The Effects of Scatter on the Measurement of Aberrations

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Overview of this presentation

- Brief discussion of factors that degrade retinal image quality
- Background of intraocular light scattering
  - Light scattering from nuclear cataract
  - Methods and current research in quantifying intraocular scatter
- Using computer & physical eye models w/ cataract to study scatter and aberrations
- Applications of models to clinical data from a cross-sectional cataract patient study conducted at the Visual Optics Institute (VOI)
  - Texas Investigation of Cataract Optics (TICO)
- Show relationships best predicting acuity from our Shack-Hartmann wavefront & forward light scatter metrics
What main factors degrade the retinal image Point Spread Function (PSF)?

- **Refractive Aberrations**
  - Monochromatic, polychromatic
- **Pupil Diffraction**
- **Intraocular Light Scatter**
Aberrations

- Cause refractive blur on the retina
- Are addressed & corrected with wavefront technology that uses Shack-Hartmann (S/H) imaging
Pupil Diffraction

- Causes a ringing effect, degrading the retinal image
  - Result of constructive & destructive interference from the pupil edge
- Causing image degradation is small compared to degradation from aberrations in a normal eye
  - The eye is diffraction limited < 2.8mm pupils
- Would remain if aberrations are corrected over larger pupils

Image of point source (PSF)
Intraocular light scatter

- Is a % of incident light that has reflected, refracted, or diffracted from particles (index differences) along the optical path of the media.
- Can occur from the surface or within the volume of ocular media.
- Degrades retinal image quality by attenuating and broadening the Point Spread Function (PSF).
- Causes diffuse blur on retina.
- Can produce halos or coronae.
Sources of intraocular light scatter

Lens 40% & higher w/ advancing age & even higher w/ advancing cataract (Yuan, 1993)

Retina – up to 20% (Delori)

Cornea – up to 30% (Vos & Boogaard, 1963)

Iris & sclera ~5% (van den Berg)

Scatter can be induced by trauma, surgery, or disease
Age Related Cataract (ARC)

- Indicates more opacity in the lens than with normal ageing
- Has 3 main classifications: Cortical, Posterior Subcapsular, Nuclear
  - Nuclear cataract is most common
    - Scatter from nuclear cataract will be addressed
- What can we do about nuclear cataract?
  - Surgically remove the crystalline lens
  - Main purpose of cataract surgery is to reduce light scatter from the crystalline lens by replacing it with a synthetic intraocular lens (IOL)
Light scatter fundamentals

Light scatter from small particles = Rayleigh Scattering

Mie Scattering

From overhead, the Rayleigh scattering is dominant, the Mie scattered intensity being projected forward. Since Rayleigh scattering strongly favors short wavelengths, we see a blue sky.

When there is large particulate matter in the air, the forward lobe of Mie scattering is dominant. Since it is not very wavelength dependent, we see a white glare around the sun.

Rayleigh Scattering  Mie Scattering  Mie Scattering, larger particles

Direction of incident light

Courtesy R. Nave, GSU Physics Dept.
Scattering from particles of different size

Scattering of unpolarized visible light by spheres of radii 0.01, 0.1, and 0.2 μm calculated according to the Rayleigh-Gans approximation.
How does light scatter from nuclear cataract?

- Crystalline lens clarity depends on an ordered fibril structure
  - Benedek & Goldman, 1967

- Cloudiness & disorganization of fibril structure (optical anisotropy) increases w/ cataract
  - Bettelheim, 1978; Bueno & Campbell, 2003; Al-Ghoul, 2001

- Small particle scatter (Rayleigh scattering)
  - Protein aggregation accelerates
    - Benedek, 1971; Jedzidiniak, 1978; Spector, 1984

- Large particle scatter (Mie scattering)
  - Compaction, folding, & breakage of lens fibers
  - Increased intracellular cytoplasm deposits & fiber interdigitations
    - Al-Ghoul, 2001-2004
  - Increased density of predominantly spherical (1 to 4 microns) Multi-Lamellar Bodies (MLB)
    - Gilliland, 2001 & 2004
  - Combinations can produce Mie scatter = to scatter from 50 µm particles
    - Hemenger, 1990

- Literature evidence: Mie scattering >> Rayleigh scattering
  - Forward scatter >> Backscatter
Forward scatter

- Reaches the retina, not backscatter
- Produces a veiling luminance from a glare source
- Reduces image contrast and visual performance
- Is difficult to measure directly
  - We cannot put a light detector on the retina
  - The relations between straylight and measures of visual performance are not straightforward
  - To get around this, backscatter methods are used in the clinic to predict forward scatter from nuclear cataract
Relating backscatter to forward scatter

- **Bettelheim, 1978-1985**
  - Reported a backscatter to forward scatter relationship using excised normal aged & nuclear cataractous lenses
  - Found that
    - Forward scatter is ALWAYS greater than backscatter relative to the incident light
      - Implies the presence of large particle (Mie) scattering
    - Ageing & cataract cause a greater increase in forward scatter than backscatter
      - Implies overall particle size to be increasing
    - Overall light transmission decreases
      - PSF attenuation (also documented among many researchers)
  - Cautioned that formulas developed had large variance & data was measured in-vitro
Backscatter: In-vivo clinical measures of nuclear cataract

- Densitometry of slit-lamp imaging
  - Brown (1973)
- Lens Opacity Classification System
  - clinician grading of slit-lamp images
  - LOCSIII Chylack (1980’s-1990’s)
- Scheimpflug densitometry
  - Hockwin (mid to late 1980’s)
- Lens Opacity Meters
  - various
Researchers are aware that backscatter measures are indirect measures of forward scatter and flawed when solely used to predict visual performance or to track small cataract changes.

Some patients see very well with high levels of measured backscatter; others do not.

Currently, vision scientists are exploring other ways to measure forward scatter more directly.
What are new developments in forward scatter measurements?

- **Elliott, Whittaker 1980’s - current**
  - Alternate visual function testing in cataract patients w/ good acuity but other visual disability from cataract, such as reading speed

- **van den Berg 1990’s - current**
  - Counter-phase flicker matching
  - Influence of scattering on the optical PSF vs. the functional PSF
What are new developments in forward scatter measurements?

- **Fujikado et al 2002-current**
  - Average width of S/H lenslet PSFs in cataract patients

- **Cox, Atchison, Smith 2003**
  - Aberration measurement in S/H images in the presence of scatter

- **Bueno & Artal 2004**
  - Measuring polarization changes from optical anisotropy

- **Gilliland, et al 2004**
  - Mie scatter modeling from electron-micrographs of excised nuclear cataractous lenses
What are new developments in forward scatter measurements?

- Applegate, Thibos, Hong 1999, 2000
  - Noticed differences in S/H images of cataract vs. normal patients, suggesting investigation

- A point source is imaged onto & reflected from the retina.

- Light forward scattered by the lens accompanies the exiting wavefront to the S/H image.
What are new developments in forward scatter measurements associated with aberrations?

- Donnelly, Applegate, et al 2001 - current
  - Extracting forward scatter & aberration metrics from S/H image of nuclear cataract patient
  - Observing relationships to acuity under 4 conditions
    - high/low contrast & high/low luminance
  - Completed cross-sectional data phase (TICO)
  - Gearing up for a longitudinal study
  - Recently developed computer & physical cataract model eyes to
    - Improve previous work
    - Optimize S/H wavefront sensor for scatter detection
Computer & Physical cataract model eyes

- Were developed to resemble an eye with nuclear cataract to be placed in a S/H wavefront sensor
- Used cataract parameters matched to Cox et al, 2003:
  - Computer: Scatter profile functions of 5 cataract levels
  - Physical: Glass cuvettes filled w/ polystyrene microsphere/ H₂O solutions
- Used some different parameters from Cox et al (both physical & computer models):
  - 5mm vs. 10mm path length cuvette
    - 5mm ~ adult crystalline lens center thickness
  - Cataract-in-a-cuvette placed behind pupil
  - Main optic chosen so system w/ cuvette matched human eye MTF
  - No confocal aperture in S/H wavefront sensor (to capture all scatter)
The Aireye: physical scattering eye model

(all metal was black anodized before use)

Retina:
1” diameter Lambertian reflector

Cuvette with scattering Micro-sphere/ H₂O solution

19mm FL Plano-convex lens

Sliding & locking adjustable pupil

Locking focus adjustment

Optic rail hard mounted to Shack-Hartmann wavefront sensor
Computer model eye within a working S/H wavefront sensor

1) Narrow source beam travels into Aireye
2) Point imaged on Aireye retina
3) Wavefront & forward scatter exit the Aireye & travel through the system to the Lenslet array & CCD
4) Path folding “trombone”
5) Lenslet array
6) CCD

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Results of Aireye computer model w/ increasing cataract
7mm pupil

- Lenslet PSF attenuation (transmission loss)
  - MAX_MAX, MAX_SD
- Increased scatter between lenslets
  - RMS_MEAN
- Unaltered wavefront until lenslet PSF peaks are undistinguishable
- Softening of pupil edge
Results of Physical model

- Scatter metrics MAX_MAX, MAX_SD, RMS_MEAN correlate w/ square root of microsphere concentration (cataract level)

**7mm pupil**

- $Y = 0.096 - 0.012 \times X; R^2 = 0.942$
- $Y = 0.077 - 2.999 \times 10^{-4} \times X; R^2 = 0.947$
- $Y = -0.019 + 0.003 \times X; R^2 = 0.915$
Let’s apply what was learned from the models to real nuclear cataract patient data

- Since our models are based on cataract literature & light scatter theory, we expected to see similar trends from our S/H images from real patients acquired w/ our research S/H wavefront sensor.

- The modeling identified forward scatter metrics that would be the most useful.

- We then performed data analysis on metrics acquired from a battery of tests on these patients.
Battery of metrics conducted on patients
- Backscatter (LOCSIII), S/H wavefront, age, S/H forward scatter, acuity

Every metric we had on a patient was stirred into the statistical kettle such that only the best predictors of acuity would surface.

Best subset multiple regressions were used to predict acuity of 148 patients under 4 conditions:
- PHC = photopic high contrast acuity
- PLC = photopic low contrast acuity
- MHC = mesopic high contrast acuity
- MLC = mesopic low contrast acuity
Acuity relationships to metrics

- Color coding of independent variables:
  - red – S/H wavefront metric
  - yellow – S/H forward scatter metric
  - green – age metric
  - purple – LOCSIII metric nuclear color

- **P HC** (Photopic High Contrast Acuity) =
  - \(-0.430 \log \text{NS} - 0.001 \text{MAX}_\text{MAX} + 0.566 \log \text{AreaOTF} + 0.056 \text{NC} + 0.119\);
  - \(R^2 = 0.488\)

- **P LC** (Photopic Low Contrast Acuity) =
  - \(0.003 \text{Age} - 0.295 \log \text{NS} + 0.001 \text{MAX}_\text{MAX} + 0.086 \log \text{VSOTF} + 0.03\);
  - \(R^2 = 0.476\)

- **M HC** (Mesopic High Contrast Acuity) =
  - \(0.037 \text{EW} - 0.001 \text{MAX}_\text{MAX} + 0.011 \text{MAX}_\text{SD} + 0.002 \text{Age} + 0.008\)
  - \(R^2 = 0.504\)

- **M LC** (Mesopic Low Contrast Acuity) =
  - \(-0.23 \log \text{NS} - 0.00043 \text{MAX}_\text{MAX} + 0.00011 \text{RMS}_\text{MEAN} + 0.555\)
  - \(R^2 = 0.498\)
Conclusions

- Our computer & physical models…
  - Agreed with Cox et al in that progressively increasing scatter does not induce refractive aberrations in the wavefront.
  - Confirmed the attenuation originating from the cataract carries through to the lenslet PSFs in the S/H image.
  - Generate forward scatter like that of nuclear cataract.
  - Verify that our forward scatter metrics are excellent predictors of nuclear cataract & exceed backscatter metrics.
  - Have led to further developments in more complex computer eye models w/intraocular scatter.

- Our combined S/H wavefront & forward scatter metrics are major contenders for predicting patient acuity in one quick measurement.
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Thanks for your attention!

Looking for a post-doc, faculty, or commercial employment position

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The End
Extra slides
Rayleigh scattering refers to the scattering of light off of the molecules of the air, and can be extended to scattering from particles up to about a tenth of the wavelength of the light. It is Rayleigh scattering off the molecules of the air which gives us the blue sky. Lord Rayleigh calculated the scattered intensity from dipole scatterers much smaller than the wavelength to be:

\[ I = I_0 \frac{8 \pi^4 N \alpha^2}{\lambda^4 R^2} \left(1 + \cos^2 \theta\right) \]

Scattering at right angles is half the forward intensity for Rayleigh scattering.

- \( N \) = # of scatterers
- \( \alpha \) = polarizability
- \( R \) = distance from scatterer

The strong wavelength dependence of Rayleigh scattering enhances the short wavelengths, giving us the blue sky.

Rayleigh scattering can be considered to be elastic scattering since the photon energies of the scattered photons is not changed. Scattering in which the scattered photons have either a higher or lower photon energy is called Raman scattering. Usually this kind of scattering involves exciting some vibrational mode of the molecules, giving a lower scattered photon energy, or scattering off an excited vibrational state of a molecule which adds its vibrational energy to the incident photon.
S/H image intensity profile traces from Computer Aireye model

Cataract level 1
Cataract level 2
Cataract level 3
Cataract level 4

Scatter outside pupil
Computer eye model w/ a S/H probe beam entering & reflecting from the retina