Corneal first surface wavefront aberrations & visual performance in normal, keratoconus and penetrating keratoplasty eyes

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Background

- Keratoconus causes loss of visual performance due to higher order aberrations.

- Penetrating keratoplasty is a standard treatment for improving vision, but is also limited due to wavefront aberrations.

- Ideal models for studying the relationships between optics and visual performance.
Aims

Which optical quality metrics are most predictive of visual performance

Which visual performance measures are most sensitive to optical degradation
(and are therefore the most appropriate for outcome research in keratoconus)
Population

- Prospective, cross-sectional
- Convenience sample of patients attending the eye clinic and Flinders Medical Centre and recruited from private practice
- Non contact lens wearers
- Keratoconus – 58 eyes
- Penetrating keratoplasty – 29 eyes
- Normals – 34 eyes
Keratoconus staging system of Krumeich et al:

Stage 1, 2, and 3 (eccentric corneal steepening, induced myopia and/or astigmatism <5D (Stage 1), <8D (Stage 2), <10D (Stage 3), corneal radii <48D (Stage 1), <53D (Stage 2), >53D (Stage 3), Vogt’s striae, no central scars, typical keratoconus topography) or Stage 4, more advanced (with central corneal scars, radii >55D and unmeasurable refraction)

Stage 1 - 33 eyes; stage 2 - 18 eyes; stage 3 - 5 eyes; stage 4 - 9 eyes
Visual performance testing

- High contrast visual acuity: HCVA
- High contrast visual acuity under glare: HCVAglares
- Low contrast visual acuity: LCVA
- Low contrast visual acuity under glare: LCVAglares
- Pelli-Robson contrast sensitivity: PRCS
- Pelli-Robson contrast sensitivity under glare: PRCSglares
- High contrast visual acuity at near: Near HCVA
- HCVA at near under glare: Near HCVAglares
- Low contrast low luminance VA at near: Near LLLCVA
- LLLCVA at near under glare: Near LLLCVAglare
Methods - Optical

- Corneal topography was taken with the Bausch and Lomb Orbscan II
- Scanning slit / Placido disc combination
- Topography data exported to VOLPro software v7.08 (Sarver and Associates)
- 10th order Zernike expansion derived for a 5.0mm pupil
Optical quality metrics

Calculated 33 metrics of optical quality designed to be predictive of visual performance*

Pupil plane, PSF, MTF, OTF

Jason Marsack and Ray Applegate, VOI

Analyses

- Descriptive statistics: mean and standard deviation
- ANOVA with Sheffé post hoc significance testing was used to compare groups
- To avoid alpha inflation, p<0.01
- Linear regression was used to analyse associations between optical and visual performance measures
- Transformation of metrics e.g. log
Results

- The three groups were similar for age.
- The normal group has much less wavefront aberrations than both the keratoconus and PK groups for all orders.
- Only fourth order, trefoil and spherical aberration were significantly different between the keratoconus and PK groups.
Figure 7.2 Means(SD) Wavefront Zernike Higher Order Error Values:
Normals, Keratoconus, Penetrating Keratoplasty

Significant difference between Keratoconus and PK
Figure 7.1 Means (SD) Higher Order Wavefront Zernike Modal Pairs Error Values: Normals, Keratoconus, Penetrating Keratoplasty

Significant difference between Keratoconus and PK
No difference between KC and PK!

- Keratoconus and PK results surprisingly similar – selection effects?
- Hospital based study encourages self-selection of cases with problems
- Exclusion of contact lens wearers encourages self selection of mild keratoconus cases which was reflected in grading (33 stage 1, 18 stage 2)
Linear regression

\[ \text{HCVA} = 0.322 \ \text{logPV} - 2.48 \ R^2=0.58 \]
\[ \text{LCVA} = 0.182 \ \text{logPFSt} - 0.72 \ R^2=0.56 \]
\[ \text{LCVA}_{\text{glare}} = 0.347 \ \text{logPV} - 0.68 \ R^2=0.52 \]
\[ \text{Near LLLCVA} = 0.662 \ \text{logPV} - 1.78 \ R^2=0.49 \]
\[ \text{PRCS}_{\text{glare}} = 0.285 \ \text{logPFSt} - 1.74 \ R^2=0.43 \]
logPV

PV = peak-to-valley difference (microns)

PV = \text{max}(w(x,y)) - \text{min}(w(x,y))

PV is the difference between the highest and lowest points in the aberration map.
Pupil fraction

Pupil fraction is defined as the fraction of the pupil area for which the optical quality of the eye is reasonably good (but not necessarily diffraction-limited).

Pupil Fraction = Area of good pupil / Total area of pupil

1. the critical pupil or central pupil method
Figure A-4. Pupil fraction method for specifying wavefront quality. Red circle in the left diagram indicates the largest concentric sub-aperture for which the wavefront has reasonably good quality. White stars in the right diagram indicate subapertures for which the wavefront has reasonably good quality.

2. the tessellation or whole pupil method which involves labeling each sub-aperture as good or bad according to some criterion

\[ PF_t = \frac{\text{Area of good subapertures}}{\text{Total area of pupil}} \]

PFSt, (which is computed over the tessellated pupil fraction when a good sub-aperture satisfies the criterion horizontal slope and vertical slope are both < criterion (e.g. 1 arcmin))

Other pupil fraction metrics
Other notable metrics

- **PFCt**, (which is computed on wave front curvature as summarised by blur strength, computed over the tessellated pupil fraction when a good sub-aperture satisfies the criterion blur ave < criterion (e.g.0.25D))

- **VOTF** (volume under the neurally weighted optical transfer function, normalised by the volume under the neurally weighted modulation transfer function) which quantifies the visually significant phase shift in the image
Discussion – optical metrics

- Pupil plane metrics perform better in diseased eyes
- Capture asymmetry, able to quantify large magnitudes of aberrations
- Similar results to smaller PK cohort reported last year – pupil plane metrics, especially PFSt

No magic metric

“Horses for courses”

Visual Strehl may be terrific in normal and super normal eyes, in spherical aberration model, but “blown out” in diseased eyes.

Pupil plane metrics work well in disease due to the capture of asymmetry and broad dynamic range.
Discussion

- Visual performance metrics of most value
- High contrast VA surprisingly good – large range
- Other measures all valuable also, but not more so: low contrast VA, contrast sensitivity, low luminance, glare
Questions and Suggestions