Understanding Aberrations By Using Double-pass Techniques

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The double-pass technique has been used extensively in physiological optics since first introduced by Flamant in 1955.[1] It is based on recording images of a point source projected on the retina after retinal reflection and double-pass through the ocular media.[2,3] From these double-pass images, the ocular modulation transfer function is calculated. The modulation transfer function yields the relationship between the contrast of an object and its associated image as a function of spatial frequency. However, in different applications, it is also necessary to have access to the retinal image of the point source, the point-spread function, and the wavefront aberration of the eye. An important advance in the technique was the understanding of the image formation process. When using a symmetric double-pass setup, with equivalent first and second passes, the double-pass image is the autocorrelation of the retinal image.[4] This means that even in the case where the retinal image has an asymmetric shape (due to odd aberrations, such as coma), the double-pass image is always symmetric. We proposed a simple modification of the technique consisting of asymmetrizing the two passes by using a small aperture in one of them.[5] In this way, the double-pass image keeps the asymmetries present in the retinal image, and the ocular point-spread function (actual retinal image) can be obtained.[6] In addition, as the wave aberration is related directly to the point-spread function by an integral equation, it can be computed by phase retrieval techniques.[7] This is a useful procedure to estimate ocular aberrations, although at present it requires a long computational time.

The double-pass method provided a number of technical solutions that were later incorporated into other techniques to measure ocular image quality, such as the Hartmann-Shack sensor.[8-10] The use of a small beam in the first pass to generate a near to diffraction-limited spot on the retina is one example. Another is the use of near infrared light for illumination. We showed that the near infrared double-pass technique captured asymmetric aberrations and provided accurate estimates of the retinal image quality, despite a higher retinal scattering.[11] Considering the practical advantages of infrared, such as comfort and safety for patients, it is now the preferred wavelength.

RETINAL IMAGE QUALITY RESULTS AND IMPACT ON REFRACTIVE SURGERY

Retinal Image Quality and Age

The modulation transfer function measured using a double-pass system in a population of healthy patients of different ages declined with age.[12,13] This indicates an increase of aberrations through life, in addition to the well known increment in intraocular scattering. Figure 1 shows averaged double pass images for young, middle age, and older patients. The retinal image increases in size with age, indicating progression in ocular aberrations with age. This implies that if an ideal ablation (leading to diffraction-limited aberration-free optics) was performed at a younger age, the continuous change of aberrations with age will lead to an aberrated eye in subsequent years.

Retinal Image Quality and Accommodation

Other result predicted by the double-pass technique is the change of aberrations with accommodation.[14] Figure 2 shows two double-pass retinal images obtained with an infrared apparatus with the subject accommodated to far and near targets. In general, aberrations are smaller for the accommodated eye (except for defocus, ie, accommodative

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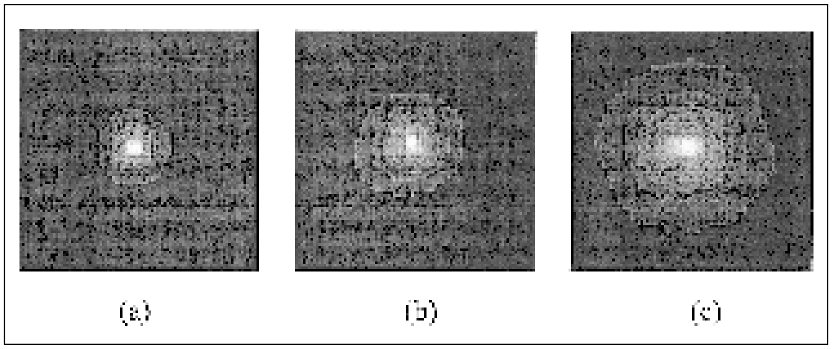

Figure 1. Averaged double-pass retinal images for **(a)** younger (20 to 30 years old), **(b)** middle age (40 to 50 years old), and **(c)** older (60 to 70 years old) patients. Each image subtends 18 minutes of arc and was recorded with a 4 mm pupil diameter.

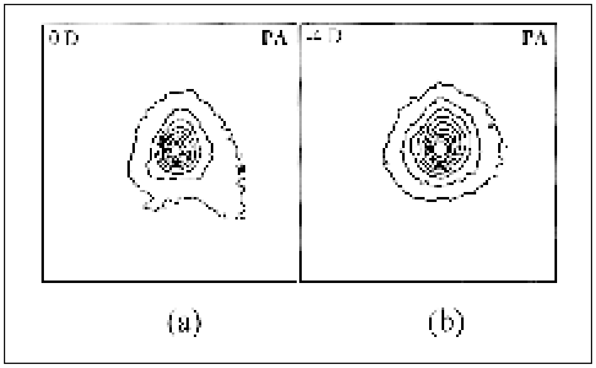

Figure 2. Double-pass retinal images (represented as contour lines) obtained with infrared light for a target placed **(a)** at infinity, and **(b)** at a vergence of 4.00 D. For the near target the retinal image is more symmetric and more compact.

lag): the image is smaller and more compact. This fact also has a direct implication for customized ablations in young subjects (where accommodation is still in place). The surgeon must decide on what aberration map to use to plan the ablation. If an ideal correction is performed from the aberrations of the un-accommodated eye, it would not be perfect for the accommodated eye, and vice-versa.

SOURCE OF ABERRATIONS IN THE EYE

What are the aberrations of the internal surfaces in the eye (the lens)? How are these aberrations coupled with those of the cornea? What is the impact on applications and in particular, on refractive surgery?

In a simple model, the aberrations for the complete eye can be assumed as the sum of those aberrations produced by the cornea and by the internal surfaces (mostly the lens). By extracting the aberrations of the complete eye (for instance from double-pass images, as mentioned previously) and the cornea from corneal topography data, the aberrations of the internal surfaces are estimated by direct subtraction. Figure 3 shows an example of typical results in young eyes: maps of wave aberrations for the cornea, the internal ocular surfaces and the complete eye, together with their associated point spread functions. In general, in young subjects, the cornea was more aberrated than the complete eye. This suggests that the lens compensates, at least in part, for the corneal aberrations.[15] Recent results[16] suggest that this is not in general the case in older eyes.

This balance of aberrations in the eye has direct and crucial implications for refractive surgery, indicating that in normal young subjects, customized ablation should be performed from the aberrations of the complete eye. If the ablation is based only on the corneal aberrations, the final aberrations of the eye could be larger than before ablation. Figure 4 shows an example to further clarify this point. The graph shows aberration maps for the eye before ideal surgery (middle map), after ideal surgery performed from the aberration data of the complete eye (flat map at the bottom), and after ideal surgery performed from corneal aberration data (map at the top of the figure). The aberration maps are placed approximately at the corresponding value of total aberrations (expressed by root mean squares). If a perfect (ideal) ablation is performed, the eye becomes limited only by diffraction (that is, without aberrations, represented by a flat aberration map). However, if the same perfect (ideal) ablation is performed from corneal aberration data (correcting only the corneal aberrations), the eye is left with aberrations corresponding to the internal surfaces; in many cases these can be more severe than in the eye before treatment. This is an ideal example and it must be noted that the situation will not be the same for highly aberrated corneas, where corneal aberrations are larger and similar to those of the complete eye.

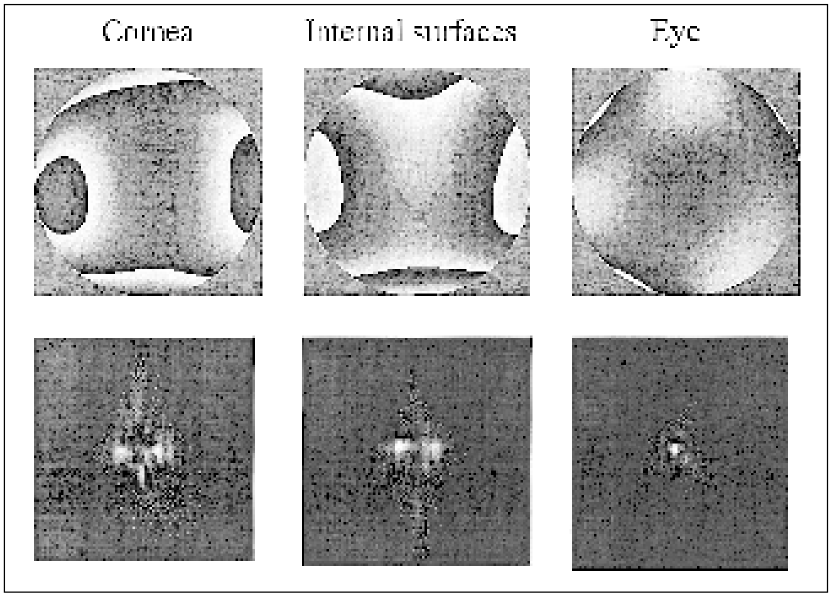

Figure 3. Wave aberration maps (for 4 mm pupil diameter) and their associated point spread functions for a young patient.

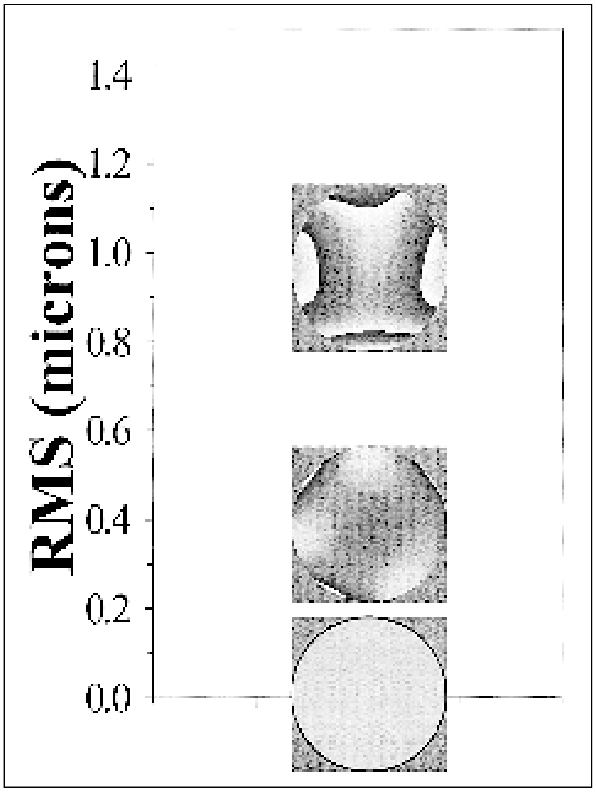

Figure 4. Aberration maps located at the approximate value of the total aberrations (expressed in microns of the root mean square).

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