·Clinical Research·

Analysis of the optical quality by determining the modulation transfer function for anterior corneal surface in myopes

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Received: 2011-12-14 Accepted: 2012-04-10

Abstract

• AIM: To describe the characteristics of modulation transfer function (MTF) of anterior corneal surface, and obtain the the normal reference range of MTF at different spatial frequencies and optical zones of the anterior corneal surface in myopes.

• METHODS: Four hundred eyes from 200 patients were examined under SIRIUS corneal topography system. Phoenis analysis software was applied to simulate the MTF curves of anterior corneal surface at vertical and horizontal meridians at the 3, 4, 5 , 6, 7mm optical zones of cornea .The MTF values at spatial frequencies of 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55 and 60 cycles/degree (c/d) were selected.

• RESULTS: The MTF curve of anterior corneal surface decreased rapidly from low to intermediate frequency (0-15cpd) at various optical zones of cornea, the value decreased to 0 slowly at higher frequency (>15cpd). With the increase of the optical zones of cornea, MTF curve decreased gradually. 3) In the range of 3 mm- 6 mm optical zones of the cornea, the MTF values measured at horizontal meridian were greater than the corresponding values at horizontal meridian of each spatial frequency, the difference was statistically significant ($P<0.05$). At 7 mm optical zones of cornea, the MTF values measured at horizontal meridian were less than the corresponding values at vertical meridian at 10-60 spatial frequencies (cpd), and the difference was statistically significant in 25, 30, 35, 40, 45, 50 cpd($P<0.05$).

• CONCLUSION: MTF can be used to describe the imaging quality of optical systems at anterior corneal surface objectively in detail.

• KEYWORDS: modulation transfer function; optical quality; cornea; point spread function; optical transfer function; phase transfer function

DOI:10.3980/j.issn.2222-3959.2012.02.16

Zheng YZ, Chen YP, Qiu Y, Zhai GG, Li YY. Analysis of the optical quality by determining the modulation transfer function for anterior corneal surface in myopes. *Int J Ophthalmol* 2012;5(2):196-201

INTRODUCTION

Since the mid-1990s, with the rapid development of excimer laser refractive surgery and phacoemulsification, the assessment and clinical research on the quality of human visual performance and image quality was promoted. As the first structure of the eye that the image was projected, the cornea accounts for 74% of the total refractive power [1] in the normal eyes, so it is the most important optical structure. Most of astigmatism and a variety of higher-order aberrations are derived from anterior corneal surface. Therefore, accurate assessment and analysis of optical quality of the anterior corneal surface is particularly important for human visual performance. In this study, Sirius corneal topography was used to measure the modulation transfer function (MTF) in the modern optical theory, which can be used to measure and evaluate the natural optical characteristics for human anterior corneal surface in detail.

MATERIALS AND METHODS

Materials

General information The data from 200 patients who have undergone excimer laser surgery in our hospital were collected. The four hundred eys from 200 patients were with simple myopic astigmatism, in which 93 patients (186 eyes) were male, 107 patients (214 eyes) were female. They were aged 18 to 39 years old, mean 26.58±5.18 years, the range of spherical myopia is -0.25- -10D, mean -4.94 ±0.13D; astigmatism -1 - 0D, mean -0.46±0.02D. The best corrected visual acuity for all patients ≥1.0D.

Inclusion criteria Slit-lamp examination of anterior segment showed that corneal transparency was confirmed without eye disease, and there was no nebula, macula, etc. Schirmer's test and break up time (BUT) values were normal. Contact lens wearers were advised to stop wearing

for more than two weeks before the examination. The result of corneal topography examination was normal.

Examination instuments 3D Sirius-Complete Anterior Segment Imaging System (Italy CSO, software version: phoenis 1.2) was used to measure the MTF curves at various optical zones of cornea, get MTF values at various spatial frequencies. All examinations were conducteded by the same doctor. The examination was conducted immediately after blink of the eyes under natural light in the room. The patients were told to gaze the blue curser of the corneal topography to fully expose the the cornea.

Methods

Data analysis The reproducible results were selected and analyzed, the phoenis 1.2 software was used to simulate the MTF curves at horizontal meridian and the vertical meridian at the 3mm, 4mm, 5mm, 6mm, 7mm optical zones of cornea and obtain the MTF values at 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55 and 60 cycles/degree (c/d) spatial frequencies. Vertical meridian represents the horizontal grating (0°-180°) forms , the horizontal meridian represents the vertical grating (90°-270°) forms.

Statistical Analysis All data was analyzed in SPSS16.0 statical sofware package. The comparison of MTF values at the same spatial frequencies at vertical and horizontal meridian were conducted using paired t-test or signed rank test, P <0.05 represents the difference is statistically significant.

RESULTS

MTF Curves of Anterior Corneal Surface In the range of 3mm-7mm optical zones of the cornea, the MTF values of human anterior corneal surface decreases rapidly when the spatial frequencies changeed from 0 to 15cpd , the MTF value decreased to zero slowly when spatial frequency is >15cpd(Figure 1, 2). In the mean time,we can conclude that the MTF curve in different position are decreasesed with the increases of spatial frequencies in 3D spatial frequency (Figure 1). It is the objective reflection of the ability of anterior corneal surface to distinguish the objects of different sizes.

MTF Curve about the Optical Zones of Cornea With the increase of the optical zones of cornea, the MTF curves of vertical and horizontal meridian reduced gradually, the decrease is more obvious at low and medium spatial frequencies (0-15cpd). The changes of MTF curves are smaller at high spatial frequency with the changes of optical zones of cornea. The MTF curve of vertical meridian direction decreased significantly within low spatial frequency from 3 to 6mm optical zones. The MTF curves are almost superposition at 6mm and 7mm optical zones. The MTF curve at horizontal meridian at 3mm-7mm optical zones decreased obviously(Figure 2).

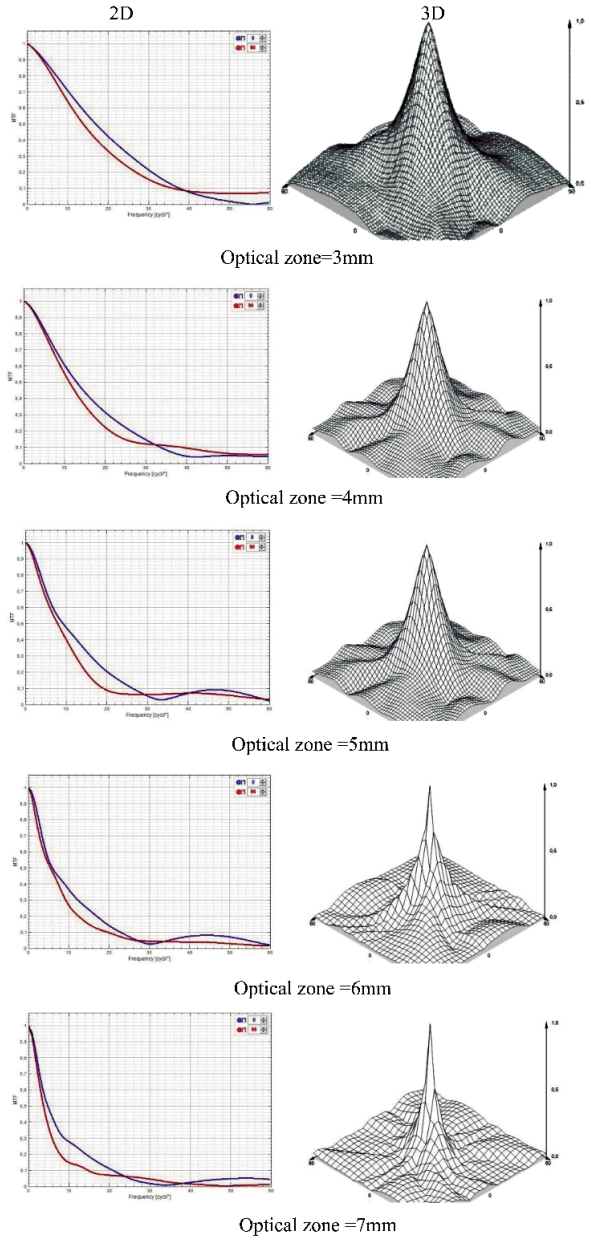

Figure 1 The curves of MTF in different corneal optical zone in normal population.

Vertical and Horizontal Meridian Direction In the range of 3mm-6mm optical zones of cornea, the MTF values at vertial meridian were smaller than the corresponding values at horizontal meridian at each spatial frequency, and the difference was statistically significant (P<0.05). At 7mm optical zone of cornea, the MTF values of vertical meridian are bigger than that of horizontal meridian at each patial frequency except at 5 cpd which is smaller. The differences are statistically significant when the spatial frequencies are at 25, 30, 35, 40, 45 and 50 (t/z=-2.346,-3.342,-3.064,-2.43, -2.098,-2.009. P=0.019,0.001, 0.002, 0.015, 0.036, 0.045). It indicates that the horizontal resolving power of human optical system of anterior corneal surface is better than the vertical resolving power when the optical zones of cornea is small.

Table 1 The 95% confidence interval of MTF value at vertical meridian in various spatial frequencies at 3-7mm optical zones of cornea

Frequency(cpd)	3mm	4mm	5mm	6mm	7mm
5	0.6051, 0.6440	0.4804, 0.5227	0.3698, 0.4079	0.3179, 0.3489	0.2861, 0.3119
10	0.3285, 0.3689	0.2489, 0.2846	0.2059, 0.2346	0.1708, 0.1932	0.1565, 0.1754
15	0.2082, 0.2401	0.1631, 0.1896	0.1337, 0.1554	0.1109, 0.1281	0.0986, 0.1129
20	0.1447, 0.1698	0.1134, 0.1344	0.0949, 0.1119	0.0804, 0.0938	0.0715, 0.0830
25	0.1091, 0.1310	0.0847, 0.1020	0.0731, 0.0868	0.0618, 0.0729	0.0553, 0.0650
30	0.0832, 0.1017	0.0641, 0.0789	0.0565, 0.0684	0.0539, 0.0643	0.0439, 0.0522
35	0.0651, 0.0815	0.0505, 0.0634	0.0458, 0.0562	0.0486, 0.0581	0.0359, 0.0434
40	0.0509, 0.0653	0.0402, 0.0515	0.0368, 0.0461	0.0328, 0.0403	0.0294, 0.0360
45	0.0409, 0.0530	0.0319, 0.0418	0.0302, 0.0385	0.0270, 0.0337	0.0250, 0.0308
50	0.0326, 0.0424	0.0255, 0.0342	0.0244, 0.0318	0.0225, 0.0287	0.0214, 0.0267
55	0.0254, 0.0332	0.0203, 0.0277	0.0196, 0.0263	0.0181, 0.0238	0.0179, 0.0227
60	0.0195, 0.0304	0.0159, 0.0223	0.0155, 0.0215	0.0149, 0.0200	0.0151, 0.01

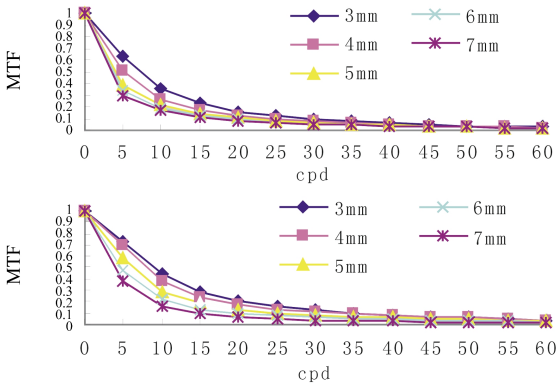

Figure 2 Mean of MTF value in different meridian (n=400).

Differences among MTF Values There are individual differences of MTF values at vertical and horizontal meridian at the same spatial frequencies and the same optical zones of cornea,and the MTF values at mately normally distributed in variousvarious spatial frequency are approxi optical zones of cornea(Table 1, Figure 3).

DISCUSSION

With the rapid development of refractive surgery technology, the requirements for the human vision do not stay in the best corrected visual acuity, instead, we do expect a better visual performance. Visual performance is defined by how well a visual task of interest can be performed by a given individual or group of individuals[2]. American Academy of Ophthalmology basic and clinical science refers it as "functional vision", i.e. the vision that influence the quality of life. Its quality is directly related to the human eye's visual performance.

Clinical Assessment Methods of Visual Performance In clinical practices used assessment methods of visual performance are subjective and objective methods. Subjective methods include measurements of visual acuity and contrast sensitivity (CS). They are the reflections of evaluation of image quality that the imaging of light emitted by an object pass through the human optical system, then be integrated by the visual passway and the cerebral cortex.

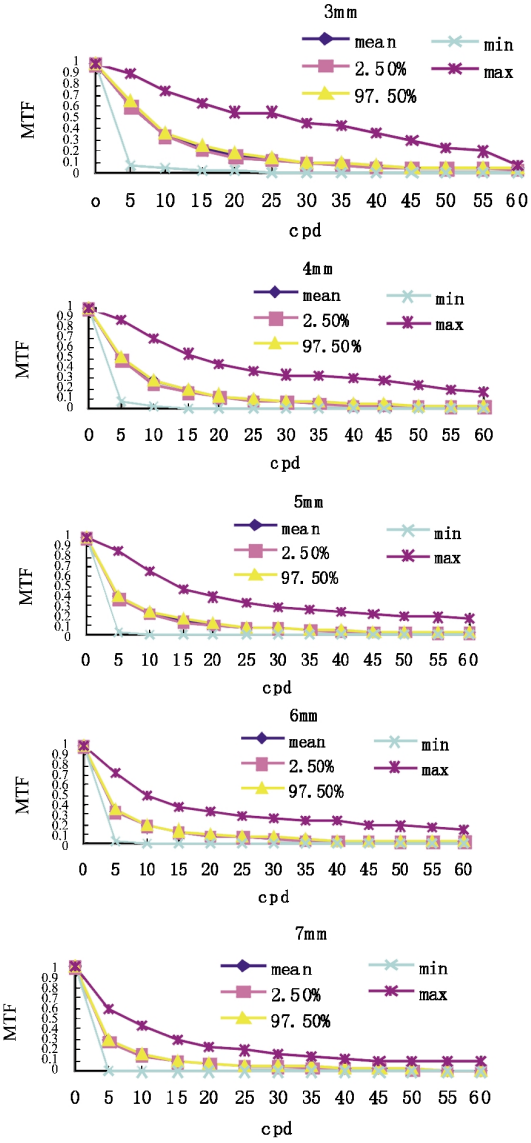

Figure 3 The mean, 95% CI, maximum and minimum values of MTF curves at 3–7mm optical zones of cornea(n=400).

Both of them are the psychophysical methods for subjective evaluations of objective stimulation. While visual acuity is the spatial resolving capacity of macula lutea to detect and identify small objects [3]. CS is the ability of human eyes to distinguish objects of different sizes at different spatial frequencies, it can exam the subjective visual function in quantitative. From the viewpoint of assessing, visual acuity is only one point on the contrast sensitivity function under high contrast ratio [4], so the CS is the significant progress compared with visual acuity measurement [5]. Aberrations and the aberration-based root means square (RMS), optical transfer function (OTF), etc., are major objective methods to assess the quality of optical quality of human eyes in clinical practices[6].

Currently, RMS is the most often used method for the evaluation of aberrations in clinical practices. RMS is the total difference of aberrations of the human eye, reflecting the size of each aberration type and its ratio in total aberration. Since the influences of different aberrations on the human visual performance are highly complex, the aberrations at the center of Zernike pyramid is more likely to affect the visual performance of the human eye. While the effects of different aberrations combinations on retinal image quality are different [7], so even if the RMS values are same, the visual performances of human eyes will be different, so the RMS value of the aberrations can not reflect the image quality of the human eye well.

OTF includs MTF, phase transfer function (PTF) and the point spread function (point spread function, PSF), *etc*[8]. OTF is the reflection on the imaging quality of the optical systems and the loss of the image contrast. It has been confirmed that modern optical theory can make more scientific evaluation on the visual function of the visual system [9]. The MTF is considered as an important function that can fully reflect the optical characteristics of human eyes in clinical practices, and MTF is closely related to CS which is a subjective evaluation indicator[10].

Modulation Transfer Function In 1948, Schneider [11] for the first time evaluated the image quality of the new television camera system using OTF concept, it is the big inspiration to the subsequent evaluation of the characteristics of optical systems. Currently, OTF concept has been widely accepted and used for the evaluation of the characteristics of optical systems.

Concept MTF is the ratio between the image contrast of a specific object through the imaging optical system and the contrast of the object itself. MTF is a function of spatial frequency [12], reflecting the responsive abilitity of the optical system to different spatial frequencies, therefore, it is also known as spatial contrast transfer function.

In the optical system, MTF values reflect the different imaging characteristics of different imaging systems. As a special optical system, the imaging capability of human optical system can also be analyzed using MTF concept, and imaging quality of the visual image can be better explained by the MTF. In general, high frequency part of the curve reflects the transfer of the details of the object, the midddle frequency part reflects the transfer of the level of the object, whereas the low frequency part reflects the transfer of the contours of the object [13]. Our research found that the MTF values of human anterior corneal surface decreases rapidly with the spatial frequency increases from 0 to 15cpd, the MTF value decreased to zero slowly when spatial frequency is >15cpd (Figure 1, 2). The spatial frequencies are in the range of 50-60cpd, the optical system of anterior corneal surface has reached the resolution limit, which is similar to the MTF curve of the whole eye and full-thickness cornea.

Formulas The value of MTF is equal to the ratio of modulation M'for the image of object through the optical system and the modulation M'of object itself, namely:

$$MTF= M' /M \qquad \text{(Formula 1)}$$

The so-called modulation(M) is the contrast. People rely on its size to see and distinguish objects.

$$M=(I_{max}-I_{min})/(I_{max}+I_{min}) \qquad \text{(Formula 2)}$$

I_{max} and I_{min} is the maximum and minimum light intensity from the object surface and the imaging surface. The modulation is reduced after the image of the object pass through the human optical system, so MTF value should range from 0 to 1.

Influencing factors for MTF Used in Clinical Evaluation The value of MTF are not only be influenced by factors such as pupil function, aberrations in physical optics evaluation, but also influenced by age, race, and tear film stability and other factors.

Pupil function In the assessment of physical optics, if the size of imaging system and the field angle are not big, the normalized two-dimensional optical transfer function is expressed as:

$$OTF(r,s)=1/A \iint_G P^*(x-\bar{r},y-\bar{s})P(x,y)dxdy \qquad \text{(Formula 3)}$$

(Note: A is the exit pupil area; x, y are the coordinates of the pupil area; r, s are spatial frequencies, P (x, y) = A (x, y) exp [jkw (x, y)] is the pupil function)

MTF value is the modulus of the OTF, i.e. amplitude, so the MTF values in this study is inversely proportional to the area of exit pupil area (optical zones of cornea). The greater the optical zones of cornea, the smaller the MTF is, the smaller the optical zones of cornea, the greater the MTF is.

Aberration In an ideal aberration-free optical system,

$$P(x,y)=1 \qquad \text{(Formula 4)}$$

Then,

$$OTF(\bar{r},\bar{s})=1/A \iint_G \exp\{jk[W(x,y)]-W(x-\bar{r},y-\bar{s})]\} \leqslant 1/A \iint_G dxdy \qquad \text{(Formula 5)}$$

Studies have shown that [6] the optical quality of the whole eye is influenced by the aberration.

Age Guirao et,al. [14] reported the corneal aberrations increased with increasing age, but the change is not big enough to reduce the MTF.

Race The MTF values at different meridian directions of whole optical system of the eye and the race are different. Carkeet *et al* [15] invesitaged the optical quality of the whole eye in children of China and Malaysia, they found that the MTF values at vertical meridian direction is slightly smaller than at other directions,they thought it is maybe related to the bigger vertical. The study on the optical quality of the whole eye in Chinese by Fang *et al* [16] have showen that the MTF value at oblique meridian is 35% smaller than that of vertical and horizontal, they think it may be related to the differenct properies of MTF curves at different meridians that depends on the race. In our study, we found that the MTF values of each spatial frequency measured at horizontal meridian were greater than the corresponding values at vertical meridian in the range of 3-6mm optical zones of anterior corneal surface(Figure 4).

Tear film stability Montés-Micó *et al* [17] have shown that MTF value of cornea and whole optical system of the eye are biggest at the 6-7 seconds after blink of the eyes, and begin to decrease after 10 seconds. The longer after blink, the smaller the MTF value is . So we select the normal subjects with normal Schirmer test and BUT test results, and measured data immediately after the blink to remove the influence of tear film on the MTF measurements.

Relationship between MTF and Other Assessment Indicators MTF is closely related to PSF and OTF. In the clinical evaluation of visual quality, it is also closely related to CS which is a subjective evaluation indicator.

MTF and PTF, and OTF is a function of a complex variable:

OTF(r,s)=MTF(r,s)exp[-jPTF(r,s)] (Formula 6)

Optical transfer function is defined as:

$$OTF(r,s)=\int_{-\infty}^{\infty}\int PSF(u,v)\exp[-j2\pi(ru+sv)]dudv$$

(Formula 7)

We can see from formula 6, 7 that the relation between OTF and PSF is Fourier transform, and the MTF is the modulus of OTF, PTF is the influence of delayed imaging time on imaging quality.

MTF and CS are both used to describe the ability of human eye to distinguish two separate objects that are close together according to their definitions. But the MTF is the objective evaluation of imaging quality of human optical systems, while the CS also reflects the patient's subjective feel besides the influences from optical characteristics of human eyes, it is also influenced by the patient's age, educational level and with other factors. CS is the product

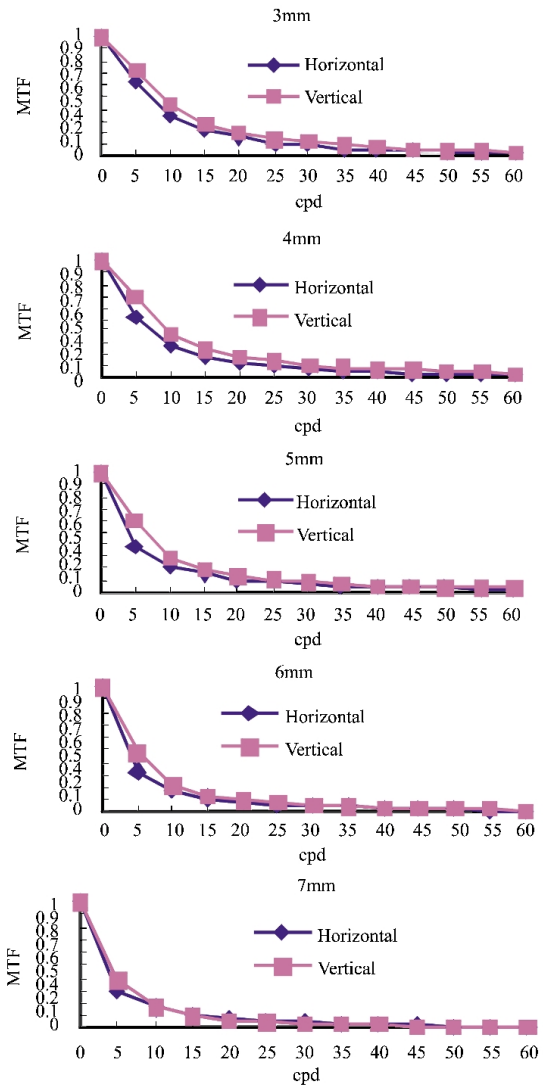

Figure 4 The curves of mean MTF value at vertical and horizontal meridian at 3–7mm optical zones of cornea (n=400).

of multiplication of OTF value and the transfer function of retinal nerve.In contrast to MTF curve, CS curve reachs peak in the spatial frequencies of 6-9c/d, and decreases gradually to both ends, this is the result of visual passway transfer and integration by the brain. When MTF and CS were used to evaluate the visual performance of human eyes, both have their advantages and disadvantages.

MTF can reflect the imaging quality of human optical systems in an objective, quantitative, and accurate way , but whether it is consistent with the subjective feels of patients needs to be further studied. Compared the values with the mean MTF of various spatial frequencies on same optical zone on full-thickness cornea: The MTF values of the anterior corneal surface are slightly smaller, which may be related to the optical compensation effect of anterior and posterior corneal surfaces [18]. it also r proves the important role of anterior corneal surface in the optical system of full-thickness cornea.

In summary, the MTF test in optical theory can make the

detailed, objective description of the optical characteristics of the anterior corneal surface,it can provide important evidence for the evaluate of corneal optical quality and refractive surgery. But the assessment of human visual performance can not be completed by one single indicator, other objective and subjective indicators should also be integrated to make an accurate assessment of human visual performance. But the MTF value at anterior corneal surface is undoubtedly an objective and accurate indicator for evaluation.

Acknowledgements: We give our thanks to the LASIK center of the beijing military general hospital of PLA for supporting clinical data.

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