Myopia is increasing in prevalence throughout the world, affecting hundreds of millions of people, and uncorrected myopia is the worldwide leading cause of vision impairment. Different options for correcting myopia exist: spectacles and contact lenses are conservative methods of choice, but several refractive surgical procedures have been developed over the years; the most recently developed corneal refractive procedure, small-incision lenticule extraction (SMILE), has been performed at our department since 2011 and has proved to be a highly predictable, safe, and efficient treatment of high myopia. Similar to other refractive procedures, however, SMILE has been shown to surgically induce higher-order aberrations (HOAs) with potential detrimental consequences for patients’ optical quality and subjective satisfaction although the impact of HOAs on visual performance is not straightforward. Several studies have shown that HOAs interact in a complex manner because each individual aberration impacts visual quality differently and interacts with other aberrations. Furthermore, the typically cited root mean square (RMS) values of HOAs experience the same shortcomings in the sense that RMS are not necessarily well correlated with measures of visual performance. Following these observations, visual image quality metrics were developed to include not only the complex interaction between HOAs but also the neural processing of the visual system to provide a complete description of the optical quality of the eye. The logarithm of one of these visual image quality metrics known as the visual Strehl ratio (logVSX) has been proved to be well correlated with change in visual acuity independent of underlying pupil size and wavefront error.

Purpose: To assess the influence of small-incision lenticule extraction (SMILE) for high myopia on the visual image quality assessed by the logarithm of the visual Strehl ratio (logVSX) and put this into a clinical context by pairwise comparing the logVSX of postoperative eyes with those of myopic controls wearing spectacles and/or contact lenses.

Setting: University hospital.

Design: Prospective and cross-sectional clinical study.

Methods: Patients with a myopic spherical equivalent of at least 6.00 diopters treated with SMILE aimed at emmetropia and correspondingly myopic controls corrected with spectacles and/or contact lenses were included. The logVSX calculation was divided into habitual logVSX based on the wavefront aberration measurement directly and optimal logVSX calculated in a theoretical through-focus experiment to obtain the best-achievable logVSX.

Results: A total of 117 eyes of 61 patients and 64 eyes of 34 myopic controls were included. SMILE did not affect the habitual logVSX but worsened the optimal logVSX ($P < .001$). The postoperative habitual logVSX was statistically significantly worse compared with contact lenses ($P = .002$). The postoperative optimal logVSX was significantly worse compared with both spectacles ($P < .01$) and contact lenses ($P = .003$). There was no statistically significant difference in habitual or optimal logVSX between spectacles and contact lenses.

Conclusions: SMILE for high myopia does not affect the habitual logVSX but decreases the optimal logVSX slightly. The postoperative habitual logVSX is worse than for contact lenses but not for spectacles, and the postoperative optimal logVSX is worse than for both contact lenses and spectacles. There is no statistically significant difference in either habitual or optimal logVSX between spectacles and contact lenses.

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being predictive of subjective best focus, able to identify an optimal refraction (ie, a spherocylindrical correction), and useful for correcting highly aberrated eyes with custom made wavefront-guided contact lenses.\textsuperscript{14–15}

The outcome of a refractive correction needs to be assessed through the resultant visual image quality by a relevant metric, for example the logVSX, which is highly correlated to visual performance such as visual acuity; this is not achieved through the use of metrics such as RMS.\textsuperscript{15}

However, to our knowledge, no study has of yet sought to ascertain the impact of SMILE for high myopia on the objectively calculated visual image quality.

A recent article published reference ranges for VSX for experimentally optimally corrected eyes as a function of age; this study adds a detailed description on the habitual values of VSX for highly myopic subjects corrected with either spectacles or contact lenses.\textsuperscript{16} A high visual quality should be considered the goal of a correction, so it is important to establish how the methods of correcting myopia affect the visual image quality; the resultant visual image quality from a correction is important for patient satisfaction.\textsuperscript{17}

The purpose of this study was to assess the influence of SMILE on visual acuity on the visual image quality assessed by VSX and put this into a clinical context by comparing the postoperative result with values seen among similarly myopic controls corrected with spectacles or contact lenses. Thus, the specific purpose of this study was to: (1) investigate the influence of SMILE on VSX for eyes with a spherical equivalent of at least 6.00 diopters (D) of myopia, (2) compare the postoperative VSX with the VSX seen in control myopic eyes corrected with either spectacles or contact lenses, and (3) compare the VSX between the control myopic eyes corrected with either spectacles or contact lenses; the questions pertained to both the habitual VSX (ie, the VSX as it was measured directly for each condition) and the optimal VSX (the theoretically best-achievable VSX, calculated to see how much the VSX could theoretically improve).

**METHODS**

The study was conducted in agreement with the tenets of the Declaration of Helsinki, and all patients gave written consent before inclusion in the study. The Danish Protection Agency and the Ethical Committee of Central Region Denmark approved the study (case number 1-10-72-92-17).

This prospective study included patients treated with SMILE aimed at emmetropia; all patients received surgery at the Department of Ophthalmology, Aarhus University Hospital, Denmark, between February 2018 and November 2019. Myopic controls corrected with spectacles and/or contact lenses were included by referral from a private clinic of optometry (Kon- taktlinse Institutet and Buris Briller, Aarhus C, Denmark) after invitation during usual check-up from April 2018 to December 2019.

Inclusion criteria for patients scheduled for surgery were a stable refraction for at least 12 months, age at least 18 years, a myopic spherical equivalent of at least 6.00 D, and astigmatism or anisometropia no larger than 1.75 D. Exclusion criteria for the patients were other ocular pathology or pregnancy/breastfeeding.

Inclusion criteria for referred controls were equivalent to those pertaining to the SMILE patients in addition to a corrected distance visual acuity (CDVA) better than or equal to at least 0.1 logMAR and subjective satisfaction with the correction used. Exclusion criteria for the controls were any other ocular pathology or pregnancy/breastfeeding.

**Measurements of Visual Acuity and Contrast Sensitivity**

Patients treated with SMILE were examined by optometrists at the Department of Ophthalmology preoperatively and 3 months postoperatively; the assessments included slitlamp examination, CDVA, uncorrected distance visual acuity (UDVA) at the postsurgical visit, subjective and cycloplegic refraction at a vertex distance of 12 mm, high-resolution Scheimpflug corneal tomography (Pentacam HR; OCULUS Optikgeräte GmbH), and combined autorefracton and keratometry (Tonoref II, NIDEK Co., Ltd.).

Controls had their visual acuity measured before referral, their correction was refined, and a slitlamp was examination performed by optometrists at the private optometry clinic. On arrival at the Department of Ophthalmology (usually a few weeks after visit to the private clinic), the controls had examinations performed by the same examiner (A.G.); examinations included assessment of CDVA, high-resolution Scheimpflug corneal tomography, and combined autorefraction and keratometry with the above-specified instruments.

Visual acuity was, for all participants, measured with an electronic Early Treatment Diabetic Retinopathy Study (ETDRS) chart at a luminance of 260 cd/m\textsuperscript{2}, with each letter read counting for 0.02 logMAR. The termination rule was to stop after patients/controls made at least 3 mistakes on a given line on the ETDRS chart.\textsuperscript{19} The postoperative visual acuity corrected for the magnification effect of moving a myopic refraction from the spectacle plane to the corneal plane was performed as explained by Applegate and Howland.\textsuperscript{17}

Contrast sensitivity was recorded because high-contrast visual acuity can be normal despite degraded optics.\textsuperscript{20,21}

Contrast sensitivity was assessed for patients preoperatively and postoperatively and for all referred controls by the same examiner (A.G.) using the same room with constant light settings (drawn blackout curtain, closed door, and ceiling lights turned on); the illuminance at the level of the patient was around 250 lux (LX-1108 light meter, Lutron Electronic Enterprise Co., Ltd.). The contrast sensitivity test used was the Freiburg Acuity and Contrast Test (FrACT).\textsuperscript{3,22,23} This test functions as an 8-alternative forced-choice program and was displayed on the same electronic screen as the ETDRS visual charts at a luminance of 260 cd/m\textsuperscript{2}. The patient is presented with a Landolt C optotype of Snellen fraction 6/75 (testing around 2 to 3 cpl), which points in 1 of 8 possible directions on the screen. The patient is asked to point in the direction of the gap in the Landolt C, and the answer is reported on a directional keypad (in all cases, in this study, operated by the examiner). Depending on the patient’s answer (correct or incorrect), the program might subsequently change the position of the Landolt C as the contrast is varied according to best parameter estimation by sequential testing algorithm to determine the contrast threshold in Weber contrast units.\textsuperscript{2}

The final result reported represents the reciprocal of the contrast sensitivity, which was then converted to logCS (base 10).

Participants were told to take their time and that they had to answer, even when in doubt. Patients wore optimal correction using trial spectacles preoperatively for the contrast sensitivity testing and no prescription postoperatively; the controls wore their habitual prescription.

**Higher-Order Aberrations**

Ocular HOAs were measured with the wavefront aberration–supported cornea ablation (WASCA) analyzer (Carl Zeiss Meditec AG), a Hartmann-Shack aberrometer; the wavelength of the infrared laser was 835 nm, and chromatic aberration correction to 555 nm was used.
HOAs were recorded up to the sixth radial order using the Optical Society of America notation. All lights were turned off during measurement with the WASCA to ensure the largest possible pupils of the participants. The quality of the wavefront analysis was ensured by examining the number, regularity, and resolution of spots. Only measurements based on a pupil diameter of at least 5.0 mm were included in the study for analysis; measurements were performed under natural pupil conditions. Measurements above 5.0 mm in diameter were rescaled as described by Schwiegerling. A pupil diameter of 5.0 mm was chosen to reflect physiological pupil sizes for young adults in photopic conditions.

Individual terms of HOAs were also calculated in addition to VSX; individual HOAs were included because of clinical familiarity and comparison with resultant VSX values. Individual terms calculated were RMS total third-order coma, RMS total HOAs, and coefficients of third-order coma and fourth-order spherical aberration. Root mean square (RMS) values of total third-order coma were calculated as follows:

$$\text{RMS(coma)} = \sqrt{\left(Z_3^\text{psf}\right)^2 + \left(Z_3\right)^2}.$$  

RMS total HOAs were calculated in the same way using all coefficients from third to sixth orders. Coefficients of third-order horizontal and vertical coma and fourth-order spherical aberration were presented directly; because of the mirror symmetry between left and right eyes, the horizontal coma coefficient for left eyes was mirrored to make them comparable with that of right eyes.

### Visual Strehl Ratio

The VSX was calculated in the spatial domain for a wavelength of 555 nm using equation A23 from the study by Thibos et al.:

$$\text{VSX} = \frac{\int_{\text{psf}} \text{PSF}(x,y) N(x,y) \, dx \, dy}{\int_{\text{psf}} \text{PSFDL}(x,y) N(x,y) \, dx \, dy}.$$  

In brief, the formula compares the volume under the point-spread function (PSF) of an eye (calculated from the wavefront measurement) with the volume under the diffraction-limited PSF for the same pupil size; both these PSFs are then weighted by the inverse Fourier transform of the neural contrast sensitivity function determined with interference fringes. Hence, the VSX metric combines the measurement of the optics of the eye with the neural processing of the visual system. The VSX calculation yields a number ranging between 0 (worst) and 1 (best), and taking the base 10 logarithm means that a perfect valued VSX of 1 equals 0 logVSX and poorer values of VSX result in negative values of logVSX (the more negative, the worse).

The logVSX was calculated under 2 circumstances: the habitual logVSX (ie, the logVSX calculated based on the actual wavefront measured) and the optimal logVSX (theoretically best-achievable logVSX with sphero-cylindrical refraction). The habitual logVSX for the preoperative eyes was based on the uncorrected wavefront measurement but corrected mathematically as described by Hastings et al. with the subjective sphero-cylindrical refraction first vertexed to the entrance pupil plane, then converted into power vectors, and finally converted into corresponding corrections of the Zernike coefficients of the second order (ie, the defocus and astigmatism terms). For the postoperative eyes and eyes corrected with spectacles or contact lenses, the habitual logVSX were rescaled as described by Schwiegerling.

### Surgery

The SMILE technique has been described in detail elsewhere. In brief, a 500 kHz Visumax femtosecond laser (Carl Zeiss Meditec AG) was used with laser cut energy index at 25 and spot spacing of 4.2 μm to perform the surgery. The cap diameter was 7.3 mm, the cap thickness was 120 μm, and the lenticule diameter was between 6.0 and 6.5 mm with a transition zone between 0.0 mm and 0.1 mm. Two drops of oxybuprocaine hydrochloride 0.4% (Novesine 0.4, CIBA Vision Ophthalmics) was used for topical anesthesia. The lenticule was dissected with a blunt spatula and extracted through a 40-degree incision at the 12 o’clock position. Postoperative treatment consisted of tobramycin–dexamethasone (Tobradex, Alcon Laboratories, Inc.) eyedrops 4 times a day tapered over 2 weeks.

### Statistical Analysis

Both eyes of all participants were included when available; only eyes with a WASCA measurement based on a pupil diameter of 5.0 mm or greater were included for analysis. Statistical analyses were performed using Stata software (version 15, StataCorp), and calculation of VSX was performed using Matlab R2018b (The Mathworks, Inc.).

Sample size calculation relied first on reference values in HOAs and later on a recent article that gave reference values on logVSX for optimally corrected eyes. In the article by Hastings et al., it is seen that the average optimal logVSX for a person in the age range of 20 to 29 years or 30 to 39 years is $-0.377$ for a 5 mm pupil diameter, and going from either a 5 mm to a 6 mm pupil or jumping a decade (ie, going from the age range of 30 to 39 years to 40 to 49 years) corresponds to a deterioration in logVSX of about 0.1; hence, using the power calculation through a simple unpaired $t$ test (using only 1 eye from each participant), given a standard deviation in each group about 0.1, it would take 2 groups with each 17 participants to find a difference in logVSX of $-0.1$ with 80% power and $\alpha = 0.05$. Given that both eyes from each individual was included whenever possible, the power calculation performed in this study was made as a conservative estimate because including both eyes rather than just 1 typically results in higher statistical power. Data were assessed for normality using QQ-plots, histograms, box plots, and the Shapiro-Wilks test. To accommodate for the correlation between right and left eyes of individuals, mixed effects models were used to calculate $P$ values and differences in means between groups. In addition to being able to accommodate for correlated data, mixed effects models have the advantage that, for example, an eye only available for analysis preoperatively but not postoperatively will still be included in the analysis and further that a mix of paired and unpaired data can be included in the same model. Models were specified using restricted maximum likelihood fitting and included testing different residual variance structures (with likelihood ratio tests determining the final model); model validations were performed.
Table 1. Number of Patients and Eyes Treated With SMILE for High Myopia. a

<table>
<thead>
<tr>
<th>Eyes contributed</th>
<th>Patients</th>
<th>Total eyes, N</th>
<th>Eyes preop</th>
<th>Eyes postop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Preop/Postop</td>
<td>RE/LE</td>
<td>RE/LE</td>
</tr>
<tr>
<td>Both preop, postop (n)</td>
<td>30</td>
<td>60/60</td>
<td>30/30</td>
<td>30/30</td>
</tr>
<tr>
<td>Both preop (n)</td>
<td>10</td>
<td>20/0</td>
<td>10/10</td>
<td>0/0</td>
</tr>
<tr>
<td>Both postop (n)</td>
<td>5</td>
<td>0/10</td>
<td>0/0</td>
<td>5/5</td>
</tr>
<tr>
<td>Both preop, RE postop (n)</td>
<td>4</td>
<td>8/4</td>
<td>4/4</td>
<td>4/0</td>
</tr>
<tr>
<td>LE preop, both postop (n)</td>
<td>3</td>
<td>3/6</td>
<td>0/0</td>
<td>3/3</td>
</tr>
<tr>
<td>RE postop (n)</td>
<td>3</td>
<td>0/3</td>
<td>0/0</td>
<td>3/0</td>
</tr>
<tr>
<td>RE preop, both postop (n)</td>
<td>2</td>
<td>2/4</td>
<td>2/0</td>
<td>2/2</td>
</tr>
<tr>
<td>RE preop, postop (n)</td>
<td>2</td>
<td>2/2</td>
<td>2/0</td>
<td>2/0</td>
</tr>
<tr>
<td>RE preop, LE postop (n)</td>
<td>1</td>
<td>1/1</td>
<td>1/0</td>
<td>0/1</td>
</tr>
<tr>
<td>LE preop, RE postop (n)</td>
<td>1</td>
<td>1/1</td>
<td>0/1</td>
<td>1/0</td>
</tr>
<tr>
<td>Total</td>
<td>61</td>
<td>97/91</td>
<td>49/48</td>
<td>50/41</td>
</tr>
</tbody>
</table>

Both = both eyes; LE = left eye; postop = postoperative; preop = preoperative; RE = right eye

aOnly eyes with a wavefront-aberration supported corneal ablation measurement based on a pupil diameter ≥5.0 mm were included for analysis, which is why some patients contributed with only 1 eye or only preop or postop
bRepresented both preop and postop, 43 patients in total
b Represented only preop, 10 patients in total
b Represented only postop, 8 patients in total; 43 patients (38 right and 33 left eyes) were included in both the preop and postop group

by comparing observed and expected within-subject standard deviations and correlations and by inspecting QQ-plots.

Means are given as a summary data of both right and left eyes unless specified otherwise, and total standard deviations representing differences between eyes between participants are reported. The Pearson correlation coefficient was used to evaluate correlations between variables (only right eyes were used). A P value less than 0.05 was considered statistically significant.

RESULTS

A total of 73 eligible consecutive patients were enrolled in the study, of which 4 did not return for follow-up (no particular reason could be identified). Because only eyes that had a WASCA measurement based on a pupil diameter of at least 5.0 mm were included, some patients and controls contributed with only eye and some patients only contributed with preoperative or postoperative measurements: of the remaining 69 patients, only 61 had satisfactory pupil size of at least 5 mm for at least 1 eye. The study thus included 117 eyes of 61 patients treated with SMILE and 64 eyes of 34 controls; 43 of the patients (38 right eyes and 33 left eyes) were in both the preoperative and postoperative groups (Table 1), and 21 controls (16 right and left eyes) were included in both the spectacle and contact lens group—all controls in the spectacle group were included in the contact lens group (Table 2). Thirteen controls wore only contact lenses as their habitual correction (Table 2). Patients and controls were of similar age, and 74% (39 out of 53) and 73% (37 out of 51) in the preoperative and postoperative SMILE groups were women, whereas 62% (13 out of 21) and 68% (23 out of 34) were women in the spectacle and contact lens groups, respectively (Table 3). The preoperative spherical equivalent was effectively reduced from −7.33 D ± 0.96 to −0.25 D ± 0.43 (Table 3); the refractive correction in the spectacle and contact lens group was similar to the level of preoperative correction in the SMILE group (Table 3). Autorefraction compared with the correction worn for the controls showed that the spectacle group was slightly more undercorrected than the contact lens group—the difference in spherical equivalent between autorefraction and habitual refraction was −0.32 D ± 0.52 for the spectacle group and −0.18 D ± 0.42 for the contact lens group. All contact lenses worn were soft and from various fabricants; 15 eyes of 9 controls wore toric soft contact lenses. The contact lenses and spectacles were of different age and origin, but all served as used methods of correction for the controls.

The results for the habitual logVSX were worse and much more variable than the results for optimal logVSX as seen in Figure 1. The habitual logVSX changed insignificantly postoperatively from −1.22 ± 0.48 to −1.17 ± 0.42 (P = .26). The postoperative habitual logVSX was not statistically significantly different from the habitual logVSX of −1.11 ± 0.46 for the spectacle group (P = .31), but statistically significantly poorer than the contact lens group (P = .002); furthermore, there was no statistically significant difference in habitual logVSX between the spectacle and contact lens groups (P = .18).

The optimal logVSX values significantly worsened postoperatively from −0.37 ± 0.11 to −0.46 ± 0.10 (P < .001); the postoperative optimal logVSX values were also significantly worse than the optimal logVSX of −0.41 ± 0.09 of the spectacle group (P = .01) and −0.40 ± 0.10 of the contact lens group (P = .003). There was no statistically significant difference in optimal logVSX between the spectacle and contact lens groups (P = .97). An overview of the statistically significant differences between the VSX-optimized refraction and habitual refractions is summarized in Table 4—the largest difference in spherical equivalent was seen for the spectacle group, followed by the postoperative group and the contact lens group, and finally the preoperative group. Correlations were weak and statistically insignificant between habitual logVSX and total
HOA RMS but negative and statistically significant between optimal logVSX and total HOA RMS (Figure 2).

Even small amounts of experimentally induced spherical defocus had a detrimental effect on the optimal logVSX (Figure 3); the effect was more or less the same across the groups within ±1.00 D of spherical defocus, whereas large amounts of spherical defocus had a different impact depending on the group analyzed and the sign of the spherical defocus. The preoperative and spectacle groups were very similarly affected by induced defocus; the contact lens group was the most affected group for negative spherical defocus but least affected group for positive spherical defocus. The postoperative group was less affected by spherical defocus than the preoperative and spectacle groups (Figure 3).

The postoperative UDVA for the SMILE patients was slightly poorer than the preoperative CDVA and also slightly poorer than the visual acuity measured for the spectacle and contact lens groups, but no difference was seen between the spectacle and contact lens groups (Table 5); the postoperative CDVA, however, significantly improved to $-0.08 \pm 0.06 \ (P < .001)$, and this result was not statistically significant from the visual acuity of neither the spectacle group ($P = .40$) nor the contact lens group ($P = .33$). The postoperative CDVA corrected for the magnification effect of moving the correction from the spectacle plane to the corneal plane was $-0.04 \pm 0.06$, which was not statistically significantly different from the preoperative CDVA ($P = .28$) but significantly poorer compared with the visual acuity of both the spectacle group ($P = .004$) and the contact lens group ($P = .001$). The contrast sensitivity (measured without correction) also decreased slightly for the SMILE patients, but no statistically significant differences were seen between the contrast sensitivity of the patients postoperatively and the spectacle or contact lens groups (Table 5).

Individual terms of HOAs and RMS values were calculated for comparison with resultant VSX values; all HOAs increased postoperatively (Table 5). Spherical aberration measured for contact lenses was significantly lower than for both the postoperative group and the spectacle group, whereas the postoperative spherical aberration was not statistically significantly different from the spectacle group; the same qualitative conclusions applied to vertical coma (Table 5). The horizontal coma for the postoperative group, however, was significantly lower than for both the spectacle or contact lens groups, but no statistically significant difference was seen between the spectacle and contact lens groups; total coma RMS was significantly higher for the postoperative group than both the spectacle or contact lens groups, but no statistically significant difference was seen between spectacles and contact lenses—this was also the case for total HOAs RMS (Table 4).

Table 3. Demographic Data of Patients Treated With SMILE for High Myopia and Myopic Controls.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Preop</th>
<th>Postop</th>
<th>Spectaclesa</th>
<th>Contact lensesa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients, eyes (both/left) (n)</td>
<td>53, 49/48b</td>
<td>51, 50/41b</td>
<td>21, 18/17b</td>
<td>34, 31/30b</td>
</tr>
<tr>
<td>Age (y)</td>
<td>32.8 ± 7.5</td>
<td>32.7 ± 7.9</td>
<td>32.5 ± 7.9</td>
<td>32.3 ± 7.1</td>
</tr>
<tr>
<td>Range</td>
<td>19.8, 51.4</td>
<td>19.8, 51.4</td>
<td>21.7, 48.6</td>
<td>20.3, 48.6</td>
</tr>
<tr>
<td>Female sex (%)</td>
<td>74</td>
<td>73</td>
<td>62</td>
<td>68</td>
</tr>
<tr>
<td>Sphere (D)</td>
<td>−10.00, −5.75</td>
<td>−1.75, 0.75</td>
<td>−6.62 ± 1.07</td>
<td>−6.17 ± 1.04</td>
</tr>
<tr>
<td>Cylinder (D)</td>
<td>−0.48 ± 0.48</td>
<td>−0.46 ± 0.36</td>
<td>−0.73 ± 0.46</td>
<td>−0.24 ± 0.44</td>
</tr>
<tr>
<td>Range</td>
<td>−1.75, 0.00</td>
<td>−1.25, 0.00</td>
<td>−1.75, 0.00</td>
<td>−1.25, 0.00</td>
</tr>
<tr>
<td>SEQ (D)</td>
<td>−7.33 ± 0.96</td>
<td>−0.25 ± 0.43</td>
<td>−6.99 ± 1.08</td>
<td>−6.29 ± 1.04</td>
</tr>
<tr>
<td>Range</td>
<td>−10.00, −6.00</td>
<td>−2.13, 0.50</td>
<td>−8.88, −5.00</td>
<td>−9.00, −4.75</td>
</tr>
</tbody>
</table>

postop = postoperative; preop = preoperative; SEQ = spherical equivalent

ab For patients with spectacles and contact lenses, the refractive correction is presented.

bForty-three patients (38 right eyes and 33 left eyes) were in both the preop and postop group.

cTwenty-one controls (16 right and left eyes) were in both the spectacle and contact lens group; all controls in the spectacle group were included in the contact lens group.
assessed the change in logVSX after refractive surgery, but our result that the optimal visual image quality decreases after SMILE is in accordance with what has been reported previously for LASIK. Bühren et al. estimated visual image quality for patients who had undergone LASIK for myopia by taking the logarithm of the metric VSOTF (Visual Strehl based on the optical transfer function), a metric very similar to logVSX, and reported habitual and optimal median values of logVSOTF of $-1.42$ and $-1.01$ for a 6 mm pupil, respectively; the values of logVSOTF are similar but not equal to logVSX, making a direct comparison difficult, but it is apparent that an experimental addition of best refraction affecting the lower-order aberrations (ie, sphere and astigmatism) improved the postoperative calculated visual image quality in their study as well.\textsuperscript{10,17,38} Sarkar et al. also reported optimal logVSOTF values for a 6 mm pupil in relation to LASIK for myopia and found a decrease in peak logVSOTF postoperatively.\textsuperscript{19} However, this study is apparently the first to describe changes in habitual visual image quality after refractive surgery. The chosen pupil diameter for analysis is relevant; we chose 5 mm in this study to reflect a physiological pupil size for young adults in photopic settings, but had we chosen, for example, 6 mm, the respective group level values of logVSX would have been poorer, given that aberrations increase with pupil diameter.\textsuperscript{15,29,33} Had we instead chosen a small pupil close to, for example, 3 mm, the effect of aberrations would be negligible, and the VSX metric would start losing accuracy in describing the visual image quality due to an increasing effect of diffraction.\textsuperscript{16}

The decrease in optimal logVSX induced by SMILE was small—the decrease in optimal logVSX of $-0.09$ for the SMILE patients approximately corresponds to an increase in pupil diameter of 1 mm for a person between 30 and 39 years or a 10-year jump for a 5 mm pupil from the 30 to 39 years ($-0.377 \pm 0.115$) to the 40 to 49 years ($-0.461 \pm 0.111$) age group; based on Figure 3, a decrease in optimal logVSX of $-0.09$ would correspond to about 0.10 D defocus.\textsuperscript{16}

However, eyes wearing trial lens prescriptions based on a subjective refraction undertaken immediately before wavefront measurement have been described to not live up to these theoretically best standards; based on data published by Thibos, Hastings et al. calculated a reference limit of $-0.580 \pm 0.239$ for a 5 mm pupil based on 200 normal eyes measured wearing a trial lens prescription.\textsuperscript{13,31} Accordingly, the expected habitual range of logVSX based on those data would be between $-0.102$ and $-1.058$, which means that many (39% of the eyes preoperatively and 52% of the eyes

<table>
<thead>
<tr>
<th>Group</th>
<th>M (D)</th>
<th>J0 (D)</th>
<th>J45 (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preop</td>
<td>$-0.31 \pm 0.90$</td>
<td>$-1.75, 1.75$</td>
<td>$-0.11 \pm 0.33$</td>
</tr>
<tr>
<td>Postop</td>
<td>$-0.46 \pm 0.55$</td>
<td>$-2.88, 0.38$</td>
<td>$-0.08 \pm 0.31$</td>
</tr>
<tr>
<td>Spectacles</td>
<td>$-0.61 \pm 0.58$</td>
<td>$-1.75, 1.00$</td>
<td>$0.02 \pm 0.24$</td>
</tr>
<tr>
<td>Contact lenses</td>
<td>$-0.37 \pm 0.57$</td>
<td>$-1.63, 0.63$</td>
<td>$0.11 \pm 0.22$</td>
</tr>
</tbody>
</table>

M = spherical equivalent; J0 = with/against-the-rule astigmatism component; J45 = oblique astigmatism component; postop = postoperative; preop = preoperative; VSX = visual Strehl ratio.
Raasch et al. have reported a habituation where corrections were more than 3 months old. The average differences in log VSX was seemingly because of the optimal log VSX being smaller than the habitual log VSX.

Unfortunately, we did not ask patients to rate their subjective visual quality with, for example, a validated questionnaire, but future work should preferably incorporate this aspect to uncover whether the small differences detected in this study in visual image quality could be noticed by the patients (and whether the perceived change was bothersome).

Returning to the observed change in habitual and optimal log VSX after SMILE, from the above-stated reasons, it would seem that the surgically induced HOAs are overshadowed from the lower-order aberrations in the habitual log VSX but become apparent in the optimal log VSX; this would agree with the fact that correlations between habitual log VSX and total HOA RMS were insignificant, but that significant negative correlations were observed between optimal log VSX and total HOA RMS. The latter is in accordance with the results of Sarkar et al. and what would be theoretically expected as the best-achievable image quality with a traditional sphero-cylindrical refraction should decrease as HOAs increase.

Because subjects were not cyclopleged in this study, even small amounts of accommodation from the subjects during testing might have introduced noise in the habitual log VSX calculation; this could also be a potential reason as to why the standard deviation was much higher for the habitual log VSX than the optimal log VSX.

Concerning the second study question, the postoperative habitual log VSX, representing the combination of induced HOAs and the residual refraction postoperatively, was significantly worse compared with that of the control contact lens group but insignificant compared with that of the spectacle group. This statistically significant difference for the postoperative group in habitual log VSX compared with contact lenses group was mainly due to uncorrected residual refraction postoperatively because the difference in optimal log VSX (against both spectacles and contact lenses) was of much smaller magnitude than the difference in habitual log VSX; even so, the surgically induced HOAs caused a decrease in optimal log VSX for the postoperative group. Furthermore, albeit the UDVA of the postoperative group was significantly worse than the visual acuity for both control corrections, the CDVA was not (however, our results showed that the gain in CDVA postoperatively was carried by magnification effects); the contrast sensitivity (which was measured unaided for the postoperative group) was not

![Image](image.png)

**Figure 2.** Correlations of RMS total HOAs with habitual and optimal log VSX for myopic patients before (blue) and 3 months after (green) treatment with SMILE, and myopic controls corrected with spectacles (red) and contact lenses (yellow). Some of the controls’ habitual corrections were more than 3 months old. The correlations were insignificant for the habitual log VSX but significant for the optimal log VSX. Only right eyes included; results were practically identical for the left eyes (log VSX = logarithm of the visual Strehl ratio; RMS = root mean square).

![Image](image.png)

**Figure 3.** Line plot showing mean optimal log VSX as a function of experimentally induced defocus for myopic patients before (blue) and 3 months after (green) treatment with SMILE and myopic controls corrected with spectacles (red) and contact lenses (yellow). Some of the controls’ habitual corrections were more than 3 months old. Even small amounts of defocus were observed to have a marked effect on mean optimal log VSX (dotted lines have been added to ease readability). Right and left eyes included (log VSX = logarithm of the visual Strehl ratio).
Table 5. Comparisons of Psychophysical Performance and HOAs.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Preop*</th>
<th>Postop*</th>
<th>P value (preop vs postop)</th>
<th>Spectacles</th>
<th>Contact lenses</th>
<th>P value (postop vs CL)</th>
<th>P value (spectacles vs CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual acuity (logMAR)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>−0.03 ± 0.05</td>
<td>0.01 ± 0.09</td>
<td>&lt;.001</td>
<td>−0.08 ± 0.10</td>
<td>−0.09 ± 0.09</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Range</td>
<td>−0.20, 0.1</td>
<td>−0.20, 0.24</td>
<td></td>
<td>−0.26, 0.18</td>
<td>−0.30, 0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contrast sensitivity (logCS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>1.61 ± 0.12</td>
<td>1.56 ± 0.14</td>
<td>.003</td>
<td>1.59 ± 0.19</td>
<td>1.58 ± 0.14</td>
<td>.34</td>
<td>.30</td>
</tr>
<tr>
<td>Range</td>
<td>1.32, 1.86</td>
<td>1.26, 2.01</td>
<td></td>
<td>1.20, 2.16</td>
<td>1.16, 1.84</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spherical aberration (µm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>0.04 ± 0.06</td>
<td>0.09 ± 0.08</td>
<td>&lt;.001</td>
<td>0.07 ± 0.07</td>
<td>−0.04 ± 0.06</td>
<td>.75</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Range</td>
<td>−0.13, 0.18</td>
<td>−0.09, 0.30</td>
<td></td>
<td>−0.05, 0.19</td>
<td>−0.18, 0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical coma (µm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>0.05 ± 0.08</td>
<td>−0.00 ± 0.16</td>
<td>.001</td>
<td>0.02 ± 0.14</td>
<td>0.08 ± 0.11</td>
<td>.52</td>
<td>.004</td>
</tr>
<tr>
<td>Range</td>
<td>−0.13, 0.25</td>
<td>−0.60, 0.39</td>
<td></td>
<td>−0.27, 0.25</td>
<td>−0.15, 0.34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal coma (µm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>0.03 ± 0.06</td>
<td>−0.10 ± 0.14</td>
<td>&lt;.001</td>
<td>0.03 ± 0.07</td>
<td>0.05 ± 0.08</td>
<td>&lt;.001</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Range</td>
<td>−0.14, 0.21</td>
<td>−0.46, 0.26</td>
<td></td>
<td>−0.13, 0.17</td>
<td>−0.13, 0.29</td>
<td></td>
<td></td>
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<tr>
<td>Total coma RMS (µm)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Mean ± SD</td>
<td>0.11 ± 0.05</td>
<td>0.20 ± 0.11</td>
<td>&lt;.001</td>
<td>0.14 ± 0.07</td>
<td>0.14 ± 0.08</td>
<td>.01</td>
<td>.007</td>
</tr>
<tr>
<td>Range</td>
<td>0.03, 0.29</td>
<td>0.02, 0.60</td>
<td></td>
<td>0.03, 0.27</td>
<td>0.02, 0.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total HOAs RMS (µm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>0.18 ± 0.06</td>
<td>0.29 ± 0.10</td>
<td>&lt;.001</td>
<td>0.23 ± 0.07</td>
<td>0.21 ± 0.07</td>
<td>.001</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Range</td>
<td>0.08, 0.42</td>
<td>0.13, 0.70</td>
<td></td>
<td>0.10, 0.48</td>
<td>0.10, 0.40</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CL = contact lenses; logCS = logarithm of the contrast sensitivity; RMS = root mean square; postop = postoperative; preop = preoperative
*Reported visual acuity and contrast sensitivity was measured with patients’ refractive error corrected with trial lenses preop but not postop

significant against the control groups either. These results in visual performance and habitual and optimal logVSX indicate that the major limitation for the postoperative group was residual sphero-cylindrical refraction. The difference in optimal logVSX for the postoperative group against spectacles and contact lenses groups was only about −0.05, a small amount in light of the reference intervals listed earlier.

Subjective refraction is traditionally used as the ultimate reference point when evaluating the outcome of refractive surgery. However, it is well-known that the quality of the image formed on the retina for a given dioptric error is highly dependent on the pupil size; this is also demonstrated in Figure 4, where the theoretical logVSX for a hypothetical eye with a given defocus errors (and no other aberrations) is demonstrated for different pupil diameters. Although the impact of spherical defocus on image quality varies as a function of pupil size, subjective refraction has, nonetheless, shown to be rather independent of pupil size. The relative independence of subjective refraction on pupil diameter might be because subjective refraction is an imprecise procedure with limits of agreement of about ±0.50 D; more precise and repeatable results have been obtained with objective methods. Accordingly, it is worth considering that merely stating the result of a refractive procedure regarding residual refractive error is not a good method of describing the resulting retinal image quality because even small dioptric errors can affect image quality for large pupil diameters (Figure 4). Hence, although the differences in logVSX found in this article are small in comparison with expected deviations in defocus from subjective refraction, one might argue that objective, less variable means of assessing patients’ refraction should be considered the gold standard for evaluating refractive surgery in the future.

Concerning the third study question, the logVSX values were equivalent between spectacles and soft contact lenses, indicating that the visual image quality is not affected by which of these modalities of conservative correction is used. The visual acuity and contrast sensitivity were also equivalent between the spectacle group and contact lens group, even though autorefration and the applied corrections needed to obtain optimal logVSX suggested that the contact lens group was better corrected than the spectacle group; this was not surprising because disposable contact lenses are more readily updated than spectacles. Ehsaei et al. also found equal visual function among patients with myopia corrected with spectacles or contact lenses, even when retinal magnification (which would be in favor of contact lenses) was taken into account. Among the differences in HOAs between spectacles and contact lenses, particularly the lower amount of spherical aberration for the contact lens group was expected because this has been well-described in the literature; the HOAs induced by spectacles, however, is less well-described and former reports have treated the induction of HOAs to the central vision by spectacles as negligible, but our data seem to indicate that even spectacles do introduce some HOAs (judging from the data of the preoperative group), but because total HOA RMS and logVSX were
The VSX-optimized spherical equivalent was considered in this study. It is doubtful that this more detailed approach is possible to conduct a meaningful statistical analysis on the eyes. However, patients scheduled for surgery quite often wear contact lenses preoperatively with measurements postoperatively; the surgery in general are known to induce higher-order aberrations (HOAs), but the significance of an individual elevated HOA to vision is difficult to predict because HOAs interact in a complex manner.

Figure 4. Simulation graph showing the impact of spherical defocus on logVSX for different pupil diameters for a theoretical eye with no other aberrations than defocus. The theoretical visual image quality determined by logVSX from any given level of spherical defocus is seen to depend markedly on the pupil size (logVSX = logarithm of the visual Strehl ratio).

WHAT WAS KNOWN
- Small-incision lenticule extraction (SMILE) and refractive surgery in general are known to induce higher-order aberrations (HOAs), but the significance of an individual elevated HOA to vision is difficult to predict because HOAs interact in a complex manner.
- Visual image quality metrics such as the logarithm of the visual Strehl ratio (logVSX) have been devised to fully describe the eyes’ optical quality based on the entire ocular wavefront and the neural processing of the eye.

WHAT THIS PAPER ADDS
- The logVSX calculated needs to be divided into habitual logVSX (ie, based on a given wavefront measurement directly) and optimal logVSX (best-achievable logVSX calculated in a through-focus experiment) because the logVSX is sensitive to spherical defocus.
- Habitual logVSX is not affected by SMILE, but the optimal logVSX is slightly lowered after SMILE; the surgically induced change in logVSX compared with myopic controls corrected with spectacle lenses and/or contact lenses is smaller than that would be expected from test-retest variation in subjective refraction.

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conclusions in this study were meant to apply to spectacle lenses and contact lenses in general.

In conclusion, this study showed the following: (1) that SMILE for high myopia did not affect the habitual logVSX but had a small impact on the optimal logVSX; (2) that the postoperative habitual logVSX was worse than what was measured for contact lenses but not for spectacle lenses and that the postoperative optimal logVSX was worse than for both contact lenses and spectacle lenses; and (3) that there was no statistically significant difference in neither habitual nor optimal logVSX between spectacles and contact lenses. Furthermore, this study showed that the optimal VSX is dependent on the amount of HOAs, and that even small amounts of spherical defocus had a detrimental effect on the calculated VSX, which likely explains the different results concerning the habitual and optimal levels of VSX. The observed differences in logVSX were smaller than what would be expected from the test-retest variation in defocus from a subjective refraction. Thus, SMILE effectively treats myopia with reassuringly clinically insignificant effects on the visual image quality compared with correction with spectacles or contact lenses; the visual image quality resulting from correction with either spectacles or contact lenses is equivalent.
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