ARTICLE

Comparison of optical quality metrics to predict subjective quality of vision after laser in situ keratomileusis

Jens Bühren, MD, Konrad Pesudovs, PhD, Tim Martin, PhD, Anja Strenger, Dipl-Ing, Geunyoung Yoon, PhD, Thomas Kohnen, MD

PURPOSE: To compare wavefront-derived metrics to predict subjective quality of vision after laser in situ keratomileusis (LASIK) for myopia.

SETTING: Department of Ophthalmology, Goethe University, Frankfurt am Main, Germany.

METHODS: One month postoperatively, wavefront sensing was performed and overall subjective quality of vision assessed under 3 lighting conditions (photopic, high mesopic, low mesopic) with a questionnaire. Four wavefront-error representations were computed for a pupil diameter of 6.0 mm and individual physiological pupil diameters at 0.4 lux: (1) the visual Strehl ratio based on optical transfer function (VSOTF), (2) the root-mean-square (RMS) value of Zernike orders 2 to 5 (total RMS), (3) higher-order aberration (HOA) RMS, and (4) a wavefront-error breakdown into the RMS of lower-order aberrations, coma, spherical aberration, and remaining HOA. The impact of the postoperative wavefront error on subjective quality of vision was calculated using linear regression analysis.

RESULTS: Fifty-six eyes (29 patients) were included. The ability of wavefront error–derived metrics to predict subjective quality of vision was limited. The VSOTF, calculated for the best-corrected eye, showed the highest predictability. Calculation of wavefront error for individual physiological pupil diameters did not improve predictive ability of the metrics. Eyes with a high theoretical retinal-image quality had a high subjective quality of vision, and eyes with a low subjective quality of vision had a low theoretical image quality.

CONCLUSIONS: Postoperative wavefront error had limited influence on the subjective quality of vision. Postoperative retinal image quality should be kept as high as possible to provide good subjective quality of vision.

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In recent years, quality of vision has become a major dimension of the outcomes of refractive and cataract surgery; therefore, basic and clinical research has focused on this aspect.[1–4] One challenge of this relatively new paradigm is that it requires operationalization—the use of 1 or more surrogate parameters—because quality of vision cannot be measured directly. As a working hypothesis, our group has proposed a paradigm for quality of vision.[5] On a basic level, anatomical features, such as characteristics of the corneal surface, corneal curvature, clearness of the optical media, and axial length of the eye, determine the optical properties of the eye and hence the quality of the retinal image. The quality of the retinal image influences basic functional tasks such as resolution and contrast detection. Finally, the image is processed by the visual system. This leads to a specific perception of the initial visual stimulus and to the viewer's final valuation of overall image quality. This final judgment could be considered the quality of vision benchmark because it is the patient who ultimately decides whether his or her vision is good or bad.

Current refractive surgical treatment modalities have a high success rate, reflected by favorable functional outcomes[6–9] and high physician and patient satisfaction. Studies report satisfaction rates of 90% and higher after laser in situ keratomileusis (LASIK).[10–12] However, there are reports of dissatisfaction,[13] which means there is room for improvement. Moreover, new procedures, such as presbyopic ablations,[14] have to be evaluated critically in terms of their performance, including quality of vision.

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The wavefront error reflects the major optical properties of the eye. Although the impact on visual performance is not fully understood, wavefront-error data have been extensively used as objective parameters for quality of vision in theoretical models and in clinical trials.[6,7,14–19] Given the objectivity and reliability of wavefront-error measurements[20,21] and the simplicity of performing them in a clinical environment, it is desirable to establish robust and clinically meaningful correlations between the results of wavefront analysis and subjective quality-of-vision ratings. This could prevent the need for time-consuming psychophysical tests to assess quality of vision and could strengthen the clinical significance of wavefront analysis. Although measurements can be obtained easily, their interpretation is more difficult. Many metrics qualitatively describe the degree of wavefront distortion or qualitatively predict retinal-image quality.[22–25] The few studies that have evaluated optical-quality metrics by correlating them with psychophysical test results[22,26–28] found high variability of the predictive value between different metrics.

The present prospective study compared the ability of different wavefront-derived image-quality metrics to predict the subjective quality of vision after LASIK for myopia. The subjective quality of vision after LASIK under different lighting conditions (photopic, high mesopic, low mesopic) was assessed using a questionnaire, and linear regression analysis was applied to compare the predictive ability of the metrics. The role of variation in pupil diameter in the patient cohort was examined by performing regression analysis with wavefront data calculated for a standardized pupil diameter (6.0 mm) and for individual physiological mesopic pupil diameters obtained at 0.4 lux.

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From the Department of Ophthalmology (Bühren, Martin), University of Rochester Medical Center, and the Center for Visual Science (Yoon), University of Rochester, Rochester, New York, and the Cullen Eye Institute (Kohnen), Baylor College of Medicine, Houston, Texas, USA; the Department of Ophthalmology (Bühren, Strenger, Kohnen), Johann Wolfgang Goethe-University, Frankfurt am Main, Germany; and the National Health and Medical Research Council Centre for Clinical Eye Research (Pesudovs), Flinders Medical Centre, Flinders University, Bedford Park, Australia.

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Corresponding author: Jens Bühren, MD, Refractive Surgery Study Group, Department of Ophthalmology, Johann Wolfgang Goethe University, Theodor-Stern-Kai 7, D-60590 Frankfurt am Main, Germany. E-mail: buehren@em.uni-frankfurt.de.

PATIENTS AND METHODS

Patient Selection

This prospective cross-sectional study comprised patients who had uneventful myopic LASIK aiming at emmetropia and patients with symptomatic eyes after LASIK. The symptomatic patients had LASIK for myopia elsewhere and presented at Department of Ophthalmology, Goethe University, for topography-guided retreatment. This group was included to obtain a larger range of subjective quality-of-vision data from patients who were satisfied and patients who were less satisfied with their subjective quality of vision. All study procedures followed the tenets of the Declaration of Helsinki. All patients were informed about the surgical procedure and the nature of the study and provided written consent.

In addition to the indication for myopic wavefront-guided LASIK aiming at emmetropia or topography-guided LASIK retreatment, inclusion criteria were consent and ability to participate in additional examinations for study purposes. Patients with previous ocular disease that could interfere with visual function, postoperative anatomical anomalies that would most likely affect optical quality (eg, dry eye, flap striae, haze), or psychiatric conditions and those not able to speak German or English were not included. As described elsewhere,[6,29] a comprehensive clinical examination was performed preoperatively to reveal potential contraindications to myopic LASIK or topography-guided LASIK retreatment.

Patients received a questionnaire on subjective quality of vision and had aberrometry preoperatively and postoperatively. For this study, only the results obtained 1 month postoperatively in the wavefront-guided LASIK group and before retreatment in the symptomatic group were analyzed.

Surgical Technique

In preparation for wavefront-guided LASIK, aberrometry was performed with a Hartmann-Shack wavefront sensor (Zywave, Bausch & Lomb/Technolas) under maximum mydriasis. The optical zone diameters were based on the mesopic pupil diameter measured at 0.4 lux using an infrared pupillometer (Procyon Instruments Ltd./Haag-Streit). The expected ablation depth was provided by the laser software, and corneal pachymetry was measured with an ultrasound pachymeter (SP-3000, Tomey).

The flap was created with a Hansatome microkeratome (Zyoptix XP, Bausch & Lomb) with a 160 μm head and 9.5 mm ring or with a femtosecond laser (IntraLase, IntraLase Corp.). Tissue ablation was performed with the Technolas 217z excimer laser (Bausch & Lomb/Technolas) using a conventional profile (PlanoScan V4.14), an aspheric profile (TissueSave aspheric), or a wavefront-guided ablation algorithm (Zyoptix V3.21) in 23 eyes.

Postoperative standard medication consisted of ofloxacin eyedrops (Floxal), fluorometholone eyedrops (Efflumidex), and artificial tears (Cellufresh). Routine visits were scheduled for 1 day, 1 week, and 1 month postoperatively.

Questionnaire

Patients were asked to estimate their overall subjective optical quality on a 6-item questionnaire written in German and English. This instrument has been described in detail.[30]

For this study, the 5 questions evaluating the frequency and intensity of symptoms were not analyzed. In a sixth question, the patient was asked to judge his or her overall optical quality (0 points = perfect; 100 points = extremely bad). The questions were answered separately for the right eye and left eye and for 3 luminance conditions, which were referred to as follows: "bright light; eg, in sunlight, outdoors, or under optimal workplace illumination" (referred to as photopic conditions henceforth), "normal light (intermediate brightness); eg, at your workplace or indoors" (high-mesopic conditions), and "in dim light; eg, in twilight or at night" (low-mesopic conditions).

Before answering the questions, the concept of quality of vision was explained comprehensively to the patients orally and on the questionnaire's instruction sheet. This was done to forestall false judgment by the patients (eg, patients mistakenly considering dry-eye problems relevant to subjective quality of vision). Points on the visual analog scale were represented using a ruler. This led to 101 possible scores along the scale. However, people cannot conceptualize 101 levels of overall optical quality or differentiate between them. Thus, portraying the scores using a linear scale, such as a ruler, will introduce nonlinearity and noise into the measurement. This problem can be avoided using Rasch analysis. Rasch analysis is a form of item-response theory that assumes that the probability of a respondent affirming an item is a logistic function of the relative distance between the item location and the respondent's choice of location on a linear scale. Hence, it is anticipated that the probability of endorsing a particular category will increase monotonically with the difference between the respondent's level of subjective quality of vision and the level of subjective quality of vision required for the item. Where the data meet the Rasch model expectations, a transformation of the ordinal raw score into a linear scale is achieved.[31,32]

Rasch analysis has been extensively used in ophthalmology for developing quality-of-life questionnaires[33] or revising existing instruments.[34] For the latter, the need to reduce the number of response categories is common and can result in noise reduction with concomitant improved power for testing significant differences or correlations.[35] It has been shown that people typically interpret visual analog scales as having a limited number of categories—as few as 4 or 5.[36] The data were assessed for fit to the Rasch model using Winstep software (version 3.63.2, Linacre[31]) and the Andrich[32] version of Rasch model estimates based on joint maximum-likelihood estimation. The 3 quality-of-vision items for the 3 lighting conditions were included in a single Andrich rating scale analysis, with estimates generated for each item. These items were functional when the data were collapsed into 11 response categories. Results are reported in logits, where 0 is the mean person value, a positive logit indicates poor subjective quality of vision, and a negative logit indicates better subjective quality of vision.

Pupillometry

All patients had digital infrared pupillometry using the Procyon pupillometer. This device has been described in detail.[37] Briefly, a 10-frame video sequence of both anterior eye segments was recorded bilaterally under 3 standardized illuminance levels (0.04 lux, 0.40 lux, and 4.00 lux). Pupil diameters were calculated automatically based on the average pupil diameter in the sequence.

Postoperative Wavefront Analysis

Aberrometry was performed under mydriasis using the same aberrometer as preoperatively. Wavefront errors were reconstructed using Zernike polynomials from the 2nd to the 5th order following the VSIA standards[38] for reporting aberration data of the eye. To determine whether reconstruction of wavefront errors for physiological conditions could increase correlation with subjective quality-of-vision scores, wavefront errors were reconstructed for a standard pupil diameter of 6.0 mm and for the individual pupil diameter obtained with the pupillometer at 0.4 lux (high-mesopic setting).

Outcome Measures and Statistics

One main outcome measure was the questionnaire scores; that is, the postoperative overall subjective quality of vision scores obtained separately for right eyes and left eyes and under 3 lighting conditions (photopic, high mesopic, low mesopic).

Another outcome measure was wavefront parameters. For postoperative wavefront aberrations, 2 categories of retinal image-quality metrics were chosen. The first was the visual Strehl ratio based on the optical transfer function (VSOTF), which has been shown to be 1 of the single-value metrics that can adequately predict visual performance and subjective best focus.[22,25] The VSOTF is the ratio of the area under the contrast sensitivity–weighted optical transfer function to the area under the contrast sensitivity–weighted optical transfer function of the diffraction-limited eye.[23,39] The contrast sensitivity weighting of the optical transfer function mimics the sensitivity of the human visual system to different spatial frequencies.[40] The VSOTF was calculated for the total wavefront error, including lower-order aberrations (LOAs) and higher-order aberrations (HOAs) (ie, the uncorrected VSOTF [UCVSOTF]), and for the combination of LOAs that provided the best VSOTF value (best-corrected VSOTF [BCVSOTF]). The BCVSOTF simulates the best possible image quality with spectacle correction (subjective refraction endpoint). All VSOTF calculations were performed using Visual Optics Lab (VOL)-Pro 7.14 (Sarver and Associates).

The second wavefront category was the root-mean-square (RMS) values of the wavefront error, which have been used as an image-quality metric for a long time. The total RMS includes Zernike coefficients of the 2nd to 5th order and is a quantitative wavefront-error representation of the uncorrected eye. The total HOA RMS value represents the HOAs (3rd to 5th order). In addition to these 2 values, a more qualitative approach was used by breaking down the wavefront error into 4 values: (1) coma RMS; that is, the RMS value of all coma terms $C(n, \pm 1)$; (2) spherical aberration; that is, the coefficient $C(4,0)$, and the RMS of the residual non-coma, nonspherical aberrations; that is, rHOAs, the RMS value of all remaining HOAs $C(n, \geq 2)$. Based on its components, this simplified breakdown was called LCSR RMS.

The VSOTF and RMS values were calculated for a standardized pupil diameter of 6.0 mm and an individual mesopic pupil diameter measured at 0.4 lux. Differences between the 2 wavefront-error reconstructions were checked with a paired Wilcoxon test for each parameter. To assess possible correlations between subjective quality-of-vision scores obtained under the different lighting conditions, a Pearson matrix was built. Linear regression analysis was used to evaluate the ability of each wavefront-error representation (logarithm of VSOTF and RMS values) to predict subjective quality-of-vision scores. Thus, the subjective quality-of-vision scores were the dependent in each model, while the wavefront parameters were the predictors. For each metric and for each lighting condition, a separate model was computed, including partial standardized regression coefficients (β) and P values for each factor. For final analysis, β values of factors of significant influence and coefficients of determination (r^2) were compared. All statistical analyses were performed using SPSS software (version 11.0, SPSS, Inc.).

RESULTS

Demographics and General Results

This study evaluated 56 eyes of 29 patients. Twenty-six patients (51 eyes) had uneventful myopic LASIK, and 3 patients (5 eyes) had retreatment for post-LASIK symptoms. The flap was created with a microkeratome in 46 eyes and with a femtosecond laser in 10 eyes. Tissue ablation was performed using a conventional profile in 8 eyes, an aspheric profile in 16 eyes, and a wavefront-guided ablation algorithm in 23 eyes.

Table 1 shows the patients' demographic and clinical data including preoperative and postoperative refraction. Figure 1 shows the distribution of pupil diameters under different lighting conditions. No patient in the primary LASIK group had intraoperative or postoperative complications.

Table 1. Patient demographics.

Parameter	Value
SE (D)	
Preoperative	
Median	−4.88
Range	−1.63 to −8.75
Postoperative	
Median	−0.25
Range	−1.25 to +2.13
Sphere (D)	
Preoperative	
Median	−4.25
Range	−8.00 to −0.75
Postoperative	
Median	0
Range	−1.00 to +2.50
Cylinder (D)	
Preoperative	
Median	−0.75
Range	−4.00 to 0.75
Postoperative	
Median	−0.50
Range	−1.50 to 0.00
Age (y)	
Median	36.5
Range	24 to 55
Programmed OZ (mm)	
Median	6.5
Range	6.0 to 7.0
Pupil diameter (mm)	
At 0.04 lux	
Median	6.6
Range	5.4 to 8.4
At 0.40 lux	
Median	5.7
Range	4.2 to 6.3
At 4.00 lux	
Median	4.1
Range	3.2 to 5.9

OZ = optical zone; SE = spherical equivalent

Questionnaire: Overall Subjective Optical Quality

The median postoperative Rasch-transformed optical quality was −7.34 (range −10.41 to 6.36) under photopic conditions, −7.54 (range −10.61 to 8.04) under high-mesopic conditions, and −5.08 (range −13.3 to 7.51) under low-mesopic conditions (Figure 2). Pearson correlation analysis showed a high correlation between the scores (photopic and high mesopic: $r = 0.86$, $P < .001$; photopic and low mesopic: $r = 0.83$, $P < .001$; high mesopic and low mesopic: $r = 0.85$, $P < .001$).

Wavefront Data

The median postoperative VSOTF for the uncorrected eye (log UCVSOTF) calculated for a 6.0 mm pupil diameter was −1.42, and the median log UCVSOTF for a physiological pupil diameter at 0.4 lux was −1.28 ($P < .05$, paired Wilcoxon test) (Figure 3). The medians for the best-corrected eye (log BCVSOTF) were −1.01 and −0.88, respectively ($P < .01$). The total RMS of the wavefront error was 1.007 μm (0.873 μm with a physiological pupil diameter; $P < .01$) and the HOA RMS was 0.591 μm (0.437 μm with a physiological pupil diameter; $P < .05$). The LCSR RMS data and the range and distribution of the values are shown in Table 2 and Figure 4.

Multiple Regression Analysis

In general, the predictive ability of all metrics was limited and did not show large discrepancies between the 3 lighting conditions (Tables 3 and 4). The BCVSOTF calculated for a 6.0 mm pupil diameter best predicted the subjective quality-of-vision scores (minimum $r^2 = 0.16$, maximum $r^2 = 0.24$), followed by LCSR RMS (minimum $r^2 = 0.09$, maximum $r^2 = 0.19$), total RMS (minimum $r^2 = 0.10$, maximum $r^2 = 0.17$), and the UCVSOTF (minimum $r^2 = 0.06$, maximum $r^2 = 0.16$). The HOA RMS values had the lowest predictive ability (minimum $r^2 = 0.08$, maximum $r^2 = 0.09$). In the multifactorial model

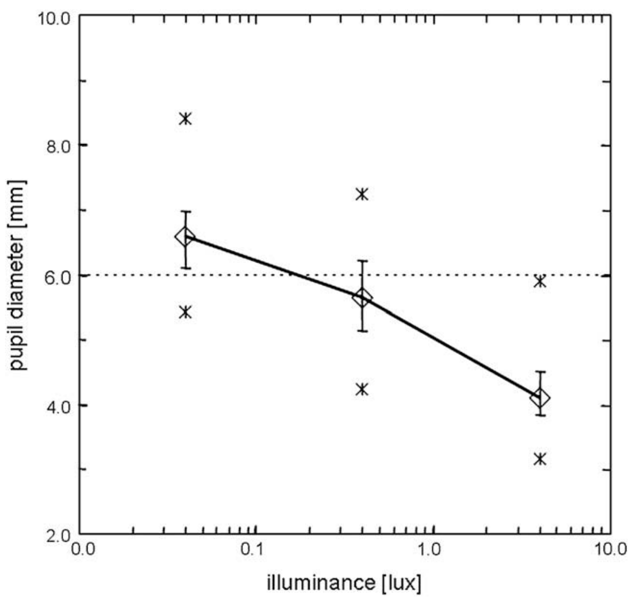

Figure 1. Nonparametric line plot showing the median pupil diameter as a function of luminance. The diamonds represent the medians; the whiskers, first and third percentiles; the asterisks, the minimum and maximum values; and the dotted line, the 6.0 mm pupil diameter.

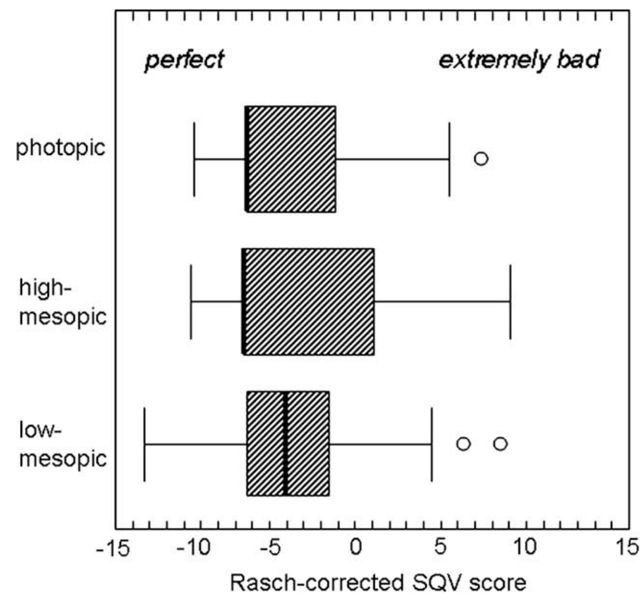

Figure 2. Box-plot diagram showing the distribution of Rasch-corrected subjective quality-of-vision questionnaire scores (SQV = subjective quality of vision).

with the LCSR RMS values, LOA RMS was a significant predictor under all lighting conditions, being the sole factor under photopic and high-mesopic conditions. Under low-mesopic conditions, coma RMS predicted subjective quality of vision significantly (Table 3). Calculation of wavefront errors for a physiological mesopic pupil diameter did not improve the predictive ability of any metric. Only UCVSOTF and LCSR RMS values showed a significant, albeit weak, predictive ability, with a tendency toward r^2 values decreasing with the lighting condition (Table 4). For the LCSR RMS representation, primary spherical aberration Z(4,0), in addition to LOA RMS, remained a significant predictor in both models.

DISCUSSION

The present study had 4 key findings. First, subjective quality of vision in eyes with a high retinal-image quality, expressed by the VSOTF metric or by RMS values, was always rated high by the patients (Figure 5). In other words, a high theoretical optical quality yielded good subjective quality of vision. Eyes for which subjective quality of vision was rated low also had a low theoretical optical quality. Conversely, a low theoretical optical quality was not always associated with a low subjective quality of vision. These findings suggest that there are different individual tolerance thresholds for wavefront aberrations, causing visual disturbances or simply "bad vision." Potential reasons are different benchmarks and expectations of the patients, as shown by Tuan.[12] These results confirm those in our preliminary study[30] and imply that post-LASIK wavefront

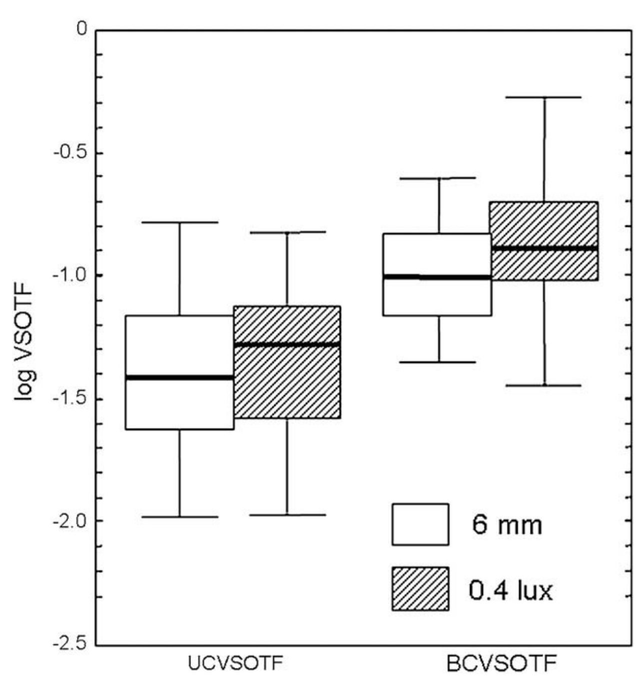

Figure 3. Box-plot diagram showing the distribution of the VSOTF visual-quality metric for a 6.0 mm pupil diameter (*white boxes*) and a physiological mesopic pupil diameter at 0.4 lux (*hatched boxes*) (BCVSOTF = simulation for best-corrected eye; UCVSOTF = simulation for uncorrected eye; VSOTF = visual Strehl ratio based on optical transfer function).

Table 2. Postoperative image-quality metrics and RMS values of the wavefront error computed for a 6.0 mm pupil diameter and a physiological mesopic pupil diameter (0.4 lux).

	Pupil Diameter	
Metric	6.0 mm	Physiological Mesopic
Log UCVSOTF		
Median	−1.42	−1.28*
Range	−1.98 to −0.79	−0.83 to −1.98
Log BCVSOTF		
Median	−1.01	−0.88†
Range	−1.35 to −0.61	−1.45 to −0.28
Total RMS (μm)		
Median	1.007	0.873†
Range	0.353 to 3.282	0.328 to 3.350
HOA RMS (μm)		
Median	0.591	0.437*
Range	0.271 to 1.067	0.110 to 1.518
LOA RMS (μm)		
Median	0.842	0.688*
Range	0.174 to 3.214	0.157 to 3.269
Coma RMS (μm)		
Median	0.290	0.236‡
Range	0.086 to 0.874	0.044 to 0.938
C(4,0) (μm)		
Median	0.331	0.274‡
Range	−0.016 to 0.724	−0.022 to 0.872
Residual HOA RMS (μm)		
Median	0.259	0.184
Range	0.071 to 0.890	0.047 to 1.358

BCVSOTF = visual Strehl ratio, based on the optical transfer function (simulation for best spectacle correction); C(4,0) = spherical aberration coefficient; Coma RMS = root mean square of 3rd- to 5th-order coma terms; HOA RMS = higher-order aberration root mean square of 3rd- to 5th-order aberrations; Residual HOA RMS = root mean square of all non-coma, nonspherical higher-order aberrations; Total RMS = root mean square of 2nd- to 5th-order aberrations; UCVSOTF = visual Strehl ratio based on the optical transfer function (uncorrected eye)
*$P < .05$, 6.0 mm pupil versus physiological pupil (paired Wilcoxon test)
†$P < .01$, 6.0 mm pupil versus physiological pupil (paired Wilcoxon test)
‡$P < .001$, 6.0 mm pupil versus physiological pupil (paired Wilcoxon test)

aberrations should be kept as low as possible to yield a high subjective quality of vision. In the preliminary study, we found that in addition to coma-like aberrations, LOAs play an important role in postoperative subjective quality of vision. In the present study, the dominance of LOAs was reflected by the results of the multiple regression analysis using the LCSR wavefront representation.

The finding that eyes with low subjective quality of vision also had low retinal-image quality and that no eye with high retinal-image quality had low subjective quality of vision suggests that after otherwise uneventful LASIK, bad subjective quality of vision is primarily caused by optical aberrations rather than by other optical phenomena, namely scatter. The role of scatter in visual function after LASIK has also been questioned in recent studies, which found that psychophysically measured straylight scores did not change with the procedure[41] and that disability glare (glare-induced loss of contrast sensitivity[42]) did not influence subjective quality of vision (unpublished data). However, that preexisting straylight (eg, from the crystalline lens) or structural post-LASIK anomalies (eg, folds, striae, snowflakes, dry eye) might affect subjective quality of vision cannot be ruled out. Thus, the contribution of straylight to subjective quality of vision in post-LASIK eyes remains to be determined. One possible limitation is that different treatment profiles were used. However, the effects of wavefront aberrations should be the same, independent of the profile used.

The second key finding was that, in general, the ability of wavefront-derived metrics to predict subjective quality of vision was limited, ranging from 0% to 24% (BCVSOTF, 6.0 mm pupil) of the variance in the reported subjective quality of vision. In preliminary experiments, we studied additional metrics but decided to report only the relevant ones to maintain clarity. Therefore, we chose to focus on the VSOTF, which yielded reasonable results in previous studies,[25,30,39] and HOA and LOA RMS wavefront errors, which are commonly used as image-quality metrics. In addition, we tested a simplified wavefront-error representation, referred to as LCSR RMS, which breaks down the wavefront error into LOA RMS, coma RMS, spherical aberration, and residual HOA RMS (RMS of Zernike terms with a frequency ≥ 2). The subjective quality-of-vision scores were highly skewed toward good values, whereas the VSOTF and HOA RMS values were symmetrically distributed. Only the RMS values including LOA data (LOAs and total RMS) had a similarly skewed distribution. Individual tolerance thresholds to aberration effects are an important reason for the limited predictive ability of wavefront-derived metrics, as mentioned at the beginning of the Discussion. The low predictive ability of the popular HOA RMS metric could be explained by its quantitative nature; that is, it does not respect aberration interaction effects.[43] Moreover, looking at the HOA RMS alone disregards the effects of LOAs on subjective quality of vision, which is supported by higher r^2 values for the total RMS value and the LCSR RMS representation. With this in mind, it was puzzling that the VSOTF was more predictive if computed for the best-corrected state with a 6.0 mm pupil diameter (BCVSOTF) than for the uncorrected eye (UCVSOTF). Although LOAs seem to play an important role in postoperative subjective quality of vision, both quantitatively and qualitatively,[12,30] it is likely that there is higher interindividual variability

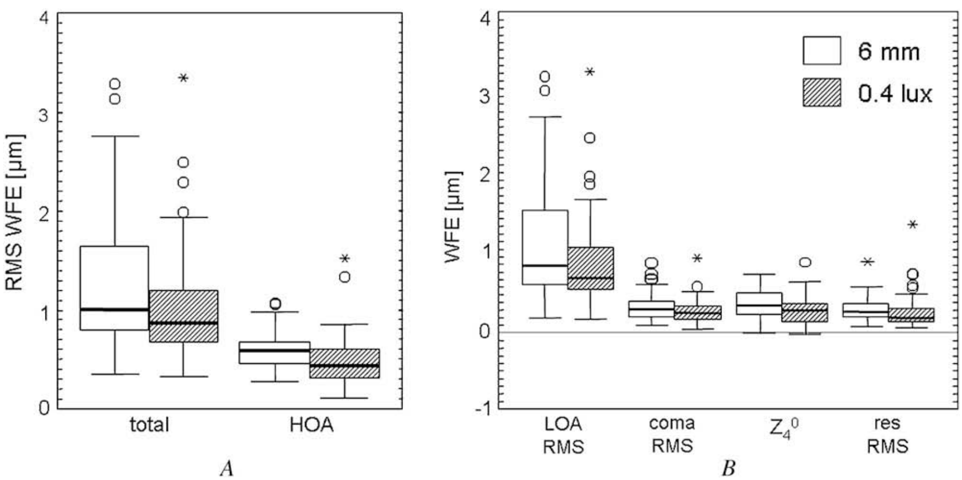

Figure 4. Box-plot diagrams showing the distribution of RMS values of the wavefront error for a 6.0 mm pupil diameter (*white boxes*) and a physiological mesopic pupil diameter at 0.4 lux (*hatched boxes*). *A*: Total RMS from 2nd to 5th orders and HOA RMS from 3rd to 5th orders. *B*: The LCSR representation comprising the LOA RMS, which is the RMS of 2nd-order aberrations; the coma RMS, which is the RMS of all coma terms Z(n,±1); Z_4^0, which is the primary spherical aberration; and the residual HOA RMS, which is the RMS of all remaining Z(n,≥2) terms (HOA = higher-order aberration; LOA = lower-order aberration; res = residual; RMS = root mean square; WFE = wavefront error).

of tolerance against defocus or astigmatic blur as opposed to HOA-induced image distortion. This leads to possible over-representation of LOA effects in the UCVSOTF value and could explain the high rating of subjective quality of vision in some cases of low retinal-image quality (relative low effect of LOA blur) and the relatively low subjective quality-of-vision rating in single cases (relative high effect of HOA image distortion). This hypothesis is supported by a finding in our preliminary study[30] that showed a very low tolerance against 5th-order aberrations (high impact of secondary coma on subjective quality of vision).

The third key finding was that calculation of metrics for an individual physiological mesopic pupil diameter did not improve the predictive ability of wavefront-derived metrics. One question that arose in our previous study[30] was whether taking the variance of pupil diameters across the patient collective into account by wavefront-error reconstruction for an individual physiologic mesopic pupil diameter would increase the ability of wavefront-derived metrics to predict subjective quality of vision. Although suggested in another study,[44] this practice did not increase the r^2 value of any of our regression models. In contrast, only the UCVSOTF and LCSR RMS were significantly correlated with subjective quality of vision. It is likely that the variance added by the calculation of individual pupil diameters rather than a standard 6.0 mm pupil diameter led to a drop rather than an increase in r^2. Moreover, the 6.0 mm pupil diameter probably contains more wavefront information than the mostly smaller physiological pupil diameter obtained at 0.4 lux.

The fourth key finding was that subjective quality-of-vision scores under different lighting conditions were highly correlated. Comparison of the r^2 values of the regression models showed that the predictive ability was similar under the 3 lighting conditions, although the model was based on wavefront-error data calculated for a 6.0 mm pupil. In fact, the subjective quality-of-vision scores were highly correlated. This correlation could be the result of the limitation that the lighting conditions were only verbally explained to patients in the questionnaire and the patients were not exposed to each specific condition, leading to an overlap between conditions. However, this finding requires further evaluation in an in-depth analysis to distinguish possible interactions between the conditions. Patients who have poor subjective quality of vision under 1 condition are likely to judge their subjective quality of vision as bad under other conditions as well. Moreover, the method for determining subjective quality of vision relied on the patient's memory, was highly subjective, and contained noise. The noise issue was addressed by Rasch transformation. The goal of the study was to assess the value of wavefront metrics in predicting subjective quality of vision based on what the patient remembered the quality to be. This highly subjective judgment is the internal reference for patients, not only when communicating with their physicians but also for personal assessment. Patient memory is likely based on the binocular perception, leading to a confounding effect, and is a potential limitation of our study.

These wavefront metrics have been shown to be highly correlated with visual-performance measures and are thus robust measures.[22–25] The poor correlations seen in our study probably illustrate a limited relationship between subjective quality of vision and optical metrics; they may also indicate a limitation

Table 3. Regression analysis for image-quality metrics computed for a 6.0 mm pupil diameter. Only significant predictors are shown.

Metric/Lighting Condition	r^2 (Adjusted)	β
Log UCVSOTF		
Photopic	0.16	−0.42*
High mesopic	0.06	−0.27*
Low mesopic	0.09	−0.33†
Log BCVSOTF		
Photopic	0.19	−0.45‡
High mesopic	0.16	−0.42*
Low mesopic	0.24	−0.50‡
Total RMS		
Photopic	0.17	0.43‡
High mesopic	0.10	0.34*
Low mesopic	0.14	0.39*
HOA RMS		
Photopic	0.10	0.34†
High mesopic	0.09	0.32†
Low mesopic	0.10	0.34†
LCSR RMS		
Photopic	0.16	0.42*,§
High mesopic	0.09	0.32†,§
Low mesopic	0.19	0.30†,§
		0.28†,¶

β = standardized partial regression coefficient; BCVSOTF = visual Strehl ratio, based on the optical transfer function (simulation for best spectacle correction); HOA RMS = higher-order aberration root mean square of 3rd- to 5th-order aberrations; LCSR RMS = lower-order aberration root mean square, coma root mean square, C_4^0 coefficient, and residual higher-order aberration root mean square; r^2 = coefficient of determination, adjusted for sample size; Total RMS = root mean square of 2nd- to 5th-order aberrations; UCVSOTF = visual Strehl ratio based on the optical transfer function (uncorrected eye)
*$P < .05$
†$P < .01$
‡$P < .001$
§Lower-order aberration root mean square
¶Coma

Table 4. Regression analysis for image-quality metrics computed for a physiological mesopic (0.4 lux) pupil diameter. Only significant predictors are shown.

Metric/Lighting Condition	r^2 (Adjusted)	β
Log UCVSOTF		
Photopic	0.13	−0.38*
High mesopic	0.08	−0.31†
Low mesopic	0.06	−0.28†
LCSR RMS		
Photopic	0.10	0.33†,‡
		−0.31†,§
High mesopic	0.08	0.28†,‡
		−0.30†,§

β = standardized partial regression coefficient; LCSR RMS = lower-order aberration root mean square, coma root mean square, C_4^0 coefficient, and residual higher-order aberration root mean square; r^2 = coefficient of determination, adjusted for sample size; Total RMS = root mean square of 2nd- to 5th-order aberrations; UCVSOTF = visual Strehl ratio based on the optical transfer function (uncorrected eye)
*$P < .01$, 6.0 mm pupil versus physiological pupil (paired Wilcoxon test)
†$P < .05$, 6.0 mm pupil versus physiological pupil (paired Wilcoxon test)
‡Lower-order aberration root mean square
§Z_4^0

of subjective measurement. By nature, subjective assessments contain noise, and although Rasch analysis can remove some of the noise, a remainder is inherent in the question. In this case, a scale of 0 to 100 was shown to actually represent only 11 levels of subjective quality of vision. More robust data might have been collected by using a shorter scale. Certainly, better subjective quality-of-vision instruments must be developed, and these may improve the relationship with optical variables.

Regarding the implications for clinical practice, the results in this study suggest that postoperative retinal image quality should be kept as high as possible (ie, aberrations should be kept as low as possible) to produce good subjective quality of vision. In particular, residual refractive error and coma were responsible for low ratings of subjective quality of vision. In the study, calculation of individual physiological wavefront errors did not add an advantage over calculation using a standard pupil diameter (eg, 6.0 mm). Moreover, a complex metric, such as the VSOTF, gave better results than the popular HOA RMS value. Breaking down the wavefront error into subcomponents (eg, LCSR RMS) could improve qualitative description of the wavefront error.

Finally, that subjective quality of vision assessed by the questionnaire used in this study is a complex construct that is dependent on many variables. The low r^2 values reflect the difficulty in predicting such a construct with a single-value metric that itself is meant to represent the complex information about the optical properties of the eye. The use of standardized tasks (eg, a reading or driving task under different lighting conditions) or a standard sharpness or blur reference to indicate good subjective quality of vision (eg, a view through a pinhole or an adaptive optics system[27]) could determine more clearly the role of optics in subjective quality of vision. Although desirable from a scientific standpoint, those experimental procedures do not reflect the everyday quality of vision the patients experience and report to their physicians. Hence, quality of vision remains a multidimensional phenomenon with common underlying biological and physical phenomena, leading to similar, yet interindividually different, results.

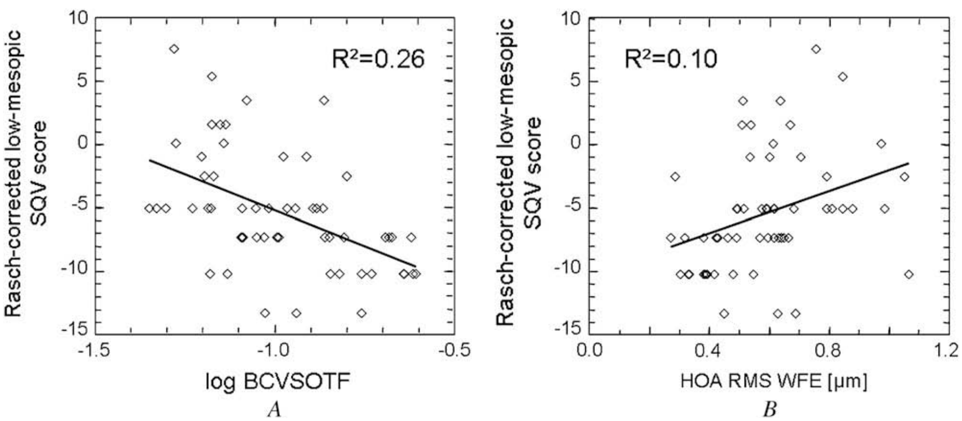

Figure 5. Scatterplot diagrams showing subjective quality of vision under low-mesopic conditions as a function of retinal image quality (6.0 mm pupil). *A*: Visual Strehl ratio, based on the optical transfer function, simulation for the best-corrected eye (log BCVSOTF). *B*: The HOA RMS values for the 3rd to 5th orders (HOA = higher-order aberration; LOA = lower-order aberration; RMS = root mean square; SQV = subjective quality of vision; WFE = wavefront error).

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First author:
Jens Bühren, MD

Department of Ophthalmology, Goethe University, Frankfurt am Main, Germany