AO Technology for Studying and Improving Vision

Geunyoung Yoon, Ph.D.

Department of Ophthalmology
Center for Visual Science
Institute of Optics
Department of Biomedical Engineering
University of Rochester
Adaptive optics for improving vision

- Liang et al. (1997): The first AO to show vision improvement in monochromatic light
- Yoon and Williams (2002): AO to demonstrate visual benefit and effect of chromatic aberration in white light
- Lawrence Livermore National Laboratory et al., (2003): AO phoroptor for clinical refraction of the eye
- Artal et al., (2004): AO to study the effect of adaptation to the higher order aberration on vision
- Chen et al., (2005): AO to assess image quality metrics to predict subjective visual performance
- Fernandez and Artal (2005): AO to study the effects of the monochromatic aberration on accommodation response
- Artal (2006): AO for vision simulator
- Ethan et al., (2007): AO to assess visual acuity at different retinal eccentricity
Stroke requirement of a deformable mirror

70 Normal myopic eyes

Required Actuator Stroke (microns)

- No Pre-correction
- Defocus Pre-corrected
- Defocus & astigmatism Pre-corrected

6 mm pupil
Error bars: ±2 stdev
Stroke requirement of a deformable mirror

**Abnormal eyes**

Keratoconus
(HORMS = 4.00 μm)

PK
(HORMS = 3.80 μm)

6 mm pupil
Large stroke membrane deformable mirror

Imagine Eyes Mirao 52d

Electromagnetic force actuators (±1V)
52 actuators
Max actuator stroke (wavefront):
  central actuators: ~38 μm
  peripheral actuators: ~27 μm
High linearity (~100%)
No hysteresis
Maximum magnitude of Zernike modes generated with the deformable mirror

- $Z_2^{-2} = 7\mu m$
- $Z_2^0 = 10\mu m$
- $Z_2^2 = 7\mu m$
- $Z_3^{-3} = 5\mu m$
- $Z_3^{-1} = 5\mu m$
- $Z_3^1 = 5\mu m$
- $Z_3^{-3} = 5\mu m$
- $Z_4^{-4} = 2\mu m$
- $Z_4^{-2} = 2\mu m$
- $Z_4^0 = 2\mu m$
- $Z_4^2 = 2\mu m$
- $Z_4^4 = 2\mu m$
- $Z_5^{-5} = 2\mu m$
- $Z_5^{-3} = 1\mu m$
- $Z_5^{-1} = 1\mu m$
- $Z_5^1 = 1\mu m$
- $Z_5^3 = 2\mu m$
- $Z_5^5 = 2\mu m$

6 mm pupil

Actual Measurement!!
Large stroke adaptive optics for abnormal eyes
AO correction of static higher order aberration induced using phase plate

Without AO

With AO

RMS = 3.5 µm
Higher Order RMS = 2.9µm

RMS = 0.037 µm
Higher Order RMS = 0.036 µm
Real-time correction of keratoconic eyes

AO on

Blinks

6 mm pupil

Wavefront rms (µm)

Time (sec)
Real time correction of the eye’s aberration, point spread function and retinal image quality

Aberration  Point spread function  Retinal image

6 mm pupil
DM gain: 20%
Applications of AO in Improving Vision

AO simulation of multifocal IOL designs

No aberration

Defocus (D) →

<table>
<thead>
<tr>
<th>0</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
</tr>
</thead>
</table>

4 mm pupil
White light

Negative spherical aberration ($Z_{4}^{0}$)

<table>
<thead>
<tr>
<th>0</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
</tr>
</thead>
</table>

Positive secondary spherical aberration ($Z_{6}^{0}$)

<table>
<thead>
<tr>
<th>0</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
</tr>
</thead>
</table>
Retinal image quality metric

Cross correlation coefficient of convolved image

Single value image quality metric
($0 \leq \text{metric} \leq 1$)
Applications of AO in Improving Vision

AO simulation of multifocal IOL designs

4 mm pupil
White light

Cross correlation coefficient of convolved image

Defocus (D)

No aberration
-0.3µm spherical aberration ($Z_0^4$)
+0.3µm 2nd spherical aberration ($Z_0^6$)
Applications of AO in Improving Vision

Increasing depth of focus with negative spherical aberration

![Graph showing Snellen acuity (20/20) vs. Defocus (D) for two subjects.

- **Subject 1**: Blue diamonds represent the acuity without negative spherical aberration (SA), and orange squares represent the acuity with negative SA.
- **Subject 2**: Similar markers and colors used.

4 mm pupil
White light

Defocus (D)

Snellen acuity (20/20)
Applications of AO in Improving Vision

Aberration Induced Blur Adaptation in Abnormal Eyes

Does providing the abnormal eyes with perfect optics result in perfect vision (20/10 visual acuity)?

Hypothesis

People who have been exposed to poor image quality may not experience the maximum benefit of correcting the aberration immediately. Moreover, adapting to better optics of the eye may improve vision in a long term although optics of the eye does not change.
Visual acuity in keratoconic eyes with AO

- **Subjects**
  - 3 normal eyes
  - 2 moderate keratoconic eyes

- **Closed-loop adaptive optics correction during visual acuity measurements**
  - Tumbling letter ‘E’
  - Pupil size for AO: 6 mm
  - Pupil sizes for visual acuity: 6 mm, 2.5 mm
  - Continuous correction but, no correction during blinks
  - Manual correction of pupil decentration
Real-time AO correction while measuring visual acuity: Normal eye

Wavefront rms (microns) vs. Time (seconds)

- Total aberration
- Higher order aberration

6mm pupil
Large stroke AO can provide high quality optics for both normal and keratoconic eyes.
With AO, visual acuity for keratoconic eyes was significantly worse than normal eyes.
Conclusion

1. Large stroke adaptive optics extends the potential to investigate optics of the eye with abnormal corneal conditions and its relationship with visual perception.

2. Adaptive optics has been becoming more affordable and easier to control for vision science and ophthalmic applications