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Wavefront shaping to correct intraocular scattering

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ABSTRACT

Cataracts is a common ocular pathology that increases the amount of intraocular scattering. It degrades the quality of vision by both blur and contrast reduction of the retinal images. In this work, we propose a non-invasive method, based on wavefront shaping (WS), to minimize cataract effects. For the experimental demonstration of the method, a liquid crystal on silicon (LCoS) spatial light modulator was used for both reproduction and reduction of the realistic cataracts effects. The LCoS area was separated in two halves conjugated with the eye's pupil by a telescope with unitary magnification. Thus, while the phase maps that induced programmable amounts of intraocular scattering (related to cataract severity) were displayed in a one half of the LCoS, sequentially testing wavefronts were displayed in the second one. Results of the imaging improvements were visually evaluated by subjects with no known ocular pathology seeing through the instrument. The diffracted intensity of exit pupil is analyzed for the feedback of the implemented algorithms in search for the optimum wavefront. Numerical and experimental results of the imaging improvements are presented and discussed.

Keywords: Wavefront shaping, intraocular scattering, cataracts

1. INTRODUCTION

Intraocular scattering is originated at the interaction of the light with smaller features of the ocular components such as cell nuclei and protein aggregates. In a common ocular pathology known as cataract, scattered light increases severely degrading the retinal image quality and vision quality. The amount of scattered light -or straylight- is often estimated through s parameter, which is equivalent to the multiplication between the retinal angle and the Point Spread Function (PSF) of the eye. Normally s is expressed in its logarithmic values (i.e., $\text{Log}_{10}[s]$).

In the last decades, adaptive optics has been widely applied for correction of the eye's aberrations¹. In general, those setups correct the aberrations of the eye using a deformable mirror or a spatial light modulator (SLM) guided by a Hartmann-Shack (HS) wavefront sensor. However, the performance of these instruments is limited when severe scatter is present, such as in cataractous eyes². As far as we know, the first and last experiment about the optical compensation of intraocular scattering in vitro was reported in 1973 by Miller *et al.*³. They could see through an extracted cataractous lens, retrieving its phase using interferometry for its posterior phase conjugation. This approach was never successfully applied in living eyes.

In this work, we applied the Wavefront Shaping (WS) technique as an alternative towards the in-vivo correction of the scattering effects induced by cataracts.

2. METHODS

2.1 Realistic reproduction of the cataract effects

The optics of a cataractous eye has been previously modelled using micro-spheres⁴ because the main effect at early states of cataract is the loss of contrast. However, this pathology blurs the retinal images too. Wideband phase maps generate angular distributions of intensity at the retina similar to those⁵ glare functions determined by the CIE (Commission International d'Éclairage)⁶. The phase maps are calculated as the weighted sum of cosine signals with both low and high spatial frequency signals. In this way, the realistic effects of the intraocular scattering are reproduced. As an example, Figure 1a shows a representative phase map for a young (30 years-old) healthy eye. Moreover, further amounts of scattered light can be addressed through their RMS amplitude as depicted in Figure 1b.

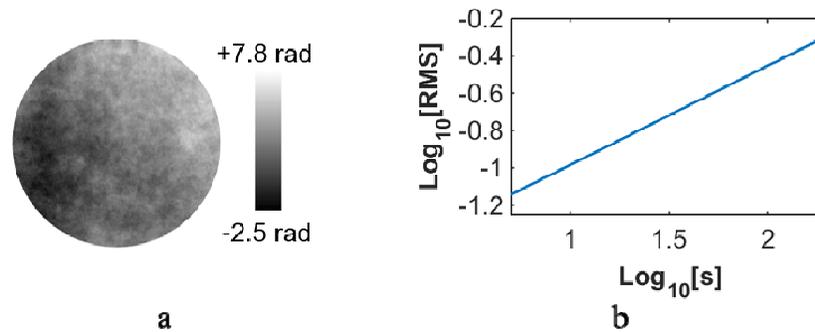


Figure 1. a) Calculated phase map that generates the intraocular scattering in a young eye. b) Relationship between the logarithmic values of straylight and RMS of wavefront.

2.2 Application of the wavefront-shaping technique

Wavefront shaping techniques are based on coherent control of multiple scattered light⁷. It increases, by means of the constructive interference, the intensity on a target behind the scattering sample. Basically, the testing procedure is to divide the pupil in regular segments, changing the phase delay of each segment from 0 to 2π radians and selecting the phase value that maximizes the intensity of a selected peak value at the image plane. This procedure is consecutively repeated for all segments. Previously, basic and advanced algorithms have been applied for recovering an image point through highly scattered layers such as biological tissues⁸ or thick layer of rutile pigment⁹. Here, we apply this basic procedure to compensate the induced effects of three amounts of intraocular straylight ranged from moderated to advanced cataract states.

2.2.1 Numerical calculations

The continuous sequential algorithm¹⁰ was numerically implemented to calculate the enhancement on the response of the simulated cataractous eyes. In this way, the phase of each segment that maximizes the intensity of selected speckle grain is preserved for the phase estimation of the next segment. It allows to register the evolution of the PSF enhancement, which is defined as the ratio between the optimized intensity at target and the initial average intensity around that position. Parameters of the matrix that represents the exit pupil correspond to the physical parameters of the SLM to be used in the experiment (described in the following section). Calculations were performed considering four different number of segments for each cataract state. In addition, the optimization impact on the extended imaging was evaluated.

2.2.2 Experimental setup

Figure 2 shows the experimental setup. The generation, testing and compensation of the intraocular scattering is carried out by a Liquid Crystal on Silicon (LCoS) Spatial Light Modulator device (Holoeye, Germany). The LCoS's area was divided in two halves, conjugated by a telescope with unitary magnification, displaying the cataractous and testing phase maps in the first and second half, respectively. Thus, while the programmable intraocular scattering is reproduced and the phase of the rectangular segments is changed, the intensity at a particular image location is registered by an electron-multiplying CCD (EMCCD) camera to feedback the optimization. An example of the intensity signal is shown in Figure 2 (inset). Signals were fitted to a cosine function to improve the accuracy of the compensating phase estimation.

Once a single point focus was recovered, extended and incoherent images were also evaluated. For this purpose, high-contrast monochromatic objects were displayed by a Digital Micromirror Device (DMD) illuminated by the same laser beam used for the correction stage. Spatial coherence was broken using a spinning diffuser in front the object. This part of the setup is the stimulus projection unit. Additional relay optics translates the object to the image plane through the same path followed by the beam in the optimization part.

3. RESULTS

3.1 Expected image enhancement for several amounts of straylight

Figure 3 shows the image enhancement evolution for each added amount of straylight and several numbers of segments. Red points represent the maximum enhancement once the phase of all segments was optimized. Results are compared with the theoretical enhancement (black line), according to previous studies developed using high-scattering samples⁹.

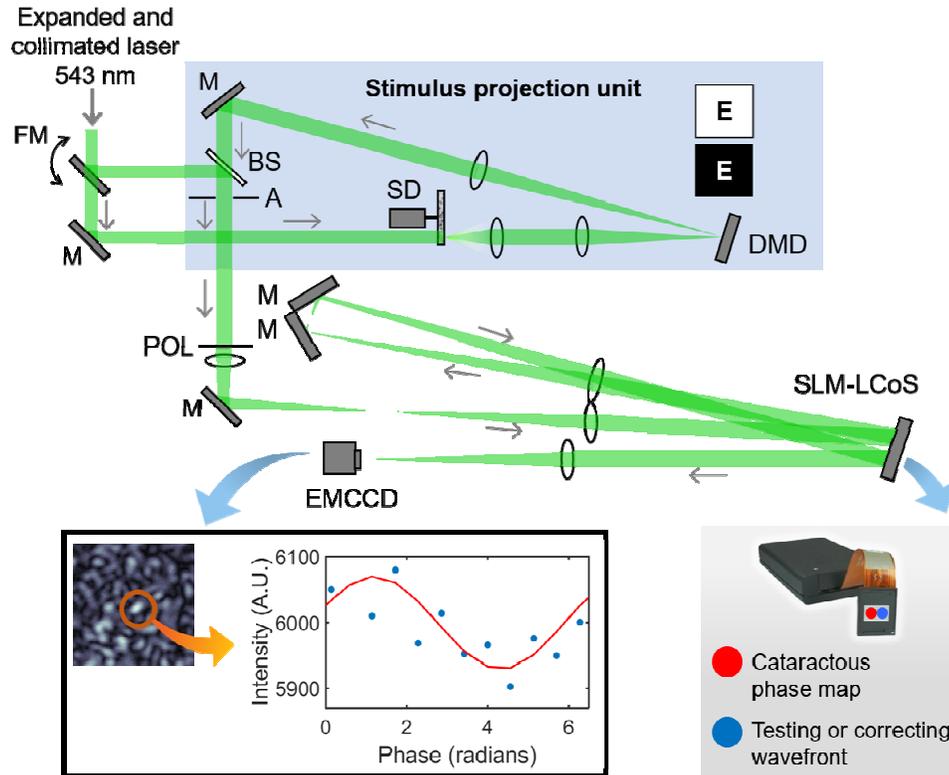


Figure 2. Experimental setup for generation and compensation of the intraocular scattering: M, mirror; FM, foldable mirror; SD, spinning diffuser; BS, beam splitter; A, circular aperture; POL, linear polarizer.

3.2 Imaging through intraocular scattering

After the application of WS technique, the direct results are PSFs conformed by a peak standing out the speckle background. However, the main aim is to evaluate the imaging capacities of the technique. Therefore, Figure 4 and 5 show numerical and experimental images of E optotypes before and after the correction of the intraocular scattering.

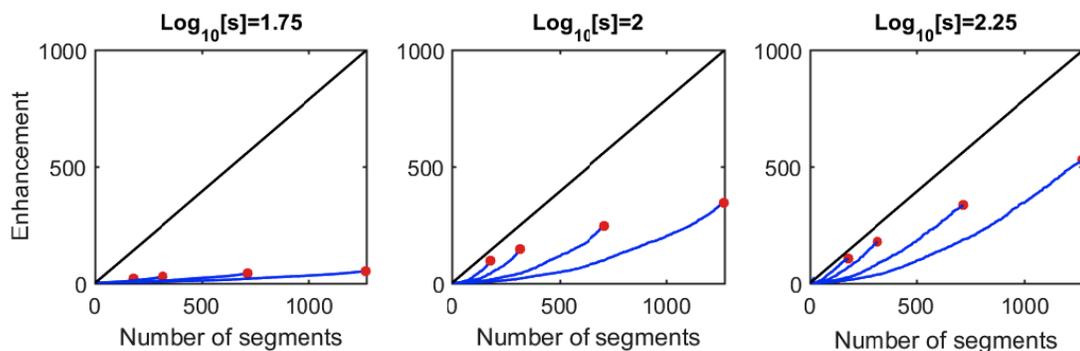


Figure 3. Evolution of the enhancement achieved by the WS technique considering three amounts of straylight and different number of segments in the correction.

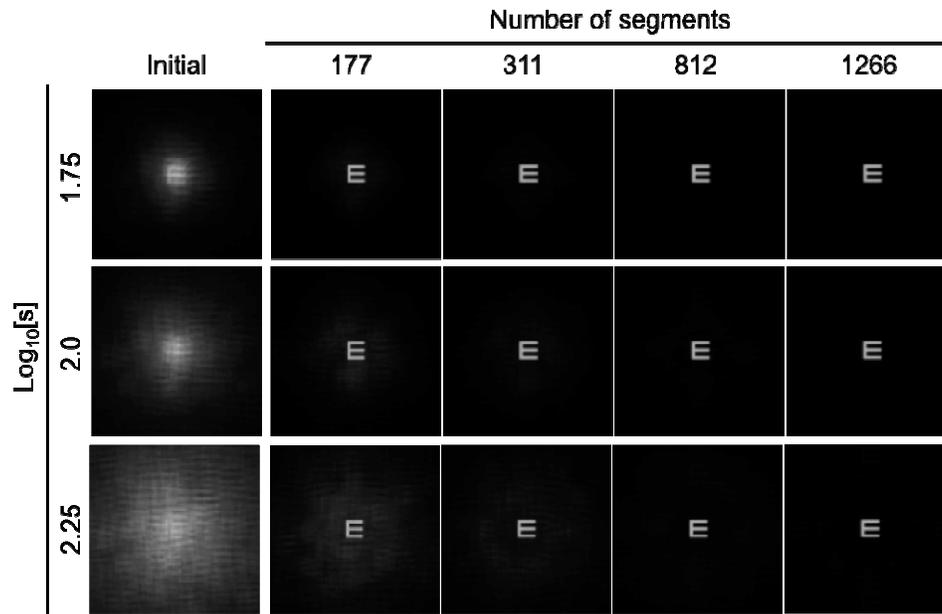


Figure 4. Calculated extended images after the application of WS technique. Size of the letter is 5 arcmin.

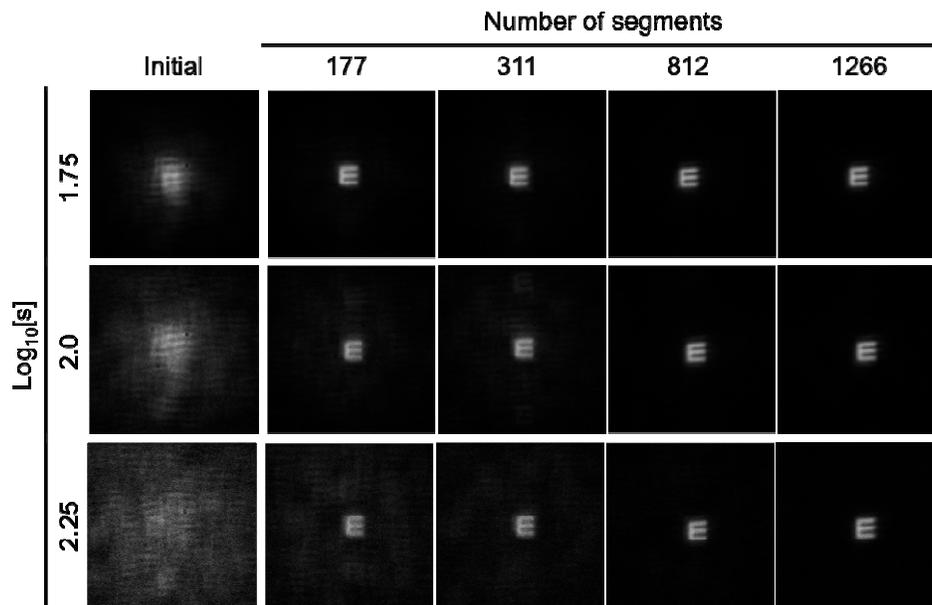


Figure 5. Experimental images using spatially incoherent illumination. Size of the letter is 3.6 arcmin.

4. DISCUSSION

Realistic effects of intraocular scattering were partially compensated applying the wavefront shaping technique. For the intraocular scattering generation, phase maps were calculated to mimic the average angular distribution of light at retina in the presence of cataracts. The compensation was verified both on the PSF enhancement and incoherent extended images. Theoretically, there is a linear relationship between the enhancement and the number of segments used with high

scattering media⁹. However, moderated and advanced cataracts don't follow this rule. Further, according to the numerical calculations shown in Figure 3, the maximum enhancement to be achieved depends of the amount of straylight. It suggests that cataract compensation using WS cannot be comparable with previous studies using high-scattering media.

Small objects were experimentally retrieved using a setup based on the double pass through a single LCoS device that simultaneously adds and compensates scattering. As shown in Figures 4 and 5, main compensation effects are deblurring. However, effects of uncorrected scattering must be evaluated.

Forty-five years after the first attempt for the in-vitro optical compensation of the intraocular scattering cataract effects³, we present the first results using an alternative solution based on wavefront shaping. Further analysis, including psychophysical visual tests, should be performed to determine the requirements and limits of this technique for cataract correction.

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