· Original article ·

Analysis of the point spread function in total corneal of normal population

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正常人眼全角膜点扩散函数的分析

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摘要

目的:探讨不同瞳孔直径下正常人眼全角膜总像差的斯特列尔比(strehl ratio, SR)与总高阶像差 SR 的正常值及其与调制传递函数(modulation transfer function, MTF)的关系。

方法:应用 SIRIUS 3D 角膜地形图仪对 200 例(400 眼)进行全角膜总像差的 SR 和总高阶像差的 SR 检查,并分析相对应的均方根值(root-mean-square, RMS)。

结果:在不同瞳孔直径组下(3.0, 5.0, 6.0, 7.0mm)全角膜总像差 100′SR 值为 0.45±0.12, 0.25±0.06, 0.17±0.05, 0.13±0.04;总高阶像差 100′SR 值为 0.69±0.14, 0.34±0.07, 0.24±0.05, 0.16±0.04;全角膜总像差 200′SR 值为 0.45±0.12, 0.24±0.06, 0.20±0.04, 0.16±0.03;总高阶像差 200′SR 值为 0.70±0.13, 0.35±0.07, 0.27±0.06, 0.20±0.04,各组均逐渐变小;全角膜总像差 SR 值和总高阶像差 SR 值与对应的 RMS 值之间均存在负相关性。当瞳孔直径小时,总像差 SR 值与 MTF 值的高频区相关性较高,而当瞳孔直径大时,总像差 SR 值与 MTF 值的低频区相关性较高。

结论:正常人全角膜总像差的 SR 值和总高阶像差的 SR 值能够很好地反映其视觉质量。

关键词:点扩散函数;斯特列尔比;瞳孔直径;均方根值;调制

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Abstract

• AIM: To explore relationship between the normal strehl ratio (SR) values of total aberrations/SR values of total higher-order aberrations and modulation transfer function (MTF) at total corneal at different pupil diameters in normal population.

• METHODS: To exam the SR values of total aberrations and SR values of total higher-order aberrations of total corneals in 200 people (400 eyes) using SIRIUS 3D topography system and analysis the corresponding root-mean-square (RMS).

• RESULTS: The subjects with different pupil diameters (3.0, 5.0, 6.0, 7.0mm)'s exam results of total corneal were as following: SR value of total aberrations 100′(0.45±0.12), (0.25±0.06), (0.17±0.05), (0.13±0.04); SR value of total higher order ab cerrations 100′(0.69±0.14), (0.34±0.07), (0.24±0.05), (0.16±0.04); SR value of total aberrations 200′(0.45±0.12), (0.24±0.06), (0.20±0.04), (0.16±0.03); SR value of total higher order aberrations 200′(0.70±0.13), (0.35±0.07), (0.27±0.06), (0.20±0.04). The SR values of each group decreases with the increases of pupil diameters. The SR values of total aberrations and SR values of total higher-order aberrations at total corneals are negatively correlated with corresponding RMS value. When the pupil diameter is small, the SR value of total aberrations is more related to higher frequency region of MTF. When the pupil diameter is big, the SR value of total aberrations is more related to lower frequency region of MTF.

• CONCLUSION: The visual performance of normal people can be well reflected by SR values of total aberrations and SR values of total higher-order aberrations at total corneal.

• KEYWORDS: point spread function; strehl ratio; pupil diameter; root-mean-square; modulation transfer function

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INTRODUCTION

The assessment of human visual performance is the basis of research and evaluation of various refractive surgeries (cornea and lens), it is also a part of ophthalmology & visual science. Most current evaluations of visual performance are subjective evaluations (visual acuity, contrast sensitivity, and others). Since these are subjective and rough evaluations, they often can not reflect the true visual performance of subjects accurately, or provide an accurate basis for further study of visual performance or refractive surgeries. With the extensive development of refractive surgeries, clinicians are in great need of more objective comprehensive assessments on the visual performance of patients. Strehl ratio (SR) is one method to evaluate the aberrations, it can assess retinal image quality objectively[1-3]. Many researchers have studied SR, but most of these studies are for the whole eye. And most of our refractive surgery perform an operation on the cornea, the surgeon also want to know the impact on the visual quality of the cornea. In this article, we conducted the study on SR of total corneal in normal population.

SUBJECTS AND METHODS

General Information Our investigations of humans follow the principles outlined in the Declaration of Helsinki. A retrospective analysis of 200 patients (400 eyes) with myopia (astigmatism≤100 degrees) who will undergo LASIK surgery in our hospital from July 2012 to November 2013, among patients, there are 95 males (190 eyes), 105 females (210 eyes), aged 18-42y (mean 26.15±5.80y). The spherical equivalent degrees of right eyes are -0.50 to -10.50D (mean -4.62±1.33D), the spherical equivalent degrees of left eyes are -0.50 to -11.00D (mean -4.35±1.78D).

Inclusion Criteria All patients underwent the routine eye examination to rule out eye disease. The results of Schirmer's test and tear break-up time test were normal. Contact lens wearers were asked to stop wearing for more than 2wk. The results of corneal topography examination were normal.

Examination Method The SIRIUS 3D topography system (CSO Co., Ltd., Italy. Software Version: phoenix1.2) and three - dimension anterior segment analysis system were utilized for data acquisition. The default degree of refraction is deemed as 0, the degree of astigmatism of cornea is controlled to less than 1.00D, and we measured the SR values of total aberrations and the SR values of total higher - order aberrations, the corresponding root-mean-square (RMS) value and modulation transfer function (MTF) values at total corneal. The SR values at 100′ and 200′ were selected from the SIRIUS 3D topography system and three - dimension anterior segment analysis system for the study, 100′ and 200′ change the amplitude of the arc, or the image's dimension: it is useful to select 100′ for less aberrated cornea's, 200′ for highly abberated cornea's.

Statistical Analysis All data were processed using SPSS 13.0 statistical software. Use single - factor ANOVA to compare the SR values of total aberrations and SR values of total higher-order aberrations at the total corneal at different pupil diameters (3.0, 5.0, 6.0, 7.0mm). Pearson correlation analysis was applied to study the relationship between two kinds of SR values and the corresponding RMS values; and the relationship between SR values of the total aberrations and corresponding MTF values. $P<0.05$ is statistically significant for differences.

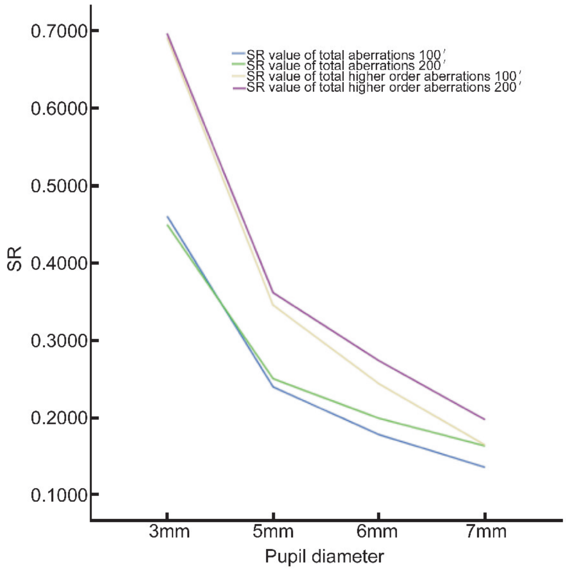


Figure 1 The SR values at totalcorneal in normal population (n=400).

RESULTS

Strehl Ratio Value at Total Corneal of Normal Population Changes in the SR value of total aberrations: the SR values of total aberrations 100′/200′ will reduce with the increase of the pupil diameter, the SR values of the total aberrations 100′ are statistically different ($F=1400.292$, $P<0.01$) with the different pupil diameters, the SR values of the total aberration 200′at the different pupil diameters are also statistically different ($F=1004.6$, $P<0.01$) (Table 1).

Changes in the SR value of total higher-order aberrations: the SR values of total higher-order aberrations 100′/200′ will reduce with the increase of the pupil diameter, the SR values of the total higher-order aberrations 100′ are statistically different($F=2475.323$, $P<0.01$) with the different pupil diameters, the SR values of the total higher-order aberrations 200′ are also statistically different ($F=2103.585$, $P<0.01$) with the different pupil diameters (Table 2).

The relationship: the SR values of total higher - order aberrations 100′ are higher than the total aberrations 100′, aberration 100′, it is also the same for 200′, so the SR values of total higher-order aberrations are higher than the SR values of total aberrations. The SR values of total aberrations 200′is obviously higher than SR values of total aberrations 100′when the pupil diameter is greater than 5mm. It means that with the increase of pupil diameter, the SR values at 200′ is bigger than SR values at 100′ even if the aberrations are equal (Figure 1).

Relationship Between Strehl Ratio and Root - Mean - Square When the pupil diameter is 3mm, SR value and

Table 1 The SR values of total aberrations at total corneal in normal population $n=400$

PD(mm)	100′ SR			200′ SR		
	$\bar{x}\pm s$	Range	95% *CI*	$\bar{x}\pm s$	Range	95% *CI*
3	0.45±0.12	0.11-0.80	0.45-0.46	0.45±0.12	0.12-0.87	0.43-0.45
5	0.25±0.06	0.10-0.48	0.23-0.22	0.24±0.06	0.11-0.53	0.24-0.25
6	0.17±0.05	0.08-0.36	0.17-0.17	0.20±0.04	0.11-0.43	0.20-0.15
7	0.13±0.04	0.07-0.25	0.13-0.13	0.16±0.03	0.08-0.32	0.15-0.86

PD:Pupil diameter; SR: Strehl ratio.

Table 2 The SR values of total higher-order aberrations at total corneal in normal population $n=400$

PD(mm)	100′ SR			200′ SR		
	$\bar{x}\pm s$	Range	95% *CI*	$\bar{x}\pm s$	Range	95% *CI*
3	0.69±0.14	0.01-0.12	0.66-0.72	0.70±0.13	0.20-0.28	0.67-0.61
5	0.34±0.07	0.12-0.53	0.33-0.34	0.35±0.07	0.14-0.12	0.34-0.28
6	0.24±0.05	0.08-0.43	0.25-0.26	0.27±0.06	0.10-0.13	0.26-0.29
7	0.16±0.04	0.06-0.28	0.16-0.19	0.20±0.04	0.05-0.56	0.19-0.16

PD: Pupil diameter; SR: Strehl ratio.

Table 3 The correlation between SR values and RMS values

Correlation betweenvalues	Pupil diameter(mm)	Total aberrations		Correlation	Total higher-order aberrations		Correlation
		SR	RMS		SR	RMS	
100′ SR	3	0.46±0.12	0.14±0.06	-0.853[a]	0.69±0.13	0.08±0.04	-0.7[a]
	5	0.23±0.08	0.42±0.14	-0.665[a]	0.3±0.09	0.22±0.23	-0.692[a]
	6	0.17±0.04	0.63±0.20	-0.642[a]	0.23±0.05	0.40±0.67	-0.592[a]
	7	0.14±0.02	1.03±0.34	-0.473[a]	0.16±0.03	0.73±0.33	-0.554[a]
200′ SR	3	0.43±0.12	0.14±0.46	-0.861[a]	0.70±0.14	0.08±0.04	-0.720
	5	0.25±0.08	0.43±0.12	-0.676[a]	0.35±0.28	0.23±0.07	-0.707[a]
	6	0.19±0.11	0.64±0.23	-0.669[a]	0.27±0.06	0.41±0.14	-0.616[a]
	7	0.15±0.04	1.03±0.34	-0.548[a]	0.21±0.04	0.73±0.35	-0.563[a]

SR: Strehl ratio; RMS: Root-mean-square; [a]$P<0.05$.

RMS value are with the highest correlation. As the pupil diameter increases, the correlation between them decreases (Table 3).

Relationship Between Strehl Ratio and Modulation Transfer Function When the pupil diameter is 3mm, the correlation of the SR values of total aberrations with the high frequency region of corresponding MTF is higher. When the pupil diameter is 5mm, the correlation of SR values of total aberrations 100′ with the high frequency region of corresponding MTF is higher. While the correlation of the SR values of the total aberrations 200′ with all 12 spatial frequencies of corresponding MTF are higher, but the correlation of SR with higher frequency region is not significantly higher than mid-to-low frequency region of MTF. When the pupil diameter is 7mm, the correlation of the SR value of total aberrations with the lower frequency region of corresponding MTF is higher. That is, when the pupil diameter is small, the correlation of SR of total aberrations with higher frequency region of corresponding MTF is higher. With the increase in pupil diameter, the correlation of SR of total aberrations with lower frequency region of corresponding MTF is higher (Table 4).

DISCUSSION

Assessment Methods for Visual Performance The most commonly assessment method for human visual performance are subjective methods, such as visual acuity and contrast sensitivity function. The object emits light, then the light penetrates the human optical system, and finally integrated by the visual pass way and cortex to form the image. These subjective measurements reflect the final imaging quality. These measurements involve not only the physical imaging of optical system, but also involve the role of the nervous system processing. Because they are subjective assessment methods, the results are often subject to interference from human factors (emotional, psychological state, *etc*).

With application and development of wavefront technology in the field of optometry, it laid a good foundation for exploring and creating new evaluation indicator of visual performance. The most commonly used objective assessment methods of visual performance (such as RMS and others.) are derived from the aberrations. The reason is that the aberrations are an objective indicator, not influenced by subjective factors. The basic principle is that the deviation of actual light rays from the ideal rays, and the basic unit of any images is light ray. Thus aberrations are the most basic indicators to describe the

Table 4 The relationship between SR values and the MTF values

PD(mm)	100′SR	Frequency region	MTF	Relationship	PD(mm)	200′SR	Frequency region	MTF	Relationship
3	0.46±0.13	5	0.58±0.19	0.053	3	0.45±0.12	5	0.59±0.17	0.156
		10	0.38±0.15	0.213			10	0.38±0.15	0.267
		15	0.25±0.14	0.236			15	0.26±0.12	0.285
		20	0.15±0.14	0.257			20	0.15±0.12	0.278
		25	0.14±0.08	0.212			25	0.13±0.09	0.247
		30	0.11±0.09	0.235			30	0.11±20.08	0.235
		35	0.09±0.06	0.251			35	0.08±0.07	0.241
		40	0.07±0.06	0.283			40	0.07±0.06	0.245
		45	0.06±0.05	0.258			45	0.06±0.05	0.267
		50	0.05±0.04	0.293			50	0.05±0.04	0.251
		55	0.04±0.04	0.345[a]			55	0.04±0.04	0.312[a]
		60	0.04±0.03	0.343[a]			60	0.04±0.03	0.319[a]
5	0.24±0.07	5	0.53±0.19	0.144	5	0.25±0.08	5	0.54±0.17	0.608[a]
		10	0.33±0.14	0.267			10	0.34±0.14	0.687[a]
		15	0.23±0.13	0.294			15	0.26±0.13	0.726[a]
		20	0.16±0.16	0.292			20	0.17±0.11	0.713[a]
		25	0.13±0.09	0.244			25	0.13±0.09	0.706[a]
		30	0.10±0.08	0.231			30	0.11±0.08	0.663[a]
		35	0.09±0.06	0.244			35	0.09±0.06	0.632[a]
		40	0.08±0.06	0.246			40	0.08±0.06	0.631[a]
		45	0.06±0.05	0.232			45	0.06±0.05	0.677[a]
		50	0.06±0.05	0.257			50	0.06±0.05	0.695[a]
		55	0.05±0.04	0.311[a]			55	0.05±0.04	0.687[a]
		60	0.04±0.04	0.322[a]			60	0.04±0.04	0.677[a]
7	0.14±0.03	5	0.41±0.12	0.724[a]	7	0.16±0.03	5	0.39±0.11	0.634[a]
		10	0.25±0.09	0.703[a]			10	0.25±0.08	0.631[a]
		15	0.16±0.07	0.645[a]			15	0.17±0.06	0.616[a]
		20	0.13±0.06	0.464[a]			20	0.12±0.06	0.467[a]
		25	0.10±0.04	0.314[a]			25	0.09±0.05	0.328[a]
		30	0.07±0.04	0.308			30	0.07±0.04	0.324[a]
		35	0.06±0.04	0.312			35	0.06±0.04	0.311
		40	0.05±0.03	0.358[a]			40	0.05±0.03	0.325[a]
		45	0.05±0.03	0.275			45	0.05±0.03	0.246
		50	0.04±0.03	0.336[a]			50	0.04±0.03	0.327[a]
		55	0.04±0.03	0.361[a]			55	0.04±0.03	0.346[a]
		60	0.03±0.03	0.365[a]			60	0.03±0.03	0.362[a]

PD: Pupil diameter; SR: Strehl ratio; MTF: Modulation transfer function. [a]$P<0.05$.

quality of optical imaging; aberrations are also the basis for creating other indicators of optical imaging.

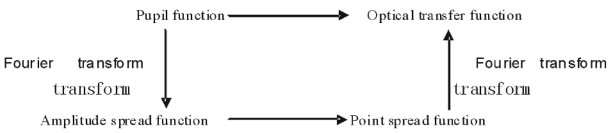
Evaluation Indicators of Aberrations

Root-mean-square Method of calculating and expressing aberrations is mainly RMS, because RMS can reflect the size of each type of aberrations, and can estimate the percentage of each type in total aberrations, RMS is the most common indicators for evaluation of aberrations. But in many cases, RMS can not well reflect the visual performance, the reasons are listed below[4-9]: 1) the light from the center of the pupil plays more important role in visual perception; 2) the aberrations that are near the center of the Zernike pyramid are more likely to affect the retinal image quality than the aberrations at the edge; 3) the different combinations of aberrations can raise or lower the retinal image quality compared with isolated aberrations; 4) the role of different neural processing on aberrations may not be same; 5) the different individuals have different adaptabilities of nerve signal processing to the altered aberrations due to aging or refractive surgeries. Therefore, other indicators that can reflect visual performance more objectively are needed.

Thus, Guirao and Williams[3] have proposed that the SR values of point spread function (PSF) should be used as the new indicator for imaging quality evaluation. Because the corresponding results of refractive error sensing from wavefront slopes are closely consistent to patient's subjective experiences, it is a good objective assessment of the best visual performance.

Point spread functionPSF is a function that reflects distribution of the diffraction spots after the light from point light source penetrate the optical system, PSF characterize the spatial properties of optical system[10]. For the human eye, PSF is used to describe the shape of image on the retina from very distant target point light source. Generally, it is believed that, if the PSF diffraction spots are smaller, and the intensity of diffraction spots is greater, it indicates that the less energy is lost after the light from a point light source penetrate the optical system, thus the retinal imaging is better.

PSF and other imaging quality evaluation indicators have the following relationship:



The value of PSF is determined by the diffraction, aberrations, and scattering occurred during the projection[11]. Their impacts on the PSF are as following [12]: 1) Diffraction: when there is no aberration and scattering in the optical system, PSF is mainly affected by diffraction, then it is known as the diffraction-limited optical system. In this circumstance, the PSF is shown as a round spot with the Airy disk as the center, surrounded by somber rings consists of fine lines. Air disc containing 84% of the energy, Airy disk radius is proportional to the wavelength, and is inversely proportional to the pupil diameter. The smaller the pupil diameter is, the bigger the Airy disk is. 2) Aberrations: the most common aberrations in human eyes are defocus, defocus will increase the width of PSF. When the higher-order aberrations exist, even if there is no defocus, the imaging will be beyond its geometry limit. There is a certain angle between the optical axis of human eye and the center of the macula, and tilt and eccentricity are existed in the each refractive interface, thus resulting in coma aberration and other aberrations, so the imaging quality at the macula will be decreased. If the aberration is less than 1/4λ, the human eye is mainly affected by diffraction effects, and the PSF is similar to diffraction-limited optical system. 3) Scattering: scattering can expand PSF.

In daily life, the role of diffraction will increase with the reduction of pupil diameter. The role of scattering will increase significantly with the decrease of the transparency of refractive media and the increase of surface irregularities. Previous aberrations measurement system ignores the role of diffraction and scattering, but PSF can express the effects of diffraction, aberrations, and scattering on retinal image quality integratedly, so it is suitable for clinical applications. PSF can be described by shape matching, symmetry, and contrast, *etc.*, so there are many different methods to describe the PSF, such as the width of the image, the half-width of intensity, half-height of intensity, and intensity, *etc*[12]. SR values can be well used to measure the height ratio of the PSF, but its clinical application is rarely seen in literatures.

Strehl Ratio In 1894, Karl Strehl proposed a indicator to judge the imaging quality of optical system based on the effect of aberrations of optical system on the brightness of center point in PSF. This indicator is SR, also known as the brightness of center point. It is expressed in S. D.

SR value is an indicator to describe the contrast. It is defined as the ratio of the center peak intensity an optical system with aberrations as compared to the corresponding center peak intensity ofa perfect imaging system working at the diffraction limit (Formula 1)[13], the value is generally between 0 and 1. For an optical system, if the SR value is greater than 0.8, it can be expected that this optical system is diffraction-limited (Rayleigh criterion)[14]. But for the human eye, SR is usually relatively low due to various reasons[12].

$$S = \frac{i_{max}}{I_{max}} \qquad \text{Formula (1)}$$

In which, Srepresents the strehl ratio, i_{max} represents the actual maximum brightness of optical system (center peak intensity of PSF), I_{max} represents the maximum brightness (central peak intensity of PSF) of diffraction-limited optical system or optical system without aberrations at the same pupil diameter. SR is also an important objective evaluation indicator for retinal image quality in optometry.

Relationship Between Strehl Ratio and Other Indicators for Evaluation of Visual Performance

Relationship between strehl ratio and root-mean-square

SR value measures the imaging performance of components to evaluate the wavefront quality. In contrast, the peak-to-valley value (PV) and RMS value measure its physical surface or wavefront shape directly. But it is usually believed that RMS and SR have a certain relationship, i. e., an approximate formula exists between RMS and SR. If RMS is already known, an approximate formula can be used to obtain the corresponding SR. It is found in practice that the surfaces with same RMS may have a greater difference in the SR values. This indicates that the SR value is not entirely determined by RMS, but should be correlated with RMS within a certain range. Our study found the SR value is negative correlated to RMS value of total corneal in normal human eyes. In a system with small aberrations, the relationships between them are expressed as formula (2) [3]: This is broadly in line with the changing trend of results in this study.

$$S = \exp[-(\frac{2\pi}{\lambda}RMS)^2] \qquad \text{Formula (2)}$$

In which, S is SR, λrepresents wavelength, RMS is root mean square value.

Relationship between strehl ratio and modulation transfer function Formula (3)[15] shows using *MTF*method to calculate the SR values in the frequency domain, the formula must be based on PTF = 0, so it can only get the approximation value of SR value.

$$SRMTF = \frac{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} MTF(f_x, f_y)\, df_x df_y}{\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} MTF_{DL}(f_x, f_y)\, df_x df_y} \qquad \text{Formula (3)}$$

In which, *SRMTF* represents the SR calculated in the frequency domain (*MTF* method), *DL* means diffraction-limited.

According to this formula, there is certain correlation between SR and MTF, which is consistent with the results of this study, *i. e.*, when the pupil diameter is small, the SR values of total aberrations are more related to higher frequency region of MTF. When the pupil diameter is big, the SR values of total aberrations are more related to lower frequency region of MTF.

Application of Strehl Ratio in Evaluation of Visual Performance In recent years, a number of scholars studied the application of SR in evaluation of visual performance[1,3,8], they found that SR value is better than RMS value in assessment of the visual performance. In the study of keratitis, cataract, and other related diseases[16-20], SR is used as one of the indicators for evaluation of visual performance.

In 1997, Liang and Williams[21] modified aberrations measurement method of Hartmamn-shack wavefront sensor, they found that after the elimination of only 2-order aberrations, the SR values of the whole eye were 0.63 and 0.06 with the pupil diameter of 3.0mm and 7.3mm respectively. Their result is basically consistent with our results with the pupil diameter 3.0mm that the SR values of total higher-order aberrations 100′ and 200′ were 0.69±0.14, 0.70±0.13 respectively at total corneal. When the pupil diameter is 7.0mm, the SR value is 0.16±0.04, 0.20±0.04 respectively, not consistent with their findings. It is maybe because that when the pupil size is reduced, the retinal image quality is mainly influenced by the impact of diffraction, the difference between the whole eye and the total corneal is relatively small. Thus when the pupil diameter is small, our results are close to the values they reported. When the pupil diameter is big, the effects of aberrations and scattering of the whole eye increased, thus cause the decline in retinal image quality, so the SR value of the whole eye is small. Since we only measured total corneal, our results were less influenced by aberrations and scattering compared with measuring the whole eye, so our SR values are higher than they reported.

In 2004, Llorente *et al*[16] measured the best SR values of the whole eye at the pupil diameter 6.5mm (after correction of 2-order aberrations) in 13 patients before the LASIK surgery for hyperopia. In which the minimum value is about 0.09, the maximum value is about 0.28. Their results are consistent with our results that the SR values of total higher-order aberrations 100′ and 200′ of total corneal at pupil diameter 6.0mm were 0.24±0.05 and 0.27±0.06 respectively.

Jiménez[17] measured the SR values of whole eye at pupil diameter 5.0mm in 18 patients with unilateral keratitis (double-pass measurements). The SR values of contralateral normal eye at pupil diameter 5.0mm is 0.23±0.04, their results are also consistent with our results that the total higher-order aberrations 100′SR and 200′SR of total corneal at pupil diameter 5.0mm been 0.25±0.06 and 0.24±0.06 respectively.

Although the results of this study is broadly consistent with the literature data, but there are some differences. The main reason is the measurement methods and measuring principle used are not same. In addition, the all values measured are SR values in the whole eye in the literatures, but we measured the SR values of the total corneal in this study. Also, the anatomical location measured and the selected pupil diameter may be different, these are also the main reason for these differences.

Limitaion and Prospects SR values here can be used to compared with the change of the SR values of the cornea refractive surgery, which is in order to assess the visual quality of the human eye surgery, and laid the foundation for further study in the SR value. Although there are many methods to evaluate the imaging quality of visual system, no one method can meet all of the requirements because all these methods has its own application scope, thus the new evaluation methods are required. For example, 1) visual SR: since the SR values in our study does not include the influence and processing effect of nervous system on imaging quality, and thus has some limitations. In contrast, in the calculation of visual SR[22,23], the role of the nervous system was taking into account, enabling better combination of visual performance and optical quality. Marsack *et al*[1] analyzed 31 indicators of imaging quality, they suggest that the visual SR is the best one for estimation of visual performance. 2) Combination of corneal topographer and wavefront analyzer: the human eye is a complex optical system, internal and external structures play a very important role in the visual performance. Therefore, only after the corneal topographer and wavefront analyzer worked together, researchers can fully understand the complexity of the human visual performance and evaluate its refractive problems correctly.

In summary, with the help of cross-disciplinary and the continuous development of visual science, the assessment methods for human visual performance will become more perfect.

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