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ORIGINAL ARTICLE

Correlation between Optical and Psychophysical Parameters as a Function of Defocus

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ABSTRACT: ***Purpose.*** **To evaluate how ocular optical image quality and psychophysical estimates of visual performance compare to each other as a function of defocus.** ***Methods.*** **We measured the optical modulation transfer function using a double-pass apparatus and psychophysical estimates of visual performance: contrast sensitivity function (CSF) and visual acuity. Both sets of data were obtained under the same optical conditions.** ***Results.*** **We measured optical and psychophysical parameters as a function of defocus. We studied the correlation between optical parameters (Strehl ratio and the logarithm of the volume in the double-pass image [log_Vol D-P]) and psychophysical parameters (the area under the fitted CSF represented in a logarithmic scale with the spatial frequency in linear scale [Area CSF-log_lin] and visual acuity) for different values of defocus.** ***Conclusions.*** **Strehl ratio is well correlated with the psychophysical estimates of the visual performance for moderate amount of defocus (within 1 D), whereas the other parameter (log_Vol D-P) is well correlated for larger ranges of defocus (within 2 D) and for different pupil diameters. These results suggest that optical measurements could be used for clinical testing of ophthalmic optics. (Optom Vis Sci 2002;79: 60-67)**

Key Words: retinal image, modulation transfer function, contrast sensitivity function, visual acuity, defocus

In most clinical studies of visual performance, visual acuity (VA) and contrast sensitivity function (CSF) are measured. Although these psychophysical estimates of spatial vision are quite useful, obtaining accurate results of the CSF is time-consuming, and the collaboration of the subjects is required. In some cases, this limits their use, in particular in those studies where a large number of conditions need to be analyzed. This is generally the case when testing the performance of ophthalmic optics. In addition, it seems appropriate to use purely optical methods to estimate the ocular image quality because they are objective. One option may be to measure the retinal image quality objectively. In recent years, different optical methods have been developed that allow the ocular optical image quality in near to clinical conditions to be obtained. The double-pass method provides the modulation transfer function (MTF) and the double-pass retinal images[1–3]. The Hartmann-Shack wave-front sensor[4–6] measures the ocular aberrations. These methods permit the optical performance to be rapidly estimated, and they are comfortable for the subjects. In general, image quality parameters can be extracted from both, double-pass images and aberrations; i.e., the Strehl ratio or the root-mean square of the wave-front. These parameters are easily computed for many conditions, which is desirable for ophthalmic testing.

However, as psychophysical estimates of visual performance are widely used and, perhaps more importantly, are well understood by clinicians, it is desirable that their relationship with optical measurements should be as fully understood as possible. Visual performance for different defocus has been widely studied[7–12] for a large variety of targets and conditions, using both optical and psychophysical measurements. Depth of focus in the eye has been also a matter of extensive interest in previous studies.[13–16]

In this context, we explore in this paper the correlation between subjective and double-pass optical estimates as a function of defocus. If optical-based parameters appear to be well correlated with psychophysical parameters, then the optical measurements, which are, in general, easier to obtain, could be used in clinical studies.

METHODS

Apparatus for Double-Pass, CSF, and VA Measurements

A schematic view of the apparatus used is shown in Fig. 1. It is a double-pass (DP) system[1–3] that has been adapted to yield objec-

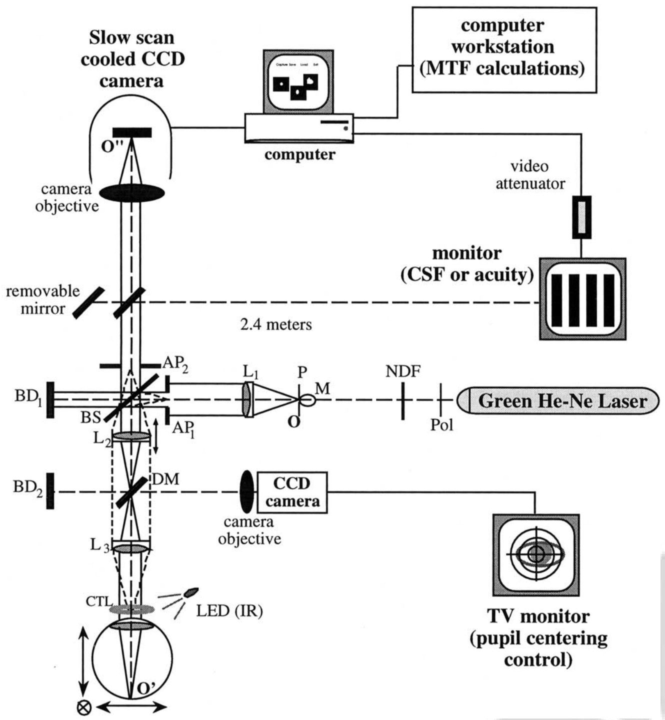

FIGURE 1.

Experimental setup. Pol, polarizer; NDF, variable neutral density filters (ND = 0.5 to 2.5); M, microscope objective; P, pinhole; O, point object; L_1, L_2, L_3, achromatic lenses; AP_1, AP_2, artificial entrance and exit pupil; BS, pellicle beam splitter; BD_1, BD_2, light traps; DM, dichroic mirror; CTL, cylindrical trial lenses; IR, infrared; O', image of point object; O'',.

tive measurements of the retinal image quality (i.e., ocular optical transfer function, MTF) and psychophysical measurements of visual performance (CSF and VA) under the same conditions.

The DP apparatus has been extensively described elsewhere. In summary, the double-pass retinal images were obtained with monochromatic green light (543-nm wavelength) from a He-Ne laser. The beam first passes through a linear polarizer (pol), and a neutral density filter (NDF) is chosen to permit the subject to use the point object as a comfortable fixation target during centering. This filter is removed during the exposure time. The beam is expanded by a 20× microscope objective (M) and filtered by a 10-μm pinhole (P), which acts as point object (O). The emerging beam is collimated by lens L_1 (f' = 200 mm). The entrance artificial pupil (AP_1) is conjugated with the eye pupil plane. The light is reflected toward the eye by a pellicle beam splitter. The beam passes through an afocal system consisting of two equal lenses, L_2 and L_3 (f' = 100 mm), and the eye forms the image (O') of the point source on the retina. A small fraction of the light is reflected back, passing again through the optical media of the eye (second pass), lenses L_2 and L_3, the beam splitter, and a second artificial pupil (AP_2). This pupil is conjugate with the eye's pupil plane and acts as the effective exit pupil if the natural pupil of the eye is dilated. In our measurements, the sizes of the pupils, AP_1 and AP_2, were equal because we were interested in calculating the MTF, at the cost of losing the phase information.[17] A camera objective with a 100-mm focal length forms the aerial retinal image in a scientific-grade slow-scan CCD camera (Compuscope CCD 800, with an array of 768 × 512 pixels of 9 μm each pixel and a 14-bit A/D converter). The exposure level at the cornea during the collection of the double-pass images was always lower than 100 nW for the 4 s exposure. This corresponds to approximately 0.5 μW/cm^2 for the 5-mm diameter entrance pupil used in this study, more than two orders of magnitude below the limit set by safety standards.[18]

The subject's head was stabilized by a chin rest attached to a three-axis micropositioner. Through the dichroic mirror, a CCD video camera monitored the centration of the natural pupil with respect to the measuring beam when the front of the eye was illuminated by an array of infrared LED's. Centration of the pupils was achieved by displacing the subject's head using the micropositioner. During the entire exposure duration, the subject was continuously recentered to the correct position. The best focus for each subject and the additional positions of defocus were obtained by moving the lens L_2 with respect to L_3. The subjects' astigmatism was corrected with cylindrical trial lenses.

By means of a removable mirror, the monitor used to produce the visual stimulus for the CSF and VA measurements was seen through the same optical path as that used for the MTF measurements. This assured that all functions (optical and pychophysical) were measured using exactly the same experimental conditions. To measure the contrast sensitivity, vertical sinusoidal patterns were generated by a computer using a MATROX-Magic frame grabber and presented using the green gun of a RGB monitor (central wavelength of 530 nm with an approximate half-width at half-height of 35 nm). We incorporated a video attenuator[19] to have enough gray levels on the monitor (12 bits). The average luminance of the screen was 40 cd/m^2; it was located at a distance of 2.4 m from the subject, with the test subtending 4° of visual field. The same monitor under the same conditions was also used for the visual acuity measurements. A computer program presenting lines of the Regan chart was used. Eight letters randomly chosen for each line were presented for each required size. By counting the number of letters correctly identified by the subject in the first line with errors, the VA was estimated (each error adds 0.0125 logarithm of the minimum angle of resolution [logMAR]).

Experimental Procedure

We evaluated how the optical (ocular MTF) and psychophysical measurements of optical performance (CSF and VA) compared with each other as a function of defocus. All measurements were obtained with two different artificial pupil diameters: 3 and 5 mm. The measurements were carried out in sessions distributed over several days, with the accommodation of the subjects paralyzed with cyclopentholate (1%). Following were the main conditions of the experiment.

The measurements were taken in three subjects with normal vision after ophthalmic testing: a 23-year-old female (subject AN) (right eye) and two males, one 36 years old (subject PA) (right eye) and one 24 years old (subject EV) (left eye). By moving the lens L_2 with respect to L_3 and placing appropriate cylindrical trial lens to maximize the peak intensity of the double-pass aerial image recorded by the CCD camera, we objectively determined the best refractive state with 3 and 5 mm pupil sizes. Thus, we obtained the refraction of the subjects:
AN: −4.35 −0.50 × 7 for a 3-mm pupil; −4.60 −0.50 × 7 for a 5-mm pupil.

PA: −1.65 for the two pupil diameters.

EA: −1.50 −0.25 × 100 for the two pupil diameters.

Complete series of measurements (DP retinal images, CSF's, and VA) were obtained for best focus (zero defocus) and eight additional positions of defocus, making the eye myopic +0.25, +0.50, +1.00, and +2.00 D and making the eye hypermetropic −0.25, −0.50, −1.00, and −2.00 D.

To obtain the CSF, for each selected spatial frequency (6, 12, 18, and 24 cpd), three values of contrast threshold were obtained using the method of adjustment (starting randomly from maximum or minimum contrast), and the mean value and standard deviation were computed.

Optical and Psychophysical Parameters

From the DP images, we computed the two-dimensional MTF and the Strehl ratio as image quality parameters. The DP images were recorded as 256 × 256 pixel × 14-bits images. A background image was acquired without the eye in the system. The final DP image is the average of two 4-s exposures with subtraction of the background image. To obtain the two-dimensional single pass ocular MTF, the square root of the Fourier transform of the final aerial retinal image was calculated. The peak that appears at zero frequency in the modulus of the Fourier transform of the retinal images due to the background in the double-pass images was removed in every image by using the procedure in the Fourier domain described previously.[2] The one-dimensional MTF was calculated as the radial projection (averaging over all orientations) of the final two-dimensional MTF. The Strehl ratio was also computed. Strictly, this parameter is defined as the quotient between the intensity peak in the system's point-spread function and the diffraction-limited point-spread function, or alternatively as the quotient between the volume under the two-dimensional MTF's of the considered system and the diffraction-limited system. Instead of using these procedures, we computed here a simplified Strehl parameter that provides a very similar description, defined as the ratio of the area under the one-dimensional MTF (Area) to that of the corresponding diffraction-limited MTF ($Area_d$) for the same pupil diameter. Fig. 2 presents a schematic diagram of the calculation procedure. In addition to the Strehl ratio, two other parameters were also computed from the DP images: the logarithm of the volume under the double-pass image when the central peak was normalized to one (log_Vol D-P) and the width of the MTF (in cycles per degree) at the arbitrary modulation value of 0.35 (W_MTF).

The CSF data expressed as log (sensitivity) and linear (spatial frequency) were fitted by linear functions. The area under the fitted CSF, between 6 cpd and the cutoff frequency (determined as the spatial frequency value yielding a CSF value of one) represented in a logarithmic scale with the spatial frequency in linear scale (Area

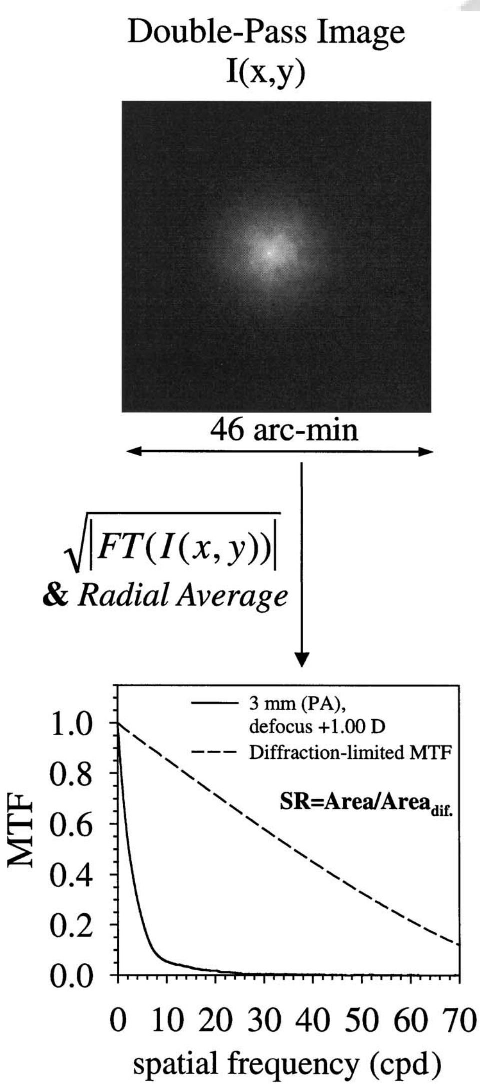

FIGURE 2.

Optical calculation procedure, for subject PA (pupil 3 mm, defocus +1.00 D). SR, Strehl ratio; MTF, modulation transfer function.

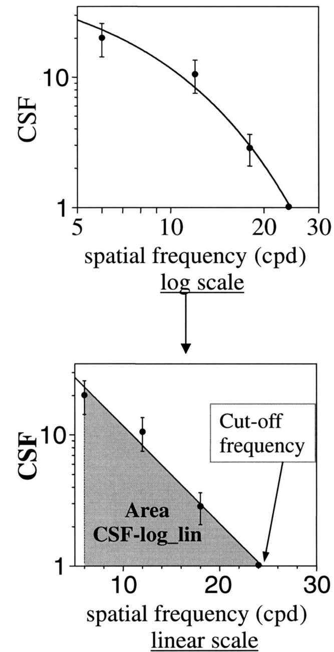

FIGURE 3.

Contrast sensitivity function (CSF) and Area CSF-log_lin for subject PA (pupil 3 mm, defocus +1.00 D). Each value is shown with error bars (standard deviation). Area CSF-log_lin, area under the fitted CSF represented in a logarithmic scale with the spatial frequency in linear scale.

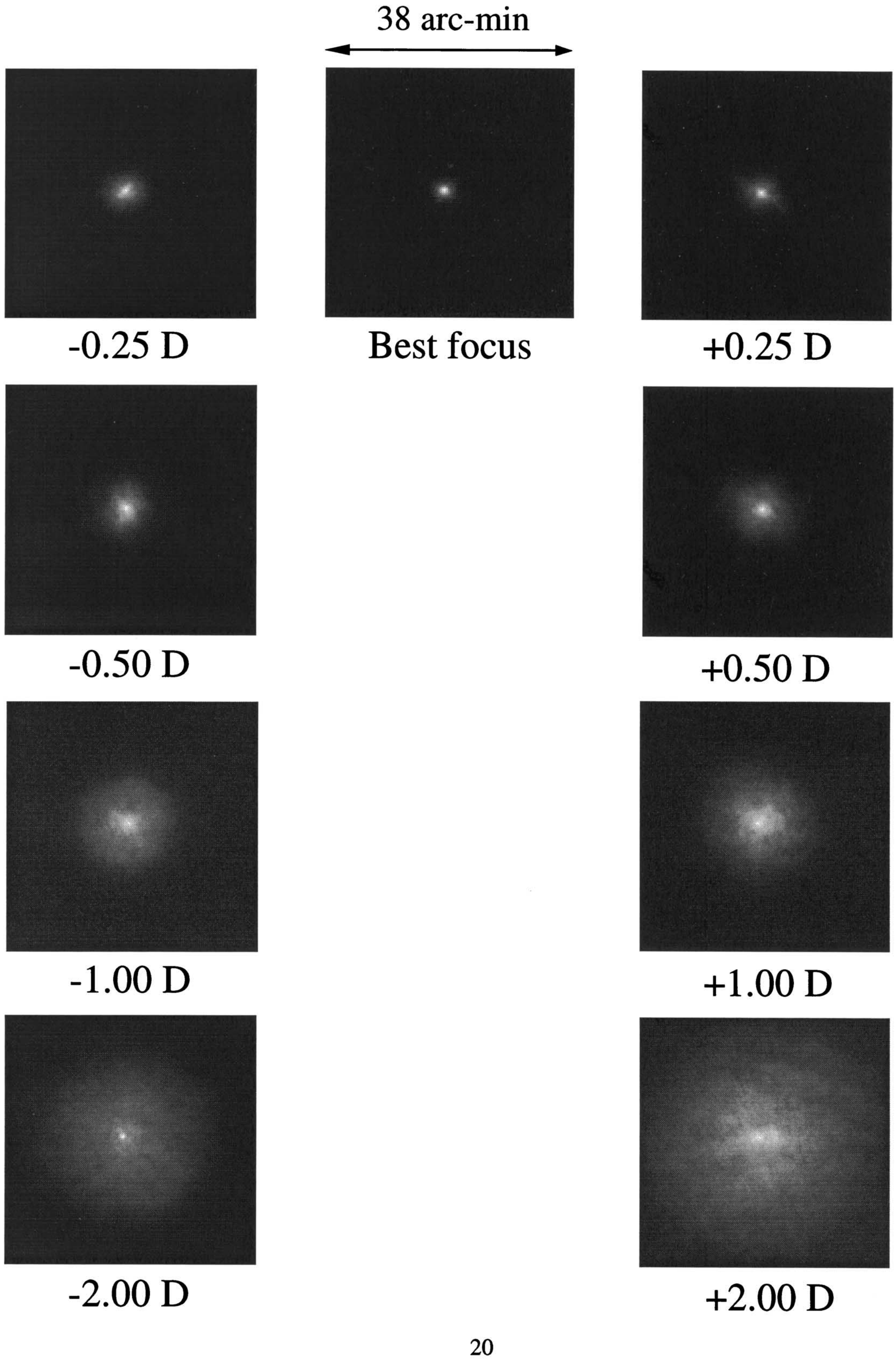

FIGURE 4.
Double-pass images of the subject PA for all defocus. Diameter pupil: 3 mm.

CSF-log_lin), was used as the parameter to characterize the CSF. Fig. 3 shows the CSF with the spatial frequency in logarithmic scale and in linear scale to clarify how this parameter (Area CSF-log_lin) is determined and its meaning.

To study the correlation between optical and psychophysical parameters, we represented two parameters in the same figure. The data were fitted to a linear equation using the least-mean-squares procedure. This algorithm seeks the values of the parameters that

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