Visual Consequences of Ocular Wavefront Error

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Where do optical aberrations arise from?

What is the impact of optical aberrations on visual quality?
Effect of aberrations

Pure defocus (0.5 D)  Real aberrations
Zernike Polynomial expansion

\[ = Z_2^2 + Z_2^{-2} + Z_3^3 + Z_3^1 + Z_3^{-1} + \ldots + Z_4^0 + \ldots + Z_7^{-5} + Z_7^{-7} \]
Optical quality metrics

Root mean square wavefront error:

\[ \text{RMS} = \sqrt{\sum (\text{error} - \text{mean})^2} \]
Wavefront aberration

Image of a point (PSF)

Modulation Transfer (MTF)
Optical vs visual performance
... Optical component of the CSF
Corneal aberrations

Aphakic

Ocular aberrations and biometry technology

Aberrometers

2nd generation LRT

Fixation channel

Pupil monitoring

Corneal topography and aberrometry

Elevation map

Biconic fitting

Q=(Qx+Qy)/2

R=(Rx+Ry)/2

Corneal asphericity & apical radius of curvature

OCT

Corneal topography

Purkinje imaging

Scheimpflug imaging

Pupil

Lens

Retina

Pupil monitoring

MRI
Purkinje Imaging System

Instituto de Optica, CSIC
Purkinje imaging system for Phakometry

Lens tilt/decentration

Equivalent mirror / Merit function approaches

\[ P_I = E \beta \]
\[ P_{III} = F \beta + A \alpha + C_d \]
\[ P_{IV} = G \beta + B \alpha + D_d \]

Rosales & Marcos, JOSA A (2006)
Crystalline lens tilt & decentration from Purkinje imaging

Rosales & Marcos, JOSA A (2006)
Crystalline lens tilt & decentration from Scheimpflug imaging

Images from Pentacam (Oculus)

De Castro, Rosales, Marcos, 2006
Phakometry (from Purkinje/Scheimpflug)

Anterior radius

Posterior radius

Rosales, Dubbelman, van der Heijde & Marcos (2005)
Individual eye modelling

Corneal topography

Crystalline lens shape

Axial length/ACD

Pupil/lens tilt & decentration

Sources of aberrations

Test of treatments (IOLS, LASIK)
Physical model eyes

For corneal ablation testing
Marcos, Dorronsoro, & Cano,
Patent #WO 2005/122873 A1

For contact lens fitting
Dorronsoro et al. 2004

For intraocular lens testing
Barbero et al. 2003
de Castro et al. 2006
From optics to vision
Clinical tests of visual performance

Contrast sensitivity

Visual acuity
Laboratory tests of visual performance

VisionTest
Dorronsoro et al.
Instituto de Optica, CSIC
Adaptive optics

Courtesy of Pablo Artal
What have we learnt on patient’s eyes?

Cataract surgery

Contact lenses

LASIK surgery
Aberrations and Cataract Surgery

Total = Corneal + Internal
Total, corneal & internal aberrations
POST CATARACT surgery

Eye #1-IOL 0 D
Eye #4-IOL 23 Dp
Eye #4-IOL 21 Dp
Eye #9-IOL 26 D
IOL wave aberrations (spherical IOLs)

Barbero, Marcos & Jimenez-Alfaro, JOSA 2003
In vitro aberrations of the spherical IOL

Barbero, Marcos & Jimenez-Alfaro, JOSA A 2003
Spherical aberration. Acrysof/Tecnis

Barbero et al. JOSA (2003)

IOL tilts

Rosales & Marcos, JOSA A 2006
IOL decentration

Rosales & Marcos, JOSA A 2006
Does tilt/decentration play a major role?

Real eye

Predictions

Rosales, Jimenez-Alfaro & Marcos, 2006
MTF in/out of focus. Spherical/Aspheric

\[ \Phi = 4.5 \text{ mm} \]

Examples

Optical quality with Contact Lenses
Change of aberrations with RGP CL

with astigmatism

<table>
<thead>
<tr>
<th></th>
<th>TOTAL</th>
<th>CORNEAL</th>
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<tbody>
<tr>
<td>wo CL</td>
<td>1.36</td>
<td>1.29</td>
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<tr>
<td>With CL</td>
<td>0.46</td>
<td>0.57</td>
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3rd & higher order

<table>
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<th>CORNEAL</th>
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</thead>
<tbody>
<tr>
<td>wo CL</td>
<td>0.77</td>
<td>0.67</td>
</tr>
<tr>
<td>With CL</td>
<td>0.39</td>
<td>0.42</td>
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Factors affecting optical performance of CLs

- Subject’s own aberrations
- Contact lens design
- Tear lens
- Material flexure.
- Conformity to the cornea

Psychophysical depth-of-focus with multifocal soft CLs

Dorronsoro, Gonzalez, Llorente, Marcos (2006)
Optical aberrations and standard myopic LASIK refractive surgery

Moreno-Barriuso et al. IOVS; Marcos 2001
Pre-LASIK

RMS=0.83 µm

RMS=2.67 µm

Post-LASIK

RMS=0.87 µm

RMS=2.66 µm

Marcos et al. IOVS (2001)
TOTAL aberrations

3rd and higher order

EYE #

PRE-LASIK
POST-LASIK

RMS (µm)

Moreno-Barriuso et al. IOVS (2001)
Increase of TOTAL Spherical Aberration with LASIK

Marcos et al. IOVS (2001)
Increase of CORNEAL Spherical Aberration with LASIK

Marcos et al. IOVS (2001)
Spherical aberration induced by LASIK

Corneal

- **Myopic LASIK**
  - Slope = 0.091
  - R = 0.63
- **Hyperopic LASIK**
  - Slope = -0.057
  - R = 0.24

Total

- Slope = 0.1701
- R = 0.86

Real patients & Simulation summary

\[\text{Asphericity} \]

PRE | POST | Munnerlyn | Parabollic Munnerlyn

\[\text{Cano, Barbero & Marcos, JOSA A 2004}\]
Corneal asphericities

Dorronsoro, Cano, Merayo & Marcos, 2006. Submitted to IOVS
Comparison with visual performance

Contrast sensitivity

PRE & POST LASIK

MTF horizontal section
Contrast sensitivity

Spatial frequency (c/deg)

Modulation transfer function

Spatial frequency (c/deg)

Area PRE = 1.51
Area POST = 1.38

Contrast ratio POST/PRE

Average 22 eyes

Contrast ratio PRE/POST vs. spatial frequency (c/deg)

MTF ratio

CSF ratio

Causes and consequences of aberrations in patients

- New technology and controlled experiments allow better understanding of the optical changes induced by LASIK, IOLs or contact lenses.

- In general, optical changes correlate well with visual changes:
  - Change in CSF vs MTF with LASIK
  - Optical vs Visual improvement with aspheric IOLs or RGP contact lenses
  - Optical and visual depth-of-focus patterns
Previous data relate to eyes with non-natural aberrations

But, what happens in normal eyes?
Ocular aberrations in normal eyes

Burns & Marcos, in *Customized Corneal Ablations*, 2000
Correlation VA/PSF in normal eyes?

Courtesy of Pablo Artal
Correlation VA/RMS in normal eyes?

(RMS_high order)

20/2
0

20/1
0

Courtesy of Pablo Artal
Optical metric that better correlates with VA?

Visual strehl ratio

31 metrics

Marsack, Thibos and Applegate, JOV 2004
Are the aberrations of the eye independent?

Are the aberrations of the eye independent?

VA with rotated PSFs. Neural effects?

(subject PA)

NO aberrations
NORMAL aberrations
ROTATED aberrations

Artal et al. JOV 2004
The aberrometers measure monochromatic aberrations but the visual world is polychromatic.
Polychromatic PSF

PSFs at various wavelengths

Interpolation

TCA Shift

Sum

Marcos et al, Vision Res. 1999
Effect of chromatic aberrations on a perfect eye

Marcos et al, Vision Res. 1999
Interactions between monochromatic and chromatic aberrations

Real eye. LCA & TCA

focused in green

Spatial frequency (c/deg)

MTF

10^0

10^2

10^4

10^6

10^8

L

M

S
Conclusions

✓ We are gaining deeper understanding of the causes for optical aberrations and their visual consequences.

✓ Combination of techniques: corneal and ocular aberrometers, ocular biometry, psychophysical, adaptive optics, models is essential.

✓ In treated eyes, there are, in general, correlations between optical changes and visual changes.

✓ Effects of interactions of aberrations, neural adaptation still to be resolved.