Calculations and Measurements of the Visual Benefit of Correcting the Higher-order Aberrations Using Adaptive Optics Technology

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ABSTRACT

Purpose: Our goal was to examine the accuracy of metrics, calculated using a numerical eye model including the measurement of the monochromatic aberrations of the eye, to predict the contrast sensitivity (CS) and visual acuity (VA) visual benefits (VB) of correcting higher-order aberrations (HO).

Methods: We measured, on the right eyes of 25 subjects (10 myopes and 15 emmetropes) aged 21 to 56 years, the 16 c/deg CS and high-contrast VA in two conditions of aberration corrections: (i) when correcting only the defocus and astigmatism terms and (ii) when dynamically correcting all the monochromatic aberration terms up to the 5th order. The measured VB was defined as the ratio of the performances between these two conditions of aberration corrections.

Results: We measured a VB of 1.25 and 1.64 respectively in term of VA and CS. We did not find any influence of age on the VB and no statistical significant difference between the myopic and emmetropic group. The contrast sensitivity VB was well correlated (r^2=0.79) with the ratio of the modulation transfer functions calculated at 16 c/deg in both conditions of aberrations corrections (i.e. $MTF_{16c/deg\ HO}/MTF_{16c/deg\ SC}$). The levels of correlation between various metrics and measured visual acuity VB were lower (r^2=0.30 in the better case), however the averaged VB was correctly predicted by the ratio of the intersections between the MTF and a typically neural contrast threshold function.

Conclusions: Metrics based on wave aberration measurements are able to predict the impact of monochromatic aberrations on CS.

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Key Words: image quality; adaptive optics; visual benefit; visual performance; monochromatic aberrations.

RESUMEN

Objetivo: Nuestro objetivo era analizar la validez y la precisión de los descriptores numéricos objetivos (calculados a partir de un modelo de ojo existente al que incorporamos las aberraciones monocromáticas del ojo de cada sujeto) a la hora de predecir los beneficios visuales (BV) sobre la sensibilidad al contraste (SC) o sobre la agudeza visual (AV) obtenidos tras corregir las aberraciones de alto orden.

Métodos: Medimos la SC a 16 c/grado y la AV de alto contraste en el ojo derecho de 25 sujetos (10 miopes y 15 emétropes) de edades comprendidas entre los 21 y los 56 años. Las medidas se realizaron en dos condiciones distintas de corrección de aberraciones: (i) cuando sólo los términos de desenfoque y de astigmatismo estaban corregidos y (ii) cuando todas las aberraciones monocromáticas hasta 5° orden fueron corregidas dinámicamente. La medida de los BV se definió como la razón de los resultados obtenidos en cada una de estas dos condiciones de corrección de aberraciones.

Resultados: Los BV sobre la AV y la SC fueron, respectivamente, de 1,25 y de 1,64. No encontramos ninguna dependencia de los BV con la edad del sujeto, ni ninguna diferencia estadísticamente significativa entre el grupo miope y el emétrope. Se obtuvo una notable correlación (r^2=0,79) entre los BV sobre la sensibilidad al contraste y la razón de los valores de la función de transferencia de modulación (MTF) para 16 c/grado en sendos casos de corrección de aberraciones (es decir, el valor de $MTF_{16c/grado\ AltoOrden}$ / $MTF_{16c/grado\ Seg.Orden}$). El grado de correlación entre diversos descriptores objetivos y los BV sobre la agudeza visual fue menor (r^2=0,30 en el mejor de los casos). No obstante, el valor promedio de los BV se pudo predecir con bastante exactitud partiendo del punto de corte de la MTF (para una condición de corrección dada) con una función de contraste umbral neural típica, y calculando luego la razón de estos valores correspondientes a las dos condiciones de corrección analizadas.

Conclusiones: Los descriptores numéricos basados en las medidas de la aberración de onda son capaces de predecir el impacto de las aberraciones monocromáticas sobre la SC.

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Palabras Clave: calidad de imagen; óptica adaptativa; beneficios visuales; calidad visual; aberraciones monocromáticas.

Introduction

It is well known that the human eye suffers from monochromatic aberrations in addition to defocus and astigmatism and that these aberrations degrade the retinal image and consequently limit the visual performance[1]. Adaptive optics (AO), recently used in the study of the human eye, enables the measurement and the correction of optical aberrations, thus permitting the evaluation of the visual benefit (VB) of correcting higher-order aberrations.

Previous measurements of the impact of the correction of higher-order aberrations on contrast sensitivity and visual acuity have been performed. In terms of contrast sensitivity, Liang et al.[2] measured a 6-fold improvement at 27.5 c/deg on 2 subjects, across a 6 mm pupil and in monochromatic light, whereas, Yoon and Williams[3] measured at 16 c/deg, on 2 subjects and with the same pupil size, an improvement of contrast sensitivity by a factor of 1.9 when only monochromatic aberrations were corrected in polychromatic light. Yoon et al. attempted to predict the VB by calculating the ratio of MTFs computed with and without HO aberrations, they found at 16 c/deg a theoretical polychromatic VB of 2.8, which is quite different from their 1.9 measured VB. In terms of visual acuity, Yoon and Williams[3] reported, on 7 subjects across a 6 mm pupil, a 1.2-fold and a 1.4-fold improvement after correcting the monochromatic aberrations in polychromatic light respec-

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tively at 575 Td (Troland, unit of retinal illuminance) and 57 Td. Poonja et al.[4] measured on 6 subjects, using an Adaptive Optics Scanning Laser Ophtalmoscope (AOSLO) (e.g., in monochromatic light) and a pupil diameter of 5.89 mm, a VB of 1.5 with an averaged visual acuity of 0.85 and 0.57 respectively before and after correction of the monochromatic aberrations.

Customized contact lenses, intraocular lenses and refractive surgery are now being developed to correct higher-order aberrations. The benefit from AO correction depends on the pupil size and the initial higher-order aberrations present in the eye. To address this issue, Guirao at al.[5] calculated the visual benefit of correcting the monochromatic aberrations of 218 normal eyes and found great variation among eyes with some normal eyes showing almost no benefit and others a benefit higher than 4 at 16 c/deg across a 5.7 mm pupil, the average VB being 2.4.

The visual benefit should also depend on the ametropia[6] since cortical and/or retinal factors are involved in the AO-corrected limit of resolution. Rossi et al.[6] measured the VA using an AOSLO, in 10 low myopes and 9 emmetropes, the impact of correcting monochromatic aberrations. The myopic group improved from a mean of 0.83' in the non-AO condition to a mean of 0.61' with AO (e.g. a VB of 1.37). The emmetropes improved from a mean of 0.8' without AO to a mean of 0.49' with AO (e.g. a VB of 1. 64). Retinal and/or cortical factors could have limited the VA in low myopes after AO correction resulting in a lower VB in this population.

Recent studies[7,8] have suggested that we might be adapted to our retinal image, which would have an impact on the visual benefit of correcting the eye's aberrations. Artal et al.[7] wondered whether the visual system was adapted to the retinal image of its own eye; in other words, is the best overall subjective image quality obtained when a perfect retinal image is presented on the retina or when the retinal image is blurred by the aberrations of the eye's optics, indicating that the neural system is adapted to the particular pattern of its own eyes, and is able to compensate for the effects of this blur. Theirs results support the hypothesis of a neural compensation for the aberrations. Moreover, several studies[9-12] demonstrated improvements in visual acuity after a period during which the subjects had been blurred by a defocus. Mon-Williams et al.[9] measured, on 15 emmetropic subjects, an average visual acuity increase of 0.1 logMAR after a 30 min wearing period of a +1.00 D defocus. George and Rosenfield[10] found, on 13 emmetropic and 18 myopic subjects, an average visual acuity increase of 0.2 logMAR after a 2 hours wearing period of a +2.50 D defocus. Rosenfield et al.[11] measured on 22 slightly myopic subjects an increase of visual acuity of 0.23 logMAR after 3 hours without compensation. Cufflin et al.[12] found after blur adaptation of 45 minutes, on 11 emmetropes and 11 early-onset myopes, an improvement in visual acuity of 0.17 logMAR and 0.23 logMAR following adaptation to +1 D and +3 D of defocus respectively. They also noted that acuity changes became significant after 30 minutes of exposure to optical defocus. These experiments show the effect of neural adaptation to a blurred retinal image on objective visual performance as well as on subjective responses. On the contrary, Pesudovs[13] did not find any evidence for an adaptation to surgically induced blur until ten weeks after LASIK. In conclusion, these experiments showed that visual acuity improved following a period of adaptation to blur and, consequently, that the optics alone could not explain the changes in performances without assuming that some neural adjustments were interfering with the optics. In this case, a metric derived from wave aberrations measurements might not be able to predict the visual benefit of correcting the higher-order aberrations. However, it is not evident that the situation will be similar with another visual task such as contrast sensitivity.

Previous authors[14-18] studied the link between metrics of image quality and visual performances or subjective image quality. The first objective was to determine the accuracy and precision of metrics for predicting the results of conventional sphero-cylindrical refraction from wavefront aberrations[14,18]. Guirao et al.[14] found that image-plane metrics such as the volume under the MTF between 0 and 60 c/deg were able to predict the subjective refraction of the eye. The mean error between predicted and subjective refraction was about 0.1 ± 0.08 D averaged across 6 eyes of 6 normal subjects whereas their five calculated image-plane metrics did not differ by more than 0.03 D. Similarly, Thibos et al.[18] compared 33 metrics calculations to subjective refractions performed to the nearest 0.25 D on 200 normal and healthy eyes from 100 subjects. All the mean predicted values varied from -0.50 D to +0.25 D. The variability between various metrics was always lower than the ± 0.75 D test-retest variability in the measurement of refractive error[19,20], meaning that the accuracy of metrics to predict subjective image quality should not be assessed this way. Marsack et al.[16] used the previous data set to investigate the ability of 31 metrics derived from wave aberrations maps to predict changes in high-contrast logMAR acuity. The visual acuity loss were measured on simulated aberrated charts generated with a commercially available program called CTView© that introduces the aberrations into the charts by directly setting the wavefront Zernike coefficient values and performing a convolution of the resulting point-spread function with an image of an acuity chart. The visual strehl ratio computed in the frequency domain was found to be well correlated (r^2=0.81) to the letters lost. However, the comparison between simulated letters and metrics - both calculated using the same input (e.g. the measured wavefront map) - is also questionable. A more rigorous experiment would have compared metrics and measured visual performances in real conditions by using real optics.

Chen et al.[15] used matching blur experiment to test the accuracy of various metrics to predict the subjective quality of vision. The subjects had to compare the blur caused by a single aberration to a combination of aberrations. However, as mentioned by the author, blur is not a unity perceptual experience, meaning that the appearance of the blur is different as a function of the origin of the blur. In other words, it appears very difficult to adjust the level of the defocus blur to equalize the blur caused by a LASIK wave aberration, for example.

In order to examine the accuracy of metrics - calculated using a previously published numerical eye model[21] including the measurement of the monochromatic aberrations of the eye - and to