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Image restoration of the open-loop adaptive optics retinal imaging system based on optical transfer function analysis

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ABSTRACT

The residual aberrations of the adaptive optics retinal imaging system will decrease the quality of the retinal images. To overcome this obstacle, we found that the optical transfer function (OTF) of the adaptive optics retinal imaging system can be described as the Levy stable distribution. Then a new method is introduced to estimate the OTF of the open-loop adaptive optics system, based on analyzing the residual aberrations of the open-loop adaptive optics system in the residual aberrations measuring mode. At last, the estimated OTF is applied to restore the retinal images of the open-loop adaptive optics retinal imaging system. The contrast and resolution of the restored image is significantly improved with the Laplacian sum (LS) from 0.0785 to 0.1480 and gray mean grads (GMG) from 0.0165 to 0.0306.

1. Introduction

Modern medicine indicates that the retina, which can be noninvasively observed in vivo, aids in the early clinic diagnoses of oculopathy as well as some other systemic diseases (glycuresis, hypertension, etc.). Therefore, retinal microscopic imaging is an important technology in ophthalmology [1–3]. However, ocular aberrations limit the resolution of retinal images. To overcome this obstacle, an adaptive optics (AO) method was introduced into the retinal imaging system to compensate for dynamic ocular aberrations [4,5]. Since then, a variety of ophthalmoscopes equipped with AO systems for retinal imaging came into existence [6,7]. This technology made it possible to noninvasively achieve diffraction-limited resolution images of retina at a microscopic cellular level.

There are two key components in AO system: the wave-front sensor and wave-front compensator. The Shack–Hartmann wave-front sensor has proved to be a reliable instrument for measuring aberrations and has been widely applied to AO systems [8]. On the contrary, there is no common compensator used in most AO systems. Deformable mirror, liquid crystal spatial light modulator (LC-SLM) and microelectro mechanical system (MEMS) are typical wave-front compensators with characteristics distinguished from each other [9–11]. Since the LC-SLM has a wider correction depth than the other two compensators, it is especially suitable to be applied to open-loop AO systems [12]. All the data of this paper were acquired in AO systems with a LC-SLM as compensator.

From the cybernetics' point of view, AO systems can be divided into two categories: the open-loop system and the closed-loop system [13]. Open-loop AO systems can improve light efficiency, compared with closed-loop ones. On the other hand, open-loop AO systems cannot obtain residual aberrations during capturing the corrected retinal image, which is an essential priori knowledge for image restoration [14]. Because too great light energy entering the human eyes within a limited time will be harmful, it is very important to improve light efficiency in retinal imaging systems. It seems that the open-loop AO retinal imaging system with high energy efficiency is more advisable, but how to acquire priori knowledge in the open-loop system is a main problem to be discussed in detail.

In this paper, a new method was introduced to measure residual aberrations in open-loop AO systems. By analyzing the optical transfer function (OTF), which was reconstructed with the residual aberrations, a significant result was found that the OTF can greatly be similar to the Lorentzian distribution. Moreover, the latter can also be approximated by the Levy stable distribution. Afterwards, an inverse problem method was introduced to restore images in open-loop AO retinal systems [15]. The results of the image restoration show that the new proposed method is able to improve the quality of the retinal images in open-loop AO retinal imaging systems without knowing the residual aberrations. At last, two objective evaluation standards were employed to calculate the numerical melioration of the image, while impressive visual contrast was achieved.

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2. Experimental setup and methods

2.1. The measurement for residual aberrations of open-loop AO system

The LC-SLM can only modulate linearly polarized light, whose polarization orientation is parallel to the modulation orientation. However, the reflected light from the retina is natural light (both S-polarized light and P-polarized light). As a result, only half of the light reflected from the retina (S-polarized light) can be modulated by the LC-SLM. In an open-loop system, the light (S-polarized light) modulated by the LC-SLM is applied to capture the retinal image while the unmodulated light (P-polarized light) is used to measure total wave-front aberrations. As shown in Fig. 1(a), the reflected light from the retina is divided by the polarizing beam splitter (PBS) into two linearly polarized light: the P-polarized light and the S-polarized light. The S-polarized light is modulated by the LC-SLM before reaching the CCD for imaging, while the P-polarized light goes through the PBS and arrives at the wave-front sensor (WFS) for total aberrations measurement. Since the P-polarized light cannot be modulated by the LC-SLM, WFS can only measure the total aberrations rather than residual aberrations. We call this imaging mode. In order to acquire the residual aberrations, we exchange the positions of WFS and CCD, as shown in Fig. 1(b). The S-polarized light is modulated by the LC-SLM and reflected by the PBS into the WFS. Since the S-polarized light is modulated by the LC-SLM before reaching the WFS, the aberrations measured by the WFS are actually residual aberrations. On the other hand, the P-polarized light cannot be modulated by the LC-SLM. Then the P-polarized light goes through the PBS and arrives at the CCD for imaging. Since the P-polarized light for imaging is not modulated by the LC-SLM, the uncorrected retinal image is useless. We call this residual aberrations measuring mode. Because we cannot obtain corrected retinal image and residual aberrations at the same time (the open-loop system can only work in either imaging mode or residual aberrations measuring mode during one time), we aim at seeking a new method to estimate the residual aberrations of the open-loop system in the rest of the paper.

2.2. Analysis of the optical transfer function

Generally, the degraded image has the form

$$g(x,y) = h(x,y) \otimes f(x,y) + n(x,y) \tag{1}$$

where $h(x,y)$ is the point spread function of the system, $f(x,y)$ is the desired deblurred image, $\otimes$ denotes convolution operator and $n(x,y)$ is the noise, which is always viewed as a separate additional degradation. By the convolution theorem we have

$$G(\xi,\eta) = H(\xi,\eta)F(\xi,\eta) + N(\xi,\eta) \tag{2}$$

where $G(\xi,\eta)$, $H(\xi,\eta)$, $F(\xi,\eta)$ and $N(\xi,\eta)$ are the Fourier transforms of $g(x,y)$, $h(x,y)$, $f(x,y)$ and $n(x,y)$, respectively. If the point spread function $h(x,y)$ is acquired, image restoration can be expressed by

$$\hat{F}(\xi,\eta) = \frac{G(\xi,\eta)}{H(\xi,\eta)} \approx F(\xi,\eta) \tag{3}$$

An experiment based on the method discussed in Section 2.1 is conducted to acquire the residual aberrations in the open-loop AO system. The wave-front compensated by LC-SLM is shown in Fig. 2. The corresponding $\log|OTF(\xi,\eta)|$ is plotted in Fig. 3, which is well fitted with a Levy stable OTF. The Levy stable OTF can be expressed as [16]

$$L(\xi,\eta) = \exp\{-\alpha(\xi^2+\eta^2)^{\beta}\}, \quad \alpha > 0, \quad 0 < \beta \le 1 \tag{4}$$

where $\alpha = 0.0323$ and $\beta = 0.0571$ in this case. Because we cannot acquire the residual aberrations when we capture the corrected retinal image (imaging mode) in an open-loop AO system, we can use the nonlinear least square method to estimate the actual OTF with the Levy stable expression.

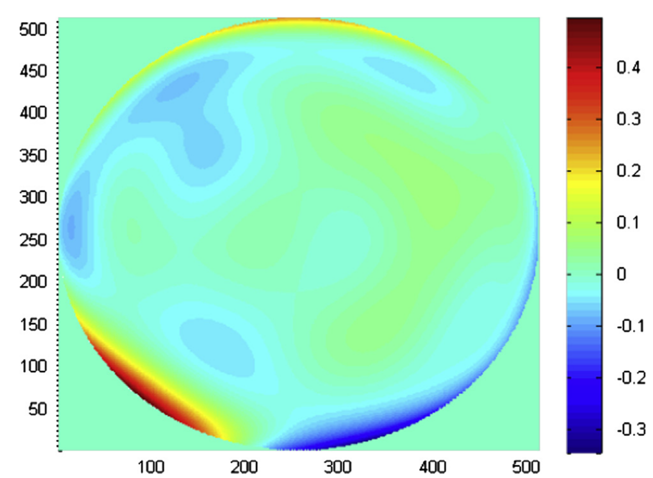

Fig. 2. Wave-front after compensation.

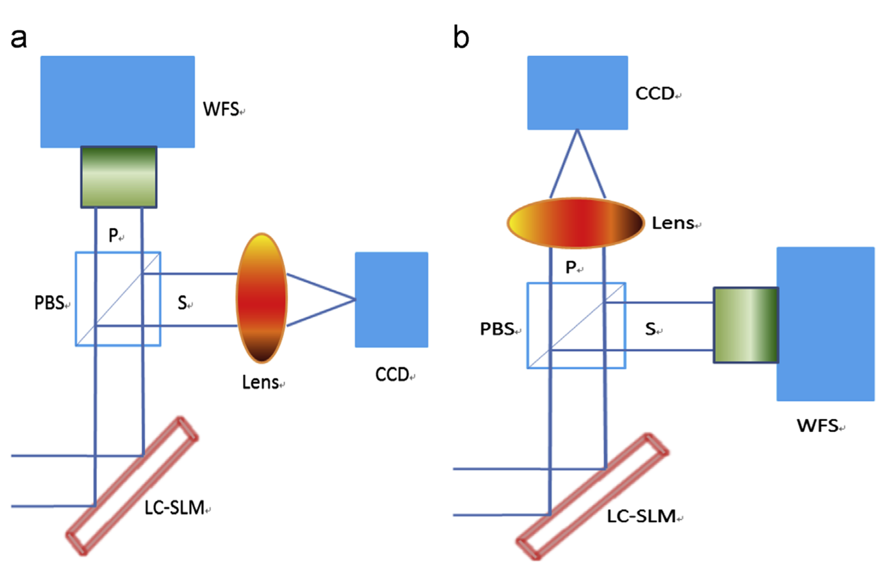

Fig. 1. Sketch of the open-loop adaptive optics system: (a) imaging mode and (b) residual aberrations measuring mode.

In a legible image with the noise $n(x,y)$ satisfies

$$\int_{R^2} |n(x,y)|dx\,dy << \int_{R^2} f(x,y)dx\,dy \tag{5}$$

We can assume $H(\xi,\eta) = \exp{-\alpha(\xi^2+\eta^2)^\beta}$ according to the previous discussion. Then we have

$$\log|G(\xi,\eta)| = \log|\exp\{-\alpha(\xi^2+\eta^2)^\beta\}F(\xi,\eta)+N(\xi,\eta)| \tag{6}$$

Based on Alfred's work [17], around a neighborhood of the origin, we obtain

$$\log|G(\xi,\eta)| \approx -\alpha(\xi^2+\eta^2)^\beta + \log|F(\xi,\eta)| \tag{7}$$

Since the right hand side of formula (7) is almost central symmetric in the (ξ,η) plane, it is reliable to consider formula (7) along a single line through the origin in the (ξ,η) plane. We choose the line $\eta = 0$ for convenience, then

$$\log|G(\xi,0)| \approx -\alpha|\xi|^{2\beta} + \log|F(\xi,0)| \tag{8}$$

As previously noted, the priori knowledge about $F(\xi,\eta)$ is unavailable, thus an approximation of it is essential. However, it is unreasonable to replace $F(\xi,\eta)$ by a constant. Although we have little priori information about $F(\xi,\eta)$, it is advisable that the amplitude of low frequency (standing for the main information) is larger than that of high frequency (standing for the details and noise). So $\exp{-\alpha_1(\xi^2+\eta^2)^{\beta 1}}$ is a more reasonable approximation of $F(\xi,\eta)$ than a constant. Hence, we obtained a convenient way to extract OTF from the blurred image:

$$\log|G(\xi,0)| \approx -(\alpha+\alpha_1)|\xi|^{2\beta} \tag{9}$$

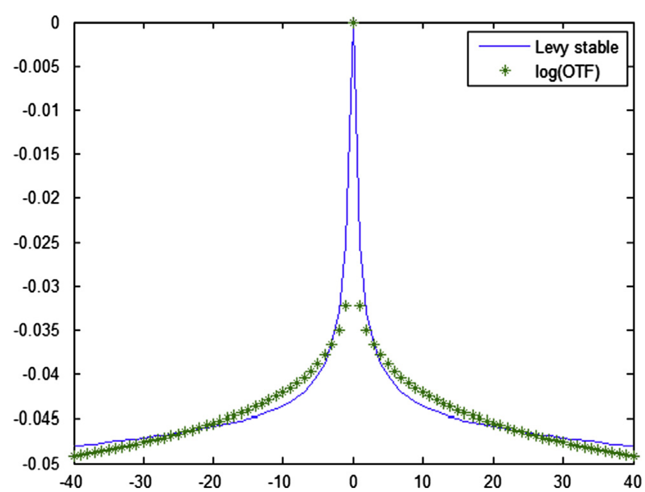

Fig. 3. OTF as well as Levy stable OTF.

2.3. A new algorithm for image restoration

According to Alfred's discussion about the inverse problem, the process of image degeneration can be described as a slow evolution [18]. That means the degeneration of the image with a single OTF equals to the degeneration of the same image with a series of $\{OTF^{Si}\}$, where $\sum Si = 1$. In practice, $\sum Si < 1$, since the OTF we acquired from (9) may be slightly different from the real one. So $F(\xi,\eta)$ takes the form

$$F(\xi,\eta) = \frac{H^t(\xi,\eta)G(\xi,\eta)}{H(\xi,\eta)+KH^s(\xi,\eta)}, \quad 0<t<1, \quad 0<s\ll 1 \tag{10}$$

where $H^t(\xi,\eta)$ stands for the modification of the difference between $H(\xi,\eta)$ and the real OTF. $KH^s(\xi,\eta)$ denotes the noise that will be discussed below.

Although we have little priori knowledge about the distribution of noise, we can confirm that the mean value of noise during a long time is available. Usually we get this mean value by calculating the statistics of the CCD signal without any exposure. So we can describe the noise as $Kf(x,y)$, where K is a small enough constant and $f(x,y)$ denotes the influence of the image. As well as $F(\xi,\eta)$, the noise is also blurred by the OTF. Since the noise is expressed as the mean value during a long time, the noise in frequency domain should be expressed as $KF(\xi,\eta)H^s(\xi,\eta)$ rather than $KF(\xi,\eta)H(\xi,\eta)$, where s is a tiny constant related to time for calculating the mean value of noise.

3. Results

The corrected image of the human retina is captured in an open-loop adaptive optics retinal imaging system. The schematic diagram of the system is shown in Fig. 4. A 808 nm laser was chosen for photoreceptor imaging, which was reflected by the beam splitter (BS) at the bottom of the diagram and entered into the human eye [19]. A diffuser was employed to eliminate the speckle noise that originates from the coherence of the laser source. The light that reflected from the eye and projected onto the LC-SLM was divided into two portions, whose polarization orientations are orthogonal to each other. Since the LC-SLM can only modulate linearly polarized light (S-polarized light in this system), this portion of the reflected light from the eye, which was

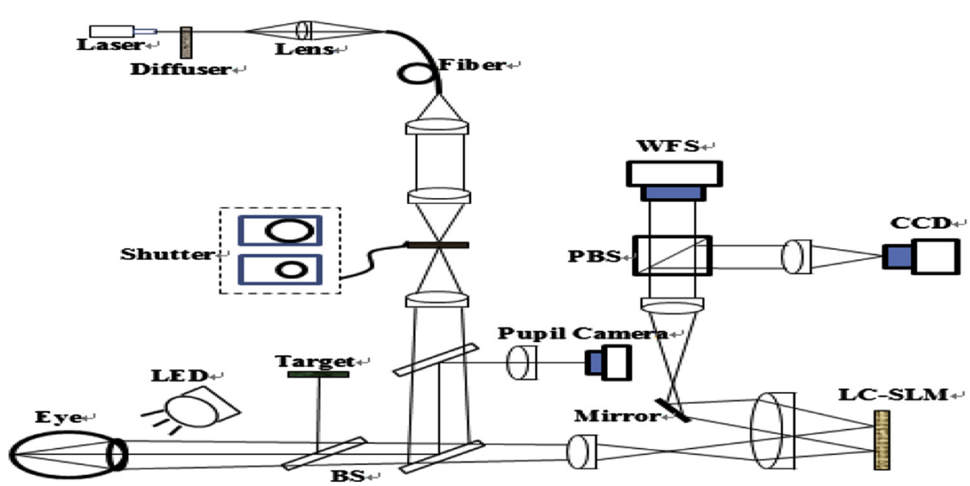

Fig. 4. The schematic diagram of the open-loop adaptive optics retinal imaging system.

reflected by the polarized beam splitter (PBS) into the imaging CCD, was modulated by the LC-SLM. And the other portion (P-polarized light), which directly struck the wave-front sensor (WFS) through the PBS, remained unmodulated.

The WFS measured the total ocular aberrations while the LC-SLM compensated them in real time. The branch path composed of LED, Target and Pupil Camera, was employed to monitor the position of the pupil while human eye stared at the Target. The result is shown in Fig. 5

As shown in Fig. 5(a), the contrast of the photoreceptor image is not good enough, although most of the ocular aberrations were corrected. The residual aberrations together with the diffraction (the pupil of eye is an aperture diaphragm, with the diameter 6 mm) blurred the image. The algorithm in 2.2 is applied to estimate the OTF of the system, as shown in Fig. 5(b). The parameters of formula (9) in this case is $\alpha = 2.5067$ and $\beta = 0.1098$. Then, we construct the OTF with obtained parameter and restore the image by formula (10). As shown in Fig. 5(c) and (d), the contrast of the origin image was significantly improved. The gray mean grads (GMG) and Laplacian sum (LS) of the origin image captured by the open-loop system are 0.0165 and 0.0785 respectively. After restoration, the GMG and LS increase to 0.0306 and 0.1480, respectively with almost 100% improvement. The photoreceptors, which were vague in the origin image, were efficiently restored with satisfactory contrast. Theoretically, the resolution of the image should also be improved, for the reason that the degeneration caused by diffraction was also eliminated by the estimated OTF. However, with $\beta = 1$, the OTF turns into Gaussian distribution, which is a perfect approximation of the Airy Disc.

While analyzing the experimental results, we found that $\log|G(\xi,0)|$ was slightly different from $\log|G(0,\eta)|$. That means sometimes the OTF is not circular symmetric, but it is still symmetric about the origin and it still fits formula (9). In this condition, we should consider both of them, and estimate the real OTF with a linear combination of them to achieve a better restoration.

The algorithm that we proposed in this paper also has some shortcomings. First of all, the residual aberrations of the system, which lead to the degeneration of the image, should be analyzed in advance to estimate the OTF of the system (in this paper, the residual aberrations were obtained in residual aberrations measuring mode of the open-loop AO system). This drawback keeps the method from being applied to a variety of imaging systems without wave-front sensors. Secondly, the parameters of formula (10) (especially t) should be modified in a few trials before the best image is acquired.

4. Conclusion

The open-loop adaptive optics retinal imaging systems can measure and compensate the ocular aberrations in real time, and

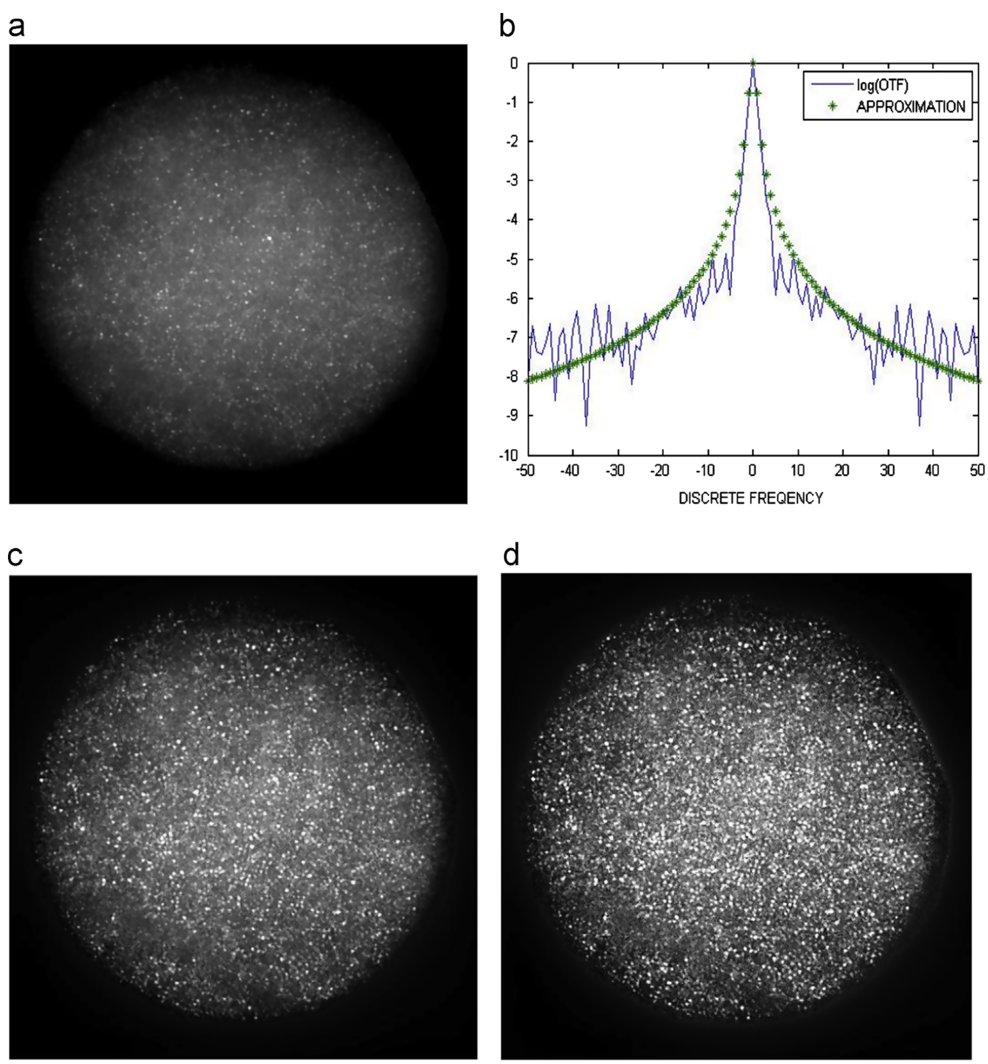

Fig. 5. (a) Photoreceptor image after compensation; (b) the OTF of the system as well as the approximation by formula (9) in logarithmic coordinates; (c) the deblurred image of the proposed algorithm with t=0.5, k=0.01, and s=0.001; and (d) the deblurred image of the proposed algorithm with t=0.2, k=0.01, and s=0.001.

capture the retinal images nearly with the diffraction-limited resolution. However, the residual aberrations and diffraction of the systems still blur the images. After an analysis of the residual aberrations of the open-loop AO system in residual aberrations measuring mode, we introduced a new method to extract the OTF from the open-loop AO systems and restore the retinal images of open-loop systems in the imaging mode. The contrast and resolution of the restored image is significantly improved with LS from 0.0785 to 0.1480 and GMG from 0.0165 to 0.0306, demonstrating that the new proposed method is effective to restore the images of the open-loop adaptive optics retinal imaging systems.

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