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TECHNICAL NOTE

Standard criterion for fluctuations of modulation transfer function in the human eye: application to disposable contact lenses

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Summary

It is well known that the modulation transfer function (MTF) characterizes the optical quality of the eye. Recently, some objective techniques have been introduced in order to measure this function *in vivo*. These techniques could be employed to display the temporal fluctuations of the eye + compensation system and to isolate the effect of the compensation element provided that the standard fluctuations for a normal observer were known. In this work we carry out a study of the MTF of the human eye over a long period of time to quantify the standard fluctuations of the retinal image quality and to establish a standard criterion of normality. We have defined a single quality parameter from each measured MTF to simplify the analysis of the results. We have evaluated this merit function on normal observers three times a day for one month. As expected, random deviations from the mean value of the merit function have been obtained, although fluctuations with no statistical differences of the merit function (P value from ANOVA test $P > 0.01$) and the standard deviation of these fluctuations (5%) can be chosen as a standard criterion. We have used this result to study the behaviour of a time-varying compensation element: a disposable contact lens. The study of the eye + contact lens system has been carried out with four types of disposable contact lenses for one month. In spite of their generally good behaviour, statistically significant differences from the standard pattern can be observed. This superimposed continuous fluctuation can be due to lens-dependent processes. ©1997 The College of Optometrists. Published by Elsevier Science Ltd.

Introduction

The design of ophthalmic elements for refractive error compensation is made by considering the usual optical quality parameters (Jalie, 1988). These parameters are obtained by taking the isolated optical element and predicting their adaptation to the eye using schematic models of the human eye. Nevertheless, the actual characterization of the optical compensation should be determined by the quality of the joint optical compensation + eye system.

The quality of this system is usually determined by subjective techniques as, for example, the measurement of the visual acuity (VA) or the contrast sensitivity function (CSF) (Bennet and Rabbetts, 1991). In both cases, the method is limited by the subjective quality criterion of the observer.

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In conventional optical systems the optical quality is evaluated in an objective way using the modulation transfer function (MTF) (Goodman, 1968). This function shows how a sinusoidal pattern of a given frequency is attenuated by the optical element. The main practical drawback of this function in the human eye is the inaccessibility of the image plane, making its measurement especially difficult. Some techniques can be found in Campbell and Gubish (1966) and Howland and Howland (1977) which determine the MTF of the eye using subjective methods. The time, cost and observer effort of these methods became the main problems in the application of these techniques to compensating lenses.

Recently, some objective techniques have been introduced in order to measure the MTF of the optical visual system. These techniques are based on the wave aberration measurement (Walsh *et al.*, 1984; Liang *et al.*, 1994) or on the registering of the aerial image of a point test projected

onto the fovea after the double pass through the ocular media (Santamaría *et al.*, 1984, 1987). This last method gives good advantages: it is an objective method and it allows us to obtain quickly the MTF with great reliability.

The objective of this work is to apply this methodology to the evaluation of the optical quality of the compensating lens + eye system. Since the eye is a dynamic system in continuous variation, it will be interesting to study the fluctuation of the MTF in the eye over a period of time. With this study, we will be able to determine when these fluctuations are due to the optical compensation.

In order to prove the reliability of the proposed method, we apply it to the particular case of disposable contact lenses. In the literature it is possible to find different works that study the optical quality given by the contact lenses as an isolated element (Grey and Sheridan, 1988; Woods *et al.*, 1994) or as an element adapted to the eye. However, in both cases the study was based on subjective measurements of the CSF (Applegate and Massof, 1975; Kirkpatrick and Roggenkamp, 1985; Tomlinson and Hann, 1985) or the VA (Ho and Bilton, 1986). The possible variations in the quality of compensation with time have been studied using the CSF (Grey, 1987) or the measurement of the corneal thickness (Grey, 1986).

In this work we use an objective method to measure the standard eye-dependent fluctuations in such a way that any other fluctuations can be due to compensation system-dependent processes.

Methods

Experimental

In order to record an image of the eye fundus, we used the double pass method developed by Santamaría *et al.* (Santamaría *et al.*, 1984, 1987). This allowed us to obtain *in vivo* an aerial image of a point test projected onto the fovea. The experimental set-up used is shown in *Figure 1*. A He-Ne laser beam is expanded and filtered with a pinhole (PH) of 20 μm diameter acting as the object and fixation test, and it is then collimated with the lens L_1 ($f' = 50$ mm). The beam is divided with a pellicle beamsplitter (BS) and directed towards the eye of the subject forming an image on the fovea. The Badal system L_2–L_3 allows us to focus the conjugate of the retina. The aerial image was recorded with a Pulnix CCD camera and stored in a computer-controlled framegrabber. A second camera (CCD-2), allows us to monitor the correct incidence of the beam in the observer's eye. Every aerial image was obtained by a temporal integration of 300 msec. In these conditions, the incident beam power at the corneal plane was 0.06 mW, within safety standards (Sliney and Wolbarsht, 1980).

The calibration process of this experimental set-up must allow us to measure accurately the spatial fequencies of an image of the retinal plane. With this purpose in mind, we placed at the observer position a schematic eye (implemented with a positive lens), and recorded the image on a calibrated microscope reticle. We repeated this

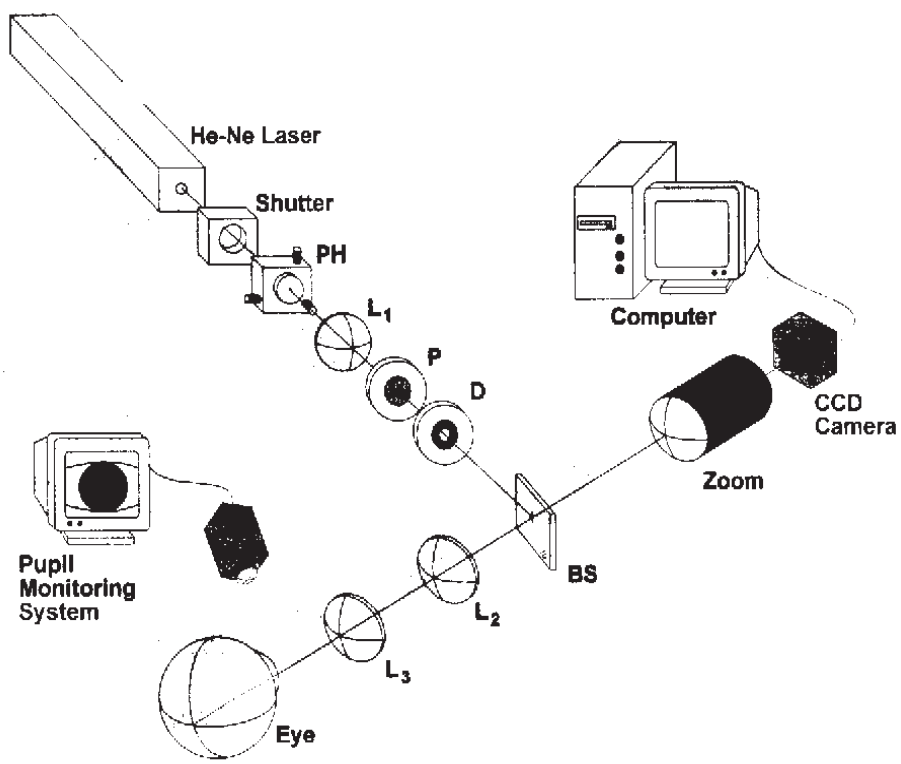

Figure 1. Experimental set-up: PH, spatial filter; O, the object test; L_1, a collimating lens; P, a polarizer; D, diaphragm; BS, a beam splitter; L_2–L_3, a Badal system; CCD camera for recording the images.

measurement with 10 different positive lenses. If we take into account the sampling rate of the CCD camera, it is easy to derive from the measurement over the reticle at the schematic eye retinal plane the correct sampling rate of the whole device at this plane. This procedure allows us to obtain an expression for the relationship between the eye's power and sampling rate:

$$\frac{f_s}{2} = 104.76 - \frac{249.31}{P} \tag{1}$$

P being the power of the eye. It is interesting to note that, if we consider as the normal power of the eye the range 56–66 D, the sampling rate given by Equation (1) only increases in a 1.006 factor over this range. This calibration process includes all the optics of the eye and the magnification rate of the device plus eye system.

The sampling rate $f_s/2$ in our experimental setup was 100.7 cpd. With this sampling rate, each image $I_o(x,y)$ was registered with an integration time of 300 msec. With this time the beam coherence is broken, removing the laser speckle (the time of coherence of the laser beam is below 10 nsec) allowing us to keep the power intensity of the laser at the corneal plane within safety limits. In each capture session a background image $I_b(x,y)$ was taken, in order to remove static noise. Then, the final image to be processed will be:

$$I(x,y) = I_o(x,y) - I_b(x,y) \tag{2}$$

The MTF of the optical visual system was calculated as the square root of the absolute value of the Fourier transform of $I(x,y)$:

$$\mathrm{MTF}(u,v) = \sqrt{|FFT[I(x,y)]|} \tag{3}$$

Merit function

To evaluate the image quality of the system characterized by its MTF, it is necessary to define a merit function (Williams and Becklund, 1989). Usually, the chosen parameter is the Strehl ratio (Williams and Becklund, 1989), but in this work, we consider it more convenient to define a new merit function evaluated as the volume of the MTF (in polar coordinates) between two frequencies ρ_1, ρ_2:

$$\mathrm{Mf} = \int_0^{2\pi} \int_{\rho 1}^{\rho 2} \mathrm{MTF}(\rho,\theta)\rho d\rho d\theta \tag{4}$$

where (ρ,τ) are the polar coordinates.

The advantages of using this function in the study of the image fluctuation are as follows:

(*a*) Like the Strhel ratio, it is an objective parameter because it is defined over an objective function and the value depends on the quality given by the MTF of the system. It is known that when the bandpass of the MTF is wide the quality of vision is better than when it is narrow, in which case only the information from low frequencies is recognized and the image quality becomes poorer. We can easily explain this fact in terms of our parameter: when the MTF is wide, the volume confined is large and the merit function is large too, but when the MTF is narrow, the volume confined is reduced and the merit function becomes lower. Therefore the fluctuations in the merit function yield information about the MTF of the eye and about image quality.

(*b*) It is possible to evaluate frequency ranges giving different values to ρ_1 and ρ_2. In our study, all the MTF is taken into account, except for the central peak that gives us only information about mean luminance; i.e. $\rho_1 = 0.016$ cpd and $\rho_2 = 100.47$ cpd.

(*c*) This function gives us more information than others defined in one dimension. The reason is that we are evaluating all directions in the space considering possible asymmetries in the MTF.

Due to the dynamic behaviour of the eye, we could not expect a constant value for the MTF of the eye optics. The changes in environmental conditions (higroscopic changes (Gellatly *et al.*, 1988), microfluctuations of accommodation (Arnulf *et al.*, 1951; Charman and Heron, 1979), etc.) will give random fluctuations of the eye's MTF.

Standard criterion

If we want to assess the quality of the optical compensation worn by a subject, the first step will be to obtain data about the normal behaviour of the MTF in subjects with no ammetropya or compensated with ophthalmic lenses (which have a constant MTF).

We selected two observers (Ronchi and Ferrara, 1963), AL (25 years old, emmetropic) and AMP (29 years old, compensated-to-emmetropy) and we measured the MTF of both subjects during a month, taking three measurements in each session.

Application to disposable contact lenses

The study was made with three observers, O1, O2 and O3. In each case, a refractive study was performed and results are shown in Table 1.

The process of measurement was developed during a month taking a block of three images per session. The study was developed with different types of disposable contact lenses: observer O1 used Focus contact lenses, observer O2 used Surevue contact lenses and the third observer used Acuvue contact lenses with replacement every 15 days, and Precision UV contact lenses during another month.

Table 1. Optometric file for each observer

	Observer O1		*Observer O2*		*Observer O3*	
	Right eye	*Left eye*	*Right eye*	*Left eye*	*Right eye*	*Left eye*
Queratometry (mm)	7.80 × 7.70	7.90 × 7.70	7.95 × 8.00	7.92 × 7.90	8.10 × 8.00	8.15 × 8.00
Biomicroscopie	OK	OK	OK	OK	OK	OK
Refraction (D)	−2.25	−2.25	−3.00	−3.00	−1.75	−1.25
AV without correction	0.2^{-1}	0.2^{+2}	0.1	0.2	0.1	0.35
AV with correction	1	1	1.25	1.25	1.25^{-1}	1.25^{-1}
Contact lenses adapted	8.80–2.25	8.80–2.25	8.80–3.00	8.80–3.00	8.80–1.75	8.80–1.25

Results and discussion

Fluctuations of the MTF on a normal observer

Figures 2 and *3* show the results of the monthly study in observers AL and AMP. The results, as we expected, confirm random fluctuations with no significant difference obtained with the ANOVA test in any case taking a criterion of $P > 0.01$ for the null test hypothesis (Hand and Taylor, 1993): AL, $P = 0.01$, AMP, $P = 0.02$. Nevertheless, it is interesting to note that the fluctuation band of the Mf parameter (estimated from the SD of the measurements) is never larger than 5%. This result must be considered as complementary to the ANOVA data because we can obtain results from this test with $P > 0.01$ but with a large SD. The results of the ANOVA test are summarized in *Table 2*.

We may consider that the behaviour of the Mf parameter derived from the MTF is normal if it is characterized by random fluctuations with no statistically significant differences ($P > 0.01$) within a band of 5% of SD.

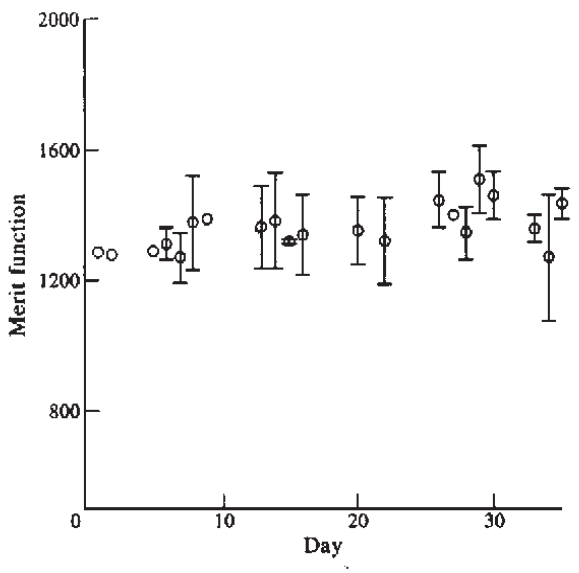

Figure 2. Monthly evolution for emmetropic observer, AL. The merit function, Mf, is represented versus the day of measurement. Random variations over this parameter are observed.

Application to disposable contact lenses

The results for the four observers selected for the study of compensations with disposable contact lenses are shown in *Figures 4–7*. Taking into account the criterion proposed, we calculated the SD for all the observers. In any case, the fluctuation band exceeds an SD of 5%. This could be expected as we followed the use prescription suggested by the lens manufacturers. When we applied the ANOVA test to our data set (*Table 2*), we obtained no significant differences in observers O2 and O3 (using Precision UV contact lenses) (O2, $P = 0.05$; O3, $P = 0.74$) but for observers O1 and O3 (using Acuvue contact lenses) the

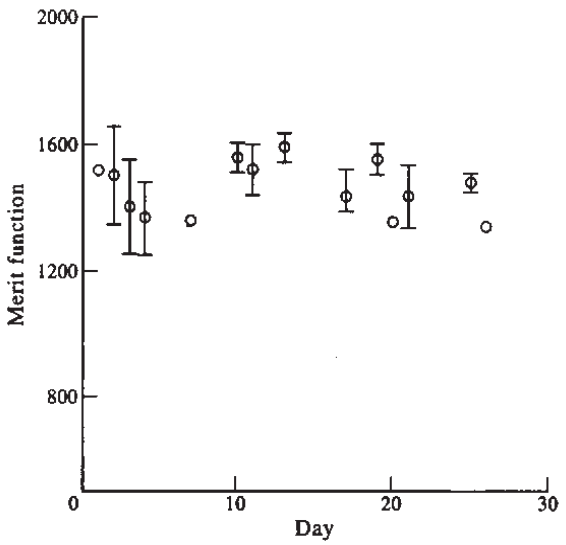

Figure 3. Monthly evolution for ammetropic observer AMP compensated with ophthalmic lenses. The merit function is represented versus the day of measurement. Random behaviour similar to that of observer AL is observed.

Table 2. Results of ANOVA test

Observer	*df*	*F*	*P*
AMP	13	2.599	0.0234
AL	21	1.607	0.1046
O1	17	2.967	0.0021
O2	13	2.025	0.0465
O3 (*a*)	12	0.6933	0.7410
O3 (*b*)	15	2.7	0.0046

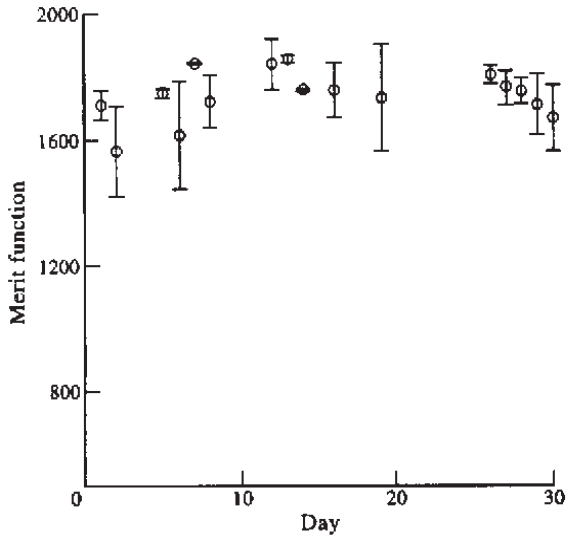

Figure 4. Monthly evolution for observer O1 compensated with Focus contact lenses. The merit function, Mf, is represented versus the day of measurement. A clear evolution for this parameter during the month is observed.

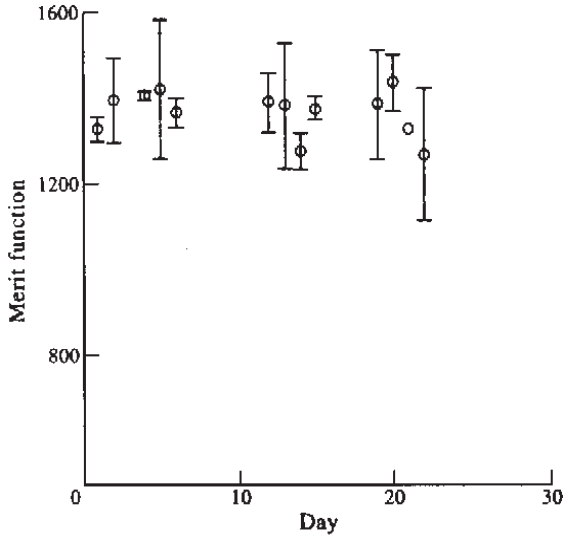

Figure 6. Monthly evolution for observer O3 compensated with Acuvue contact lenses. The merit function, Mf, is represented versus the day of measurement. A clear evolution for this parameter during the month is observed.

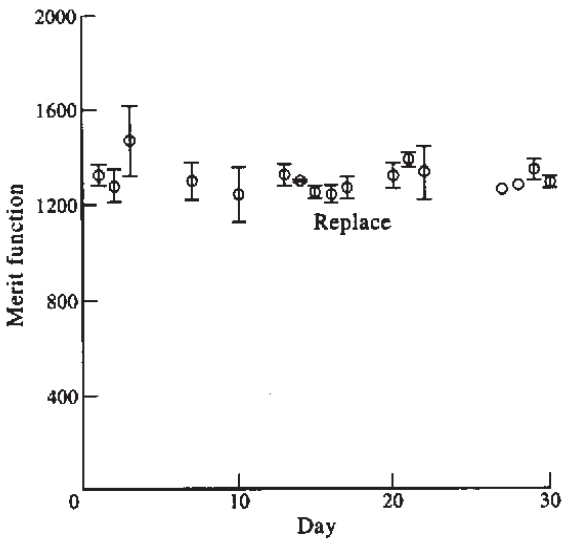

Figure 5. Monthly evolution of observer O2 compensated with Surevue contact lenses. The merit function, Mf, is represented versus the day of measurement. Random behaviour similar to that of an observer compensated with ophthalmic lenses is observed.

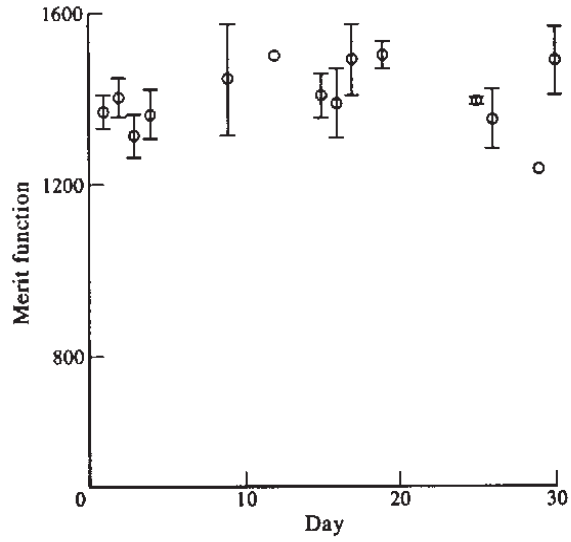

Figure 7. Monthly evolution for observer O3 compensated with Precision UV contact lenses. The merit function, Mf, is represented versus the day of measurement. Random behaviour similar to that of an observer compensated with ophthalmic lenses is observed.

variation will be considered as significant (O1, $P = 0.005$; O3, $P = 0.002$.

For observer O1 (compensated with monthly disposable contact lenses), we can see how fluctuations of the Mf parameter are modulated for the adaptation process in the first days of use (the Mf roughly increases); after this initial period, a constant value of Mf is observed and finally the parameter decreases sharply in the last days of use of the contact lens, due to their progressive degradation.

Observer O3, wearing fortnightly disposable contact lenses, shows a similar behaviour in the two evaluated periods of fifteen days: a rapid increase of the parameter until the 3rd or the 4th day and then a slow decrease from this maximum value of the Mf until the replacement date.

In both cases, the behaviour of the compensation can be due to the adaptation process of the contact lens to the subject's cornea (quality improvement) and the following continuous quality loss can be attributed to the presence of deposits, contact lens degradation, etc.

In no case did the observers report discomfort or vision troubles, confirming that the established criterion assures a comfortable optical compensation.

In this work a new version of the double pass method is proposed. While we have not introduced any significant changes in the process of capturing the aerial image, the analysis of the image is carried out in a different way since

the images have been temporally integrated and the parameter used to interpret the results (Mf) is also different.

As a result of our study, a standard criterion for the merit function is established. Fluctuations with no statistically significant differences (P value from ANOVA test $P > 0.01$) that meant a flat curve within a band of ±5% SD were found to be the normal behaviour.

Finally, these studies allow us to derive new studies which involve a temporal evolution in the quality image with another type of correction. From the results of our study of contact lenses we can conclude that in all cases the measurements satisfy the established criterion. For that reason, the observer does not experience discomfort or bad vision at the end of the use period. Therefore, although an evolution in the Mf is observed during a month, in general, the behaviour of the contact lens is good in all cases.

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