The Impact of Modulation Transfer Function (MTF) on Quality of Vision, Cataract Surgery and Aspherical Implants

By Damien Gatinel, M.D., Ph.D.
AP-HP Hôpital Bichat Claude Bernard, Fondation Ophtalmologique
A. de Rothschild, University Paris VII, Paris, France.

The restoration of the quality of vision is a legitimate goal after cataract surgery. The ablation of the opaque crystalline lens and insertion of an implant into the capsular bag restore transparency to the ocular areas, while suppressing the attenuation and the light dispersion caused by the opaque crystalline lens. The reduced size of the corneal tunnels and the sophistication of the modern extraction techniques of the crystalline lens are quasi-neutral procedures for the non-crystalline ocular structures such as the cornea.

Despite a perfectly performed surgery, certain subjects, often somewhat young and more active than the average for patients operated on for cataracts, show certain bothersome visual phenomena, such as the sensation of a loss of sharpness or slight doubling of images. These symptoms occur more in a mesopic environment and are not reduced or are only slightly reduced by a spherical-cylindrical optical correction. They are caused by a rise in the level of certain high-degree aberrations, themselves secondary to the spherical geometry of the implant. In effect, it has been shown that the spherical implants do not permit the restoration of a quality of vision equivalent to that of a young pseudophakic eye after cataract surgery, due to the inducing extensive optical aberrations.

The measure of visual acuity at strong contrast (done for example by means of black optotypes test chart on a white background) does not constitute an exhaustive indicator of the quality of vision. It is however quite sensitive to the presence of a spherical (myopia, hypermetropia) or cylindrical (astigmatic) defocalization; a demi-diopter of myopic defocalization is enough, for example, to reduce the visual acuity to a maximum contrast of two decimal lines. On the other hand, certain large aberrations (spherical aberration, coma) are compatible with the maintenance of visual acuity tested in the classical fashion, but they induce a marked reduction of contrast sensitivity.

The optical performance of the human eye in terms of resolution and of contrast sensitivity may be evaluated by one and the same function, the "Modulation Transfer Function (MTF)." Besides the purely basic approach that involves the understanding of optical concepts involved in its elaboration, this parameter opens interesting clinical and therapeutic perspectives to which this article is principally dedicated.

Images and spatial frequencies

The MTF represents the manner in which the optical system under consideration attenuates the contrast of the image that it forms with regard to the observed object.

This indicator may be calculated on the basis of the study of the aberrations deforming the wave front. It is applied to any isolated optical system (cornea, implant) or a system composed of different optics (entire eye, camera lens, telescope, astronomical telescope, etc.).

To understand the relevance of the MTF, it is necessary to be familiar with the decomposition properties of an image into its elementary constituent parts.

The decomposition of an image into an set of elementary points is quite intuitive (e.g., pixels). Each point of the image observed is defined as a luminous point source of a given intensity. If one recognizes the way in which the optical system treats the image of an "elementary" point (point spread function or PSF), it is then possible to apply this transformation to the set of points composing the initial image to obtain a simulation of the image rendered. This operation is called convolution of the image by the point spread function. (Figure 1)

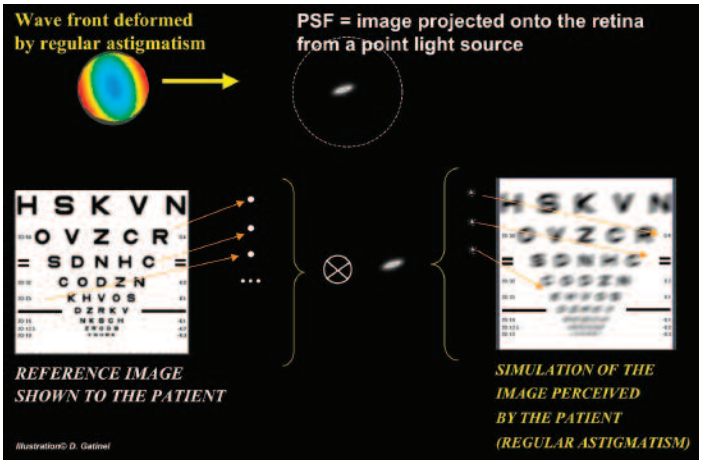

Figure 1 (Illustration D. Gatinel) The convolution, denoted by the symbol composed of a circle with a cross, consists in predicting the effect of an optical aberration on the image perceived by the patient.

Besides the optical aberration responsible (here the regular astigmatism), this operation requires knowing the retinal point spread function (PSF). Its mathematical formulation is relatively complex and will not be illustrated here.

Schematically, the convolution operation may be likened to the following 3 stages, which occur successively:

1) The image shown is broken down into a sum of elementary light points.

2) Each elementary point undergoes the PSF deformation.

3) The representation of the perceived image is done by recomposition of the elementary "deformed" points.

In the absence of optical aberration, the PSF is quasi-point (for the purpose of the near diffraction). From this fact, stage no. 2 does not change the morphology of the elementary points, and the image perceived (after recomposition) is unaltered (this is true only if the diffraction is moderate, that is, if the pupil diameter is larger than around 2.5 mm).

The image convolution technique allows objectifying certain visual complaints of optical origin, but does not allow the direct assessment of the effect of the optical aberrations implicated in the contrast sensitivity.

A monochrome image may also be broken down into a combination of spatial frequencies. Each of these frequencies corresponds to an array composed of alternate dark and light bands (monochromatic light), allowing them to be oriented in a variable fashion within the image.

The number of pairs of dark and light bands per unit of distance defines the value of the spatial frequency.

Each of the frequencies present in the decomposition of the image is balanced by a value that reflects its "amplitude," that is, the brightness interval between the darkest and brightest part of the array.

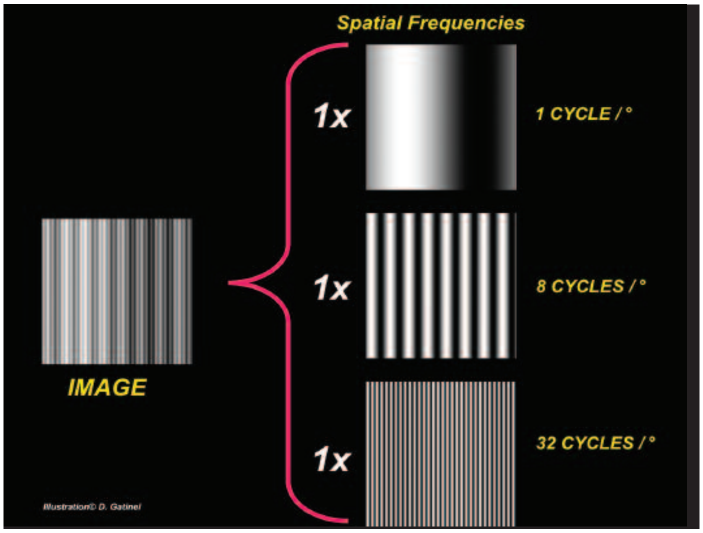

Figure 2 (Illustration D. Gatinel) Schematic example of decomposition of an image into spatial frequencies. The extent of the image presented corresponds arbitrarily to one degree of visual angle. The reference image chosen is voluntarily "simple" since it may be fully recomposed with three spatial frequencies of equal contrast. The patterns of each of these spatial frequencies are moreover easily discernable in the image.

This decomposition principle (Fourier transform) is applied however to more complex images, where the decomposition calls on a wide range spatial frequencies of variable contrast and variable orientation. This operation comes down to assessing the relative importance of different spatial frequencies within the image analyzed (a coefficient proportional to the contrast intensity of each spatial frequency is calculated.)

The superposition of these different ranges of spatial frequencies allows the recomposition of the fixed image (Figure 2). A visual acuity of 10/10 corresponds approximately to the power to distinguish that allows the discerning of a spatial frequency of 30 cycles per degree (Figure 3).

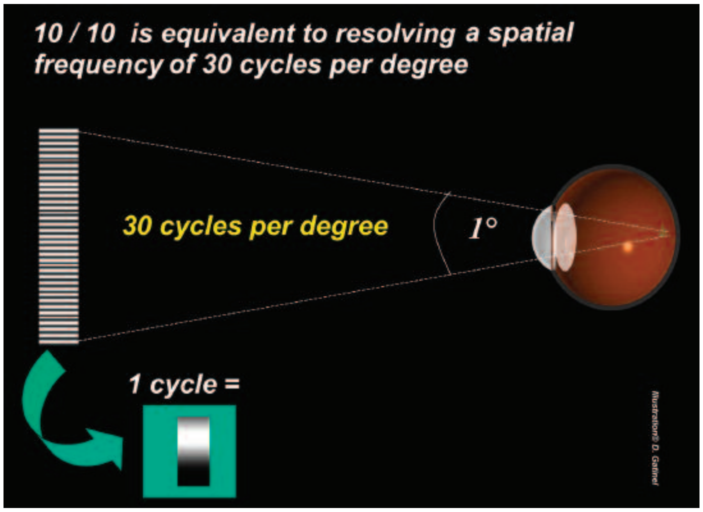

Figure 3 (Illustration D. Gatinel) The ocular separator power is directly linked to the "spatial frequencies." In this example, visual acuity equal to 10/10 for a maximum frequency contrast is equivalent to the ability to "separate" 30 cycles each composed of a maximum (white) and a minimum (black) of brightness.

One degree of angle corresponds to 60 minutes of arc; the total of black and white bars equals 60. If the maximum acuity of a patient is 10/10, this implies that the minimum angle of resolution is 1 minute of arc.

When the spatial frequencies are presented with a maximum contrast, most healthy and properly corrected eyes in fact have an acuity close to 15/10, even 20/10. In effect, it can be demonstrated that the size of the foveal photoreceptors and the diameter of the PSF under optimum conditions (low level of optical aberration, weak diffraction) permit a range of samples of spatial frequencies close to 60 cycles per degree.

The fact that an image may be broken down into an set of elementary periodic signals called spatial frequencies follows from Fourier analysis, which is applied to practically any complex signal. This approach, familiar to the physician, the electronics expert, or the specialist in signal treatment, is however less familiar to the clinician who is more accustomed to having a visual pattern represented as the juxtaposition of luminous points.

In order to make it more familiar, this method may be compared to the spectral decomposition of a sound into various sound frequencies. The spectrum of spatial frequencies extends from the very lowest (the "lows," which correspond to the coarsest elements of the image), to the highest (the "highs," which permit the representation of fine details). The MTF calculated for the set of ocular diopters may be approximated for the visual function by the audiometric curve (audiogram), where it is attached to study the auditory sensitivity in order to determine the perception threshold of intensity for each sound frequency.

Thus the current examination of visual acuity does not explore the capacity of the horizontal ocular resolution for a target of maximum contrast, and is limited to the information contained on the horizontal axis of the MTF. It is reminiscent of an audiometric exam that would test the auditory perception of various sound frequencies only at maximum volume! For a healthy eye corrected for optical aberrations, the maximum discriminatory power is generally close to 20/10 when the target presents maximum contrast. This resolution corresponds to the maximum sampling capacity of the mosaic of fovea cones.

Spectrum in spatial frequencies of an image and the Fourier transform

The Fourier transform of an image comes down to performing a spectral decomposition. In contrast to the human ear, which is capable of breaking down a chord into its elementary different notes (sound frequencies) and thus capable of carrying out an operation similar to a Fourier transform (Figure 4), the eye is not capable of processing the visual information in terms of spatial frequencies. On the other hand, techniques of digital imaging exist that permit making this transformation in a quasi-instantaneous manner.

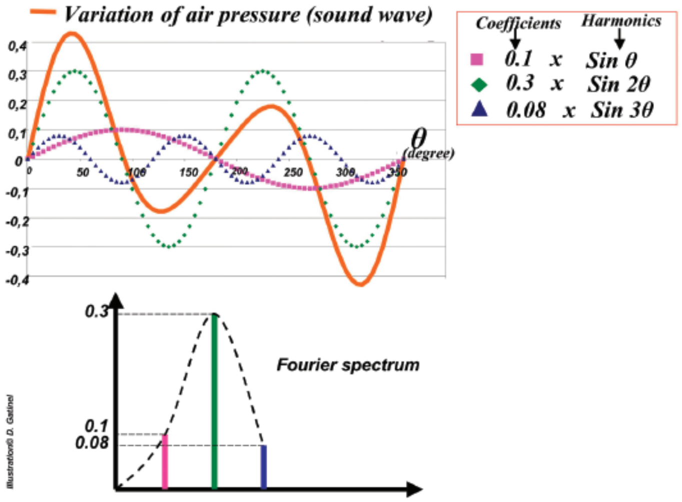

Figure 4 (Illustration D. Gatinel) Schematic representation of a cycle of air pressure variations causing a sound (full curve in orange).

It can be decomposed into three "pure" sounds (dashed curves) and conversely, the sum of these three sound vibrations reproduces the overall perception of "sound" (the variations in pressure are added or subtracted according to their sign). A musical, trained ear can decompose this sound into its three constituent harmonics.

The Fourier spectrum represents the importance of the respective contribution of each of the harmonics present within the sound perceived. The human ear is capable of making Fourier type transforms. The decomposition of an image into spatial frequencies is an analogous optical procedure, where the spatial frequencies correspond to "pure harmonic sounds" from the acoustic domain. And given the two-dimensional nature of an image, the representation of its Fourier spectrum is itself two-dimensional.

The frequency spectrum is represented by an image in gray levels. The intensity of each pixel of this spectral image is proportional to the amplitude of the coded spatial frequency. The frequencies are distributed from the center toward the edges of the image based on their level. The richer the image in fine details, the more marked will be the presence of higher spatial frequencies within the decomposition (Figure 5). Conversely, an image poor in details has a spectral content dominated by low and medium spatial frequencies (Figure 6).

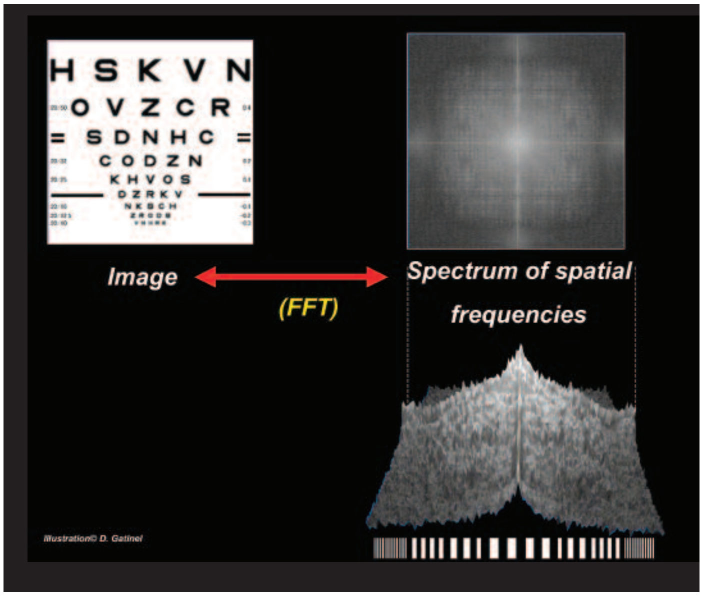

Figure 5 (Illustration D. Gatinel) Example of decomposition by Fast Fourier Transform (FFT) of the image of a optotype test chart of decreasing size (Snellen acuity chart). The frequency spectrum is represented in gray levels on the right. The luminosity of each pixel is proportional to the importance of the spatial frequency present in the image, considered for that of this pixel code. Below, the 3D representation of the spectrum allows the visualization of "peaks" of these frequencies - the higher the peak, the greater the brightness amplitude of the corresponding frequency is raised within the analyzed image.

The peaks for the low frequencies are clustered at the center of the spectral image; the peaks for the high frequencies are close to the edges. The cross appearance with "bulges" visible at the edges of the spectrum presented in this example corresponds to the fact that the optotypes are presented in a fully aligned manner both horizontally and vertically, and are themselves coded by the spatial frequencies oriented primarily in these same directions.

This spectral representation of an image should not be confused with the two-dimensional representation of the MTF in gray levels.

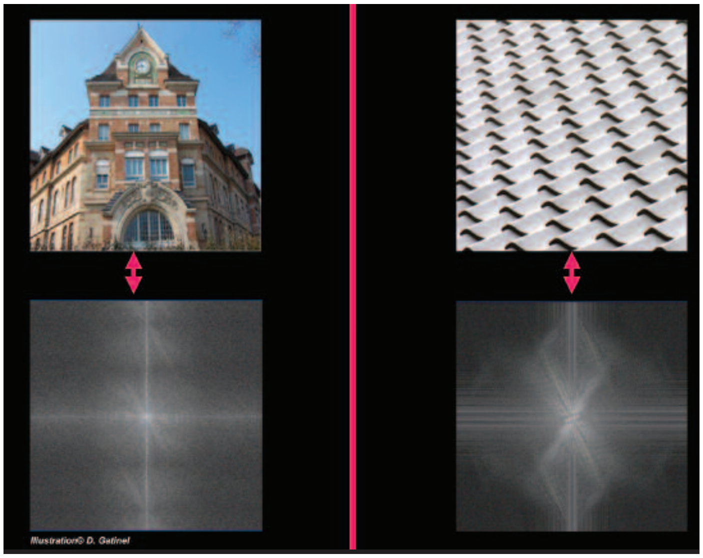

Figure 6 (Illustration D. Gatinel) Examples of images (above) accompanied by their respective Fourier transforms (below).

On the left, the image represents the front wall of the Rothschild Foundation and has many details (various architectural patterns decorating the facade). The spectral content extends homogeneously from the low frequencies (center of the spectral image) to the high frequencies (edge of the spectral image).

On the right, the image corresponds to an arrangement of tiles from a Zen temple pavilion (Kyoto, Japan). It presents a regular, repeated pattern that is made up of primarily low and medium frequencies. It is interesting to note that the spectral content in this example is clustered toward the center of the diagram (weak expression of high spatial frequencies in this image). The oblique orientation of the most important peaks in the frequency space indirectly reflects the oblique arrangement of the tiles in the actual image.

These frequencies have a variable effect on visual perception. For example, it has been shown that the recognition of patterns like familiar faces and landscapes is done essentially on the basis of correct perception of medium spatial frequencies (Figure 7). This notion is reflected in the relative tolerance by certain elderly persons with regard to a moderate myopic ametropia that does not hamper them or hampers them only slightly in their daily life in identifying things close to them or to navigate within a familiar environment. Moreover, neuro-ophthalmologic processing of the visual information acts as a filter in attenuating the perception of the low spatial frequencies in favor of the medium frequencies.

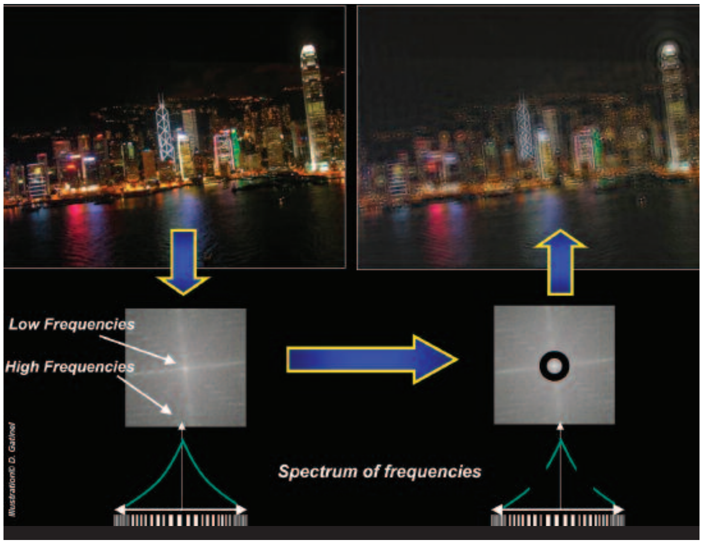

Figure 7 (Illustration D. Gatinel) Effect of removal of some medium and high frequencies by a frequency filter in the decomposition into spatial frequencies of an image representing Hong Kong Bay. After reconstitution of the image (without the suppressed spatial frequencies), the landscape is identifiable, but the contrast is reduced, and certain details are absent. The absence of certain frequencies in the final recomposition also explains the presence of "double contours" in the image. This type of filtering may be used to rid an image of "noise", such as rasterization (for that it is sufficient to remove one or more spatial frequencies that code for the undesirable raster).

Interest in the MTF

The MTF corresponds to a ratio between the respective contrasts of the projected image and the image formed for each spatial frequency. As a function of the diffraction and the importance of optical aberrations of the system studied, it is possible to determine the fashion in which the optical system attenuates the contrast between specific spatial frequencies, and to deduce from that the optical quality of the image that is rendered (Figure 8). The closer this relationship is to 100%, the better is the optical quality of the system tested for this spatial frequency. For a "perfect" optical system, devoid of optical aberrations, the MTF curve is a straight line with negative slope, due to the effects of the diffraction, which reduces the contrast of the high spatial frequencies. The presence of high-degree optical aberrations reduces "the height" of the curve, since the aberrations reduce the contrast that is transmitted.

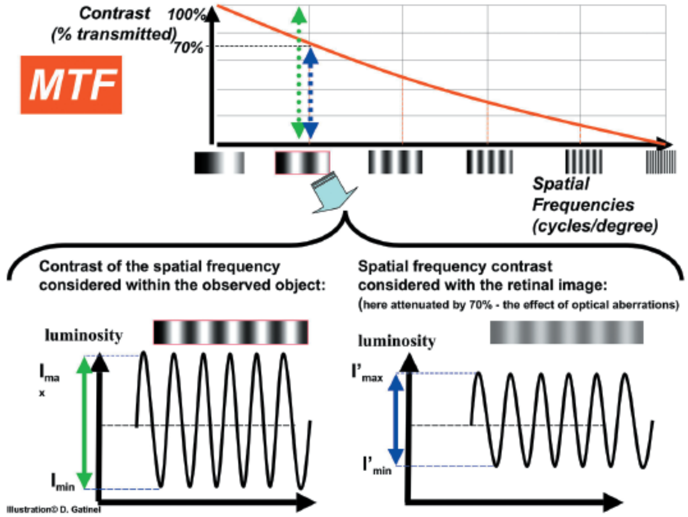

Figure 8 (Illustration D. Gatinel) Principle of contrast transfer modulation — The MTF curve represents the loss of optical contrast for each spatial frequency, brought about by the combined effects of refraction errors and diffraction.

Each of the spatial frequencies constituting the fixed object corresponds to a sinusoidal vertical array (brightness variation). After refraction by the ocular optical surfaces, this array has a reduced contrast within the image because of diffraction and because of optical aberrations. The modulation for this frequency is given by:

Modulation (M) = (I'max –I'min) / (Imax + Imin)

In this example, 70% of the contrast is transmitted for the spatial frequency corresponding to 2 cycles per degree.

The spatial frequencies have a variable orientation, and the MTF is at first calculated for each of these frequencies (two-dimensional MTF generally represented in gray levels). The curve presented as a graph is calculated as the mean of the respective MTF curves of each of the hemimeridians of the pupil of the optical system under consideration.

When the optical system is free of optical aberrations, only the effect of the pupillary diffraction reduces the optical quality. From this fact, the theoretical MTF curve of a system limited by diffraction is not a horizontal straight line, but one slightly inclined to the right.*

** The effect of the dispersion is not really taken into account when the MTF is calculated after receipt of the wave front, but may be so if the MTF is calculated on the basis of the direct receipt of the PSF. The phase shift effect caused by certain aberrations, in particular the asymmetrical or unpaired ones (coma), is not represented in this curve.*

Calculation of the MTF thus allows predicting the effect on the visual envelope of a disturbance of the wave front (optical aberrations of low and high degree). An equal visual acuity tested for maximum optotype contrast depends on the emmetropization of the rays crossing the center of the pupil. The visual acuity tested for reduced optotype contrast is correlated to the emmetropization of the periphery of the pupil (Figure 9). This is particularly interesting for aberrations in which the type and the rate are insufficient to induce a decrease of the best corrected visual acuity, but which provoke a reduction of the sensitivity to optical contrasts for certain spatial frequencies, such as the coma or spherical aberration. For example, these last items induce a reduction of the predominant MTF for the medium spatial frequencies. The value of the RMS rate (Root Mean Square — mean square or effective value) of the high degree aberrations of the eye is not always proportional to the deterioration of the optical quality that they induce, since certain high-degree optical aberrations compensate for them. The MTF curve is a more pertinent piece of information than the RMS level of a given aberration or a group of aberrations because it illustrates the expected effect of these aberrations on the various spatial frequencies and for different pupil diameters (Figure 10). If the MTF curve can be calculated for the set of optical errors (poor focus, astigmatism, high-degree aberrations), in general it is calculated for the best spherical-cylindrical correction in order to reveal the effect of the high-degree aberrations alone.

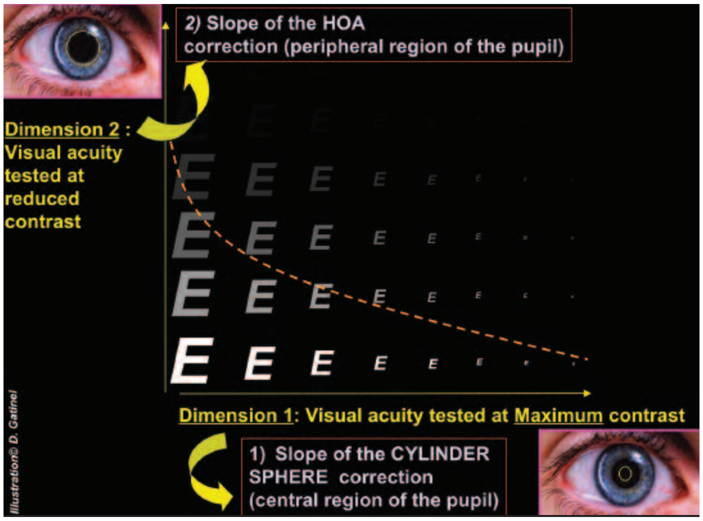

Figure 9 (Illustration D. Gatinel) Correlation among MTF, clinical factors, and the visual envelope — The emmotropization of the light rays passing through the center of the pupil is correlated to good visual acuity at maximum contrast, but does not guarantee the maintenance of this acuity at reduced contrast. The MTF curve, which may be matched to sensitivity to predicted contrasts by considering optical defects, is as "high" as the "emmotropized" pupillary surface is large.

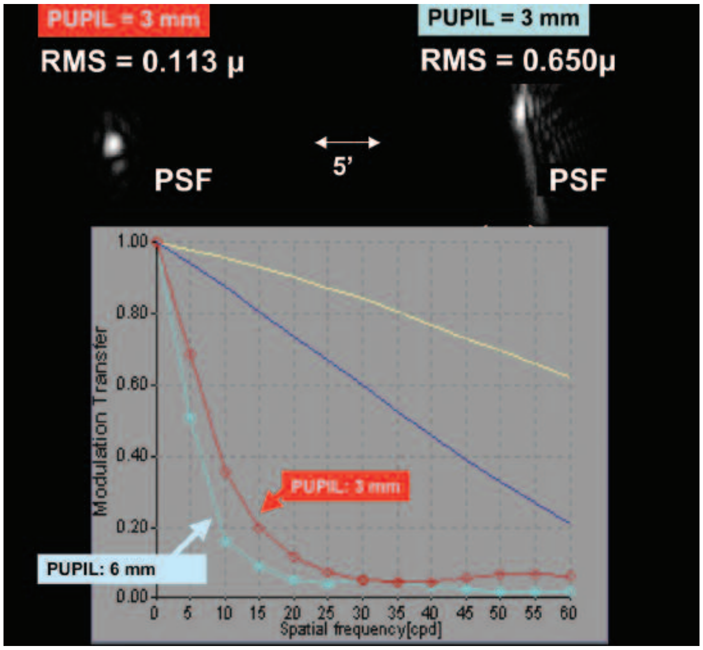

Figure 10 (Illustration D. Gatinel) Representation of the PSF and the average MTF curve for the same eye analyzed at two different pupil diameters (3 mm and 6 mm) and best corrected in eyeglasses for sphere and cylinder. The eye analyzed is pseudophakic (hydrophobic acrylic spherical bioconvex implant), and the patient complains of a reduction in the quality of night vision on this side. The corrected visual acuity tested with high contrast optotypes is about 10/10. The MTF is calculated after receipt of the wave front for aberrations of high degree only (that is, for the best spherical-cylindrical correction).

Note the broadening and the vertical distortion of the PSF with pupillary dilatation (deleterious effects of coma type optical aberrations present in the wave front). The contrast transfer is more reduced in the 6 mm pupil diameter than in the 3 mm pupil diameter for the set of spatial frequencies. The yellow and dark blue straight-line curves correspond respectively to the average theoretical MTF curve in the absence of optical aberration (diffraction only) for the 6 mm and 3 mm diameters.

The presence of an high level of optical aberrations has deleterious consequences for the MTF and thus for the visual acuity at maximum contrast and/or the sensitivity to the contrasts of certain spatial frequencies. If the MTF is narrowly linked to the function of contrast sensitivity, the measure of this latter in clinical practice depends as well on neurological factors and is limited essentially to lower and medium spatial frequencies. In general, the visual cortex brings about a special "processing" of the information transmitted by the receiver (eye) and the visual pathways, and can "compensate for" or conversely "accentuate" the effect of certain optical aberrations on visual perception.

The natural crystalline lens is aspherical and compensates for one part of the aberrations induced by the corneal diopter, the one that does not allow the spherical implants. Reduction of the quality of vision after cataract surgery and insertion of a pseudophakic spherical implant is connected principally to the inducing of a higher level of high-degree spherical aberrations, such as the spherical aberration and the coma type aberration. Certain aspherical implants improve contrast sensitivity by means of a reduction of the rate of total post-operative spherical aberration. This gain may be reduced or voided in case of imperfect centering by the inducing of a coma-type aberration. The threshold between the gain made by asphherizing and the loss linked to the inducing of coma is difficult to evaluate on the basis of the study of the respective RMS rates of these aberrations. Moreover, the existence of physiologic decenterings among the various ocular diopters is neglected in the design of aspherical implant suppliers of first-generation negative spherical aberration.

MTF and the design of a pseudophakic implant

Calculation of the MTF may be used to refine the design of an aspherical pseudophakic implant. The Invent ZO and the XL Stabi ZO (Carl Zeiss) implants are the first implants to have been specifically conceived according to the predicted effect on the quality of vision by the calculation of the ocular MTF. (Figure 11)

A theoretical model of the eye incorporating the aspherical corneal surfaces, the physiologic pupil decentering, and the eccentricity of the fovea has been chosen ("Liou and Brennan" model). The MTF calculated for the whole eye and implant allows the incorporation of the combined effects of spherical aberration and coma. For each geometry of an implant tested in this theoretical eye, the calculation of the total eye MTF is done. The geometry used for the design of the aspherical implant is the one that supplies the best MTF curve on the set of the tested spatial frequencies. Calculation of the MTF on the basis of the receipt of the wave front by the patient who has received this type of implant must logically allow the verification of the theoretical relevance of this model and has a significant clinical application.

Conclusion

Modern optical correction devices, be they medical or surgical, are today elaborated not only to restore good visual acuity, but also to better preserve or to improve contrast sensitivity. This opportunity appears particularly interesting for patients who are active and who perform certain activities in a mesopic ambiance and/or a strong visual stresses such as those of driving at night. The asphcrization of the optics of the implants in the rear chamber is an important first step in this direction. Taking into account the potentially deleterious role of other optical aberrations like coma or the existence of physiologic pupil decentering represents an additional theoretical advance for second-generation aspherical implants. The modulation transfer function allows the integration of the combined effect of all high-degree aberrations. This parameter should thus occupy a major place in the evaluation of the optical quality of the eye and in the development of innovative optical correction devices.

Figure 11 The aspherical lenses by Carl Zeiss.

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