Improving the accuracy of MTF estimations in double-pass systems

Carlos E. García-Guerra[1,2]*, Joan A. Martínez-Roda[1], Mikel Aldaba[1], Fernando Díaz-Doutón[1], Meritxell Vilaseca[1], Brian Vohnsen[2], and Jaume Pujol[1]
[1]Centre for Sensors, Instruments and Systems Development (CD6), Universitat Politècnica de Catalunya (UPC), Terrassa, Spain
[2]Advanced Optical Imaging Group (AOI), School of Physics, University College Dublin (UCD), Dublin 4, Ireland

*Corresponding author: carlos.enrique.garcia@upc.edu

In this work, the effect of fundus scattering in double-pass (DP) systems is reduced to improve the accuracy of modulation transfer function (MTF) estimations of the eye. The method is based on combined data processing of simultaneous measurements using a symmetric and an asymmetric DP configuration. Measurements in 19 healthy eyes indicate that, although fundus scattering imposes a shift on the estimations, DP systems can be used to predict the optical quality of the eye within a population.

Keywords: optical quality, ocular fundus, fundus scattering, double-pass, MTF

1. Introduction

The optical properties of the eye are estimated with the double-pass (DP) technique from the image of a point source projected on the ocular fundus [1]. At certain wavelengths the light may penetrate up to the choroid, and diffuse laterally due to forward scattering by blood [2]. Although DP images contain this information, fundus scattering may not be equally relevant to vision.

In this work, the accuracy of modulation transfer function (MTF) estimations is improved by reducing the impact of fundus scattering. To do this, simultaneous images are captured using a symmetric (equal entrance and exit pupils) and an asymmetric (unequal pupils) DP configurations with a common first-pass of light. The MTF for the asymmetric second-pass diameter pupil (4 mm) is obtained after eliminating the influence of the first-pass of light and reducing fundus scattering effects using data from the symmetric configuration.

2. Methods

Eliminating the influence of the first-pass response

Assuming that fundus scattering effects (MTF_{FS}) can be modelled in a multiplicative form in the Fourier domain [3], the MTF for a symmetric (MTF_S) and a asymmetric (MTF_A) DP configuration may be expressed as follows,

$$\begin{aligned} MTF_S &= MTF_{2mm} \cdot MTF_{FS} \cdot MTF_{2mm} \\ MTF_A &= MTF_{2mm} \cdot MTF_{FS} \cdot MTF_{4mm} \end{aligned} \quad (1)$$

where MTF_{2mm} and MTF_{4mm} represent respectively the responses for pupil diameters of 2 and 4 mm. The first-pass response of the eye is approximated by the diffraction limited response for the corresponding diameter pupil (MTF_{DL2mm}) [4], and the MTF for a 4 mm diameter pupil is estimated as,

$$\widehat{MTF}_{4mmC} = \frac{MTF_A}{MTF_{DL2mm}} \approx MTF_{FS} \cdot MTF_{4mm} \quad (2)$$

We propose to estimate the MTF for the asymmetric second-pass response using information for the symmetric arrangement as follows,

$$\widehat{MTF}_{4mmP} = \frac{MTF_A}{\sqrt{MTF_S}} = \sqrt{MTF_{FS}} \cdot MTF_{4mm} \quad (3)$$

This procedure filters the first-pass response of the eye in the asymmetric configuration, and reduces fundus scattering effects.

Experimental procedure and data processing

The measurements were performed with the instrument shown in Figure 1-Left. Collimated light from a light source (SLD, λ=801 nm) reaches the eye after passing through a telescope (L_1-L_2, m=-1) and a defocus corrector (L_T-L_C, ΔD=±6D), and being reflected by different optical elements (BS_1, BS_2, M_1, M_2, DM, and HM). The circular 2 mm aperture P1 acts as entrance pupil of the system. After being reflected by the fundus, the light returns to the position of the beam splitter BS1. The light transmitted to beam splitter BS_3 reaches the circular apertures P_2 and P_3 of 2 and 4 mm, respectively located in front of the DP cameras CM_{DP1} and CM_{DP2} (resolution 0.182 arcmin/pixel). The combination of pupils P1-P2 and P1-P3 permits the system to record simultaneous images from a symmetric and an asymmetric DP configuration.

19 healthy right eyes were measured (age range: 21-38; mean and standard deviation: 27.68±4.97). 6 images per DP camera and subject were recorded after compensating for spherical refractive errors. The recordings were averaged to obtain images unaffected by speckle. After subtracting the corresponding background image, cropped versions of the DP images (256×256 pixels) were Fourier transformed to obtain representations in the frequency domain for the symmetric (MTF_S, data from camera CM_{DP1}) and asymmetric (MTF_A, data from camera CM_{DP2}) DP configurations. Then, the MTF of the eye for a 4 mm diameter pupil was obtained following a conventional data processing ($\widehat{MTF}_{4mmC}$) and the proposed method ($\widehat{MTF}_{4mmP}$) by applying Equations (2) and (3) and performing a peak correction using the radial profile of the computed data. The Strehl ratio (SR) was estimated as the ratio between the area under the MTF and that obtained for the diffraction limited case for a pupil of 4 mm considering frequencies between 0 and 30 cyc/deg.

3. Results

The asymmetric responses MTF_A, and the estimations $\widehat{MTF}_{4mmC}$ and $\widehat{MTF}_{4mmP}$ are plotted in Figure 1-Right. In general, the estimations obtained by following the proposed method presented higher magnitudes (MTF at 10 cyc/deg of 0.25 versus 0.16; SR=0.358±0.062 versus 0.271±0.058). Nevertheless, both estimations showed a strong correlation in terms of their SR (Pearson correlation coefficient r=0.94, p<0.0001). A mean and standard deviation of 0.086±0.021 was found for the differences between the SR computed from the two estimated curves MTF_{4mm}. This difference is mainly attributed to the contribution of fundus scattering to the DP response, which has been reduced in the case of the proposed method. The deviation between the first-pass response and the diffraction limited case may also play a role.

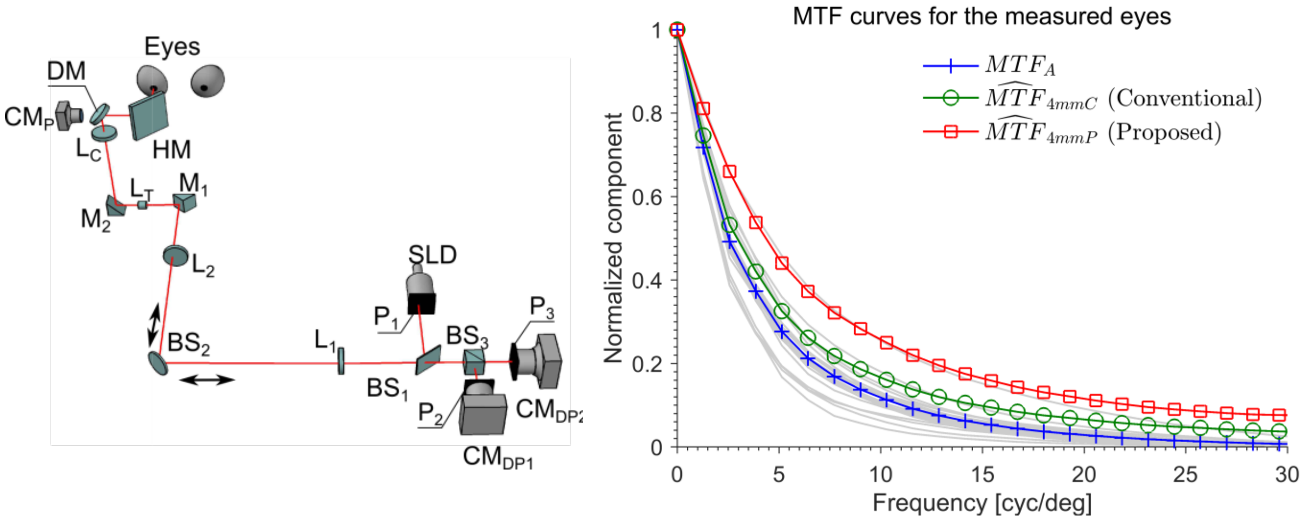

Figure 1. Left: DP system used during the experimentation. Right: Individual (lines in light gray) and average (line with plus signs) response using the asymmetric DP images; estimations by conventional data processing (line with circles) and the proposed method (line with squares).

4. Conclusions

A deconvolving method that reduces the impact of fundus scattering on MTF estimations of the eye has been proposed. The results indicate that fundus scattering effects may result in underestimations of parameters such as the MTF or the SR obtained by conventional data processing. However, the behaviour of a population may be predicted by following either a conventional data processing or the proposed method based on the strong correlation that exists between both estimations.

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