3 Clinical Significance of the Main Parameters of the Double-Pass Optical Visual Quality Analysis System

A-Yong Yu

3.1 Objective Scatter Index

1. OSI contains forward scattering of the lens.

The lens is one of the main sources of intraocular scattering, which includes forward and backward scattering. The physiological structure and morphology of the lens change with age, and the color changes from colorless to pale yellow to dark yellow. This change causes an increase in the amount of lens scattering. In other words, there is a physiological scattering of the lens itself [1], and pathology can augment this scattering, e.g., when opacification occurs [2, 3].

The OSI value can reflect the amount of forward scattering of the lens to a certain extent. It can be more consistent with the patient's subjective perceptions when assessing the cataract and can be applied to the objective grading of cataract [4–9]. An increase in the OSI value may reflect an increase in the forward scattering caused by lens opacification.

(a) OSI between 2.0 and 4.0 corresponds with early cataract.
(b) OSI greater than 4.0 corresponds with mature cataract.

Conversely, a decrease in the OSI value may indicate a decrease in the forward scattering of the lens for certain reasons, e.g., a significant decrease in intraocular scattering after cataract extraction [10, 11].

Another significant value for OSI lies in the assessment of the objective impact of lens opacity on visual quality [4, 7–9]. As mentioned previously, the OSI value contains forward scattering. Clinically, a patient with a large degree of lens opacity observed under slit-lamp may have a low OSI value. This is because the opacity of

A.-Y. Yu (✉)
Cataract Clinical Center, The Eye Hospital of Wenzhou Medical University, Wenzhou, Zhejiang, China

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the lens we observed by the slit-lamp is the result of backward scattering; however, the OSI reflects forward scattering, which is the main factor affecting visual quality. Contrarily, if the cataract opacity observed by the slit-lamp is light (backward scattering) and the OSI value is greater than 3.0 (forward scattering), it may indicate that the cataract has caused significant degradation of visual quality. Therefore, the results of the slit-lamp examination cannot fully reflect the actual severity of the patient's cataract. Understanding the significance of OSI is important for evaluating the real impact of cataract on visual quality.

2. OSI can measure corneal-derived scattering.

The cornea is one of the important sources of intraocular scattering [12]. Corneal scattering in normal eyes does not change with age. However, corneal morphology or pathological changes and corneal surgery can affect the scattering, for instance, corneal edema, scar, and other pathological changes can increase corneal scattering [13, 14]; possible complications after corneal refractive surgery, such as corneal epithelial haze, interlayer tissue debris, corneal epithelial endogenous, can increase corneal scattering [12, 15]. OSI can provide guidance on the selection of indications for corneal refractive surgery and contact lens fitting as follows:

(a) The selection of indications for corneal refractive surgery:
   - OSI < 2.0: Indicates that the refractive medium is transparent and corneal refractive surgery can be performed.
   - OSI ≥ 2.0: Need to clarify the reason for the increase of OSI, whether it is a tear film etiology or a cataract etiology. If it is a tear film issue, it needs to be treated before corneal refractive surgery. If it is a cataract etiology, it needs to be fully discussed with patients and determine whether or not to perform the surgery.

(b) Contact lens fitting instructions:
   - Wearing a contact lens for a long time can cause corneal edema and morphological changes, leading to an increase in scattering [16].
   - Early detection of epithelial damage caused by contact lens: If the OSI is increased significantly after wearing contact lens and there is no accompanying significant corneal edema, corneal epithelial damage is indicated and the patient may consider discontinuing contact lens wearing, and begin on treatment.

3.2 Modulation Transfer Function

1. MTF can reflect the performance of the refractive system.

   (a) MTF cutoff ≥ 30 c/deg.: The resolution limit of the eye is normal, the refractive system has no obvious abnormality, and the visual quality is good. For cataract surgery, it can be used for comparison and follow-up of visual quality before and after surgery; if corneal refractive surgery is to be performed, no wavefront aberration-guided surgery is required.

(b) 20 c/deg. < MTF cutoff <30 c/deg., OSI < 2.0: The resolution limit and refractive system of the eye is abnormal, the visual quality is poor, but the OSI is normal, indicating that optical quality issues are derived from aberrations. For cataract surgery, the treatment plan needs to be fully assessed. If corneal refractive surgery is to be performed, wavefront aberration-guided surgery is required.
(c) 20 c/deg. < MTF cutoff <30 c/deg., OSI ≥ 2.0: The resolution limit and refractive system of the eye is abnormal, the visual quality is poor, the eye's resolution limit is abnormal, and the OSI is increased, considering the optical quality issues are partly due to the opacity of the refractive medium. If corneal refractive surgery is to be performed, the etiology of opacity of the refractive medium (possibly cataract) must be first considered.
(d) Comparison of MTF cutoff between eyes: If the MTF cutoff of the right eye is higher than the left, this indicates that the visual quality and imaging clarity of the right eye is better than the left. The right eye should then be selected as the dominant eye for corneal refractive surgery and vice versa.

2. The MTF value can reflect the optical quality of different treatment methods.

(a) MTF cutoff value before and after treatment (including surgery): If the MTF cutoff value increases after treatment, the visual quality is said to be improved; if the MTF cutoff value after treatment is decreased, it indicates that the visual quality has not improved after the treatment, and the reasons need to be clarified.
(b) By evaluating the changes of MTF between different treatment methods, the influence of different treatment methods on the transmission ability of the human eye can be assessed in order to choose the appropriate treatment.
(c) By evaluating the MTF cutoff, the fitting of orthokeratology lenses or rigid gas permeable lenses is ensured from the aspect of optical quality, and the therapeutic effect is evaluated during the follow-up.

3.3 Strehl Ratio

1. SR helps to understand a patient's visual complaints.

SR can be used to describe a point spread function (PSF). PSF, which represents the characteristics of the optical system in the airspace, is a function of the distribution of diffraction spots formed by a point source through the optical system. For the human eye, PSF is used to describe the shape of the retinal image formed by a distant point light source. It is generally believed that the smaller the area of PSF spot and the greater the intensity of the light spot, indicating that the less light energy loss after passing through the optical system, so that better retinal imaging can be achieved. As SR describes the light intensity of the image point of the actual optical system (with aberrations), it can indirectly reflect the light intensity of the spot formed by the PSF and is a description method to help understand the PSF as well as the patient's visual complaints.

2. SR can reflect the influence of aberration on visual quality.

SR describes the ratio of the center peak intensity of the PSF of a refractive system with aberrations to a corresponding diffraction-limited system under the same pupil diameter [17]. For the refractive system of the human eye, the SR value is usually low because it cannot reach the level of the diffraction-limited optical system due to the aberrations.

The normal eye has an SR of about 0.3 at a pupil diameter of 4 mm. The larger the SR, the smaller the influence of the aberration on the human eye and the better the visual quality. The smaller the SR, the greater the influence of the aberration on the human eye and the worse the visual quality. In the double-pass objective visual quality analysis system, the mathematical value of SR can represent the area under the MTF curve. Therefore, SR combined with the MTF cutoff value can be used to analyze the resolution range of the human eye, and thereby provides a more objective and comprehensive assessment of the visual quality for cataract surgery, corneal refractive surgery, and other treatments.

3.4 Predicted Visual Acuity

The visual function of the human eye includes the ability to distinguish small targets with high contrast, and also the ability to distinguish the difference in brightness between various points, lines, and spaces. Predicted visual acuity can visually reflect the visual acuity of the human eye under different contrasts and can evaluate the sensory function of the visual system in a more comprehensive way than traditional visual acuity examination. It helps identify visual abnormalities in certain diseases, and thus contribute to disease diagnosis and treatment decision-making.

1. Predicted visual acuity can predict postoperative visual acuity.

By comparing the Predicted visual acuity with the BCVA measured by subjective refraction, the function of the visual nervous system can be assessed. The result is used to predict postoperative visual acuity, which plays an important role in the selection of surgical indications for certain conditions such as corneal refractive surgery and cataract surgery.

(a) Cataract patients with Predicted visual acuity 100% ≥ BCVA: It indicates that the decline of visual acuity is not all due to cataract, but to the existence of retinal or optic nerve disease. Simple cataract surgery cannot completely solve the vision issues. Postoperative vision outcome is often poor and the decision for performing cataract surgery should be done with caution.
(b) Cataract patients with Predicted visual acuity 100% < BCVA: It indicates that the vision loss is caused by cataracts, and the predicted postoperative vision improvement should be significant; therefore, surgery is recommended.

2. Predicted visual acuity can be used for the diagnosis and early detection of amblyopia.

By comparing the Predicted visual acuity with the BCVA measured by the subjective refraction, we can now identify the cause of amblyopia, whether it is due to the abnormality of refractive medium or dysfunction of the visual nervous system.

(a) Predicted visual acuity ≥1.0: The amblyopia is due to the dysfunction of the visual nervous system.
(b) Predicted visual acuity < 1.0 & Predicted visual acuity ≥ BCVA: The amblyopia is caused by a combination of the abnormality of the refractive medium and the dysfunction of the visual nervous system.
(c) Predicted visual acuity < BCVA: The amblyopia is caused by the abnormality of the refractive medium.

3.5 Mean Objective Scatter Index

1. Analyzing the effect of tear film optical quality on visual function.

The double-pass objective visual quality analysis system analyzes the tear film as an optical medium from the perspective of visual function and is the only device that can objectively, rapidly, and noninvasively assess the optical quality of the tear film. This is different from the previous analysis of the tear film which only assesses the morphology or structural variability [18, 19]. The assessment of tear film optical quality has important values for clinical practice and scientific research [20].

2. Early diagnosis and objective quantification of dry eye disease.

The double-pass objective visual quality analysis system can objectively quantify the optical quality of the tear film by calculating the mean objective scatter index and investigating the variation of the OSI curve. Due to the high sensitivity of the mean objective scatter index and OSI curve, the instrument is especially suitable for the screening and diagnosis of early or subclinical dry eye disease [20–23]. It is used to find the objective causes of visual complaints in patients with tear film abnormality, so as to carry out early interventions and subsequently quantitatively analyze the changes in optical quality of tear film.

3. Objective assessment of the dry eye treatment.

For the assessment of therapeutic effects of dry eye patients, most of clinical practice relies on the patient's complaint and certain anatomical indices related to the amount or composition of tear film. The lack of an objective, direct, and quantitative evaluation index is not conducive to assessing the optical impact of dry eye on visual quality. The mean objective scatter index and the OSI curve can be used for objective and quantitative recording of the tear film optical quality after dry eye treatment [24]. The therapeutic effect is evaluated by comparing the results before and after treatment, and a reasonable treatment plan is developed to improve the curative effect.

3.6 Pseudo Accommodation and Accommodative Range

1. Helping to understand the near vision function of the pseudophakic eye.

After IOL implantation, the patient also has a certain amount of near vision function in the case of far correction; this accommodation-like effect is called pseudophakic accommodation. Pseudophakic accommodation can improve a patient's near vision to a certain extent. The factors affecting the pseudophakic accommodation of IOL include refractive state, corneal astigmatism, anterior chamber depth, pupil diameter, IOL mobility, and age [25–27]. The accommodation of the IOL has certain limits and needs to be evaluated objectively.

The double-pass objective visual quality analysis system uses the diopter value when the MTF is reduced by 50% as an objective criterion for the accommodative range. The higher the value, the better the patient's accommodation. The accommodative range can be used to understand the near vision function of the pseudophakic eye and objectively evaluate the postoperative accommodation, including accommodative IOL, in a long-term follow-up. If the measured value is less than 1.00D, the patient's near vision function is decreased.

2. Objectively reflecting the accommodation of presbyopia patients.

Presbyopia patients have decreased accommodation. Under the premise of excluding other factors affecting accommodation (cataract, high myopia), the accommodative range measured by the double-pass objective visual quality analysis system can determine whether it is presbyopia or not and also clarify the progress of presbyopia.

The normal range of the double-pass objective visual quality analysis system is over 1.00D. If the measured value is less than 1.00D, it is considered as mild presbyopia; less than 0.50D is considered as moderate presbyopia.

3.7 Normal Reference Values in Chinese Population

The reference value of the optical quality of the eye is of great significance for establishing ophthalmic standards in diseases diagnosis and treatment evaluation as well as the development of public healthcare strategies. Our team has initially established a reference range for the main parameters of the double-pass objective visual quality analysis system for adults at different ages, this will provide a reference for future research [28].

The characteristics and the optical quality of the visual system of subjects at different ages are shown in Table 3.1.

Table 3.1 Characteristics and optical quality of the visual system of subjects at different ages

Age (years)	Number of eyes	Best-corrected visual acuity	Spherical equivalent (D)	MTF cutoff (cpd)	SR	OV100%	OV20%	OV9%	OSI
20~29	99	5.01 ± 0.03	−1.79 ± 1.42	43.91 ± 7.43	0.26 ± 0.06	1.47 ± 0.24	1.51 ± 0.33	1.14 ± 0.26	0.42 ± 0.24
30~39	80	5.01 ± 0.04	−1.69 ± 1.21	40.93 ± 9.92	0.24 ± 0.06	1.36 ± 0.33	1.40 ± 0.38	1.41 ± 0.40	0.53 ± 0.32
40~49	89	5.01 ± 0.03	−0.46 ± 1.33	37.16 ± 9.04	0.20 ± 0.05	1.24 ± 0.30	1.22 ± 0.36	1.20 ± 0.37	0.54 ± 0.34
50~59	84	5.00 ± 0.02	0.63 ± 1.10	36.69 ± 7.87	0.20 ± 0.04	1.22 ± 0.26	1.20 ± 0.28	1.18 ± 0.28	0.54 ± 0.26
60~69	80	4.97 ± 0.04	0.21 ± 1.34	28.52 ± 8.31	0.16 ± 0.04	0.96 ± 0.28	0.91 ± 0.32	0.89 ± 0.28	1.06 ± 0.56

Table 3.2 The reference range of the optical quality parameters of the subjects at different ages

Age (years)	MTF cutoff (cpd)	SR	OV100%	OV20%	OV9%	OSI
20~29	42.43~45.39	0.25~0.27	1.42~1.52	1.45~1.58	1.09~1.19	0.17~0.97
30~39	38.72~43.13	0.22~0.25	1.29~1.44	1.31~1.48	1.31~1.50	0.17~1.20
40~49	35.26~39.07	0.19~0.22	1.18~1.30	1.14~1.29	1.12~1.28	0.10~1.25
50~59	34.98~38.40	0.19~0.21	1.17~1.28	1.14~1.26	1.12~1.24	0.23~1.13
60~69	26.67~30.37	0.15~0.17	0.89~1.02	0.84~0.98	0.82~0.95	0.30~2.23[a]

[a]indicates a skewed distribution, the reference range takes the fifth and ninety-fifth percentile

MTF, SR, OV100%, and OV20% were significantly different between groups ($P \leq 0.02$, ≤ 0.006, < 0.02, < 0.03) except for the 40–49-year-old group and the 50–59-year-old group ($P = 0.72, 0.75, 0.73, 0.70$). OV9% was significantly different between groups ($P \leq 0.001$) except for the 20–29 age group, the 40–49 age group, and the 50–59 age group ($P > 0.19$). OSI was significantly different between groups ($P \leq 0.04$) except for the 30–39 age group, the 40–49 age group, and the 50–59 age group ($P > 0.70$).

Table 3.2 shows the reference range of the optical quality parameters of the subjects at different ages. The normal distribution parameter takes the mean ±1.96 standard deviation as the reference range, and the skewed distribution parameter takes the fifth and ninety-fifth percentile as the reference range.

For MTF cutoff, the younger groups are superior to the older groups, with the exception of the similarities between the 40–49 age group and the 50–59 age group. The OV100% and OV20% of the younger groups are better than the older groups, which was consistent with the distribution of MTF cutoff. The OV9% of the 60–69 age group was lower than that of other age groups, suggesting that with the increase of spatial frequency, the optical quality of the elderly declines faster than young people, and the optical quality of young people in the high spatial frequency range is superior to that of the elderly.

For SR, the younger groups are superior to the older groups, with the exception of the similarities between the 40–49 age group and the 50–59 age group. SR is related to the aberration of the eye, so the larger the aberration, the smaller the SR. The human eye aberration increases with age, so SR tends to decline with age.

For OSI, the younger groups are superior to the older groups, with the exception of the similarities among the 30–39 age group, 40–49 age group, and 50–59 age group. In the past, the data on the degree of intraocular scatter was based on the study of Caucasian populations. The choroid and iris contained different pigments due to the ethnic differences between the East and West. After the light is imaged on the retina, the light passing through the retina is absorbed by the pigments to reduce the light scatter in the eye. We examined the Chinese population and the results were similar to foreign studies, but the OSI of the Chinese population plateaued in the 30–59 age range.

Among the various optical quality parameters, the integrated optical quality of the younger groups is superior to that of the older groups, and there is a plateau in the middle-aged population. In clinical practice, the upper limits of the reference values of the MTF cutoff, SR, OV100%, OV20%, and OV9% have no clinical significance, and the lower limits of the reference values can be used to distinguish the optical quality between normal and abnormal eyes. For OSI, the upper reference limit can be used to distinguish ocular scattering between normal and abnormal eyes. Limited by the sample size, the data we have initially presented may not be representative of the general population, but we hope to further improve the normal reference values through follow-up studies. This is expected to be used in early screening for patients with reduced visual quality as well as to provide a clinical reference for evaluating the surgical effects of corneal refractive surgery and refractive cataract surgery.

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