Adaptive Optics Optical Coherence Tomography Based on a 61-Element Deformable Mirror

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Abstract. When optical coherence tomography (OCT) is used to image human retina, its lateral resolution is deteriorated by the aberrations of the human eye. To get over this disadvantage, a high-resolution imaging system combining OCT with adaptive optics (AO) is being developed. The AO system consists of a 61-element deformable mirror and a 16×16 array Shack-Hartmann wave front sensor. In this paper, the configuration of the AO/OCT system is described, the simulation comparison among the 19-, 37- and 61-element adaptive optics systems and the experiment results for OCT with opened-loop AO are presented.

1. Introduction

Optical coherence tomography (OCT) [1] is similar to ultrasound B mode imaging except that it uses light instead of sound. It has a high resolution (1-15μm), which is one or two orders of magnitude higher than the conventional ultrasound technique. OCT can also be used to perform real-time cross-sectional tomography imaging. The unique features of this technology enable a broad range of clinical applications.

Human eyes is not a perfect optical system, it has wave front aberrations [2] which deteriorate the transverse resolution of OCT. Human’s aberrations are different from person to person and change with time, it is therefore difficult to correct the aberrations by a static way. Adaptive optics (AO) can correct the aberration in real time [3] but traditionally it has a bulky size, complicated configuration and high cost, and it was mainly used in astronomical telescope. Recently with the development of low-cost components, AO has been applied in ophthalmic imaging [4-7]. The teams combined AO/OCT systems were also reported by several groups [6-7].

In this paper, the experimental configuration of an AO/OCT system is described. The simulation results for a 61-element AO system and the experiment results for OCT with opened-loop AO are presented.

2. The AO/OCT system

2.1. The OCT system

The optical arrangement of the OCT system is shown in Figure 1. Light form a broadband optical source (λo=1305, Δλ=94nm, P=6.9mw) passes through an optical circulator and is then splitted equally
by a fiber coupler into reference and sample paths. Light reflected from a frequency-domain optical delay line (FD-ODL) interferes with light backscattered from the sample under investigation. The interference signal is measured by a detector and then processed by a computer. In order to improve the signal-to-noise ratio of the system, a phase modulator is used to modulate the signal and a polarizer is applied to control the polarization of the light in the sample path. The axial scan is achieved by a FD-ODL.

2.2. The AO system

Figure 2 is the configuration of the AO system, which is consist of a 61-element deformable mirror, a 16×16 array Shack-Hartmann wave front sensor, a beacon (laser diode) and a X-Y scan system.

The beacon passes through the whole optical system and is focused on the retina, thereby it experiences the wave front aberrations of the eyes. The wave front sensor detects the back-reflected light and measures the displacements of light centroids in all sub-apertures. The wave front slope is reconstructed from the centroid displacements. The control signal calculated from the wave front slope is amplified by a voltage amplifier and the used to control the deformable mirror to correct the wave front aberrations of eyes. This leads to a diffraction-limited resolution in the transverse direction of the OCT imaging.

3. Simulation

The key component of AO system is the deformable mirror, its number of actuators and arrangements between actuators with relative to the wave front sensor’s sub-apertures determine the correction capability [8] of the AO system. Two AO systems using a 19- and a 37-element deformable mirrors have been previously set up at our Institute for human retina imaging [5]. Here we compare the performance of the there three AO systems employing 19-, 37- and 61-element deformable mirrors respectively.
Figure 3 shows the arrangements of the three AO systems. The 19-element AO system uses a 8×8 array Shack-Hartmann wave front sensor which has 52 effective sub-apertures. The 37-element AO system uses a 11×11 array Shack-Hartmann wave front sensor which has 97 effective sub-apertures, and the 61-element AO system uses a 16×16 array Shack-Hartmann wave front sensor which has 188 effective sub-apertures. All three Shack-Hartmann wave front sensor’s sub-aperture arrangements are square. In the simulation program, we simulate a single mode Zernike wave front aberration [9] of a different order (from first order to 65th order). The RMS of wave front aberration is one wavelength, then calculate the control signal to control the deformable mirrors surface to counteract the simulated aberration. The residual aberration represents capability of correction [10].

![Figure 3](image)

**Figure 3.** Arrangements between deformable mirror’s actuator with wave front sensor’s sub-apertures. (A) 16 element system, (B) 37 element system, (C) 61 element system.

Human eyes aberrations can be divided into two categories: the first category includes defocus, astigmatism, coma and so on (the first ten orders of Zernike aberration). The higher order Zernike aberrations can be classified as the second category [2]. In order to get reasonably good correction of the eyes aberrations, the AO system must correct the first ten orders Zernike aberrations effectively. Figure 4 shows the fitting RMS errors of the three AO systems. The 19-element system just reaches an effective correction to the first nine orders, the 37-element system effectively corrects the first twenty orders, and the 61-element system effectively corrects the first thirty orders. Obviously, the 61-element system corrects not only the first ten orders more effectively, but the higher order Zernike aberrations as well.

![Figure 4](image)

**Figure 4.** Fitting RMS error of the three AO system.
4. OCT result
Currently the X-Y scanner of the 61-element AO system still under test, and the AO system can not function properly yet. Here we give the OCT results with AO loop opened.

First we use chub eyes as samples. The two pictures (a, b) in figure 5 are images of the center and edge of the cornea respectively. Both pictures have the same size of 5mm length × 3.44mm depth. From picture a, we can see the whole structure of chub eye’s foreside such as cornea, lens and two cyclotomys. In picture b, the fiber of cornea is clearly presented. According to the formula in Ref [1], the ideal axial resolution is 8μm. Picture c in figure 5 is the interference signal recorded by oscilloscope. By calculating its full wave at half maximum, the actual axial resolution estimated to be 9μm. The transverse resolution of 10μm is determined by the F number of the objective.

Figure 5. Image of chub eyes. (a) Image of cornea center, (b) Image of cornea edge, (c) Image of interference signal.

We then scan the rabbit retina in-vitro. An achromatic objective function as the eye’s lens, whose focal length and diameter are 17mm and 8mm respectively. The diameter of the incidence beam is 6mm. This leads to a transverse resolution of about 4.7μm. Figure 6 shows the result. The picture size is 6mm length × 1.27mm depth. In this picture, the RPE layer shows strong scattering, and on the top of the RPE is a layered structure of the retina. The infrastructure is choroid whose layered structure is noticeably presented as well.

Figure 6. Image of rabbit retina in-vitro.

5. Conclusion
We have presented the configuration of our AO/OCT system, simulated the 61 element AO system correction capability and compared its performance with the 19- and 37-element AO systems. The simulation result has show that the 61-element AO system is capable of correcting the first thirty orders of Zernike aberrations. High axial resolution and deep image depth OCT pictures have been obtained.

References
[1] Huang D, Swanson E A, Lin C P, Schuman J S, Stinson W G, Chang H, Hee M R, Flotte T and Gregory K 1991 Puliafito C A and Fujimoto J G J. Scienc 254 1178-81
[2] Liang J , Grimm B and Goelz S et al 1994 J. Opt. Soc. Am. (A) 11 1949-57
[3] Jiang Wenhan, Tang Guomao, Li Mingquan et al 1995 J. Opt. Engng. 34 15-20
[4] Liang J., Williams D R and Miller D T 1997 J. Opt. Soc. Am. (A). 14 2884-92
[5] Li Ning, Zhang Yudong, Rao Xunjun, Li Xinyang, Wang Chen, Hu Yiyun and Jiang Wenhan 2004 J. Acta Optica Sinica 24 1153–58
[6] Robert J Zawadzki, Steven M Jones, Scot S Olivier, MingTao zhao, Bradley A Bower, Joseph A Izatt, Stacey Choi, Sophie Laut and John S Werner 2005 J. Opt. Express. 13 8532–46
[7] Yan Zhang, Jungtae Rha, Ravi S jonnal and Donaid T Miller 2005 J. Opt. Express 13 4792–4811
[8] Jiang Wenhan and Li Huagui 1990 J. Proc. SPIE 1237 64–67
[9] Wang J W and Silva D E 1980 J. Appl. Opt. 19 1510–18
[10] Jiang Wenhan 1988 J. Acta Optica Sinica. 8 441–447