Average Optical Performance of the Human Eye as a Function of Age in a Normal Population

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PURPOSE. To determine the average optical performance of the human eye, in terms of the modulation transfer function (MTF), as a function of age.

METHODS. An apparatus was constructed to measure the ocular MTF, based on the recording of images of a green, 543-nm laser-point source after reflection in the retina and double pass through the ocular media. MTFs were computed from the average of three 4-second-exposure double-pass images recorded by a slow-scan, cooled charge-coupled device camera. The ocular MTF was measured for three artificial pupil diameters (3 mm, 4 mm, and 6 mm) with paralyzed accommodation under the best refractive correction in 20 subjects for each of three age categories: young subjects aged 20 to 30 years, middle-aged subjects aged 40 to 50 years, and older subjects aged 60 to 70 years. The selected subjects passed an ophthalmologic examination, excluding subjects with any form of ocular or retinal disease, spherical or cylindrical refractive errors exceeding 2 D, and corrected visual acuity lower than 1 (0.8 in the older age group).

RESULTS. The average MTF was determined for each age group and pupil diameter. A two-parameter analytical expression was proposed to represent the average MTF in each age group for every pupil diameter. The ocular MTFs declined as age increased from young to older groups. The SD of the MTF results within age groups was lower than the differences between the mean for each group.

CONCLUSIONS. The average optical performance of the human eye progressively declines with age. These MTF results can serve as a reference for determining mean ocular optics according to age. (*Invest Ophthalmol Vis Sci.* 1999;40:203-213)

Aging affects different aspects of the visual system in humans (see references 1 and 2 for a review). In particular, spatial vision deteriorates with age: The contrast sensitivity function (CSF) is lower in older subjects, especially at mid and high spatial frequencies.[3] The relative contribution of optical versus neural factors to this deterioration is still a matter of some controversy, although the optical performance of the eye seems to be reduced on average with age. Artal et al.[4] showed that the mean ocular modulation transfer function (MTF) in a group of older subjects was lower than the average MTF in a group of younger subjects. This result, although it was obtained in a small sample, suggests that ocular aberrations, besides intraocular scattering, increase with age. Burton et al.,[5] by comparing CSFs obtained with laser interferometry and con-

ventional gratings, also support the idea of a decreasing optical image quality with age.

In this context, an extended and more detailed study of ocular optics according to age contributes to better understanding of how the eye's optics change with age and defines standards of the average retinal image quality, representing subjects of different ages. The definition of an average reference of the optical image quality for different age groups is useful for ophthalmic optics design and manufacturing. If substantial changes in the ocular performance occur with age, it is unreasonable to use as a reference for older subjects the same estimates of ocular optics obtained in a young, and usually small, population.

The purpose of this study was to evaluate the influence of age on retinal image quality by determining the average optical performance of the human eye, in terms of the MTF, in three groups of healthy subjects in different age ranges. To minimize systematic errors that could affect the results, the experiments were performed under carefully controlled optical conditions in every subject (i.e., best focus under paralyzed accommodation), with fixed-diameter artificial pupil and controlled relative centering of the artificial pupil in relation to the natural pupil. The criteria for selection of the subjects for each group were previously determined to represent a normal healthy population. A major problem was defining the conditions of normality,[6] especially in older subjects.

Finally, because previous measurements of the retinal image quality were not performed routinely, but only under laboratory experimental conditions, an initial important part of this study consisted of developing an adapted version of the
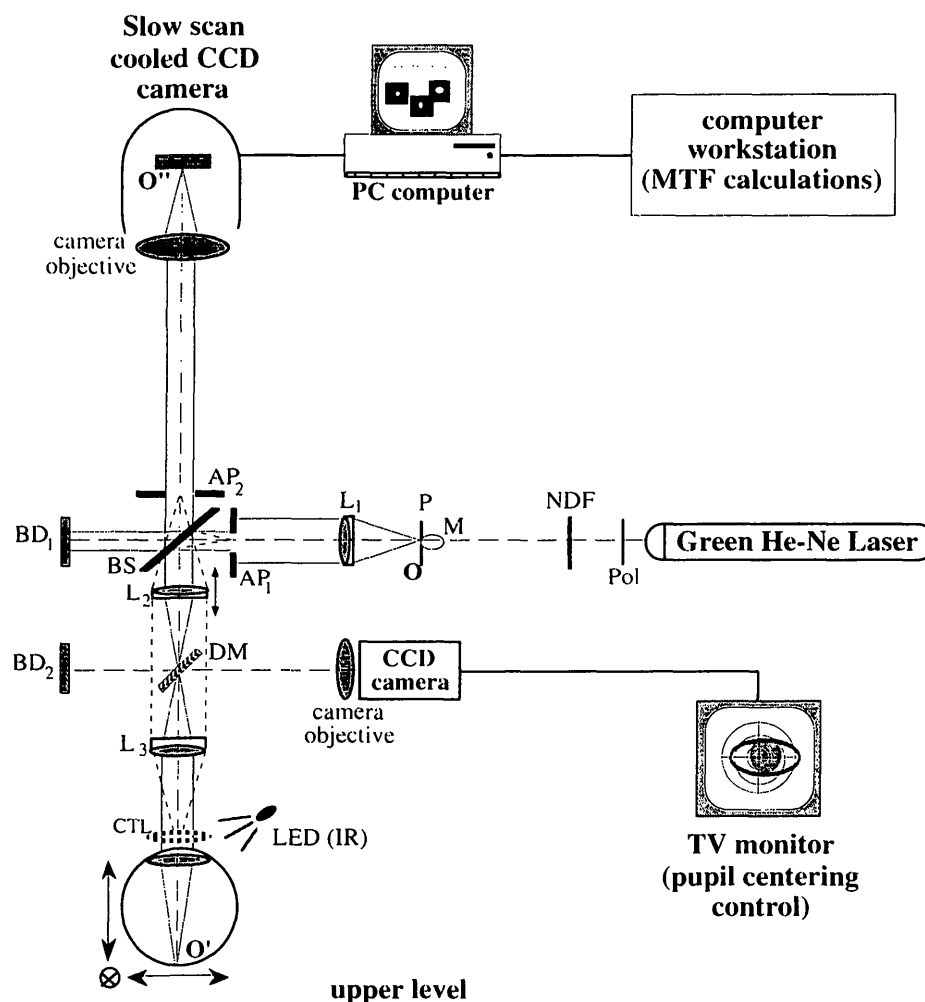
FIGURE 1. Schematic of the double-pass apparatus (see the Methods section for details). CCD, charge-coupled device; MTF, modulation transfer function; O", double-pass retinal image; AP, artificial pupil; BD, black diffuser; BS, beam splitter; L, lens; P, pinhole; M, microscope objective; NDF, neutral-density filter; Pol, polarizer; DM, dichroic mirror; CTL, cylindrical trial lens; LED (IR), infrared light-emitting diode; O', point source on retina.

double-pass apparatus to measure the ocular MTF accurately in a relatively large population under conditions that were comfortable for the subjects.

METHODS

Subjects

Sixty healthy subjects, distributed in three age groups participated in the study: group A, 20 young subjects (13 women, 7 men; age range, 20–30 years; mean age, 24 ± 3 years); group B, 20 middle-aged subjects (12 women, 8 men; age range, 40–50 years; mean age, 46 ± 3 years); group C, 20 older subjects (9 women, 11 men; age range, 60–70 years; mean age, 63 ± 3 years). The subjects were selected after they passed a complete ophthalmologic examination. We used the the following exclusion criteria to limit the study population to healthy eyes: refractive error (spherical equivalent) more than 2 D, keratometric astigmatism more than 1.5 D, corrected visual acuity lower than 1 (0.8 in subjects in group C), any previous surgery on the eye to be tested, amblyopia, any

known ocular or retinal disease (assessed by slit lamp with and without retroillumination using standard clinical criteria), and any systemic diseases affecting refractive error (diabetes or disorders of the nervous system). The study followed the tenets of the Declaration of Helsinki, and signed informed consent was obtained from every subject after the nature and all possible consequences of the study had been explained.

Double-Pass Apparatus to Measure Ocular MTF

The MTF is widely used for image quality evaluation of optical systems.[7] It yields the relation between the contrast of an object and its associated image at every spatial frequency. MTF is probably the most comprehensive function known for analyzing the overall optical performance of the eye and can be compared with the commonly used psychophysical CSF. An objective procedure for measuring ocular MTF is based on recording and processing double-pass retinal images of a point source—the ophthalmoscopic or double-pass method.[8-10]

We constructed a double-pass apparatus, similar to that proposed by Santamaría et al.,[10] incorporating new and im-
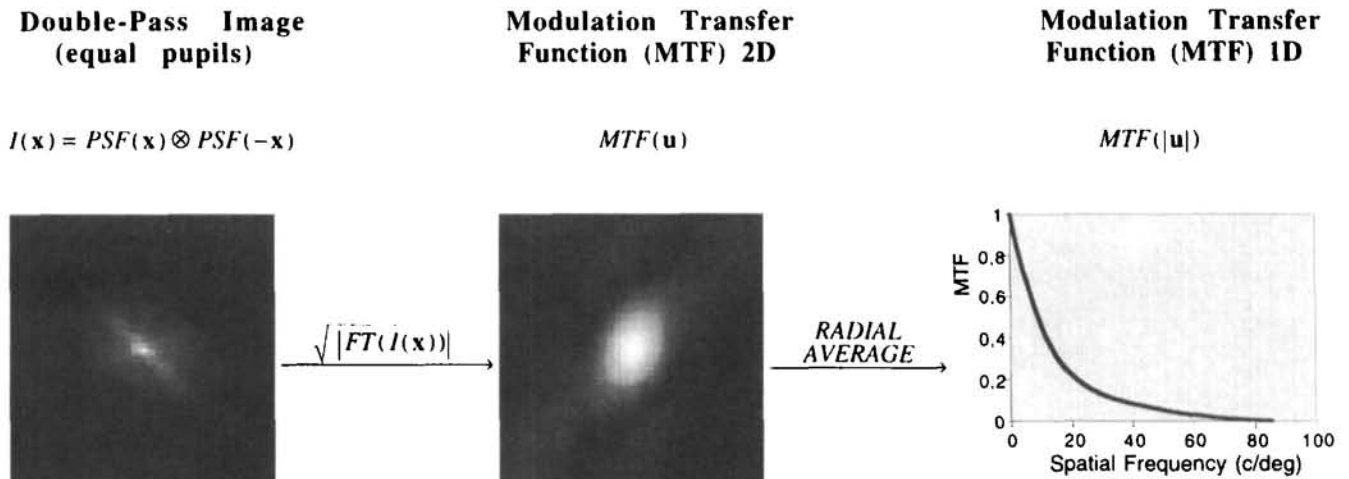
Double-Pass Image (equal pupils)	Modulation Transfer Function (MTF) 2D	Modulation Transfer Function (MTF) 1D
$I(x) = PSF(x) \otimes PSF(-x)$	$MTF(u)$	$MTF(|u|)$

FIGURE 2. Diagram of the calculation procedure. The double-pass image ($I[x]$), recorded with equal pupil diameters, is the autocorrelation of the retinal point-spread function (PSF[x]), where x is a two-dimensional spatial coordinate. $MTF(u)$ is the square root of the modulus of the Fourier transform (FT) of the double-pass image, with a two-dimensional spatial frequency coordinate. The one-dimensional modulation transfer function (MTF) was computed averaging the two-dimensional MTF across all directions (radial average).

proved features adapted to routine measurement of ocular MTF in naive subjects. Additional details on the basis, operation, and limits of the double-pass method are found in several recent articles.[11-14] The technique is based on recording images of a point source projected on the retina after retinal reflection and double pass through the ocular media. From these images (double-pass images) the retinal image of the point source, the point-spread function (PSF), and ocular MTF are calculated. A schematic diagram of the apparatus is shown in Figure 1. The light source is a 5-mW green (543-nm) He-Ne laser (05 LGR 193; Melles Griot, Irvine, CA). This wavelength is approximately centered in the visible spectrum and provides the best double-pass image quality.[15] A neutral-density filter (NDF) and a linear polarizer (Pol) are placed in front of the laser. The beam is spatially filtered (microscope objective [M] 10× and a 25-μm pinhole [P]) and collimated by a 100-mm lens L_1. The artificial entrance pupil (AP$_1$) is conjugated with the eye pupil plane. After reflecting in the pellicle beam splitter (BS), the beam passes the 100-mm lenses L_2 and L_3, and the eye forms the image of the point source (O) on the retina (O'). Lenses L_1, L_2, and L_3 are achromatic doublets with antireflection coatings for the visible spectrum. A second artificial pupil (AP$_2$), placed after the pellicle, is also conjugated with the eye's pupil plane and acts as the effective exit pupil (when the natural pupil of the eye is dilated). A camera objective with 100-mm focal length forms the double-pass retinal image (O") on a slow-scan, scientific-grade, cooled charge-coupled device (CCD) camera (Compuscope CCD 800; Santa Barbara, CA) that integrates the light coming back from the retina during the exposure time. The retina and the CCD camera's plane are conjugated with a magnification of 6.06. The field of view for the 256 × 256-pixel images is 79.3 minutes of arc, with a sampling rate in the double-pass images of 0.31 minutes of arc. This corresponds to a resolution in the Fourier domain of 0.75 cycles/deg. This double-pass apparatus was specifically designed for this study in a two-level setup (the shaded area in Fig. 1 shows the elements placed in the upper level of the setup) with mirrors to direct the beam appropriately in the illumination and recording paths (not included for the sake of clarity in Fig. 1). The subject's head was placed on a chin rest mounted on 2-D

positioners allowing the centering of the natural pupil in relation to the artificial pupils.

Experimental Procedure

The subject, positioned on the chin rest with the eye aligned by the experimenter using the control system described later, was instructed to fixate on the point source, conveniently attenuated by an additional neutral-density filter (not included in Fig. 1). During the exposure, this neutral-density filter was removed, and the double-pass image was captured by the CCD camera. For each condition of pupil size or focus, three double-pass retinal images and one background image (with a light trap in place of the eye) were recorded. The duration of each exposure was 4 seconds. Each double-pass image was digitized with 256 × 256 pixels and 14 bits/pixel. The exposure time of 4 seconds was chosen to be long enough to break the coherence of the incident light and to blur the speckle,[10,13] but short enough to avoid eye blinks or subject discomfort.

The ocular image quality largely depends on three factors that must be accurately controlled during the experiments: pupil size, relative centering of the measuring beam and the dilated natural pupil, and the subject's refractive state. In every subject, double-pass images were collected for three artificial pupil diameters (3 mm, 4 mm, and 6 mm) in the first (aperture AP$_1$) and second passes (aperture AP$_2$). The pupil was dilated and the accommodation paralyzed by instilling two drops of 1% cyclopentholate, allowing 5 minutes between drops, and waiting 30 minutes before beginning the measurements. In some of the subjects of group C, a drop of 2.5% phenylephrine was also instilled to dilate the pupil up to 6 mm in diameter.

A subsystem in the setup was used to monitor pupil centering in relation to the measuring beam. It consisted of an infrared light-emitting diode (LED) to illuminate the anterior eye, and a CCD video camera (XC-75; Sony, Tokyo, Japan) with the protective infrared filter removed, which formed the image of the pupil after reflection in a dichroic mirror. The position of the pupil relative to the measuring beam is controlled by the experimenter in a TV monitor. As a practical tool, the corneal reflex was used to follow the eye movements while the double-pass image was captured. Double-pass images collected with
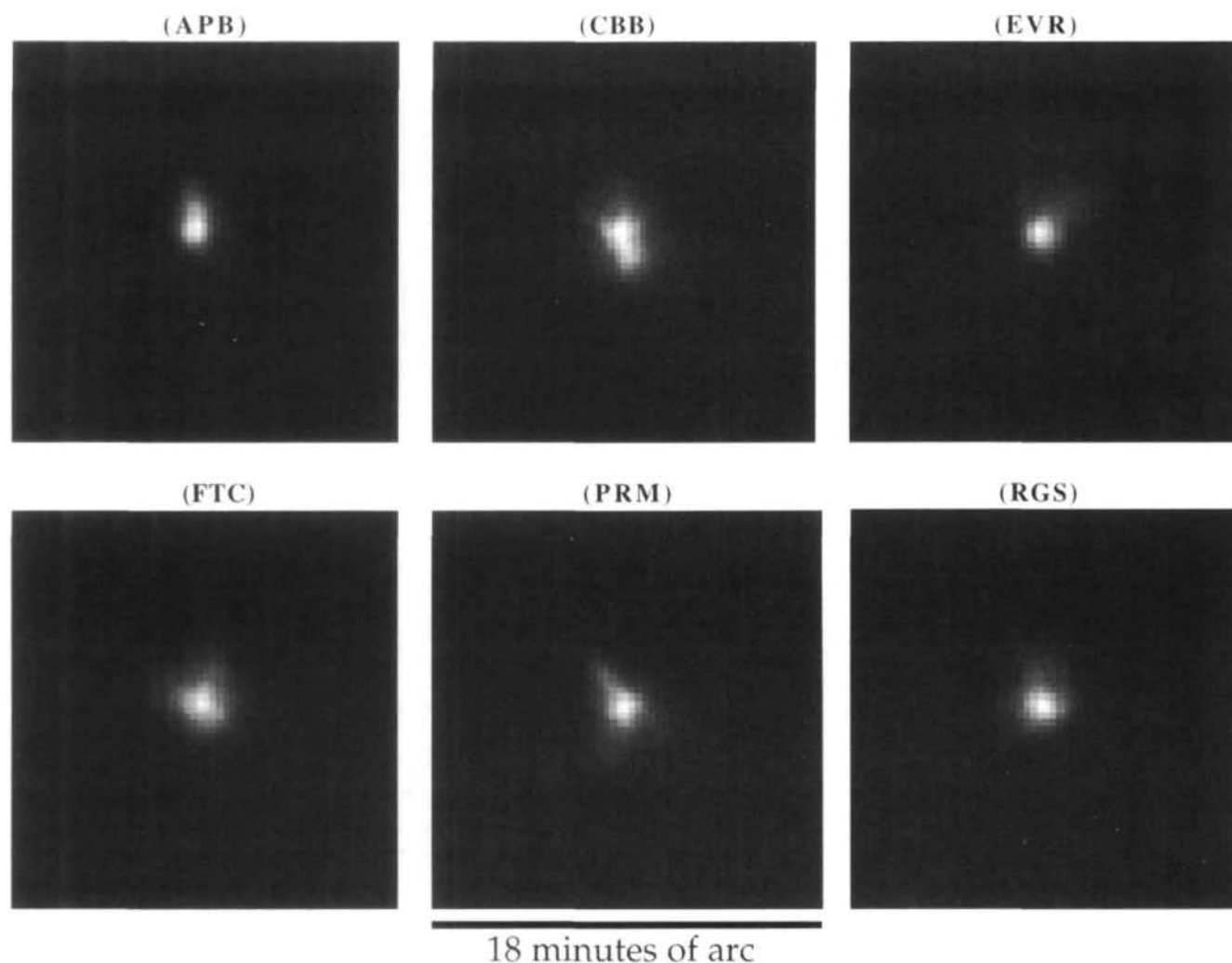
(APB)   (CBB)   (EVR)

(FTC)   (PRM)   (RGS)

18 minutes of arc

FIGURE 3. Central parts (subtending 18 minutes of arc) of the double-pass images obtained with unequal diameters (1.5 mm and 4 mm) in the entrance and exit pupils in six subjects of the younger age group A.

displacements of the corneal reflex larger than 1 mm during the 4-second exposure time were rejected. The number of images rejected because of these movements depended on the subject, ranging from none in most of the younger subjects to a maximum of 25% of the total number images in some of the older subjects.

The spherical refraction in every subject was corrected by moving the relative position of lens L_2 in relation to lens L_3 to achieve the best image quality. In the setup, with those lenses of 100-mm focal length, a displacement of 1 mm corresponded to a change in focus of 0.1 D. If correction for astigmatism was also necessary, an appropriate cylindrical trial lens was placed in front of the eye. The subject's refractive error was estimated first by conventional techniques (subjective refraction and autorefractometer) and was refined in the double-pass experiment by moving lens L_2 (in steps of 0.1 D) in relation to lens L_3 to maximize the peak intensity of the double-pass image recorded by the CCD camera.

The conventional version of the double-pass apparatus with equal size entrance and exit pupils only produces even-symmetric double-pass images.[12] This implies that the information on the ocular asymmetrical aberrations is lost, although

the MTF can be correctly computed from the double-pass images. A simple modification of the double-pass apparatus[13] to obtain information on the actual shape of the retinal PSF consisted of the use of unequal entrance and exit pupil sizes, with one of them, usually the entrance pupil, being small enough (we used 1.5-mm pupil diameter) to produce a retinal image similar to a diffraction-limited pattern. We recorded additional double-pass images with a 1.5-mm and a 4-mm diameter pupil in the entrance and exit pupil, respectively, in several subjects.

The typical exposure level in the cornea during the collection of double-pass images was approximately 50 nW. This corresponds to approximately 0.4 μW/cm^2 for a 4-mm diameter entrance pupil. The maximum permissible exposure, according to the standards for safe use of lasers for intrabeam viewing is approximately 1 mW/cm^2 up to a 100-second exposure (American National Standard Institute Z136.1; 1993). The used light levels in the apparatus are more than three orders of magnitude below safety standards. We have assumed a cumulative exposure time of up to 240 seconds, which should correspond to approximately 60

exposures of 4 seconds' duration obtained one after the other, clearly exceeding the actual procedure performed.

Calculations from Double-Pass Images

All the double-pass images were first stored in a personal computer and transferred later to a UNIX computer workstation, where the whole image-processing analysis to calculate the MTF was performed. The final double-pass image was the result of averaging three 4-second exposure images and subtracting the background image. The double-pass image was the autocorrelation of the retinal image (PSF),[12] and the MTF was the square root of the modulus of the Fourier transform of the average double-pass image. Because a low-light-level pedestal appeared in the double-pass images, an appropriate DC peak correction in the MTF had to be performed (see reference 13 for additional details on this analysis). From the two-dimensional MTFs, one-dimensional MTFs were obtained by averaging across all directions (example in Fig. 2). The Strehl ratio[16] characterized optical performance. The ratio is defined as the quotient between the intensity peak in the system's PSF and the diffraction-limited PSF, or alternatively, as the quotient between the volumes under the 2-D MTFs of the considered system and the diffraction-limited system. As an optical quality index, we computed a simplified Strehl parameter: the quotient between the area under the measured 1-D MTF and the area under the diffraction-limited MTF for the same pupil diameter.

RESULTS

A sample of double-pass images recorded with unequal entrance (1.5-mm) and exit (4-mm) pupil diameters in the apparatus in six young subjects of group A is shown in Figure 3. These images depict the intersubject variability in the retinal image. Although the average spread of every image is approximately similar within the same age range, there are substantial differences in the shape of the images, indicating the variability of the aberrations among subjects.

The MTFs for every subject of group A for equal 4-mm entrance and exit pupil diameters are shown in Figure 4A, and the average MTF for that group and error bars representing the SD are shown in Figure 4B. These figures show the variability in MTFs among subjects within a single group, in this case the younger subjects. As an example, with a spatial frequency of 10 cycles/deg the mean modulation is approximately 0.5 ± 0.07 (SD). Figure 5 shows the MTFs obtained in every subject who participated in the study (groups A, B, and C) for the three pupil diameters used. These figures show the actual distribution of MTFs in all the subjects.

The average double-pass images for every age group and pupil diameter are shown in Figure 6. As a result of the averaging process, these images tended to a radially symmetric shape. A direct comparison of the spread of these double-pass images showed a net decrease of the optical performance with age for every pupil diameter. The relative increase in the spread of the double-pass images was larger with the 3-mm pupil diameter. Within the same age group, the double-pass images became more extended as the pupil diameter increased, with the relative increase being smaller in the group of older subjects. In Figure 7 the average MTFs for every age group and pupil diameter are shown: 3 mm (Fig. 7A), 4 mm
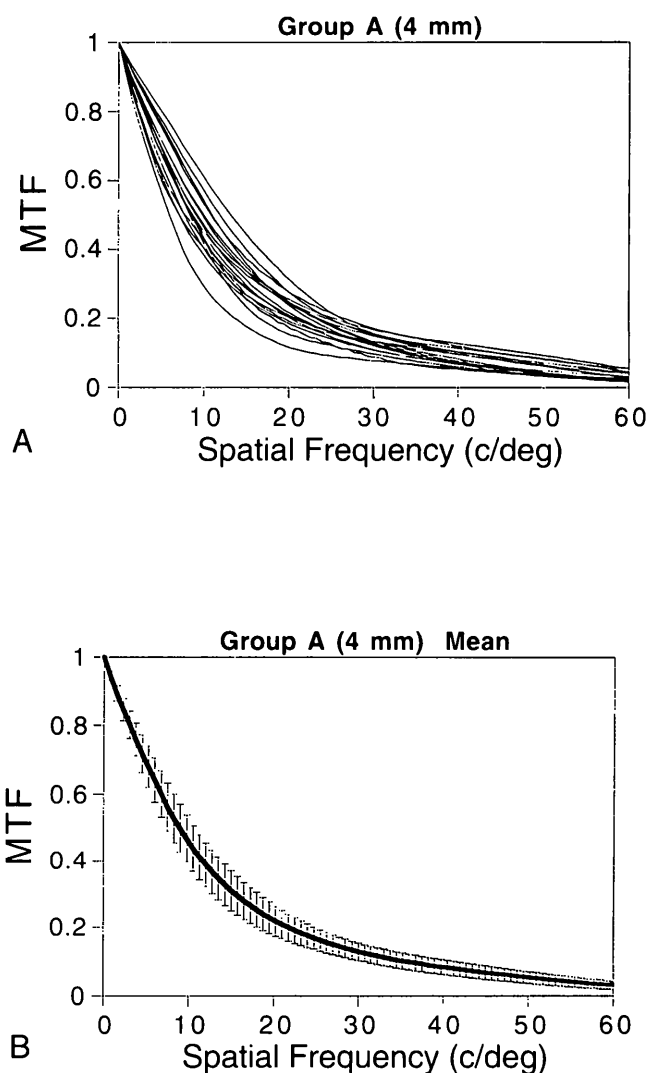

Group A (4 mm)

Group A (4 mm)   Mean

FIGURE 4. (A) Modulation transfer functions (MTFs) for every subject tested in group A with a 4-mm pupil diameter. (B) Mean MTF for group A with 4-mm pupil diameter, with error bars representing the SD. c/deg, cycles per degree.

(Fig. 7B), and 6 mm (Fig. 7C). In Figure 8 the same results are shown but with each panel containing the average MTFs for the three pupil diameters studied in each age group: A (Fig. 8A), B (Fig. 8B), and C (Fig. 8C). These results show the well-known reduction of the MTF with larger pupil diameters in every group and also a consistent decline of the average MTF in the older groups compared with the MTFs in the younger group.

We performed a curve fit to the average MTFs using a two-parameter analytical expression similar to that proposed by Artal and Navarro[17] and provided by:

$$M(u) = \frac{1}{4}\,[3\,\exp(-u/a) + \exp(-u/b)] \qquad (1)$$

where $M(u)$ is the one-dimensional MTF, u is the spatial frequency (in cycles per degree), and a and b are the two parameters (in cycles per degree). This sum of two exponential functions provides a good fit to the experimental MTF data.
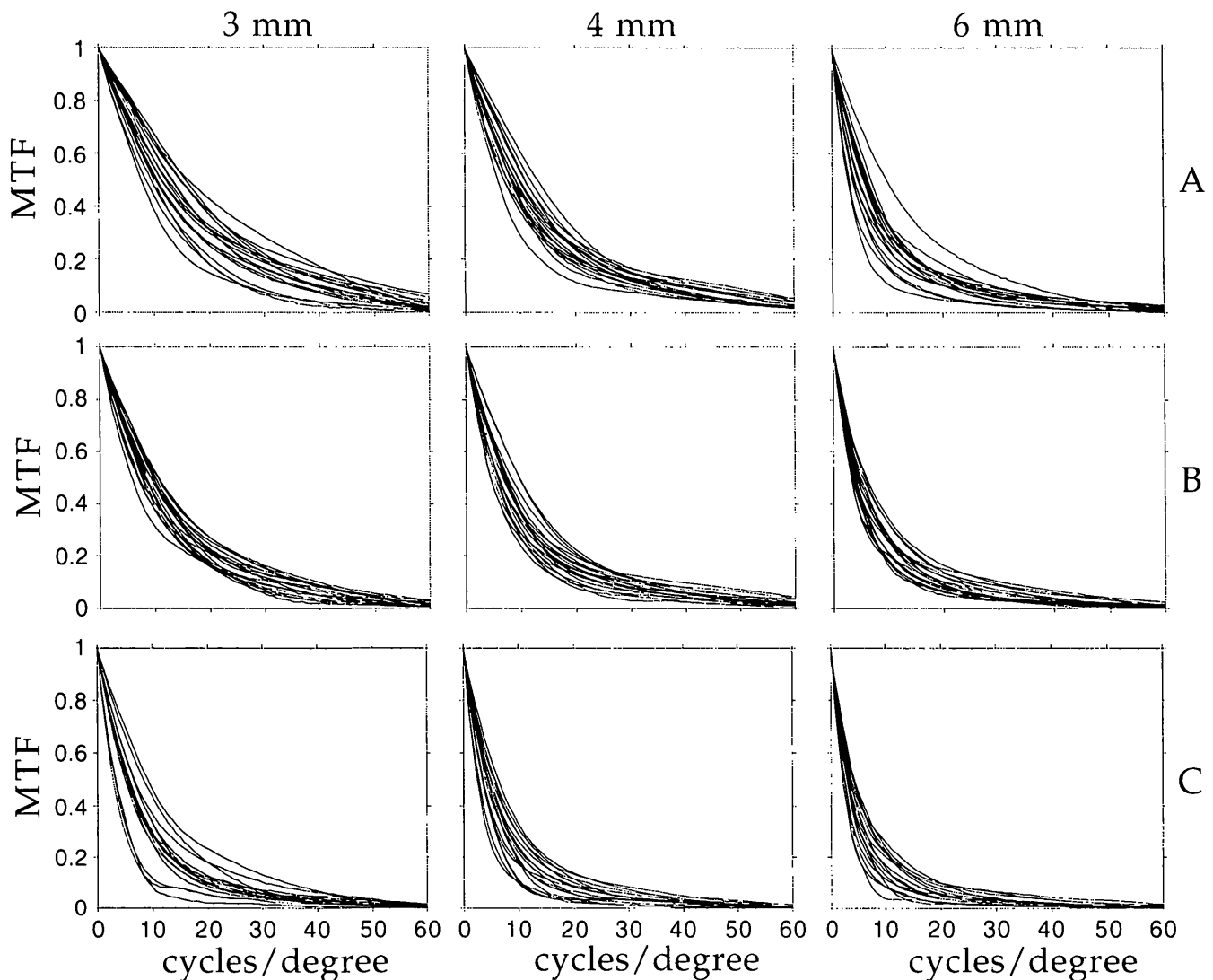
FIGURE 5. Modulation transfer functions (MTFs) for every subject tested in the three age groups (A, B, C) with three pupil diameters: 3 mm, 4 mm, and 6 mm.

Parameter *a* is an approximate estimate of the width at one-third height in the MTF and consequently can be regarded as a global index of image quality, similar to the Strehl ratio. Parameter *b* in the second weighted exponential is mainly used to improve the quality of the fit at mid to high spatial frequencies. It has no direct meaning, in contrast with parameter *a*. In fact, a single-parameter function (for instance, only an exponential function) could also be used to fit the MTFs, although with a lower-quality fit. Each MTF for every subject and condition was fitted using equation 1. In Table 1 the average values and the SD of the parameters *a* and *b* are shown for every MTF in each of the three age groups and pupil diameters. Table 1 and equation 1 allow easy calculation of the mean MTF for each condition and range of variability. In addition, the values of the SD, especially in parameter *a*, gives an indication of the significance in the differences between age groups and pupil sizes. Based on this parameter, the differences in MTFs among age groups were statistically significant with a confidence level of 99.9%.

The Strehl ratio was computed from the MTFs, as described in the Methods section, for every subject and pupil

diameter. In Figure 9A, the Strehl ratio as a function of every subject's age is shown for 3-mm, 4-mm, and 6-mm pupil diameters, together with a linear regression to the Strehl ratio values for every subject as a function of age. It shows an approximately linear decline in average from ages 20 to 70 (the slopes and regression coefficients for 3-mm, 4-mm, and 6-mm pupil diameters are -0.0046, -0.0032, -0.001; 0.8, 0.83, 0.62, respectively). The average values of Strehl ratio and error bars corresponding to the SD for each group and pupil diameter are shown in Figure 9B. These results further show the decline of the average retinal image quality with age. The differences in the average Strehl ratio among age groups are statistically significant within a confidence level of 99.9% (excepting differences between group A and B with a 6-mm pupil diameter, which yield a confidence level of 95%).

DISCUSSION

We performed a detailed study of the average retinal image quality, using a modified version of the double-pass apparatus,
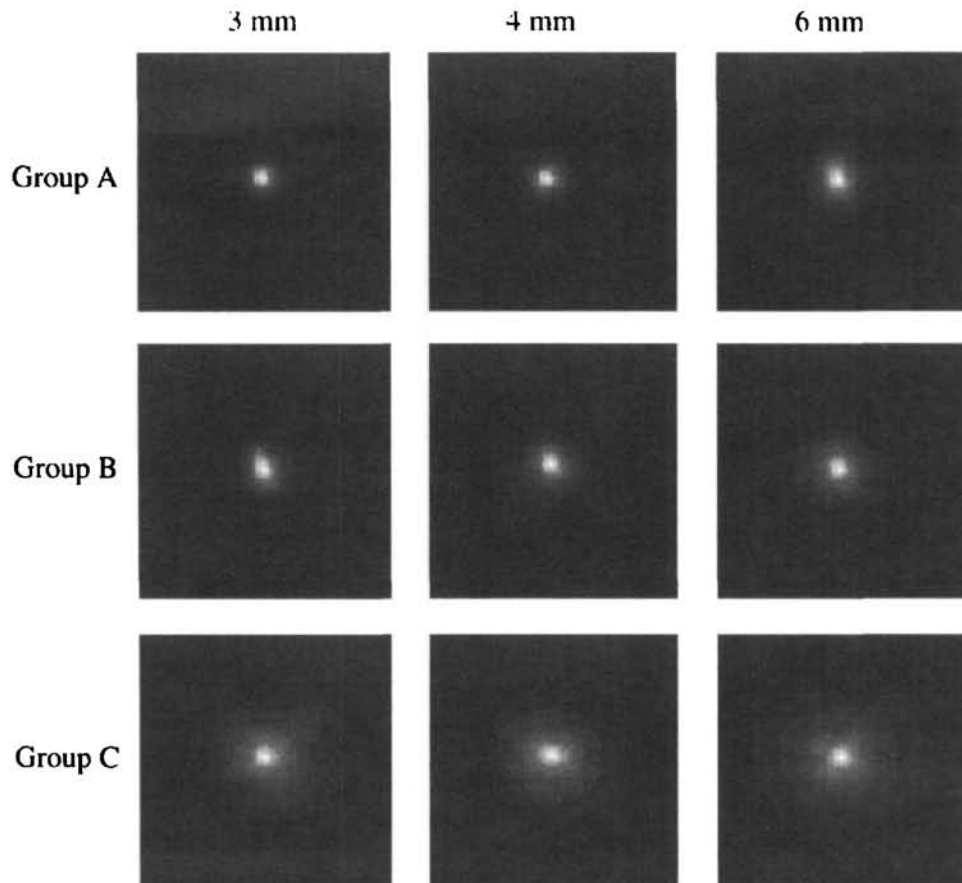
FIGURE 6. Average of the double-pass images recorded in the 20 subjects of each group (A, B, C) with each diameter pupil (3 mm, 4 mm, and 6 mm).

in three groups of healthy subjects of different ages. The apparatus permitted us to obtain the ocular MTF under conditions in which focus, pupil size, and centering were controlled.

The intersubject variability of the retinal image quality within each age group was studied first. After defocus and astigmatism were carefully corrected in every subject, substantial asymmetrical aberrations were found in the fovea, as previously reported.[13,18-21] These asymmetrical aberrations varied greatly from subject to subject. The range of variability in the overall image quality of MTFs within an age group was also significant, although smaller than that found in other studies,[19,21] perhaps because of our careful correction of defocus and astigmatism. The intersubject variability was similar in the three age groups, with the largest variability occurring in the younger subjects with a 3-mm pupil diameter (note the largest value of SD for parameter *a* for that condition in Table 1). This variability is mainly attributable to the actual differences in ocular optics in different subjects. However, several sources of possible errors in the procedure could have contributed to an increase in variability: uncorrected amounts of defocus and astigmatism, errors in pupil centering, abnormal eye movements during double-pass image recording, or small changes in accommodation that occur even in the presence of cycloplegia. These factors were carefully controlled during the collection of the double-pass images, and their impact was thought to be limited. We also evaluated the variability in the measurements in a subject for a given condition. As an example, the SD to estimate the Strehl ratio in a single subject was approximately 5% of the average Strehl ratio value. For comparison, in the case in which we found one of the largest variabilities (group A with 3-mm pupil diameter), the mean Strehl ratio was 0.4 with an SD of 18%.

The average MTFs for the age groups showed a systematic decline in optical performance with age. This result was obtained with every pupil diameter but was more pronounced with small and mid-sized pupil diameters. The differences in ocular optical performance among age groups were statistically significant, with larger reductions in image quality between age groups than those found among subjects of the same age group. These results showed an increase in optical aberrations that caused a deterioration of retinal image with age. We found no differences in retinal image quality with age as a function of the sex of the subjects.

In the present study, ocular optical performance declined approximately linearly throughout adulthood (Fig. 9A). Other parameters in the eye also exhibit a linear variation with age — for instance, the amplitude of accommodation[1] or the thickness of the lens.[22] Incidentally, the Strehl ratio data, when regressed, reaches zero at approximately 120 years of age, in common with other properties of the eye (expect for accommodation).[23,24] However, this linear reduction in overall optical performance differs from the idea that spatial vision functions remain stable up to 50 to 60 years of age and then undergo a rapid decline.[25]

Fitting the average MTFs with a simple two-parameter function (Eq. 1) was a convenient way to summarize the results
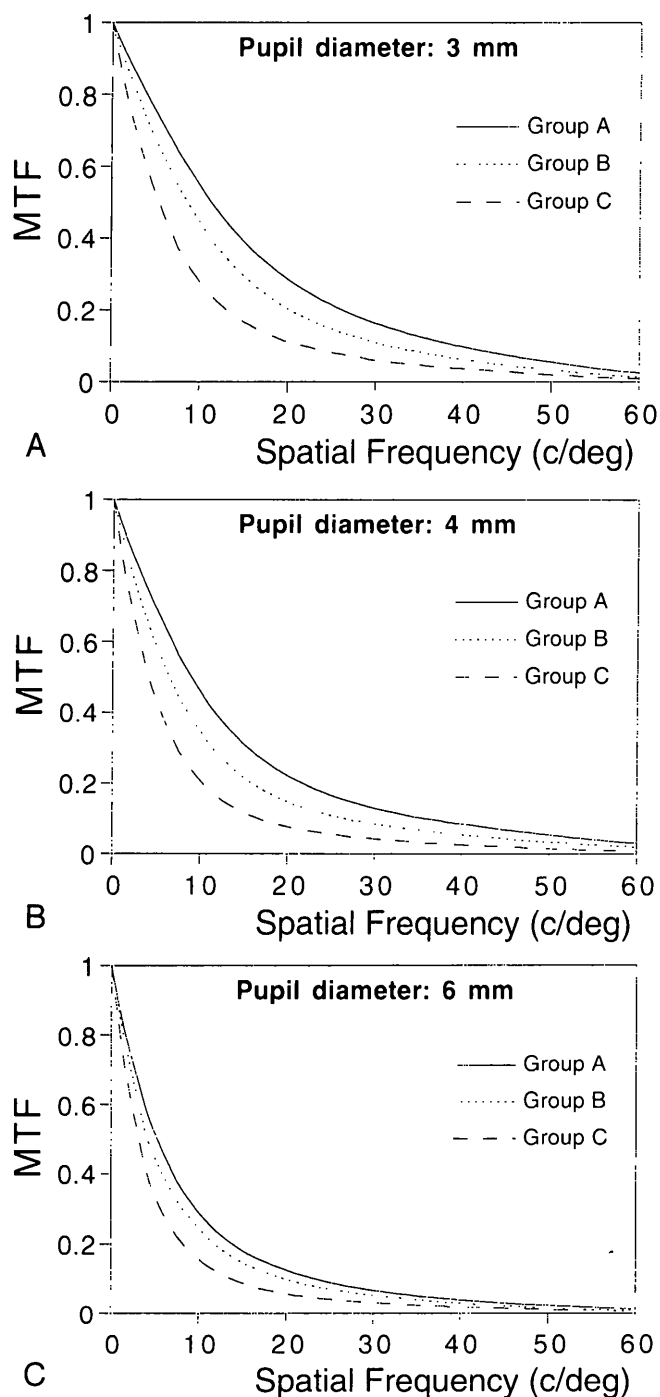
FIGURE 7. Average modulation transfer functions (MTFs) for each group: A (*solid line*), B (*short dashed line*), and C (*long dashed line*), at three pupil diameters: (A) 3 mm, (B) 4 mm, (C) 6 mm. c/deg, cycles per degree.

an increase in optical aberrations, it is important to determine whether some factor other than aberrations could have affected the double-pass measurements with age. One of those factors is intraocular scattering, which increases with age.[26] Scattering produces an approximately uniform halo in the retinal image. Although the relative intensity between the peak in the image and the background was lower in the older subjects, we subtracted a constant value from the double-pass image before computing the MTF. Optical aberrations and intraocular scattering affect the retinal image under normal
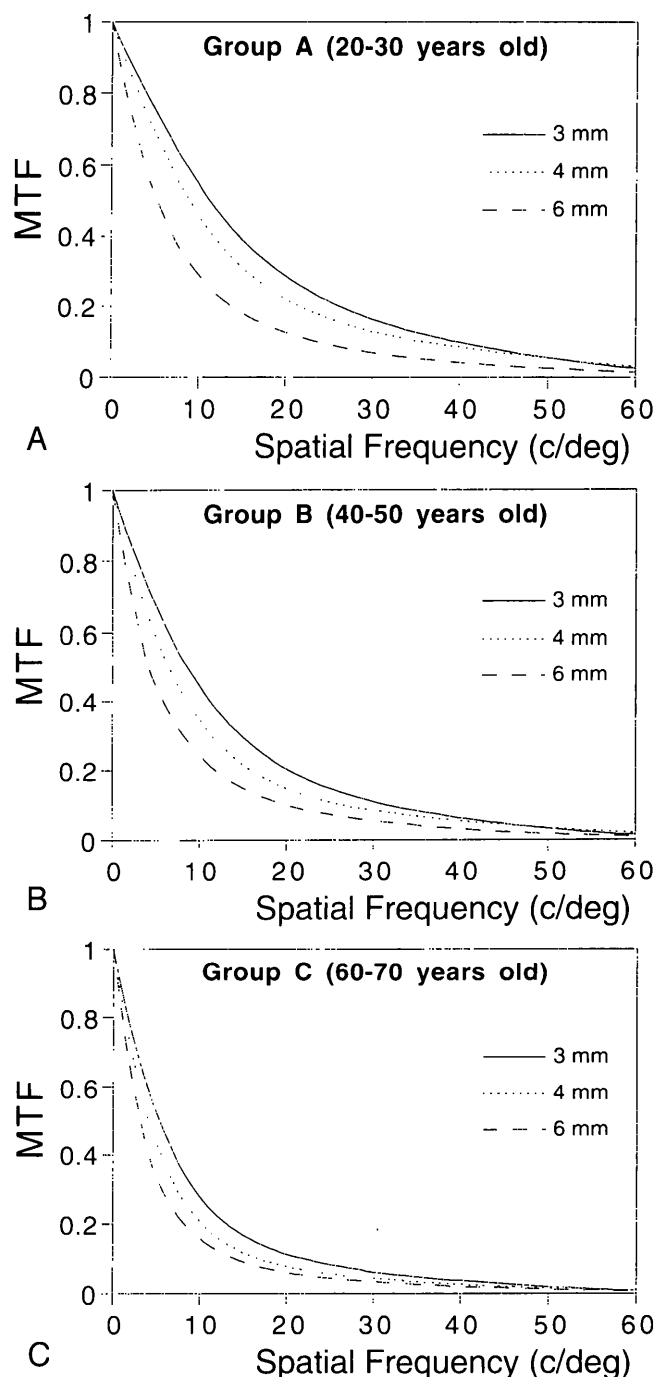

FIGURE 8. Average modulation transfer functions (MTFs) plotted together for the same group for each pupil diameter: 3 mm (*solid line*), 4 mm (*short dashed line*), and 6 mm (*long dashed line*). (A) Group A; (B) group B; (C) group C.

and show the degree of significance of the differences among age groups. It also allows incorporation of these results in any further study in which average optical performance as a function of age is required. In particular, these results could be used as a reference in studies of aging and visual performance or as new standards for different ophthalmic optics applications in which age is considered a relevant factor.

Although the reduction in the MTFs obtained from double-pass images as a function of age seemed to be mostly caused by

TABLE 1. Average Values and Standard Deviation of the Two Parameters in the Analytical Expression of the MTF (Eq. 1) for the Three Age Groups and Pupil Diameters

Pupil Diameter	Group A		Group B		Group C	
	a	*b*	*a*	*b*	*a*	*b*
3 mm	16.12 ± 3.16	17.50 ± 2.42	10.52 ± 1.74	21.30 ± 2.36	5.89 ± 2.10	19.26 ± 4.00
4 mm	10.46 ± 2.30	27.26 ± 1.76	7.15 ± 1.60	23.58 ± 4.15	4.48 ± 1.12	16.01 ± 4.86
6 mm	5.81 ± 1.87	21.68 ± 3.72	4.72 ± 0.84	19.31 ± 4.65	3.34 ± 0.77	14.14 ± 4.67

Values are expressed in cycles per degree and are derived using Equation 1, with *u* representing spatial frequency. MTF, modulation transfer function.

conditions. However, we did not include the effect of scattering in our MTFs because of the procedure we used to compute it. Other investigators have attempted to incorporate the effect of scattering on the MTF by normalizing this function, not to 1,
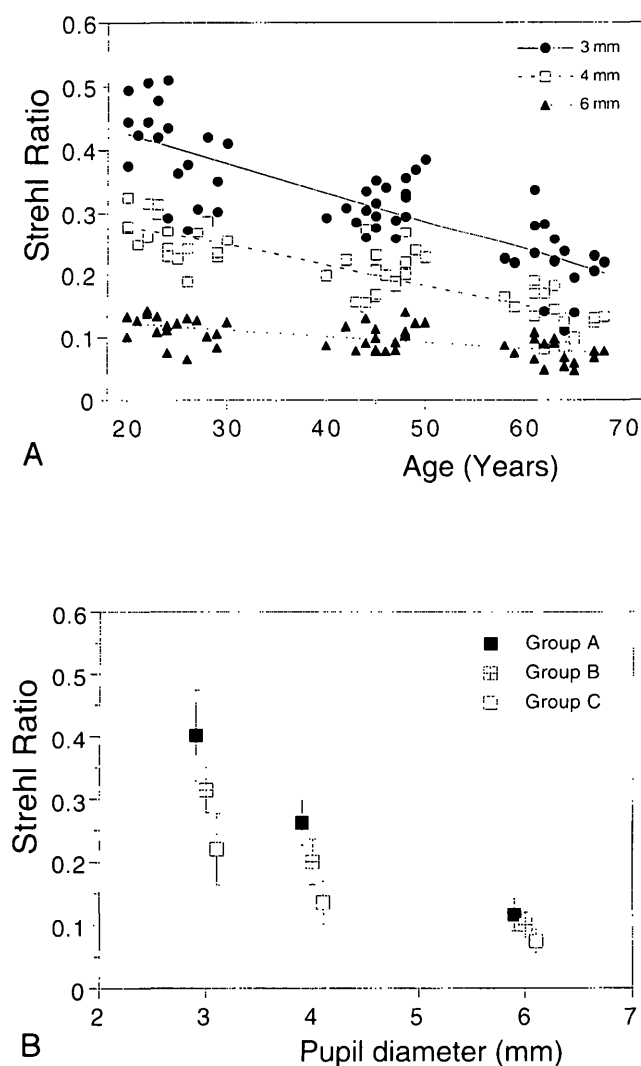

FIGURE 9. (A) Strehl ratio as a function of every subject's age at the three pupil diameters: 3 mm (*solid circles*), 4 mm (*open squares*), and 6 mm (*solid triangles*). Lines are the best linear fit. (B) Average Strehl ratios for each group and pupil diameter, with error bars representing the SD.

but to a lower number, depending on the level of the scattering halo.[27] We preferred to follow the traditional approach of analyzing aberrations and stray light separately, discounting most of the effect of scattering in our MTF results by subtraction of the constant value. It should be noted that it is not possible to separate the exact contribution of aberrations, in particular higher order aberrations, from the contribution of scattering. However, in the double-pass retinal images (Fig. 6) the increase in size near the image peak seems mainly to be caused by aberrations of a larger magnitude than by scattering's producing an approximately uniform background. In addition, higher intraocular scattering and reduced transmission through the ocular media produced dimmer double-pass images in the older subjects, for which we compensated in our experiment by selecting a different value of neutral-density filter for different age groups to keep approximately constant the average intensity in the double-pass images across the age groups.

If the properties in the retinal reflection change with age, the double-pass results could be affected differently. Several studies have shown that retinal reflection seems to have a relatively unimportant effect on the double-pass estimates of image quality,[28] particularly in green light.[15] These studies were performed in young subjects, and in consequence, there could be additional effects of retinal reflection in the double-pass measurements in older subjects, degrading the MTF. However, other studies in which retinal reflection characteristics where analyzed as a function of age did not show a significant variation—for instance, in the retinal reflection directionality[29] and the Stiles-Crawford effect.[30] This suggests that the effect of retinal reflection on double-pass measurements is approximately the same at all ages.

The ocular MTF results presented in this study reflect the overall degradation in optical performance as a function of age. Additional experiments are required to understand the underlying causes that produce the reduction in the retinal image quality with age. However, it is useful to discuss briefly how different changes occurring in the eye can produce an age-related increment in the amount of aberrations. The structural changes of the lens with age suggest an increase of aberrations. Glasser and Campbell[31] showed that the spherical aberration of isolated crystalline lenses increases with age, and in principle, this could explain an overall reduction of image quality. However the spherical aberration of the lens can be compensated, in part, by corneal aberrations,[32] and therefore an increase of aberrations in the isolated lens does not necessarily imply a
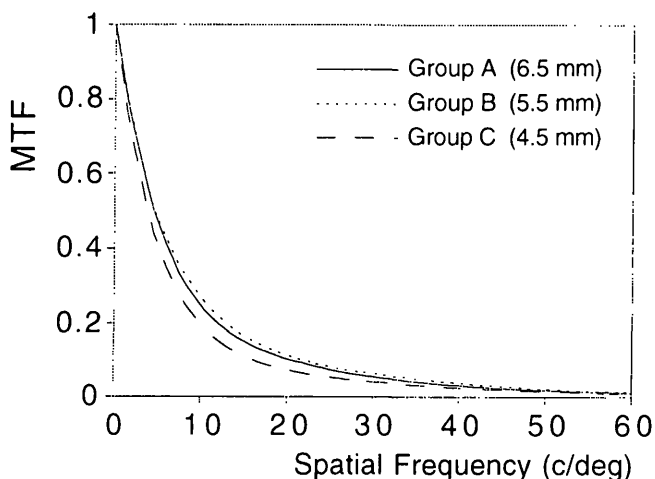
FIGURE 10. Calculated modulation transfer functions (MTFs) using Equation 1 for the three age groups: A (*solid line*), B (*short dashed line*), and C (*long dashed line*) for the average natural pupil diameter of each age at low luminance levels: 6.5 mm in group A, 5.5 mm in group B, and 4.5 mm in group C.

reduction in the overall MTF. In fact, what is important for final retinal image quality is the balance among the aberrations of cornea and lens, and with age that balance could be degraded. The results of MTFs previously measured in old patients with monofocal intraocular lens implants[33] may support this hypothesis. Those MTFs were similar to those obtained in older subjects, even though the optical quality of the isolated polymethylmethacrylate intraocular lenses[34] assessed by theoretical calculations, or at the optical bench, were practically diffraction limited and probably largely exceed that of the lens. This suggests that an uncorrected balance of aberrations may occur after intraocular lens implantation. A similar situation, a decoupling of corneal and lenticular aberrations, may also occur in the aging eye. Another two alternatives may explain the reduction in optical performance with age in healthy subjects: an average increase of corneal aberrations with age and a significant increase of higher order aberrations (related to intraocular scattering) with age.

The reduction in the eye's optical performance with age could account for a substantial part of the reported decline of the CSF with age,[3] in agreement with the results of other experiments that found the postoptical CSF, measured by projecting interference fringes on the retina, to be similar in younger and older subjects.[5] Although it is difficult to determine exactly the fraction of the reduction in CSF caused by increases in optical aberrations, the results in this study indicate that it is an important part, on average, under conditions of optimum focus and fixed pupil diameter.

It is important to point out that the average reduction we found in MTF as a function of age was obtained with artificial pupils. However, in normal viewing with a given luminance, the values of the pupil diameter are on average lower in the older subjects (senile miosis), meaning that the effect of the pupil size would tend to diminish the differences in the overall image quality within age groups. This would be especially important at medium and low luminance levels. As an example, we computed the MTFs using equation 1, by interpolating the values in Table 1 for pupil diameters representing the average

for subjects in the three age groups[35] at low luminance levels. In Figure 10, the resultant MTFs in group A (6.5-mm pupil diameter), group B (5.5-mm pupil diameter), and group C (4.5-mm pupil diameter) are shown. When the effect of natural pupil diameter was considered, the differences among age groups were reduced. We can confirm that the average MTF is approximately constant in all age groups at low luminance with natural pupil. In addition, under normal viewing conditions, small refractive errors could also reduce the relative differences in MTFs across age groups, because a smaller reduction is expected in image quality with defocus in systems with a reduced overall performance. That is to say, possible small refractive errors should reduce the relative MTF by a larger fraction in a younger subject (with better image quality at best focus) than in an older subject (with worse image quality). These two factors, senile miosis and a better tolerance to defocus in older subjects, indicate that the differences in image quality among younger and older subjects found under controlled laboratory conditions of fixed pupil diameter and best focus would become much smaller under normal viewing conditions, especially at low luminances.

Acknowledgments

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