The Effect of Optical Zone Decentration on Lower- and Higher-Order Aberrations after Photorefractive Keratectomy in a Cat Model

Jens Bühren,1 Geunyoung Yoon,1,2 Shawn Kenner,1,3 Scott MacRae,1,2 and Krystel Huxlin1,2

PURPOSE. To simulate the effects of decentration on lower- and higher-order aberrations (LOAs and HOAs) and optical quality, by using measured wavefront error (WFE) data from a cat photorefractive keratectomy (PRK) model.

METHODS. WFE differences were obtained from five cats’ eyes 19 ±7 weeks after spherical myopic PRK for −6 D (three eyes) and −10 D (two eyes). Ablation-centered WFEs were computed for a 9.0 mm pupil. A computer model was used to simulate decentration of a 6-mm subaperture in 100-µm steps over a circular area of 3000 µm diameter, relative to the measured WFE difference. Changes in LOA, HOA, and image quality (visual Strehl ratio based on the optical transfer function; VSOTF) were computed for simulated decentrations over 3.5 and 6.0 mm.

RESULTS. Decentration resulted in undercorrection of sphere and induction of astigmatism; among the HOAs, decentration mainly induced coma. Decentration effects were distributed asymmetrically. Decentration >1000 µm led to an undercorrection of sphere and cylinder of >0.5 D. Computational simulation of LOA/HOA interaction did not alter threshold values. For image quality (decrease of best-corrected VSOTF by >0.2 log units), the corresponding thresholds were lower. The amount of spherical aberration induced by the centered treatment significantly influenced the decentration tolerance of LOAs and log best corrected VSOTF.

CONCLUSIONS. Modeling decentration with real WFE changes showed irregularities of decentration effects for rotationally symmetric treatments. The main aberrations induced by decentration were defocus, astigmatism, and coma. Treatments that induced more spherical aberration were less tolerant of decentration. (Invest Ophthalmol Vis Sci. 2007;48:5806–5814) DOI:10.1167/iovs.07-0661

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C orrect alignment of the ablation to the visual axis of the eye is an essential requirement for optimal outcome in laser refractive surgery (LRS). Decentration of the ablation zone leads to incomplete refractive correction and induction of higher-order aberrations (HOAs), especially coma.1-4 The expected benefit of less HOA induction in eye tracker–controlled treatments has been demonstrated.5 However, decentration still occurs as a result of misalignment of the tracking system,6 static registration errors due to surgeon offsets,7 and pupil center shifts as a function of dilation.8 In most cases, the magnitude of such misalignments is <500 µm.1,7,9,10 A recent study showed that in uneventful wavefront-guided LASIK, coma induction occurred in a random fashion, independent of factors such as attempted correction and optical zone (OZ) diameter.11 Thus, microdecenterations can be considered ubiquitous, random errors; however, their impact on optical quality is poorly understood.11 In contrast, gross decentrations of >500 µm are one of the most visually disturbing complications after LRS. Besides causing severe deterioration of visual quality, such complications are difficult to treat, and success is often limited.12-18

Although several studies on decentration-induced aberrations after conventional1-7 and wavefront-guided LRS1,4,8,19 have been published, all assumed a perfect ablation and did not consider the inherent induction of HOA which occurs in real corneas as a result of wound healing and biomechanical effects.20,21 The present study was conducted to investigate the effects of decentration of the laser ablation relative to the entrance pupil of the eye on LOA, HOA, and optical quality, in a cat photorefractive keratectomy (PRK) model. Although the optical effects of PRK for myopia, such as reduction of defocus, induction of coma, and positive spherical aberration are similar in cats and humans,22,23 the greater corneal surface area and the naturally large scotopic pupil diameter (PD) of ~12 mm in cats allowed us to measure wavefront changes well beyond the ablation OZ. A simplified computational model was used to simulate decentration effects over a circular area of 5000 µm in diameter by calculating wavefront errors (WFEs) for systematically offset subapertures of 3.5 and 6.0 mm. Using this paradigm, we assessed (1) the nature and magnitude and spatial distribution of optical aberrations induced by different amounts of decentration, (2) the impact of such aberrations on theoretical optical quality, (3) whether residual refractive errors could be partially attributed to microdecenterations (<500 µm), and (4) the impact of optical aberrations induced by laser refractive surgery on tolerance of decentration.

MATERIALS AND METHODS

Subjects

Data were obtained from five eyes of five normal, male domestic short hair cats (Felis catus), who underwent myopic PRK with an uncomplicated follow-up of at least 3 months and in which wavefront aberrations could be measured over a PD of 9 mm. Procedures were

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Table 1. Treatment Characteristics and WFE Changes for the Centered Treatment ($\Delta W(x, y)$) over 6- and 9-mm PDs

<table>
<thead>
<tr>
<th>Eye</th>
<th>Treatment (D)</th>
<th>OZ (mm)</th>
<th>TTZ (mm)</th>
<th>PD (mm)</th>
<th>Sphere (D)</th>
<th>Cylinder (D)</th>
<th>Axis (°)</th>
<th>Total HOA RMS (µm)</th>
<th>Coma RMS (µm)</th>
<th>SA RMS (µm)</th>
<th>eHOA RMS (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>c1-005 OD</td>
<td>−6</td>
<td>8</td>
<td>11.1</td>
<td>9</td>
<td>+3.33</td>
<td>−0.58</td>
<td>172</td>
<td>2.412</td>
<td>1.019</td>
<td>1.838</td>
<td>1.118</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td></td>
<td></td>
<td>6</td>
<td>+4.71</td>
<td>−0.61</td>
<td>12</td>
<td>0.541</td>
<td>0.197</td>
<td>0.333</td>
<td>0.388</td>
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<tr>
<td>c2-001 OS</td>
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<td>6</td>
<td>9.1</td>
<td>9</td>
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<td>−0.37</td>
<td>91</td>
<td>1.790</td>
<td>0.516</td>
<td>1.585</td>
<td>0.650</td>
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<td>+2.56</td>
<td>−0.24</td>
<td>40</td>
<td>0.307</td>
<td>0.120</td>
<td>0.039</td>
<td>0.280</td>
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<tr>
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<td>9.1</td>
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<td>+2.49</td>
<td>−0.28</td>
<td>29</td>
<td>2.182</td>
<td>0.414</td>
<td>2.108</td>
<td>0.381</td>
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<tr>
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<td>6</td>
<td>+4.11</td>
<td>−0.28</td>
<td>37</td>
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<td>0.296</td>
<td>0.426</td>
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<tr>
<td>c5-026 OD</td>
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<td>+3.24</td>
<td>−0.45</td>
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<td>0.423</td>
<td>2.924</td>
<td>0.409</td>
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<td>6</td>
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<td>−0.47</td>
<td>160</td>
<td>0.430</td>
<td>0.291</td>
<td>0.262</td>
<td>0.178</td>
</tr>
</tbody>
</table>

OZ, diameter of the programmed optical zone; TTZ, diameter of the total treatment zone; total HOA RMS, root mean square value of 3rd- to 10th-order aberrations; coma RMS, RMS value of 3rd- to 9th-order coma; SA RMS, RMS value of 4th- to 10th-order spherical aberration; eHOA RMS, residual RMS of all non coma, nonspherical HOA.

Conducted according to the guidelines of the University of Rochester Committee on Animal Research (UCAR), the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research, and the NIH Guide for the Care and Use of Laboratory Animals.

Photorefractive Keratectomy

Three cats’ eyes underwent PRK for −6 D, two with a programmed OZ of 6 mm and one with an 8-mm OZ; two eyes received a PRK for −10 D (6 mm OZ). The procedure has been described in detail elsewhere. Briefly, all eyes received a conventional spherical ablation (Planoscan 4.14; Bausch & Lomb, Inc., Rochester, NY) performed by one of two surgeons (SM, JB) in animals under surgical anesthesia (Technolas 217 laser; Bausch & Lomb, Inc.). The ablation was centered on the pupil, which was constricted with 2 drops of pilocarpine 3% (Bausch & Lomb). After surgery, the cats received 2 drops of 0.3% tobramycin +0.1% dexamethasone per eye, once a day, until the surface epithelium healed.

Wavefront Sensing

As described previously, the cats were fixed to single spots of light presented on a computer monitor. Wavefront measurements were performed before surgery and 19 ± 7 (12–24) weeks after surgery, with a custom-built Hartmann-Shack wavefront sensor. The wavefront sensor was aligned to the visual axis of one eye, while the other eye fixated a spot on the computer monitor. At least 10 spot-array patterns were collected per imaging session per eye.

Calculation of Centered WFE Differences

From each single spot–array pattern, WFES were calculated with a 2nd–10th-order Zernike polynomial expansion according to Vision Science and Its Application (VSIA) standards for reporting aberration data of the eye. WFE changes were calculated in a multistep process. The first step included the determination of the center of the OZ. Because PRK was performed with the cat under general anesthesia and the ablation was registered to the pupil center, an alignment to the visual axis of the cat’s eye during surgery could not be ensured, and possible decentration effects had to be compensated for. Therefore, the centroiding area (analysis pupil) of 6-mm diameter was shifted manually in steps of 300 µm according to the distance between the lenslet centers to find the wavefront that yielded the most negative Z20 value (i.e., the maximum treatment effect). This was defined as the centered, postoperative wavefront ($W_{post}(x, y)$), which was then averaged from single measurements over a PD of 9 mm. In the second step, the horizontal and vertical offsets between the center of the OZ and the center of the original pupil were used to calculate preoperative WFEs ($W_{mean}(x, y)$), for the position that equaled the later treatment center. Like $W_{post}(x, y)$, $W_{mean}(x, y)$ was computed for a 9-mm PD. In a third step, the change in WFEs, $\Delta W(x, y)$, were obtained by subtracting the pre- from the postoperative Zernike coefficients. Thus, $\Delta W(x, y)$ reflected the treatment effect over a 9-mm PD, for a perfectly centered OZ, minimizing the potential influence of internal aberrations. The Zernike coefficient spectrum of each $\Delta W(x, y)$ (Table 1) was consistent with data obtained in humans after PRK.

Computer Modeling of Treatment Decentration

For each eye, decentration of a 6-mm subpupil relative to $\Delta W(x, y)$ was simulated using custom software (MatLab 7.2; The MathWorks Inc., Natick, MA). Decentered WFE differences $\Delta W(x', y')$ were calculated for the size of the 6-mm subaperture along Cartesian decentrations $\Delta x$ and $\Delta y$, where $\Delta x$ and $\Delta y$ were changed in steps of 100 µm, covering the entire 9-mm centroiding area and resulting in a maximum decentration range of 3000 µm over a circular region. Zernike polynomials for the 2nd to the 6th order were fitted to the data of each decentred wavefront $\Delta W(x', y')$ by using a singular value decomposition algorithm to calculate the pseudoinverse of the Zernike data to get the centered subapupil Zernike coefficients. As a refinement of the manual determination of the centered position, the algorithm assigned the centered coordinates ($\Delta x = 0, \Delta y = 0$) to the $\Delta W(x', y')$ with the lowest $Z_{20}$ value. For each eye, 709 WFES, 1 centered and 708 decentred were calculated over a 6-mm PD.

Simulation of Decentered Treatment Effects and VSOTF Calculation

Theoretical optical quality was investigated by calculating the VSOTF metric (visual Strehl ratio based on the optical transfer function [OTF]). The VSOTF is the ratio of the contrast sensitivity–weighted OTF to the contrast sensitivity–weighted OTF of the diffraction-limited eye. Because the preoperative WFES were centered, calculating the VSOTF from preoperative HOA could lead to misinterpretation of optical quality due to over- or underestimation of HOA. Thus, we calculated a standard preoperative WFE, $W_{mean}(x, y)$, from all eyes included in this study. For the calculation of $W_{mean}(x, y)$, all preoperative, pupil-centered WFES were averaged, resulting in a WFE representing the typical preoperative range of HOA (Table 2). Simulated postoperative WFES, $W_{mean}(x', y')$, were calculated by subtracting the $W_{mean}(x, y)$ from each $\Delta W(x', y')$. This treatment simulation relative to a standard preoperative WFE allowed us to eliminate interindividual differences in preoperative optical quality and internal optics. Therefore, the independent variables in this experiment were the five different centered treatment effects $\Delta W(x, y)$ and
their corresponding $\Delta \log W(x', y')$. A computer program (Visual Optics Laboratory, VOL-Pro 7.14; Sarver and Associates, Carbondale, IL) was used to calculate the VSOTF over an analysis PD of 3.5 and 6.0 mm. The VSOTF for a given WFE was calculated for the combination of LOA terms that provided the highest VSOTF simulating the optical quality with best sphero-cylindrical correction (BCVSOTF). Thus, for each simulated $W_{\text{post}}(x', y')$, an LOA-derived refractive error based on 2nd-order terms and an “effective” refractive error based on the BCVSOTF were obtained. Differences between refractive errors were expressed as dioptric power vectors $(M, J0, J45)$, where $M$ corresponds to the spherical equivalent and $J0$ to the $0^\circ/90^\circ$ and $J45$ to the $45^\circ/135^\circ$ astigmatic components. The difference between the VSOTF- and 2nd-order–based power vectors could be considered a function of the interaction between HOA and LOA. Since “sphere” and “cylinder” are most commonly used in clinical settings, we displayed most of the results in terms of sphere and cylinder magnitude. To visualize decentration effects for single eyes, color maps plotting $\Delta \log W$, $\Delta \log \text{BCVSOTF}$ against horizontal and vertical decentration were created. For further statistical analysis, data for decentration along the $0^\circ$, $90^\circ$, $180^\circ$, and $270^\circ$ meridians were averaged for each eye.

**Calculating Decentration Tolerance**

Analysis of tolerance was performed by calculating the maximum permissible decentration that yielded a critical refraction or BCVSOTF difference. For sphere and cylinder, this threshold value was defined a priori as $-0.5$ D. For the optical quality metric BCVSOTF, we chose a critical decrease of 0.2 log units, which roughly equals a decrease of 2 logMAR steps. For each parameter investigated, vectors $\mathbf{r}$ between the centered position $(x, y)$ and each outmost coordinate below the criterion (threshold coordinates $x', y'$) were calculated. The mean value, $\mathbf{r}$, reflects the average maximum permissible decentration (in micrometers) that allows one to remain below the threshold criterion and equals the radius of a circle around the centered position. The standard deviation (SD) of $\mathbf{r}$ and the coefficient of variation (CV) of $\mathbf{r}$ served as metrics for regularity of decentration effects, where $SD$ of $\mathbf{r}$ reflects the absolute and $CV$ of $\mathbf{r}$ the relative irregularity. The smaller the $SD$ and $CV$, the less variable were the decentration effects along different meridians (i.e., the more circle-shaped was the decentration pattern).

**Statistical Analysis**

All analyses were based on the difference values $\Delta W$ and $\Delta \log \text{BCVSOTF}$, which reflected the treatment effects. Main outcome measures were the change of log BCVSOTF, the change of LOA, expressed in diopters, and the change of HOA as a function of decentration. All differences for the center position $(x, y)$ were normalized to zero. Thus, values for decentered coordinates $x'$ and $y'$ reflect the deviation from the centered treatment effect. The difference between wavefront- and VSOTF-based refraction was considered an effect of interaction between LOA and HOA. Tolerance metrics were calculated as de-

**TABLE 2.** The Averaged Preoperative Mean WFE $W_{\text{pre}}(x, y)$, Computed for 3.5- and 6-mm PDs

<table>
<thead>
<tr>
<th>PD (mm)</th>
<th>Log BCVSOTF</th>
<th>Total HOA RMS (µm)</th>
<th>Coma RMS (µm)</th>
<th>SA RMS (µm)</th>
<th>rHOA RMS (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>$-0.05$</td>
<td>0.036</td>
<td>0.031</td>
<td>0.012</td>
<td>0.014</td>
</tr>
<tr>
<td>6.0</td>
<td>$-0.38$</td>
<td>0.185</td>
<td>0.145</td>
<td>0.078</td>
<td>0.083</td>
</tr>
</tbody>
</table>

For all calculations LOA were set to zero. BCVSOTF (visual Strehl ratio based on the optical transfer function, simulated for best correction); total HOA RMS, root mean square value of 3rd- to 6th-order aberrations; coma RMS, RMS of 3rd to 5th order coma; SA RMS, RMS of $Z_4^{00}$ and $Z_4^{0}$; rHOA RMS, residual RMS of all noncoma, nonspherical HOA.
Bonferroni adjustment for multiple tests.

Chicago, IL), assuming a significance level of
were performed with a commercial program (SPSS 11.0; SPSS Inc.,
decentration tolerance for PDs of 3.5 and 6.0 mm. All statistical tests
their VSOTF-based equivalents using a nonparametric test for matched
variables were the mean vectors
r
\( Z_{n}^{v} \) (the RMS of all coefficients
\( Z_{n}^{v} \)), and the RMS of the residual
noncoma, nonspherical aberrations (rHOA, the RMS value of all re-
mainling HOA
\( Z_{n}^{v} \)).

The influence of the magnitude of HOA induction on decentration
tolerance was assessed with linear regression analysis. The dependent
variables were the mean vectors \( \hat{r} \) and their SD. To investigate the
impact of HOAs on log BCVSOTF, we applied a multiple-regression
model using HOAs as predictors and log BCVSOTF as dependent
variables. The role of interaction on decentration tolerance was inves-
tigated by comparing \( \hat{r} \) and SD for 2nd-order sphere and cylinder with
their VSOTF-based equivalents using a nonparametric test for matched
pairs (Wilcoxon test). The same test was also applied to compare
decentration tolerance for PDs of 3.5 and 6.0 mm. All statistical tests
were performed with a commercial program (SPSS 11.0; SPSS Inc.,
Chicago, IL), assuming a significance level of \( P < 0.05 \) and using the
Bonferroni adjustment for multiple tests.

RESULTS

Change in Second-Order Aberrations

For all eyes examined, increasing decentration caused increas-
ing undercorrection of 2nd-order sphere and induction of 2nd-
order astigmatism. However, the pattern of decentration ef-
effects was triangular in shape rather than rotationally
symmetric, as might have been predicted from the intended
refractive correction (Fig. 1). These irregularities were more
pronounced for 3.5-mm PDs which also showed reduction of
cylinder magnitude with decentration (Figs. 1A, 1B). When
averaging over all five eyes, decentrations of \( \geq 1000 \) \( \mu m \) had a
limited effect on sphere and cylinder magnitude, since the
average undercorrection and cylinder induction were \( > -0.5 \)
D (Fig. 2). In contrast, decentrations \( \geq 1000 \) \( \mu m \) resulted in
larger deviation from the central treatment effect. The mean
induction of astigmatism was higher for 6- than for 3.5-mm
PDs; however, the differences between the two PDs for de-
centrations \( \geq 900 \) \( \mu m \) reached only local significance of \( P < 0.05 \), which was nonsignificant with the Bonferroni correction.

Decentration Effects and the Interaction between
HOAs and LOAs

VSOTF-based refraction data included interaction effects of
LOA with HOA. Apart from a tendency of VSOTF-based \( M \)
values to be more hyperopic at the centered position, there
were no significant differences between 2nd-order and VSOTF-
based power vectors (Table 3). Decentration effects were more
irregular for VSOTF-based refraction data than for the
respective wavefront-derived data, particularly for sphere
measured over 6-mm PDs (local \( P < 0.05 \); Table 3). The effects
of decentration on the VSOTF cylinder magnitude also showed
high interindividual variability among the eyes.

<table>
<thead>
<tr>
<th>TABLE 3. Effects of Interaction between LOAs and HOAs on Treatment Effects as a Function of Decentration</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PD (mm)</strong></td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>3.5</td>
</tr>
<tr>
<td>3.5</td>
</tr>
<tr>
<td>3.5</td>
</tr>
<tr>
<td>3.5</td>
</tr>
<tr>
<td>3.5</td>
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</tr>
<tr>
<td>6.0</td>
</tr>
<tr>
<td>6.0</td>
</tr>
</tbody>
</table>

The data are averaged from the 0°, 90°, 180°, and 270° meridian and expressed as mean and SD of the
difference between second-order and VSOTF-based dioptic power vectors \( M, J0, \) and \( J45 \). Differences
were not statistically significant. VSOTF refraction, simulated endpoint of the subjective refraction based
on the BCVSOTF; \( M \), spherical equivalent; \( J0, 0^\circ/90^\circ \) astigmatic component; \( J45, 45^\circ/135^\circ \) astigmatic component.
Changes of HOAs and BCVSOTF

HOAs induced by decentration were dominated by coma (Table 4). As for 2nd-order aberrations, the decentration patterns for coma RMS were not rotationally symmetric, and displayed flatter slopes but higher irregularity for 3.5- than for 6-mm PDs (Fig. 3). We found a significant influence of the amount of decentration on the induction of coma RMS at a PD of 6 mm (adjusted $R^2 = 0.51$; $B = 0.7 \times 10^{-3}$, $P < 0.001$). At 3.5 mm, although much less pronounced (adjusted $R^2 = 0.23$, $B = 0.08 \times 10^{-3}$, $P < 0.001$), the same tendency was observed (Fig. 4). The induction of SA RMS and rHOA RMS was less influenced by decentration (no significant correlation), with irregular decentration patterns and high variability between individual eyes at the two PDs.

In all eyes, theoretical best-corrected optical quality expressed as BCVSOTF decreased by $-0.41 \pm 0.13$ log units for 3.5-mm pupils and by $-0.55 \pm 0.19$ log units for 6.0-mm pupils after a centered treatment. Decentration resulted in even higher decrease in log BCVSOTF (Figs. 5, 6). Furthermore, if $\Delta$log BCVSOTF was computed for a 3.5-mm PD, the position that yielded the minimum decrease of BCVSOTF was located paracentrally in all eyes (Fig. 5A). The regression model revealed a significant influence of the HOAs on log BCVSOTF at both PDs (adjusted $R^2 = 0.84$ for 6-mm PD, $R^2 = 0.81$ for 3.5-mm PD) with the highest impact of coma RMS in both models.

**Table 4. Change of VSOTF and Induction of Higher-Order Aberrations as a Function of Decentration**

<table>
<thead>
<tr>
<th>PD (mm)</th>
<th>Decentration (µm)</th>
<th>$\Delta$log BCVSOTF</th>
<th>$\Delta$ Coma RMS</th>
<th>$\Delta$ SA RMS</th>
<th>$\Delta$ rHOA RMS</th>
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</thead>
<tbody>
<tr>
<td>3.5</td>
<td>0</td>
<td>$0 \pm 0$</td>
<td>$0 \pm 0$</td>
<td>$0 \pm 0$</td>
<td>$0 \pm 0$</td>
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<tr>
<td></td>
<td>200</td>
<td>$0 \pm 0.04$</td>
<td>$0 \pm 0.017$</td>
<td>$0 \pm 0.006$</td>
<td>$0 \pm 0.014$</td>
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<td></td>
<td>500</td>
<td>$-0.03 \pm 0.09$</td>
<td>$0.004 \pm 0.041$</td>
<td>$-0.001 \pm 0.015$</td>
<td>$-0.001 \pm 0.031$</td>
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<tr>
<td></td>
<td>1000</td>
<td>$-0.12 \pm 0.18$</td>
<td>$0.059 \pm 0.069$</td>
<td>$0.011 \pm 0.025$</td>
<td>$0.002 \pm 0.044$</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>$-0.22 \pm 0.21$</td>
<td>$0.112 \pm 0.079$</td>
<td>$0.015 \pm 0.034$</td>
<td>$0.003 \pm 0.058$</td>
</tr>
<tr>
<td>6.0</td>
<td>0</td>
<td>$-0.14 \pm 0.19$</td>
<td>$0.058 \pm 0.039$</td>
<td>$0.270 \pm 0.149$</td>
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<td>$-0.18 \pm 0.17$</td>
<td>$0.111 \pm 0.080$</td>
<td>$0.275 \pm 0.138$</td>
<td>$0.187 \pm 0.041$</td>
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<tr>
<td></td>
<td>500</td>
<td>$-0.24 \pm 0.18$</td>
<td>$0.500 \pm 0.147$</td>
<td>$0.295 \pm 0.147$</td>
<td>$0.195 \pm 0.047$</td>
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<td></td>
<td>1000</td>
<td>$-0.29 \pm 0.20$</td>
<td>$0.660 \pm 0.289$</td>
<td>$0.338 \pm 0.184$</td>
<td>$0.223 \pm 0.048$</td>
</tr>
<tr>
<td></td>
<td>1500</td>
<td>$-0.29 \pm 0.20$</td>
<td>$0.932 \pm 0.403$</td>
<td>$0.317 \pm 0.188$</td>
<td>$0.252 \pm 0.042$</td>
</tr>
</tbody>
</table>

The data are averaged from the $0^\circ$, $90^\circ$, $180^\circ$, and $270^\circ$ meridian and expressed as mean and standard deviations. The values are normalized to the values for the centered position for a 3.5-mm pupil diameter (PD), i.e. each value reflects the difference to the value obtained from centered position over a 3.5 mm PD. $\Delta x$, horizontal decentration; $\Delta y$, vertical decentration. log BCVSOTF, visual Strehl ratio based on the optical transfer function, simulated for best correction; coma RMS, RMS of 3rd and 5th order coma terms; SA RMS, RMS of $Z_4$ and $Z_6$; rHOA RMS, residual RMS of all noncoma, nonspherical HOA.

Analysis of Decentration Tolerance and Irregularity

Table 5 shows the mean vectors $\vec{r}$ and their SDs. Both for wavefront-derived and for VSOTF-based sphere, the critical $\vec{r}$ for an undercorrection of 0.5 D was greater than 1000 µm in all cases. The mean change of decentration tolerance due to interaction was $82 \pm 232$ µm for 6-mm PD and $-92 \pm 73$ µm for 3.5-mm PD (both $P < 0.05$). For the 6-mm PD, $\vec{r}$ of cylinder magnitude decreased by $-160 \pm 42$ µm when interaction was simulated ($P > 0.05$). At the 3.5-mm PD, values remained almost constant $(14 \pm 153$ µm; $P > 0.05$). While the $\vec{r}$ of sphere and cylinder was similar at the two PDs, the data (Figs. 5, 6) suggested a higher decentration tolerance at the 3.5-mm PD with regard to log BCVSOTF. This was confirmed by analysis of $\vec{r}$ (Table 5; local $P < 0.05$). Analysis of the $SD$ and $CV$ of $\vec{r}$ showed that the 2nd-order sphere (6.0-mm PD) had more regular decentration patterns than did the other parameters (Table 5).

Linear regression analysis revealed that decentration tolerance $\vec{r}$ was influenced significantly by spherical aberrations induced by the centered treatment. At 6-mm PD, 2nd-order sphere ($R^2 = 0.87$, $B = -181$; $P < 0.05$), 2nd-order cylinder (adjusted $R^2 = 0.80$, $B = -278$; $P < 0.05$), and the VSOTF sphere ($R^2 = 0.80$, $B = -407$; $P < 0.05$) were significantly influenced by $\Delta$SA RMS but not by the amount of defocus or coma and rHOA RMS changes. Likewise, sphere and cylinder obtained over a 3.5-mm PD appeared not to be influenced by defocus change or HOA induction of the treatment. Steeper
Decentration and Aberrations after PRK in the Cat

DISCUSSION

Decentration Effects Followed an Irregular Pattern

The present experiments revealed that decentration effects were distributed asymmetrically, although the treatment involved only rotationally symmetric ablation patterns. This behavior affected all parameters investigated and was more pronounced at the smaller (3.5-mm) pupil size. The fact that only decentrations affected all parameters investigated and was more pronounced only rotationally symmetric ablation patterns. This behavior affected all parameters investigated and was more pronounced at the smaller (3.5-mm) pupil size. The fact that only decentrations affected all parameters investigated and was more pronounced at the smaller (3.5-mm) pupil size.

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induced was not affected by decentration, the SDs increased with decentration, reflecting high interindividual differences. In all eyes examined, log BCVSOTF decreased asymmetrically as a function of decentration, displaying asymmetric decentration patterns. The obvious relationship between coma and log BCVSOTF in the decentration maps (Figs. 3, 4) was confirmed by regression analysis that revealed a highly significant, numerical impact of coma on log BCVSOTF at both 3.5- and 6-mm PDs. The large discrepancy between decentration tolerance at 3.5- and 6-mm PDs suggests that microdecentrations could be one cause of night vision disturbances in eyes that are asymptomatic under photopic conditions, particularly if center shifts between constricted and dilated pupil are involved. Indeed, significant amounts of coma have been reported in such symptomatic eyes.34,35 Another potential reason for a high interindividual variability of symptoms is the compensation of corneal astigmatism. However, the decentration tolerance of sphere undercorrection of the defocus term and the induction of coma aberrations by the lens.36 Further studies involving ray tracing models will be necessary to investigate the role of internal optics on decentration effects.

CONCLUSIONS

Anatomy, optics, function, and subjective perception are key levels in the concept of quality of vision after refractive surgical procedures. The model described herein allowed us to investigate decentration tolerance as a novel dimension of the “optics” level in the quality of vision concept. Our calculations reduced possible biases resulting from aberrometer misalignments or internal optics so that “pure” WFE changes could be investigated. Although these computations are laborious, an evaluation of decentration effects on novel treatment modalities (e.g., presbyopia-correcting laser profiles or new multifocal intraocular lenses) is now possible. As demonstrated in the context of image quality, it appears logical that different aberrations should interact, affecting decentration tolerance. A limitation of our computational model, however, is that it simulates decentration by pupil shifts rather than by shifts of the treatment zone. Given that some of our treatments were centered themselves, this could be a problem, especially if different portions of the central cornea yield significantly different biological responses.

Nevertheless, the computational model described in the present study is a powerful and versatile tool for the analysis of decentration effects on refractive outcome. Although based on a small sample of experimental eyes, it allowed us to reach conclusions of potential interest for refractive surgical practice: (1) Decentration of myopic treatments leads to consistent undercorrection of the defocus term and the induction of astigmatism. However, the decentration tolerance of sphere and cylinder (including simulated interaction effects) makes it unlikely that microdecentrations ≤500 µm are a significant cause of residual refractive errors in otherwise asymptomatic

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Threshold Value</th>
<th>SD of $\overline{r}$ (µm)</th>
<th>$\overline{r}$ (µm)</th>
<th>CV of $\overline{r}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3.5-mm PD</td>
<td>6-mm PD</td>
<td>3.5-mm PD</td>
</tr>
<tr>
<td>Δ2nd-order sphere</td>
<td>-0.5 D</td>
<td>1255 ± 160</td>
<td>1313 ± 136</td>
<td>228 ± 60</td>
</tr>
<tr>
<td>Δ2nd-order cylinder</td>
<td>-0.5 D</td>
<td>1304 ± 150</td>
<td>1008 ± 214</td>
<td>208 ± 64</td>
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<tr>
<td>ΔVSOTF sphere</td>
<td>-0.5 D</td>
<td>1348 ± 104</td>
<td>1232 ± 314</td>
<td>204 ± 63</td>
</tr>
<tr>
<td>ΔVSOTF cylinder</td>
<td>-0.5 D</td>
<td>1289 ± 201</td>
<td>1167 ± 271</td>
<td>226 ± 100</td>
</tr>
<tr>
<td>Δlog BCVSOTF</td>
<td>-0.2</td>
<td>1219 ± 210</td>
<td>800 ± 512</td>
<td>248 ± 82</td>
</tr>
</tbody>
</table>

The radius $\overline{r}$ is the mean length of the vectors between the center and the locations with threshold values. The SD and CV of $\overline{r}$ reflect the irregularity of the decentration behavior. All data are expressed as the mean and SD. PD, analysis pupil diameter. VSOTF sphere/cylinder, simulated endpoint of the subjective refraction based on the BCVSOTF.
eyes. (2) In contrast to effects on LOAs, microdecentrations appear to be a source of HOA-related visual symptoms under mesopic conditions in a proportion of eyes that would be asymptomatic under photopic conditions. (3) Given the intra- and interindividual variability of effects in our model, it appears that only some eyes will experience symptoms in clinical practice. (4) Finally, our results suggest that minimizing the induction of spherical aberration by maximizing the functional optical zone of the cornea using aspheric ablation profiles or large OZ diameters could significantly increase decentration tolerance and by doing so, optimize refractive outcome.

References


