Comparison Between Corneal and Total Aberrations Before and After Myopia Correction

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The human eye is affected by aberrations that degrade the retinal image.
Recent studies have found that in pre-presbyopic patients, the magnitude of high order aberrations of the cornea or the lens individually are larger than for the complete eye (El Hage 1973, Guirao 1998, Artal 2001, Kelly 2001)

Furthermore, despite variation in size and shape the average magnitude of HO aberrations of emmetropic eyes is similar to that found in groups of mild to moderate myopes and hyperopes (Cheng et al.)

Artal et al. proposed a passive, simple geometric model for the ocular compensation of aberrations.

They suggest that the components of the eye behave as an *auto-compensating design* producing similar overall average optical quality for different refractive errors, despite large structural variations.

We thought it would be interesting to investigate the effect of corneal changes such as those occurring after corneal refractive surgery.
To date only one study (Marcos et al.) reports the corneal and internal aberrations before and after corneal refractive surgery.

However a small sample size (N=12 eyes) and separate instruments were used to measure corneal and total aberrations.

In the current study, we used a combined ocular aberrometer and corneal topographer to measure and compare preoperative and postoperative corneal and total aberrations of consecutive eyes that underwent myopic laser in situ keratomileusis (LASIK).
MATERIAL AND METHODS
Making Examinations with the OPD Scan

Patients View

Surgeons View

6 mm circle

Eye Lashes
Nose Shadow

OPEN WIDE - KEEP OPEN
KEEP OPEN, KEEP OPEN,
KEEP OPEN - Blink
once - OPEN WIDE
Spatial Dynamic Skiascopy Method

The array of 8 sensors take retinoscopy-like measurements at 1 degree intervals around 180 degrees. This provides 1440 measurement points across a 6 mm diameter.
Basic Information OPD-Scan

The principle of the OPD Scan Aberrometry measurement
By rotation of the photo diode array 1440 local refractions are measured within a 6 mm Pupil and directly displayed on the OPD map in diopters. Neither Zernike nor Fourier interpolation is used at this stage!
Spatial Dynamic Skiascopy Method

**OPD Maps**
The resulting map from this type of aberrometry is an OPD Map. This map shows the measurement results in *diopters* instead of microns like other aberrometers.
Local Refractions → WF Slope

The WF slope is calculated point by point. By integration of the WF slopes we get the WF Error map.

The formula for the tangent of the local refraction is:

\[ \tan \beta = \frac{r}{d} = r \cdot D \]

The WF slope is given by:

\[ \frac{\partial W(r, \theta)}{\partial r} \]

where \( r = 0 \ldots R \), \( \theta = 0 \ldots 359^\circ \)

The WF Error is:

\[ W(0, \theta) = 0 \]

\[ W(r, \theta) = \int_0^R \frac{\partial W(r, \theta)}{\partial r} dr \]
OPD & Wavefront Maps

The wavefront maps are calculated from the OPD map.
The OPD-Scan measures aberrations in respect to the **corneal reflex (VK axis)** as the patients fixates and the operator aligns the OPD-Scan on the coaxial corneal reflex. (This is different to most other aberrometers!) This does **not** conform to ANSI Z80.28 standards.
Photopic Conditions: 100-150 cd/m²

Mesopic Conditions: 10-12 cd/m²

Reference between Pupil Center and Corneal Reflex
Indication of Alignment Quality

'Offsets' indicates the amount of misalignment b/t OPD measurement axis and corneal reflex.

Difference between photopic (CT) and mesopic fixation (Automated Skiascopy) (Both images have a bright corneal reflex).
These bright spots serve as reference points when matching both images. The amount of translation needed to match both images is called Offsets and can be an indicator for bad fixation; it is color coded green-yellow-red for good-ok-bad.

'Offsets' indicates the amount of misalignment b/t OPD measurement axis and corneal reflex:

0.00 - 0.30mm Ideal range
0.30 - 0.40mm Acceptable
>0.40 mm Unacceptable
Corneal Aberrations: $0.376 \times$ physical distance between the anterior cornea and the corresponding “cartesian oval” surface of same apical curvature.
Consecutive patients who underwent conventional myopic LASIK by the same surgeon (DG) were included in this study.

- Pre op S.E. < 10D  CYL < 0.75D
- Post op S.E. +/- 0.50D
- No operative complications
• Forme fruste keratoconus, keratoconus, pellucid marginal degeneration, contact lens warpage, marked corneal irregularity and less than 490 microns of central corneal thickness preoperatively

• Patients with mesopic pupil diameter <6mm
Percentage of Increase = \( \frac{(\text{Post op RMS group} / \text{Pre op RMS group})}{100} \)

Ratio of Compensation = \( \frac{(\text{Cornea RMS group} - \text{Ocular RMS group})}{\text{Cornea RMS group}} \)
SURGICAL PROCEDURE

CONVENTIONAL MYOPIC LASIK (NIDEK EC 5000)
RESULTS

57 eyes from 114 patients (58 males and 56 females) were included

- Mean age was 33.24 ± 9.09 years.
- Examinations performed 27 ± 39 days before and 73 ± 17 days after LASIK surgery.
- Mean central 3 mm K: from 7.63 ± 0.252 mm preoperatively to 8.41 ± 0.46 mm postoperatively (p <10-3).
- The mean preoperative SE was -4.19 ± 2.19 D.
- The mean postoperative SE was -0.39 ±0.65 D) (p <10-11).
- 37 (64.7 %) eyes → postoperative MRSE between -0.50 D and +0.50 D.
- 51 (89.4%) eyes → postoperative MRSE within ±1 D of the intended correction.
- Preoperatively, the astigmatism was -0.32 ± 0.33 D.
- The mean postoperative astigmatism was -0.31 D ±0.27 D) (p=0.75).
The RMS of each CORNEAL aberration group increased significantly after LASIK ($p<0.05$).

The RMS of OCULAR T. Trefoil and T. Higher Order Astigmatism did not increase significantly ($p >0.05$).

However, all other OCULAR groups showed a statistically significant increase in RMS postoperatively ($p<0.05$).
<table>
<thead>
<tr>
<th>Aberration Group</th>
<th>Preoperative Values (Mean±SD) (µ)</th>
<th>Postoperative Values (Mean±SD) (µ)</th>
<th>Mean PI (% Increase) (Mean±SD)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Eye T.HOA</strong></td>
<td>0.33±0.11</td>
<td>0.53±0.31</td>
<td>1.77±1.26</td>
<td>&lt;2 10⁻⁵</td>
</tr>
<tr>
<td>Corneal T.HOA</td>
<td>0.85±0.51</td>
<td>1.71±1.64</td>
<td>2.47±2.25</td>
<td>&lt;3 10⁻⁴</td>
</tr>
<tr>
<td><strong>Total Eye T.Coma</strong></td>
<td>0.151±0.07</td>
<td>0.277±0.217</td>
<td>2.43±2.61</td>
<td>&lt;6.1 10⁻⁵</td>
</tr>
<tr>
<td>Corneal T.Coma</td>
<td>0.385±0.276</td>
<td>0.715±0.777</td>
<td>2.56±2.66</td>
<td>0.0030</td>
</tr>
<tr>
<td><strong>Total Eye T.Trefoil</strong></td>
<td>0.214±0.103</td>
<td>0.249±0.167</td>
<td>1.42±1.22</td>
<td>0.18</td>
</tr>
<tr>
<td>Corneal T.Trefoil</td>
<td>0.478±0.403</td>
<td>0.85±0.91</td>
<td>2.92±3.67</td>
<td>0.0075</td>
</tr>
<tr>
<td><strong>Total Eye T.Sph</strong></td>
<td>0.108±0.066</td>
<td>0.231±0.178</td>
<td>1.46±1.83</td>
<td>&lt;3.5 10⁻⁶</td>
</tr>
<tr>
<td>Corneal T.Sph</td>
<td>0.307±0.12</td>
<td>0.688±0.467</td>
<td>2.64±2.24</td>
<td>3 10⁻⁸</td>
</tr>
<tr>
<td><strong>Total Eye T.Tetrafoil</strong></td>
<td>0.075±0.062</td>
<td>0.10±0.10</td>
<td>2.13±2.66</td>
<td>0.0536</td>
</tr>
<tr>
<td>Corneal T.Tetrafoil</td>
<td>0.284±0.241</td>
<td>0.671±0.79</td>
<td>4.38±6.69</td>
<td>0.00054</td>
</tr>
<tr>
<td><strong>Total Eye Hi.Astig</strong></td>
<td>0.068±0.11</td>
<td>0.078±0.042</td>
<td>1.84±1.40</td>
<td>0.51</td>
</tr>
<tr>
<td>Corneal Hi.Astig</td>
<td>0.23±0.19</td>
<td>0.52±0.57</td>
<td>4.66±13.38</td>
<td>5 10⁻⁴</td>
</tr>
</tbody>
</table>
Ratio of compensation between corneal and total eye aberrations

None of the computed ratio showed statistical significant differences between the pre and postoperative periods.

<table>
<thead>
<tr>
<th>Aberration Group</th>
<th>Av. Preoperative Ratio</th>
<th>Av. Postoperative Ratio</th>
<th>p value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T. HOA</td>
<td>0.51±0.25</td>
<td>0.59±0.28</td>
<td>0.09</td>
</tr>
<tr>
<td>T.Coma</td>
<td>0.44±0.40</td>
<td>0.40±0.50</td>
<td>0.31</td>
</tr>
<tr>
<td>T.Trefoil</td>
<td>0.29±0.59</td>
<td>0.36±0.77</td>
<td>0.27</td>
</tr>
<tr>
<td>T.Sph</td>
<td>0.62±0.20</td>
<td>0.64±0.19</td>
<td>0.39</td>
</tr>
<tr>
<td>T.Tetrafoil</td>
<td>0.55±0.60</td>
<td>0.65±0.55</td>
<td>0.17</td>
</tr>
<tr>
<td>Hi Astig</td>
<td>0.61±0.38</td>
<td>0.69±0.28</td>
<td>0.15</td>
</tr>
</tbody>
</table>

* Statistically significant difference (p<0.05)

T. HOA denotes the total high-order aberrations group all terms included in the 3\textsuperscript{rd}, 4\textsuperscript{th}, 5\textsuperscript{th} and 6\textsuperscript{th} Zernike order
DISCUSSION
LASIK is a corneal procedure that does not induce change to the crystalline lens yet produce significant changes in optical aberrations and corneal power as seen in the current study.

If we hypothesize that no changes other than those incurred on the anterior corneal surface occur after LASIK, the net increase in total aberrations should be equal to the increase in corneal aberrations.

Thus, the balance between corneal and internal aberrations should be disrupted.

Disruption of the balance between corneal and internal aberrations does occur with age in non-surgical eyes (internal optical aberrations increase three-fold between ages 20 and 70 years), whereas corneal aberrations increase only mildly (Artal, Cheng, Glasser)

In our study, the corneal aberrations were higher than the total aberrations both preoperatively and postoperatively.

A decrease in the magnitude of the total eye aberrations indicates some degree of compensation by the internal optics, as corneal and internal aberrations combine to give total eye coefficients.

The results of the current study indicate that internal aberrations continue to reduce the impact of the induced corneal wavefront changes after LASIK!!
These results concur with those reported by Marcos and colleagues for SA.

Total aberrations were measured using a laser ray-tracing technique, whereas corneal aberrations were obtained from corneal elevation data measured using a corneal topographer with custom software.

However, contrary to our findings, the same analysis for post-LASIK 3rd order aberrations showed no statistically significant difference between corneal and total aberrations.

This discrepancy may be due to the limited sample size in the Marcos et al study (14 eyes in the Marcos et al study vs 57 eyes in the current study) and to the difference in the wavefront acquisition method.
Marcos et al. attributed the increase in the internal compensation of spherical aberration observed after myopic LASIK to changes in the posterior curvature of the cornea due to biomechanical remodeling.

Early studies using slit scanning topography reported a forward shift after myopic LASIK. However, the accuracy of the changes reported with slit scanning topography after corneal refractive surgery have been subject to skepticism and later refuted by rotating Scheimpflug imaging as instrument artifact (Nishimura et al.).

Due to the difference in the indices of refraction, the anterior interface is 10 times greater than the posterior interface, hence the contribution of the posterior surface to the corneal aberration would be minimal.

Dubbelman et al. concluded that the posterior corneal surface coma compensates approximately, 6% of the anterior corneal surface coma.


Artal et al report a higher compensation of internal optics, particularly coma in hyperopic eyes, which usually have a larger angle kappa.

Artal et al provided evidence that a displacement of the cornea with positive spherical aberration induces positive coma, while this same displacement for the lens, with a similar but negative spherical aberration, induces negative coma, that nearly cancels that of the cornea.

These results support a simple passive mechanism for the compensation.

Our data show a consistent match in the magnitudes of aberrations preoperatively and postoperatively, which suggests that a process may exist to proportionally increase internal aberration compensation for the eye.

Due to the surgically induced profile change of the anterior corneal surface, the angle of incidence of the light rays emerging from the posterior corneal surface and striking the crystalline lens is modified compared to preoperatively.

This may passively change the optical properties of the internal optics and partially explain our results.
We hypothesize that an active mechanism for this auto-compensation could be partially explained by a subtle shift or tilt of the physiologic lens, which would thus also make the eye robust to structural variations such as LASIK induced corneal aberrations.

This hypothesis is supported by the fact that the ratio of internal compensation were not statistically different before and after LASIK surgery.

An alternate explanation may be a mild change in the gradient refractive index of the lens (or the cornea?) that allows active compensation of the induced corneal aberrations.

In both cases the mechanisms behind such changes have yet to be determined.
There seems to be sufficient plasticity in the optical design of the eye that allows for this “emmetropization” to occur across the range of refractive error treated in the current study. However the range of induced corneal change over which this compensation occurs remains unanswered.

One requirement of an auto-compensation mechanism the presence of an active feedback loop that enables changes over a relatively short temporal scale.

There are examples abound of such rapid ocular auto-compensating mechanisms. (e.g; retinal photoreceptors realignement within ten days after IOL implantation of a patient with bilateral congenital cataracts for 4 decades (Smallman et al.)

Difference between the axis of measurement and the L.O.S?

Inaccuracies in the W.F. calculations?

Systematic error?
The Optical Society of America Standards Committee (OSA) recommends the use of the line of sight (LOS) (axis joining the fovea with the natural pupil center) as the reference axis for measurement of aberrations of the eye.


PLANE OF CALCULATION OF THE CORNEAL W.F. (VERTEX VS PUPIL PLANE)

A difference of WF_Int._aberration in two calculations vs Power(Sph.Equivalent)@VD12

\[ y = 0.0001x^2 + 0.0041x - 0.0028 \]

Error (%)

-14.00 -12.00 -10.00 -8.00 -6.00 -4.00 -2.00 0.00 2.00 4.00 6.00 8.00

Power (Diopter)
Some drawbacks of this study include:

- the short follow up period / corneal wound healing may still be occurring;

- the lack of normative data over the same time period.

Ideally a randomized, contralateral study design treating one with LASIK and not treating the fellow eye would have been provided conclusive data.
CONCLUSION

In summary, we measured corneal and ocular optical aberrations on one instrument using the same axis to show that the compensation for corneal aberrations by the internal aberrations of the eye relatively increases after myopic LASIK surgery.

In our study, this effect was observed in all high order aberration groups that were tested.

This systematic compensation suggest an automated mechanism and supports the concept of an optically robust design not only to developmental variation in the ocular shape and geometry but to acquired variation in the corneal shape.