Corneal refractive surgery: Are we treating the wrong location with the wrong correction?

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Corneal refractive surgery is arguably good enough

Yet most refractive surgeons would like to increase accuracy and precision to minimize and preferably eliminate surprises.
WFG-LASIK Induced HO RMS as a Function of Pre-op Levels

\[ y = -0.70x + 0.25 \]
\[ R^2 = 0.27 \]

PreOp HOA RMS (microns)

Change in HOA RMS (microns)

6mm pupil

Slide courtesy of Steve Schallhorn
In corneal refractive surgery it is argued that one gets better visual outcomes if the surgery is centered between center of the pupil and Purkinje image I.
If the observation holds that centering the surgery between Purkinje I and the pupil center on average provides a better outcome for a given platform, then the wrong correction on average was designed for the intended location and it is unlikely the best correction on average for the location being treated.
There is no shortage of papers that have looked at the issue of where to center the ablation profile.
Here I wish to argue that our industry would be in the drivers seat if we could measure the optical errors of the eye, use these measurements to design the desired correction, execute the correction design with accuracy and precision and obtain the intended desired correction.
Today I wish to stimulate open discussion as to the next steps in improving accuracy and precision.
For the sake of discussion here let’s define the goal of refractive surgery to reduce the optical errors of the eye for **visually relevant light** such that acuity and **foveal visual retinal image quality** is equivalent or better to what one had with single vision glasses or contact lenses.
What is visually relevant light?

It is light that enters the limiting aperture.
What is the retinal location of critical importance to detailed vision?

The locus of fixation which is typically within the foveola
Do we have the necessary instrumentation to

Correct the refractive errors of the individual eye with sufficient accuracy and precision to insure that retinal image is equal to or better than the individual is able to obtain with glasses or contact lenses.
First, let’s examine the two of the key measurement tools (corneal topographers and wavefront sensors) and how measurements are taken.
Both instruments require the eye to fixate a target for a proper measurement.

Said differently, one asks a patient to fixate the target of interest when making a measurement as the instrument is aligned to the eye.
Location of pupil center with respect to VK center

Mean 0.15 mm T; 0.04 mm S
SD 0.14 mm;     SD 0.12 mm
This 2 dimensional image shows the lateral displacement of the pupil center as viewed with respect to the VK axis. Because the instrument is not required to be centered over the pupil when the eye is fixating a target on the optical axis of the instrument.

If treating along the LoS the pupil border traced here does not identify the corneal area that should be treated. Why?
Subject-fixated coaxially sighted corneal light reflex
When the wavefront sensor is not aligned properly, the wavefront sensor is not aligned properly.

The wavefront sensor is not aligned properly.

When the wavefront sensor is not aligned properly, the axis of the wavefront sensor is not aligned properly with the center of the pupil, the eye rotates.

ANSI Standard
Alignment of Line of Sight (LoS) to VK instrument axis

A camera co-axial with the VK axis captures images of entrance pupil center coincident with fiducials.

When instrument axis is aligned to the line-of-sight, the region of cornea overlying the pupil is most relevant to foveal vision.

In general, the LoS is NOT perpendicular to the corneal surface.

Courtesy Larry Thibos  WFC 2015
Aligning an Instrument to the Eye

Instrument translation induces ocular rotation
With these factors in mind, let’s now consider three key factors in the design of a WFG correction.

- Design of the correction for the refractive errors of the eye
- Design compensation for the angle of incidence of the ablating beam
- Design compensation for the bio-mechanical response of the cornea
If the monochromatic optical errors of the eye are fully corrected over the largest entrance pupil of the fixating eye, the eye will be diffraction limited in the foveal area for all smaller pupil diameters for that wavelength despite small movements of the pupil center with pupil constriction or dilation.

Coordinate system for the coding of the correction.
The real world is polychromatic. Would it not be better to align to the achromatic axis to minimize the impact of transverse chromatic aberration.
Thibos/Bradley
achromatic
alignicator
Figure Legend:

AcP positions relative to those of PI. Those eyes where distances between AcP and PI were found to be statistically significant (P < 0.05) are shown with a red outline.
Location of pupil center with respect to VK center

Mean 0.15 mm T; 0.04 mm S
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Transverse chromatic aberration is an important factor limiting visual performance for small pupils (e.g., pupil inlay (1.6mm)), it is not an important factor for larger pupils.
Design compensation for the angle of incidence of the ablating beam

Less effective ablation

More effective ablation
Design compensation for the angle of incidence of the ablating beam
Each different axis will have a slightly different eye rotation.

Given corneal elevations are measured with corneal topography it is likely the compensation for the angle of incidence was designed using data gathered with respect to the VK axis.

Shifting the compensation on the cornea with respect to LoS will shift the resulting spherical aberration correction with respect to the eye’s inherent spherical aberration.
Design compensation for the biomechanical response of the cornea

The cornea is not a piece of Plastic

Biomechanical Response to Refractive Surgery

Biomechanical *Central Flattening* and *Peripheral Steepening*

- **Enhances** a Myopic Procedure
- **Reduces** the effect of a Hyperopic Procedure
- Flattening (hyperopic shift) in a “non-refractive” PTK
  - Including the PTK profile in one axis of an astigmatic procedure

- **Induces** unintended para-central and peripheral shape changes that result in **aberrations**!!

Cynthia J. Roberts, Ph.D.
Corneal response as a function of magnitude of the correction

Tangential corneal topography maps

Magnitude of the correction

N = 25
N = 321
N = 635
N = 622

< 2 D
2 to 4 D
4 to 6 D
6 to 8 D

Tangential dioptic maps courtesy of Cynthia Roberts
Compensation for the biomechanical response is another sph. aberration correction and has to be appropriately registered with the LoS.
Each different axis will have a slightly different eye rotation
Laser platform alignment to the eye

Most all laser platforms for corneal refractive surgery have eye tracking to place the surgery in the intended location.

How is the eye rotated when the landmarks for registration are selected?
Displacing SA corrections with respect to an underlying SA induces coma.

The most common induced aberration after refractive surgery is coma.
A misalignment of the attempted correction;
with a small misaligned compensation for the angle of incidence correction;
with a small misalignment for biomechanical response correction;
and accuracy and precision goes down.

Combine:
All measurements of the refractive errors of the eye, design of the correction and implementation of the correction need to be made using a common reference system.
Next Steps to improving outcomes

• Common reference system
• Know the design of each individual eye and their properties
• Use optimizing algorithms with objective metrics
• Two step procedure
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