there in. Also, it has been used to observe the physiological processes in a single photoreceptor *in vivo*⁹.

The performance of deformable mirrors (DMs) to correct ocular aberrations is of great importance in AO systems to acquire diffraction-limited correction. The number of actuators and the dynamic range of the DMs must be sufficiently large in order to compensate high-order aberrations¹⁰. The firsts DMs were used for astronomical telescopes to correct the aberrations due to atmospheric turbulences. The system's pupil size for ocular AO systems is orders of magnitude smaller than the one for astronomical AO, therefore the use of DMs with smaller diameter size to correct ocular aberrations is preferred. Ideally the DM diameter should match that of the imaged eye pupil it is ~7mm. There are different types of deformable mirrors used for ocular and atmospheric aberrations correction, e.g., bimorph deformable mirrors, magnetic deformable mirrors, membrane micromachined deformable mirrors (MMDM), microelectromechanical systems (MEMS) mirrors, and MEMS segmented mirrors. A detailed comparison of various deformable mirrors has been reported in 2008 by Devaney *et al.*¹¹.

This paper summarizes performance of the UC Davis AO flood-illuminated fundus camera equipped with a new DM (ALPAO DM97, voice coil technology) for correcting ocular aberrations. These results with model eye were acquired using a set of trial lenses with different optical power placed in front of it to test system dynamic range for low order aberration correction. We also present images acquired with this system *in-vivo* of the human retina.

2. MATERIALS AND METHODS

The UC Davis AO-flood illuminated fundus camera system consists of three main units: light delivery for retinal imaging, AO for compensating ocular aberrations (i.e., wavefront sensor and wavefront corrector) and retinal imaging camera. The previous AO-flood system was described in details by Choi *et al.*⁸. Briefly, the DM used to correct the ocular aberrations was a Litton ITEK. It has 109 actuators arranged in a hexagonal array below a continuous front-surface mirror, and an approximate surface mirror stroke of $\pm 2\mu\text{m}$. Flood illumination was delivered from a 300 W xenon arc flash lamp (Oriel, Stratford, CT) which emits in the visible range but has a strong UV emission as well that was filtered out. This bright white light was collimated with a Nikon aspherical lens in order to shape the beam. It was shaped spectrally using a filter wheel with three different interference filters in the visible range, e.g., 550, 650, and 750 nm with a bandwidth of 25 nm. Recently, two main upgrades to the flood system were made, a new deformable mirror from ALPAO was installed with a higher actuator stroke and a superluminescent diode (SLD) was used as the light delivery unit. The AO-correction unit consists of a Shack-Hartmann wavefront sensor (WFS) that measures aberrations and corrects aberrations with a closed-loop DM. The imaging unit consists of an optical system to image the eye pupil onto WFS and DM as well as imaging the retinal plane onto a cooled CCD camera (VersArray XP; Princeton Instruments, Monmouth, NJ). A sub-system for aligning purposes was used. This system consists of a helium-neon laser with a wavelength center at 633 nm, and a collimator lens with a focal length of 250 mm to assure good collimation of the beam. This light source is used to align three arms of the system it is AO and for imaging light delivery and detection.

2.1 Experimental setup

The new configuration for the AO arm of the system is shown in red in Fig.1; the DM from ALPAO has 97 actuators, for wavefront control. A superluminescent diode (SLD) with center wavelength of 753.6 nm and FWHM of 21.6 nm is used to form at the retina reference the spot for wavefront sensor. The power of this wavefront beacon delivered into the eye cornea was set at 6.1 μW , see Table 2 for more details. The output beam is imaged by a set of telescopes giving a beam of about 1 mm on the cornea plane, over a 7mm pupil diameter. The size of the beam on the retina is $\sim 15\mu\text{m}$. The back scattered light fills the whole pupil. The conjugate pupil plane is relayed to the WFS, after the passing through 3 telescopes to rescaled the size of the beam, via the reflection from a dichroic (Semrock: FF801-Di01-25x36) placed in front of the WFS entrance. The WFS consists of a 20x20 lenslet array with a focal length of 24 mm and a pitch between them of 400 μm (Adaptive Optics Associates, Inc., Cambridge, MA) and a CCD camera (model CA-D7; Dalsa, Waterloo, Ontario, Canada) which is located in the back focal plane of the lenslet array. The DM works in closed loop with the WFS in order to correct the ocular aberrations. This is achieved when that the light backscattered from the eye will reach the WFS, which in turn will send the information of the wavefront aberration as imaged by WFS at the eye's pupil plane to a computer. The computer calculates the necessary shape of the DM to cancel these aberrations using

matrix multiplication and sends this information to the DM in order to modify its shape. After the correction the light will travel again into the WFS sending the information to the computer about remaining wavefront error to be corrected. These steps are continuously repeated during imaging ensuring correction of dynamic components of the aberrations. The value that is used to evaluate the precision of the correction made by the DM is the amplitude and RMS of uncorrected part of the wavefront.

Fig.1 Schematic of the UC Davis AO-flood-illuminated fundus camera.

The imaging path black-red-black in Fig.1 represents mainly the flood illumination source (Superlum SLD-381) with center wavelength of 842 nm and FWHM of 40 nm, which may emit up to 180 mW from multimode fiber (N.A. 0.22, 55 μm diameter). It is collimated with an aspherical lens of 11 mm focal length giving an output beam size of 3.1mm, which is conjugated with the retinal plane. The size of this beam is rescaled with the use of 3 telescopes (L13-L12, L11-L9 and L8- eye lens of 17 mm focal length), resulting in a 500 μm (1.7°) retinal field of view and a 1 mm entrance beam at the pupil plane. The SLD power for *in vivo* imaging is set to reach 285 μW at the pupil plane, see Table 2. The imaging beam is modulated with a shutter (Model: VMM-D1, UNIBLITZ Electronics) set at 10msec, which is synchronized with the internal shutter of the science camera. The backscattered light from the eye travels the same AO path simultaneously with the beacon, assuring that the eye aberrations will be also canceled for this beam, passing through the dichroic (Semrock: FF801-Di01-25x36) to be captured with the science camera (VersArray XP, Princeton Instruments). A fixation target is used to reduce eye motion and to control the retinal area being imaged. This target consists of concentric circles, the radii of which corresponded to different retinal eccentricities, and it is placed in a retinal conjugate plane.

2.2 ALPAO 97-actuator membrane hi-speed magnetic deformable mirror

The ALPAO DM, as we have mentioned, has replaced the Litton ITEK (DM109) which had 109 actuators arranged in a hexagonal array within an active area of 68 mm of diameter. In order to ensure that ocular aberrations will be corrected with the new DM, the performance of the ALPAO DM was evaluated. To quantify performance for correcting low-order static aberrations we used trial lenses introducing defocus and cylinder of different magnitudes into the system and then

corrected it with our AO system. Also, high order dynamic aberrations in human eyes can be compensated. Both science camera images and HS-WFS data were saved to allow evaluation of the AO-system performance. These trial lenses were placed in front of a model eye and then with the help of the DM these induced aberrations were compensated.

Figure 2 shows the ALPAO DM and its actuator geometry. The gray circular area represents mirror surface of the DM. The image of the subject's eye pupil (7 mm) matches the 13.5 mm active area of the mirror (red circle) on the ALPAO mirror. This DM has a dynamic range greater than 30 μm correcting astigmatism and defocus, and an inter-actuator stroke larger than 3 μm . More detailed specifications are shown in Table 1.

Fig. 2. ALPAO-97 DM and its actuator geometry. Gray area represents mirror surface active area of the DM (13.5mm), which it is matched by the subject's eye pupil of 7mm (red circle).

Table 1. Specifications of ALPAO-97 DM.

Specifications of the ALPAO-97 DM	
Active area	13.5mm
Number of actuators	97
Mirror surface	Continuous
Stroke (wavefront)	Tip/tilt: +/- 60 μm Inter actuator: > 3 μm 3x3: > 30 μm
Speed	Bandwidth: 750Hz

2.3 Laser safety levels

The levels of light entering into the eye must be below safety limits ensuring no retinal damage during imaging. To ensure our light levels are below the maximum permissible power exposure (MPP) for imaging purposes we followed ANSI standards for safe use of lasers¹². This standard is set at the power levels ten times below powers creating changes to the retina visible during clinical examination. Recently, Delori *et al.*¹³, published a paper where the ANSI Standard is applied to several ophthalmic imaging systems. Following the Standard, the calculated maximum permissible power (MPP) values for the flood illuminating source and the wavefront sensor beacon are shown in Table 2. In the case of the flood illuminating source the Standard for a extended source is applied, and on the contrary for the beacon source, which the Standard of a point source must be applied. The fields of view for both light sources on the retina are set approximately to be 500 μm and ~15 μm , respectively.

The first part of Table 2, MPP for the AO correction light source, consists of four columns. The first column represent the total imaging exposure time, the second represents the MPP calculated from ref.12, third column is about the maximum MPP that we have calculated, and last column is the MPP that we are actually using to be delivered into the eye. All of these MPP are for continuous wave illumination.

Table 2. MPP values for both light sources used in AO-Flood illuminated fundus camera system.

Maximum Permissible Power (MPP) for ~15μm point source				
Total exposure [sec]	MPP _{beacon} [μW]	Max MPP _{beacon} [μW]	Used MPP _{beacon} [μW]	
30	378	150	6.5	
300	212	100	6.5	
Maximum Permissible Power (MPP) for 1.7° (~500μm) field of view at 840nm				
Total exposure [sec]	MPP _{SLD} [mW]	MPP _{SLD} per pulse [mW] (600 pulses)	Average MPP _{SLD} [μW]	Used MPP _{SLD} [μW]
300	3.7	9.8	197	285

The second part of Table 2, MPP for flood illumination, has to be calculated as a power exposure by repetitive pulses. This is due the modulation of 10 msec over a five minutes exposure to acquire the images. In order to calculate the permissible power under these conditions three rules must be satisfied; first rule refers to calculate the power exposure of one pulse, this is to prevent thermal damage (third column, Table2). The second rule refers to preventing photochemical damage and it considers the average power of the train of pulses, e.g., continuous-wave (fourth column). And, the third rule protects against subthreshold of cumulative thermal damage (second column). In our case, the duration of each of the pulses is 10 msec, so in accordance to Ref. 13, only rules second and third applies, fourth and second columns of Table 2, respectively. The last column is the total MPP that we are using for *in vivo* imaging. The power level of the SLD is set at 285 μ W for the flood illumination, which is three times below ANSI Standard for a wavelength of 842 nm and total exposure of 5 minutes. This is approximately ten times below the total MPP. The duration of each pulse is 10 msec. And, the power level for the beacon used for the aberration correction is set at 6.5 μ W, which is ten times below the permissible power for a wavelength of 753 nm for the same exposure time as the SLD.

3. RESULTS

In this section we present our preliminary results of compensating ocular and induced aberrations with the AO-Flood system. Also, the performance of the ALPAO-DM is presented using a set of trial lenses in the pupil and a model eye. *In vivo* retinal images acquired with this system from a 30 Yr old male volunteer are shown as well.

3.1 Performance of ALPAO-DM

We introduced different types of low order aberrations (e.g. spherical and astigmatism) by placing trial lenses in front of the model eye, which are located at the eye pupil plane. Figure 3 shows three different stages of the AO correction, by using the Flood system with the AO off (DM is set as flat mirror) and AO on (active correction), in order to correct the defocus refractive error of +2.0 diopters induced in the pupil of the model eye.

Fig. 3. Image of the model eye without AO (a), starting the AO (b), and with AO (c).
The refractive error added to the model eye is +2.0 diopters of defocus.

In fig.4 the comparison of performance of the ALPAO DM for correcting defocus and astigmatism is presented. By using the AO correction of the flood system we can correct astigmatism from -4 to 4 diopters, and defocus from -3.5 to 3.5 diopters.

Fig.4. Performance of ALPAO DM: RMS before and after AO correction of (a) spherical and (b) astigmatism aberrations.

3.2 In vivo retinal images acquired with AO-Flood System

In this subsection we present the first retinal images acquired with AO-Flood System using ALPAO-DM. Figure 5 shows a set of images of the cone mosaic of a young male volunteer with and without AO compensation. In Fig. 5b we can even see a shadow of a vessel on the upper right hand side of the image.

Fig. 5. Image of the photoreceptor mosaic of a young volunteer, without (a) and with (b) AO correction.

The wavefront plot before and after AO compensation over a 7 mm pupil of the same young volunteer is shown in Fig. 6. This data is acquired simultaneously by our control AO system.

Fig. 6. Wavefront (WF) plot before (a) and after (b) AO correction over a 7 mm pupil of a young volunteer.

In the following figures we show the performance of the AO sub-system to correct ocular aberration. Figure 7 shows the point spread function before and after correction, while in Fig.8 the Strehl ratio during the AO correction is shown.

Fig. 7. Point spread function (PSF) plot before (a) and after (b) AO correction over a 7 mm pupil of a young subject.

Fig. 8. Strehl ratio.

The Strehl ratio without AO compensation is less than 0.1 and after AO compensation is 0.7, we are very close to the diffraction limit of the system.

4. CONCLUSIONS

We present the changes of the UC Davis AO Flood illumination system for acquiring retinal images. The performance of ALPAO DM to correct static low order aberrations as well as dynamic ocular aberrations is shown. These are the first *in vivo* retinal images taken using the ALPAO-DM in the UC Davis AO-Flood illuminated system. The results presented here show a good potential of ALPAO DM for retinal imaging. Improved AO correction is of great importance in retinal imaging as it allows improved image quality to allow detection of photoreceptor changes in retinal degenerative diseases in earlier stages, or to follow up any changes with higher accuracy. Some improvement is still needed in flood illumination light delivery subsystem. We plan to work on ensuring more uniform beam intensity at the retina and reduction of speckle pattern seen on retinal images. This would help to better visualize the potential of this improved AO subsystem.

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