Ocular Scatter

- The are several sources of stray light in the eye including the cornea, transmission through the iris and the crystalline lens.
- Cornea tends to have Rayleigh Scatter
- Lens follows inverse power law, but not quite $1/\lambda^4$
- Scatter can be quantified as the ratio of the unwanted scattered light to the desirable non-scattered light. Usually given in log units.

Rayleigh Scattering

http://woelen.scheikunde.net/science/physics/exps/scattering/rayleigh_scattering.jpg
Scatter

Scatter creates a large halo around the PSF that can reduce contrast of a scene.

Tom van den Berg Netherlands Institute for Neuroscience

PSF and MTF with Scatter

The scattered light act like a dc offset to the PSF, which turns to a delta function in frequency space. Contrast is reduced at all spatial frequencies.
Scatter

Defocus - VA 20/50 | Normal | Log(s)=1.47

Against-the-light face recognition

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Scatter

Defocus - VA 20/50 | Normal | Log(s)=1.47

Tom van den Berg Netherlands Institute for Neuroscience
Scatter Measurement

White ring source surrounds a dark target. Ring source flickers, so that stray light falling on the target makes the target appear to flicker.

Adjusting the target with a counter-phased flicker can eliminate the intensity variation.

Scatter

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Cataract

Cataracts are an opacification of the crystalline lens in the eye. Early stages cause reduced light levels and scatter. Advanced stages cause (preventable) blindness.

Cataract extraction with intraocular lens implantation is the most widely performed surgery in the US.
Cataract Types

Cortical - opacities in the periphery working towards the lens center.
Nuclear - opacities in the center of the lens working outwards.
Subcapsule - opacities on the surface of the lens.

• Secondary cataract: Cataracts can from eye surgery, diabetes and steroid use.
• Traumatic cataract: Cataracts can develop after an eye injury.
• Congenital cataract: Some babies are born with cataracts or develop them in childhood, often in both eyes.
• Radiation cataract. Cataracts can develop after radiation exposure.

Cataract Symptoms

• Cloudy or blurry vision.
• Colors seem faded.
• Glare. Headlights, lamps, or sunlight may appear too bright. A halo may appear around lights.
• Poor night vision.
• Double vision or multiple images in one eye. (This symptom may clear as the cataract gets larger.)
• Frequent prescription changes in your eyeglasses or contact lenses.
Harold Ridley

Ridley noticed that shards from the canopy (PMMA) of RAF pilots lodge in their eyes did not get rejected by the body’s immune system. Proposed making an implantable lens out of the material.

Intraocular Lenses

Need to calculate the power of the iol that needs to go into the eye.
SRK Formula

The SRK formula is essentially a linear regression formula. It is widely used because it is easy to memorize and can be calculated quickly. It is inaccurate for “non-normal” patients.

\[ A - 0.9K - 2.5L = \phi_{iol} \]

A = A constant (Fudge factor provided by the manufacturer
K = Average corneal power in diopters
L = Axial length of the eye

Example: A = 118, K = 42 D and L = 24 mm
\[ \phi_{iol} = 20.2 \text{ D} \]

Theoretical Formulas

\[ \phi_{IOL} = \frac{n\left(\frac{n}{K} - L\right)}{(L - \text{ACD})\left(\frac{n}{K} - \text{ACD}\right)} \]
Theoretical Formulas

• Can usually measure K fairly accurately (Keratometry), L and ACD are more difficult.

A-scan gives L and ACD for existing lens. The A constant essentially describes where the lens sits with the region of the cataractous lens.

Definitions

• Aphakia – without lens. Older patients did not get implants, so they had to wear extreme hyperopic corrections. Uncommon these days.

• Pseudophakia – Fake lens. IOL implant following cataract extraction.

• Phakic Lens – Lens implant while leaving crystalline lens intact.
Capsulorhexis

Phacoemulsification
Lens Injection

Lenses are rolled up and injected through the small incision. They unroll as they exit the injector. The surgeon then adjusts the IOL position to ensure proper placement inside the capsule and behind the iris.

Posterior Capsule Opacification

![Image of posterior capsule opacification]
Multifocal come in a variety of forms, but the basic concept is to have two different powers simultaneously on a single lens. One power allows for distance vision, while the other allows for near vision.

Variations in zone size, number of zones, power distribution, progressives, aspherics and diffractives all exist.
Simulated Images

Multifocal Lens  Single Vision Lens

Distance Vision

- In prehistoric times, man’s survival depended in large measure on the clearness of his distance vision. His ability to side-step the saber-toothed tiger or find food on the hoof was essential to his existence. For him blurred distance vision would have been fatal.

Near Vision

- In prehistoric times, man’s survival depended in large measure on the clearness of his distance vision. His ability to side-step the saber-toothed tiger or find food on the hoof was essential to his existence. For him blurred distance vision would have been fatal.

Refractive Multifocal Optics

- A refractive lens has alternating zones of varying refractive power.
- The zones of a refractive multifocal lens are typically the same size and width and act as independent annular refractive lenses.
Blazed Grating

- Triangular steps of transparent material.
- Light diffracts from the steps and is primarily split into three beams.
- Angle of step shifts the amount of energy in each order.

Chirped Grating

- Spacing between steps changes across grating.
- Diffraction angle changes with step spacing.
Diffractive Lens

• Addition of refractive lens causes light to converge to two points

Full Aperture Diffractive IOLs

• Step heights set so that roughly 40% in near focus and 40% in distance focus.
• Relative energy does not change with pupil size.
• Remainder of light diffracted into other orders.

3M Diffractive

Pharmacia Multifocal
Diffractive vs. Refractive Multifocals

- **Diffractive**
  - Distance
  - Near

- **Refractive**
  - Distance
  - Near

**Apodized Diffractive Lens**

- Reduce blaze angle towards lens periphery.
- Apodization causes a shift in the relative amounts of energy in each focus.
Alcon Restor

Comparative Nighttime Images
(5 mm Aperture, IOL in Wet Cell)

Monofocal

AcrySof ReSTOR

AMO Array
Defocus Transfer Function

- Optical Transfer Function (OTF) of rotationally symmetric systems
- Relationship to the Defocus Transfer Function
- Applications to techniques for treating presbyopia.
- Examples

OTF of Rotationally Symmetric Systems

If the pupil function is given by \( P(x, y) = P(r) \)

Then the OTF is related to the autocorrelation of the pupil function

\[
\text{OTF}(\rho) = \iint P\left(x - \frac{\rho}{2}, y\right)P^*(x + \frac{\rho}{2}, y)\,dx\,dy
\]

Suppose, we want to look at the performance of this pupil function for different levels of defocus.

\[
P(x, y) \exp\left(\frac{i2\pi}{\lambda} W_{20} r^2\right)
\]
OTF of Rotationally Symmetric Systems

In this case, 

\[
\text{OTF}(\rho) = \iint P\left(x-\frac{\rho}{2}, y\right) P^*\left(x+\frac{\rho}{2}, y\right) \exp\left(\frac{-2\pi W_2}{\lambda} x \right) dx dy 
\]

which reduces to 

\[
\text{OTF}(\rho) = \iint P\left(x-\frac{\rho}{2}, y\right) P^*\left(x+\frac{\rho}{2}, y\right) \exp\left(\frac{-2W_2\rho}{\lambda} x \right) dx dy 
\]

Defocus Transfer Function (DFT)

Define the 2-D function 

\[
\text{DTF}(\rho, z) = \iint P\left(x-\frac{\rho}{2}, y\right) P^*\left(x+\frac{\rho}{2}, y\right) \exp(\imath 2\pi zx) dx dy 
\]

then the OTF is given by 

\[
\text{OTF}(\rho) = \text{DTF}\left(\rho, \frac{-2W_2}{\lambda} \rho \right) 
\]

In other words, the OTF for a given level of defocus is simply a slice through the DTF at an angle $-2W_2 / \lambda$. 
DTF Algorithm

- Pick a value of $\rho = \rho_o$
- Integrate along the y axis.
- 1-D Fourier transform result
- Store in $\text{DTF}(\rho_o, z)$
- Repeat for new value of $\rho_o$

Example - Aberration-Free System

Slope = $-2W_{20} / \lambda$
Annular Inlay

Effectively a 2 mm pupil. Pinholing!!
Annulus with 4 mm Pupil

Annulus with 6 mm Pupil
Full Aperture Diffractive IOLs

- Step heights set so that roughly 40% in near focus and 40% in distance focus.
- Relative energy does not change with pupil size.
- Remainder of light diffracted into other orders.

3M Diffractive  
Tecnis Multifocal

Apodized

Alcon ReStor
Apodized vs. Full Aperture

Apodized Diffractive

Full Aperture Diffractive

3mm Pupil 4mm Pupil 6mm Pupil

Zonal Refractive Multifocals

- A refractive lens has alternating zones of varying refractive power.
- The zones of a refractive multifocal lens are typically the same size and width and act as independent annular refractive lenses.

AMO ARRAY®
### Zonal Refractive

- **Apodized Diffractive**
  - **Zonal Refractive**
    - 3mm Pupil
    - 4mm Pupil
    - 6mm Pupil

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### Polychromatic DTF

- **Four Chromatic Issues to take into account**
  - Phase introduced by step heights depends on $\lambda$.
  - Ocular Longitudinal Chromatic Aberration
  - Cutoff Frequency of OTF depends on $\lambda$.
  - Spectral Sensitivity of the photoreceptors.
Defocus Transfer Function (DFT)

Define the 2-D function

$$\text{DTF}(\rho, z) = \iint \mathcal{P}\left(x - \frac{\rho}{2}, y \right) \mathcal{P}^*\left(x + \frac{\rho}{2}, y \right) \exp(i2\pi z \rho) \, dx \, dy$$

then the OTF is given by

$$\text{OTF}(\rho) = \text{DTF}(\rho, \frac{-2W_{20}}{\lambda})$$

In other words, the OTF for a given level of defocus is simply a slice through the DTF at an angle $-2W_{20}/\lambda$. 

Tecnis MF Steps

![Graph showing Tecnis MF Steps](image-url)
Cutoff Frequency vs. $\lambda$

![Graph showing Cutoff Frequency vs. Spatial Frequency (cyc/deg) for different wavelengths (700 nm, 600 nm, 500 nm, 400 nm).

Ocular Chromatic Aberration

Diagram illustrating the effect of Badal lenses on ocular chromatic aberration.
Ocular Chromatic Aberration

Best Focus 560-580 nm

Ocular Chromatic Aberration

$\lambda = 400$ nm  $\lambda = 500$ nm

$\lambda = 600$ nm  $\lambda = 700$ nm
Luminosity Functions

Polychromatic OTF

\[ \text{POTF}(\xi, \eta) = \frac{\sum \lambda V(\lambda) \text{OTF}(\xi, \eta; \lambda)}{\sum \lambda V(\lambda)} \]

- Conventional definition of polychromatic OTF.
- Assumes single sensor with spectral sensitivity of \( V(\lambda) \).
- But this is not how the eye operates.
Polychromatic Defocus Transfer

Polychromatic Defocus Transfer
Phakic IOLs

Phakic IOLs are currently in trials. This is a means of implanting a lens in the eye to correct for refractive error.

Concerns:
- Damage to corneal endothelium causes corneal opacities
- Contact with crystalline lens causes cataracts.

Source: Webvision.med.utah.edu - Photograph was made by James Gilman of the Moran Eye Center.
Accommodation

Relaxed ciliary muscle pulls zonules taut and flattens crystalline lens.

Constrict ciliary muscle releases tension on zonules and crystalline lens bulges.

Accommodating IOLs

Accommodating IOLs are based on a mechanical translation of the lens within the eye. As the ciliary muscle contacts, it presses on the hinged haptics and causes the lens to move forward.
Accommodating IOL

Dual Optic Accommodating IOL
Adjustable IOLs are implanted in the eye. Several weeks following surgery, a UV beam is used to “write to” the IOL and modify its shape. The shape is then fixed, allowing for a permanent customized correction.

Blue-Light Absorbing Lenses

- Reduces the amount of blue light (which can be harmful) hitting the retina
- Reduces the effects of chromatic aberration of the eye.
- Reduces scattered light within the eye.
Scatter

Environmental conditions such as fog and haze, or corneal haze cause scatter that is blocked by the Natural chromophore, resulting in a higher contrast on the retina.

Scatter

Blue light is filtered by IOL, so scatter is reduced following lens

Internal scatter in the vitreous is reduced by Natural chromophore since blue light is filtered prior to getting to scattering bodies. Aspheric optics in addition, result in higher contrast on the retina.
Scatter Experiment

- Blue light scatters more than longer wavelengths.
- Sodium bicarbonate added to wet cell to introduce scatter.
- Concentrations of 0.0 g/L, 52.8 g/L and 105.6 g/L.
- Photographs of bar targets under white light illumination captured with model eye.

Scatter Experiment Results

AcrySof (SA60AT) Lens

Increasing Scatter

AcrySof IQ (SN60WF) Lens
Aphakic Scotopic Response Curve

Spectral Changes

Results

Conventional Material

50% Gray Patch

Natural Material