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Effects of Optical Blur Reduction on Equivalent Intrinsic Blur

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Abstract

Purpose—To determine the effect of optical blur reduction on equivalent intrinsic blur, an estimate of the blur within the visual system, by comparing optical and equivalent intrinsic blur before and after adaptive optics (AO) correction of wavefront error.

Methods—Twelve visually normal individuals (age; 31 ± 12 years) participated in this study. Equivalent intrinsic blur (σ_{int}) was derived using a previously described model. Optical blur (σ_{opt}) due to high-order aberrations was quantified by Shack-Hartmann aberrometry and minimized using AO correction of wavefront error.

Results— σ_{opt} and σ_{int} were significantly reduced and visual acuity (VA) was significantly improved after AO correction ($P = 0.004$). Reductions in σ_{opt} and σ_{int} were linearly dependent on the values before AO correction ($r = 0.94$, $P = 0.002$). The reduction in σ_{int} was greater than the reduction in σ_{opt} , although it was marginally significant ($P = 0.05$). σ_{int} after AO correlated significantly with σ_{int} before AO ($r = 0.92$, $P < 0.001$) and the two parameters were related linearly with a slope of 0.46.

Conclusions—Reduction in equivalent intrinsic blur was greater than the reduction in optical blur due to AO correction of wavefront error. This finding implies that VA in subjects with high equivalent intrinsic blur can be improved beyond that expected from the reduction in optical blur alone.

Keywords

adaptive optics; intrinsic blur; optical blur

The amount of blur within the visual system is one factor that limits visual acuity (VA) in visually normal individuals,¹⁻³ and in subjects with visual dysfunction.^{3,4} Equivalent intrinsic blur is an estimate of the amount of blur within the visual system,^{1,4,5} and is comprised of optical blur due to the presence of ocular aberrations and neural blur attributable to neural filtering.^{2,6} However, the extent to which optical and neural sources of blur contribute separately to equivalent intrinsic blur is presently unclear. A number of studies have examined how neural mechanisms adapt to the optically blurred retinal image,⁷⁻¹⁰ suggesting the dependence of neural blur on optical blur. For example, neural

adaptation to optical defocus can lead to improvements in visual acuity,^{11, 12} and altering an individual's pattern of ocular aberrations can result in a decrease in perceived image quality,^{13, 14} suggesting an individual's level of neural blur may, at least in part, depend on optical blur. Furthermore, VA ultimately depends on cortical neurons that are tuned to the highest spatial frequencies conveyed by the photoreceptors. If the optical quality of the eye is reduced due to elevated high-order aberrations, high frequency retinal images will not be conveyed, which may alter cortical channel tuning. Consequently, neural processing at stages subsequent to sampling of the retinal image may depend on the quality of the retinal image.

Optical blur can be reduced with adaptive optics (AO) technologies that minimize high-order aberrations of the eye, thereby improving VA and contrast sensitivity, as reported in previous studies.¹⁵⁻¹⁸ However, the effect of reducing optical blur on equivalent intrinsic blur has not been described. Reducing optical blur likely decreases equivalent intrinsic blur either by an equal amount, suggesting that neural blur is not strongly affected by optical blur, or by an unequal amount, suggesting that neural blur is dependent on optical blur. The purpose of the present study was to investigate these two possibilities by determining the effects of optical blur reduction on equivalent intrinsic blur by comparing these parameters before and after AO correction of wavefront error in visually normal individuals.

Patients and Methods

Subjects

This prospective research study was approved by an Institutional Review Board at the University of Illinois at Chicago. Prior to enrollment, the research study was explained to the subjects, and informed consent was obtained according to the tenets of the Declaration of Helsinki. Twelve visually normal subjects (9 males and 3 females) with a mean age of 31 ± 12 years (mean $\pm$ standard deviation) participated in the study. Data from one additional subject who was considered an outlier were not included. This subject had increased equivalent intrinsic blur, despite a decrease in optical blur following AO, likely due to lack of reliability in the visual performance measure. One eye per subject was randomly selected for testing. Table 1 provides the characteristics of the subjects including sex, age, spherical and cylindrical refractive errors, and chart VA as assessed with the Lighthouse Distance Acuity Chart. Mean spherical and cylindrical refractive errors were -0.66 ± 2.00 D and 0.83 ± 0.56 D ($N = 12$), respectively. The subjects had chart VA that ranged from 20/13 to 20/25 Snellen equivalent. One randomly selected eye of each subject was dilated with one drop of 1% tropicamide prior to imaging.

Adaptive Optics Wavefront Error Correction

Our previously described bench top AO system¹⁹ was employed to obtain measurements of optical and equivalent intrinsic blur with and without correction of wavefront error. Subjects were seated in front of the AO system and a movable chin and forehead rest was used to align the pupil along the optical axis of the system. Alignment was monitored using a charge couple device (CCD) camera and real-time display of the pupil. A collimated 780 nm laser diode (40 μ W) was projected into the eye and focused on the center of the fovea. A lenslet

array generated a Shack-Hartmann (SH) image that was captured by a CCD camera (Princeton Instruments, Trenton, NJ) for measurements of low and high-order wavefront aberrations. The subject's eye was optimally refracted using a badal optometer in the AO system and a cylindrical trial lens placed near the pupil plane. This refraction was performed while spherical and cylindrical errors were calculated from the live SH image. Wavefront error was corrected using a microelectromechanical system deformable mirror with a stroke of 6 μm (Boston MicroMachines, Cambridge, MA). Closed loop AO control minimized residual low-order (2nd) and high-order (3rd to 7th) wavefront aberrations in 20 iterations, requiring less than 1 second.

Equivalent Intrinsic Blur and VA Measurements

The bench top AO system was modified to incorporate an organic light-emitting diode (OLED) microdisplay (eMagin, Bellevue, WA) for visual stimulus delivery. The size of the microdisplay was 12 mm $\times$ 9 mm with a screen resolution of 800 $\times$ 600 pixels and a 60 Hz refresh rate. The microdisplay was positioned in a plane conjugate to the retinal image plane using an additional lens incorporated into the system. The visual test stimuli consisted of unblurred and blurred tumbling E optotypes. Examples of the letter stimuli at different sizes and blur levels that are identical to the stimuli used in the current report have been presented elsewhere.² The blurred Es were generated by convolution with 2D low-pass Gaussian functions of 4 different standard deviations (σ_{stim}): 0.0 (unblurred), 0.4, 1.6, and 6.5 arcmin. The stimuli were presented on the microdisplay for duration of 100 ms and viewed through a 5 mm artificial pupil positioned in a plane conjugate to the subject's pupil. Before AO correction, the test stimuli were presented to the subjects with the deformable mirror held flat, thereby not compensating for high-order aberrations of the optical system. After AO correction, the test stimuli were presented to the subjects with the deformable mirror profile shaped to minimize the aberrations of the eye. Testing was performed immediately after wavefront aberration measurement with the mirror profile held constant (either flat or corrected) and the SH laser turned off. Threshold log MAR for each value of σ_{stim} was then determined using a four-alternative forced-choice staircase procedure.

As previously published,²⁻⁴ equivalent intrinsic blur (σ_{int}) was derived from the log MAR values measured for each level of stimulus blur. In brief, the threshold log MAR values were plotted as a function of log σ_{stim} and were fit with the log form of the following equation:⁴

$$\text{MAR} = \text{MAR}_0 \left(1 + (\sigma_{\text{stim}} / \sigma_{\text{int}})^2 \right)^{1/2}, \quad (1)$$

where σ_{stim} is the standard deviation (arcmin) of the low-pass Gaussian function convolved with the stimulus. MAR_0 (the asymptotic VA in the absence of blur) and σ_{int} (equivalent intrinsic blur) were free parameters that were adjusted to minimize the mean squared error using the generalized reduced gradient algorithm. According to equation 1, σ_{int} is equal to the value of log σ_{stim} that increases log MAR_0 by 0.15 log units. Measurements of VA for each value of σ_{stim} and σ_{int} were obtained before and after AO correction.

Optical Blur Measurement

Optical blur was derived from SH wavefront aberrometry as described previously.² Briefly, the wavefront aberration function was calculated for a 5.5 mm pupil diameter and included residual low-order and high-order (3rd to 7th) aberrations. From the wavefront aberration function, the two-dimensional optical point spread function (PSF) was derived according to standard transformations.²⁰ The PSF was then radially averaged to provide a one-dimensional line profile, normalized to unity, and fit with a Gaussian function for each level of σ_{stim} . The standard deviation of the best-fit Gaussian function defined optical blur (σ_{opt}) for that level of σ_{stim} . Measurements of root mean square (RMS) wavefront error and σ_{opt} were obtained before and after AO correction. Eight measurements of σ_{opt} were obtained from each subject (4 before AO and 4 after AO). The four measurements of σ_{opt} before AO correction were averaged. Similarly, the four measurements of σ_{opt} obtained after AO correction were averaged. The total RMS wavefront error was calculated based on residual low-order and high-order aberrations and averaged before and after AO correction, respectively.

Statistical Analysis

Measurements of VA, RMS wavefront error, σ_{int} , and σ_{opt} before and after AO correction were compared by paired t-tests. σ_{int} reduction was defined as the difference between σ_{int} before and after AO correction. Likewise, σ_{opt} reduction was defined as the difference between σ_{opt} before and after AO correction. Reductions in σ_{int} and σ_{opt} were compared using a paired t-test. The relationships between reductions in σ_{int} (or σ_{opt}) and the values before AO were determined by linear regression analysis. The relationship between σ_{int} before and after AO correction was also determined by linear regression analysis. Estimated values of σ_{int} after AO (σ_{int} before AO - optical blur reduction) were calculated, assuming equal reductions in σ_{opt} and σ_{int} . Statistical analysis was performed using SPSS version 21 (SPSS Inc, Chicago, IL, USA) and statistical significance was accepted at $p < 0.05$.

Results

Figure 1 displays the relationship between log MAR and log σ_{stim} before (closed circles) and after (open circles) AO correction. Solid lines represent the model fit (i.e. Eq. 1) to the data. These functions transition from a slope of 0 at low values of log σ_{stim} to a slope of 1 at high values. The effect of AO correction on log MAR depended on the level of σ_{stim} . That is, AO correction improved log MAR for the unblurred and minimally blurred stimuli ($\sigma_{\text{stim}} = 0$ and 0.40 arcmin, respectively). However, AO correction had no effect on log MAR for the two highest levels of σ_{stim} (1.61 and 6.45 arcmin). Consequently, the effect of AO was to shift the function downward and leftward by similar amounts (approximately 0.1 log unit).

Values of mean VA (log MAR for $\sigma_{\text{stim}} = 0$), σ_{int} , σ_{opt} , and RMS wavefront error before and after AO correction are listed in Table 2. VA improved significantly after AO correction ($P < 0.001$) and the improvement was about 0.1 log unit, which is equivalent to one line on the early treatment of diabetic retinopathy study chart. As expected, there was a significant reduction in RMS wavefront error and σ_{opt} after AO correction ($P < 0.001$). Likewise, σ_{int} was significantly reduced after AO correction ($P = 0.004$). Figure 2A shows σ_{opt} reduction

plotted as a function of σ_{opt} before AO, indicating a significant correlation ($r = 0.97$, $P = 0.001$), such that subjects with the highest σ_{opt} before AO had the greatest reduction after AO. The relationship between σ_{int} reduction and σ_{int} before AO is displayed in Figure 2B. The σ_{int} reduction was significantly correlated with σ_{int} before AO ($r = 0.94$, $P = 0.002$), indicating subjects with the highest σ_{int} before AO had the greatest reduction after AO.

The mean reduction in σ_{int} (0.30 ± 0.29 arcmin) was greater than the mean reduction in σ_{opt} (0.11 ± 0.07 arcmin), although the difference was marginally significant ($P = 0.05$; $N = 12$). To further examine the equivalence in the reductions of σ_{int} and σ_{opt} , we assumed that the reduction in σ_{int} due to AO correction was equal to the reduction in σ_{opt} , which allowed the relationship between σ_{int} before and after AO correction to be estimated. Figure 3 displays the relationship between σ_{int} after and before AO correction. The solid black line is the best fit line to the measured data, which showed a high linear correlation between the values of σ_{int} before and after AO correction ($r = 0.92$, $P < 0.001$; $N = 12$). The slope of this line is 0.46 and y-intercept is 0.50. The dashed line is the best fit line that describes the relationship between σ_{int} before and after AO, estimated based on the assumption that a reduction in σ_{opt} produces an equal reduction in σ_{int} (σ_{int} after AO = σ_{int} before AO - σ_{opt} reduction). This estimated line has a slope of 1.0 and y-intercept of -0.11 ($r = 0.99$, $P < 0.001$, $N = 12$). The identity line (dotted line) is shown, which represents no change in σ_{int} with AO correction. The slope of the line describing the data points (0.46) was less than 1. Data points obtained in subjects with low σ_{int} before AO correction were close to the estimated line, indicating minimal reduction in σ_{int} . For subjects with higher σ_{int} before AO, the data points deviated from the estimated line, such that the reduction in σ_{int} was larger than the reduction in σ_{opt} .

Discussion

Adaptive optics can be used to minimize ocular aberrations and reduce the optical blur of the eye, thereby improving visual acuity. However, to our knowledge, it has not been described how equivalent intrinsic blur within the visual system is affected by a reduction of optical aberrations of the eye. In this study, we demonstrated that the reduction in equivalent intrinsic blur was greater than the reduction in optical blur due to AO correction of wavefront error. Furthermore, reductions in equivalent intrinsic and optical blur were correlated with the levels of these parameters before AO correction.

Measurements of σ_{opt} obtained with our bench top AO-based system were similar to our previous data using a stand-alone aberrometry system.³ As expected, RMS wavefront error and σ_{opt} were reduced due to AO, consistent with previous studies.^{15, 21-23} The range of σ_{int} measured through the AO system was consistent with previously reported measurements obtained with the use of a CRT monitor.^{2, 3} σ_{int} was reduced due to AO correction of wavefront error, which resulted in improvement of VA measured with an unblurred stimulus, in agreement with previous studies.^{16, 24-28} The extent to which log MAR was improved due to AO depended on the level of stimulus blur. That is, log MAR was reduced more for low stimulus blur levels, since the blur of the visual system dominated across this range and this blur could be reduced due to AO correction. Once the stimulus blur exceeded that in the visual system, AO correction resulted in minimal improvement in log MAR values.

In the current study, the reduction in σ_{int} was found to be greater than the reduction in σ_{opt} , although this difference was marginally significant. To further examine the equivalence in the reductions of σ_{int} and σ_{opt} , the best fit line describing the relationship between σ_{int} before and after AO correction was shown to have a slope less than 1, indicating a larger reduction in σ_{int} as compared to σ_{opt} . This finding is important because subjects with high σ_{int} before AO correction demonstrated a substantial reduction in σ_{int} and improvement in VA beyond that expected from the reduction in σ_{opt} , probably due to a concurrent reduction in neural blur. This finding suggests a dependence of neural blur on optical blur, which may be explained by adaptation aftereffects.^{7, 8, 10} In the present study, subjects were adapted (long term) to their natural wavefront aberrations, and following AO correction of wavefront error when optical blur was minimized, unblurred stimuli may have appeared even sharper.

The finding that reductions in σ_{opt} and σ_{int} due to AO correction were correlated with baseline (before AO) blur levels may be potentially clinically-relevant. For subjects with low σ_{opt} and σ_{int} , there is likely a floor effect, such that σ_{opt} and σ_{int} in these subjects cannot be reduced substantially beyond their baseline values. Consequently, for subjects with low σ_{opt} and σ_{int} , only a modest reduction of σ_{int} and improvement in VA can be expected due to AO correction of wavefront error. However, as previously reported, subjects with retinal disease can have higher optical,^{3, 21, 29, 30} and equivalent intrinsic blur,³ and these subjects are more likely to have larger reductions in σ_{int} due to AO correction. Future larger prospective studies are required to assess the effects of reduction of optical aberrations on σ_{opt} and σ_{int} in subjects with retinal diseases.

One limitation of the present study was the relatively small sample size. Nevertheless, significant linear relationships with high correlations were observed. A second limitation was that wavefront error was not continuously measured and corrected during stimulus presentation. Consequently, alterations in the wavefront error due to tear film or pupil position changes were not accounted in the measurements and correction of wavefront error.

In summary, reduction in equivalent intrinsic blur was greater than the reduction in optical blur due to AO correction of wavefront error, suggesting a concurrent decrease in neural blur and a potential dependence of neural blur on optical blur. This finding implies that VA in subjects with high equivalent intrinsic blur can be improved beyond that expected from the reduction in optical blur alone.

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Figure 1. Mean log MAR plotted as a function of log external blur (σ_{stim}) before (closed circles) and after (open circles) adaptive optics (AO) correction. Error bars denote standard deviation of means.

Figure 2. Optical blur reduction (**A**) and intrinsic blur reduction (**B**) due to adaptive optics (AO) correction of wavefront error plotted as a function of σ_{opt} and σ_{int} before AO, respectively. The lines are the best fit linear regression to the data points.

Figure 3.

σ_{int} after AO plotted as a function of σ_{int} before AO. The solid line is the best fit linear regression line. The dashed line is the best fit line that describes the relationship between σ_{int} before and after AO, estimated based on the assumption that a reduction in σ_{opt} produces an equal reduction in σ_{int} . The dotted line is the identity line, which corresponds to no change in σ_{int} with AO correction.

Table 1

Demographic characteristics and clinical data in visually normal subjects.

Subject No.	Sex	Age	Refraction sphere (diopter)	Refraction cylinder (diopter × angle)	Chart VA (Log MAR)
1	M	34	-2.75	0.00	-0.06
2	M	34	-2.00	0.50 × 45	-0.12
3	M	35	0.00	0.75 × 105	-0.16
4	M	32	-2.25	1.75 × 90	-0.12
5	M	23	0.00	0.50 × 10	-0.06
6	M	24	1.50	1.25 × 90	-0.08
7	F	63	1.00	1.50 × 110	0.00
8	M	28	-4.00	0.75 × 10	0.06
9	M	32	0.00	0.50 × 72	0.08
10	F	22	-2.75	1.25 × 65	0.02
11	F	18	1.00	0.00	0.10
12	M	23	2.25	1.25 × 95	-0.18

Table 2

Mean $\pm$ standard deviation of total root mean square (RMS) wavefront error, visual acuity (VA) (log MAR for stimulus blur level 0), intrinsic blur (σ_{int}), and optical blur (σ_{opt}) before and after adaptive optics (AO) correction (N = 12).

Variables	Before AO	After AO	P value
VA (log MAR)	-0.12 ± 0.07	-0.19 ± 0.06	<0.001
σ_{int} (arcmin)	1.49 ± 0.50	1.19 ± 0.25	0.004
σ_{opt} (arcmin)	0.35 ± 0.06	0.24 ± 0.02	<0.001
RMS (μm)	0.37 ± 0.06	0.08 ± 0.01	<0.001