Optimizing Shack-Hartmann Wavefront Sensors for the Extraction of Forward Scatter

William J. Donnelly III, PhD
Outline

- Introduction
  - Brief overview of intraocular scatter
  - Application of Shack-Hartmann Wavefront Sensors (SHWS) to measure forward scatter
- Wavefront & Forward scatter channels
- Optimizing two wavefront sensors for scatter
  - Roorda/Applegate/Donnelly RAD Trombone SHWS
    - Issues & Improvements
  - Wavefront Sciences COAS/COASHD Slider SHWS
    - Configuration for assessing forward scatter
    - Software application
Intraocular light scatter

- Is a % of incident light that can deviate from its original direction by reflection, refraction, or diffraction from particles along the optical path of the media.
- Occurs at surfaces or within the volume of ocular media where there are abrupt index changes.
- Occurs mostly from the lens due to cataract.
  - Other scattering sources: cornea, iris, retina, sclera.
Forward scatter & backscatter

- Light can scatter in any direction
- We use forward scatter & backscatter terms to describe two general directions relative to the incident light
Forward scatter

- Is what we care about because it reaches the retina, not backscatter
- Reduces light transmission, image contrast, & visual performance
- Is difficult to measure directly whereas backscatter is easily accessible.
  - Clinical measures use backscatter to estimate forward scatter
  - However, the backscatter to forward scatter relationship is not constant
Rayleigh & Mie scatter in cataract

Rayleigh Scattering

Mie Scattering

Mie Scattering, larger particles

Forward scatter = Backscatter
Forward scatter > Backscatter
Forward scatter >> Backscatter

Small particles $\lambda/10 < \lambda/2$
Large particles $\lambda/2$
Larger particles $\lambda/2$

Direction of incident light
Backscatter ~ Forward scatter?

- There is mixture of particle size & density in cataract, hence a mixture of forward & backward scatter
- Backscatter measures are flawed when solely used to predict visual performance or to track small cataract changes that generate forward scatter
- Better methods are desired that quantify forward scatter more directly
We have been using the wavefront sensor to assess forward scatter.

- A point source (guide star) from the SHWS probe beam is imaged onto & reflected from the retina.
- Light forward scattered by the lens accompanies the exiting wavefront to the S/H image.
S/H derived forward scatter is correlated to vision by optics reversibility

Vision with forward scatter from nuclear cataract

SHWS to assess forward light scatter

Forward scatter from the lens is correlated

Guide star PSF from SHWS probe beam

So how is wavefront & scatter data acquired?
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Basic SHWS layout

Wavefront channel

Forward scatter channel
Scatter & wavefront data coexist in a raw S/H image

Both wavefront & scatter channels

Lenslet array

CCD

Pixel intensity profile of lenslet PSFs in a S/H image

Wavefront sensors normally ignore or filter intraocular scatter because they only need to detect the centroid displacement of a lenslet PSF
Light scatter reduces visual performance in addition to aberrations

- Light scatter attenuates the actual retinal PSF
  - A reconstructed retinal PSF should include the effects of scatter
- Advantages: Wavefront & Scatter measured in 1 image
  - Time, minimal data coordination, reduced optical components, localization of scattering sources
  - This 1-pass system minimizes corneal surface reflections due to the small diameter probe beam (typically < 1mm diam) vs. methods that use the full pupil diameter
- We reported relationships of our SHWS derived forward scatter metrics to acuity ($R^2 = 50\%$) in a cross-sectional study (JRS Oct 2004)
- Currently, we have optimized our original system for longitudinal use & anticipate even better results for an upcoming study
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RAD Trombone SHWS

RAD produced reliable wavefront data but required some modifications for scatter.
Early S/H image of dense nuclear cataract in RAD SHWS

Original image
+ contrast & brightness

Original image w/ adaptive histogram equalization
Improvements include:

- **Silvered rails were blackened**
- **Steerage plate AR coated**
- **Blackened non-optical Hardware throughout**
- **Improved Light traps**
- **Improved Prism baffling**

Computer & Physical models used to simulate system scatter.
Fold mirror tunnel widened

Mirror tunnel vignetted scattered light

Mirror Tunnel assembly
Trombone ghosts

Light scatter could pass above, below, or beside the prism on cheater paths creating ghosts.
Larger prism to widen forward scatter channel

Larger mirrors

Larger prism
High efficiency reflectance coatings & near infrared (NIR) hot mirror

- Original system used 4 aluminum coated mirrors at 88% reflectance each
  \[ R_{\text{total}} = 88\% \times 88\% \times 88\% \times 88\% = 60\% \]

- New optimized system uses gold & NIR hot mirror coatings
  \[ R_{\text{total}} = 98\% \times 98\% \times 98\% \times 99\% = 93\% \]

- Reflectance gain of 33%
Visible light suppression using a hot mirror

Ambient visible light & NIR light reflected from the eye

Visible light is absorbed here

Gold mirror coatings 98%

Right prism leg NIR Hot mirror 99% Reflectance of NIR light

Only NIR light from retinal guide star gets to SHWS CCD
To measure scatter, exposure must be strictly controlled

- Transmission decreases with dense cataract
- Both under- and over-exposure can add variance to forward scatter and wavefront metrics
- We recently reported that an optimized exposure is best for longitudinally tracking forward scatter and cataract progression (JRS, Oct 2005)
Auto-exposure optimizes the S/H image

- We developed software to automatically adjust exposure time until S/H image exposure is optimized for the patient on an initial visit.
- The optimal exposure time is tagged to patient files & automatically re-used for return patient visits.
Lower exposure times are better

- The improved system efficiency allowed lower exposure time for an optimally exposed image
  - Exposure times now average ~ 50-120 ms (versus older 250 - 500 ms) for similar source intensity power
- Reduce motion blur from eye movements
- Reduce wavefront & scatter metric variance
- Allow for better dynamic image capture
Adaptive histogram equalization on both S/H images to illustrate suppression of instrumentation stray light.
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To open the forward scatter channel in the COAS, the range limiting aperture (RLA) was removed.
Instrumentation noise suppressed with baffling in the COAS w/ the RLA removed

Beam delivery path

Reflection noise from top assembly

RLA chamber, site of tubular baffle

Some reflection noise is absorbed by beam-splitters

Some reflection noise gets into the lenslet array & image

ASAP analysis
Scatter analysis software

Scatter metrics and graphics output for high resolution wavefront sensors
COAS system
COASHD system

SCATTER METRICS

<table>
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<th>Max</th>
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<tbody>
<tr>
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<tr>
<td>Max</td>
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Summary stats

Mean Mean 26.90
% above (10.00) 85.01
Max SD 27.69
Mean SD 21.80

RMS stats

Mean 28.61
SD 8.19
Min -1.00
Max 53.34
Range 54.34

HISTOGRAM

Log Qty

Peak 1: (13.167397), Valley 1: (0.59), *Peak 2: (46.24660)

S/H IMAGE

SCATTER MAP
Summary

- Optimizing Shack-Hartmann Wavefront Sensors for the Extraction of Forward Scatter
  - Instrumentation stray light & visible light suppression
  - Forward scatter channel enlargement
  - Absence of a Range Limiting Aperture (RLA)
  - Increased efficiency & faster exposure times
  - Optimal exposure using auto-exposure
    - Avoid over & underexposure
  - Software improvements & adaptation to higher resolution commercially available COAS/COASHD systems
Acknowledgements

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Thanks for your attention!

Seeking contracts

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Extra slides
Optical system for measuring diffuse density
A basic scatterometer

- Surface scatter is characterized by its Bidirectional Scatter Distribution Function (BSDF) calculated from data collected by the detector swept through $\theta$ at various incident angles $\theta_0$. 
Optical conditions for projection density measurement
Before measuring light scatter in the eye...

- We must reduce instrumentation noise as much as possible
  - Background subtraction is only effective for low level static noise
  - Optics and other hardware in the system can contribute to additional reflections
FIGURE 9 Effect of stray light in the microdensitometer on the apparent density distribution at an edge.