Original article

Comparison of ocular modulation transfer function determined by a ray-tracing aberrometer and a double-pass system in early cataract patients

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Keywords: cataract; contrast sensitivity function; double-pass system; modulation transfer function; retinal image quality; wavefront aberration

Background The evaluation of retinal image quality in cataract eyes has gained importance and the clinical modulation transfer functions (MTF) can obtained by aberrometer and double pass (DP) system. This study aimed to compare MTF derived from a ray tracing aberrometer and a DP system in early cataractous and normal eyes.

Methods There were 128 subjects with 61 control eyes and 67 eyes with early cataract defined according to the Lens Opacities Classification System III. A laser ray-tracing wavefront aberrometer (iTrace) and a double pass (DP) system (OQAS) assessed ocular MTF for 6.0 mm pupil diameters following dilation. Areas under the MTF (AUMTF) and their correlations were analyzed. Stepwise multiple regression analysis assessed factors affecting the differences between iTrace- and OQAS-derived AUMTF for the early cataract group.

Results For both early cataract and control groups, iTrace-derived MTFs were higher than OQAS-derived MTFs across a range of spatial frequencies (P <0.01). No significant difference between the two groups occurred for iTrace-derived AUMTF, but the early cataract group had significantly smaller OQAS-derived AUMTF than did the control group (P<0.01). AUMTF determined from both the techniques demonstrated significant correlations with nuclear opacities, higher-order aberrations (HOAs), visual acuity, and contrast sensitivity functions, while the OQAS-derived AUMTF also demonstrated significant correlations with age and cortical opacity grade. The factors significantly affecting the difference between iTrace and OQAS AUMTF were root-mean-squared HOAs (standardized beta coefficient=-0.63, P<0.01) and age (standardized beta coefficient=0.26, P<0.01).

Conclusions MTFs determined from a iTrace and a DP system (OQAS) differ significantly in early cataractous and normal subjects. Correlations with visual performance were higher for the DP system. OQAS-derived MTF may be useful as an indicator of visual performance in early cataract eyes.

Clinically, it is becoming common to quantify ocular optical quality in order to predict visual performances.1,2 Clinical aberrometers are useful tools for evaluating higher-order aberrations (HOAs) in eyes with cataract1 and optical quality improvement after implantation of wavefront-corrected IOLs.4,5 For these instruments, optical quality is commonly described by wavefront aberration through sets of Zernike polynomials and root-mean-squared (RMS) values.6 Many other metrics have also been described for measuring optical aberrations,2,8 but these metrics are not easily calculated from Zernike polynomials and/or the formulas/software for calculation are not provided with commercially available instruments. More importantly, they do not relate directly to retinal image quality, and other metrics such as point spread function and modulation transfer functions (MTFs) and their derivatives have been used.1

Image quality metrics based on aberrometers are likely to overestimate image quality because they do not take into account the intraocular scattering, which has been reported to increase with age and crystalline lens opacification.9,10 Systems that used a double-pass (DP) method of estimating image quality considered both aberrations and scattering information.5 Liang and Williams5 first reported that wavefront-derived MTF tended to be higher than those derived from DP or psychophysical methods. Diaz-Doulton et al12 reported with a small sample that a DP system gave

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similar image quality results to an aberrometer in normal young eyes, but considerable poorer quality in older precataractous eyes.

At present, there is only one commercially available DP system, the Optical Quality Analysis System (OQAS; Visiometrics, Terrassa, Spain), which has been used in a number of studies. Some studies reported the OQAS-derived MTF as a function of age. Ortiz et al. found that the measured MTF decreased with increasing nuclear cataract density. The OQAS-derived MTF cutoff frequency is correlated with visual acuity (VA) in cataract patients and residual spherical aberration after cataract surgery. OQAS is the only clinically available instrument that can quantify the effect of both optical aberrations of the eye and intraocular scatter from the cataractous lens in human eyes. Hence, this instrument would potentially be a better predictor of the visual performance than other objective techniques.

There is no gold standard for clinical MTF assessment and it is unknown whether the measurements between devices are interchangeable. To our knowledge, no studies have compared the MTF obtained by an aberrometer and DP system in cataractous eyes. The main purpose of this study was to compare MTF obtained by a ray-tracing aberrometer (iTrace, Tracey Technologies, Houston, TX, USA) and the OQAS DP system in early cataractous and normal eyes. In order to investigate the scattering effect on measurements, we also conducted a comparative test on a model eye.

METHODS

Population
The study protocol was approved and monitored by the Beijing Tongren Hospital Ethical Committee, and written informed consent was obtained from all the participants. All procedures were in adherence to the principles outlined in the Declaration of Helsinki for research involving human subjects.

The data for this prospective study were collected from a subgroup of subjects who participated in a population-based Handan eye study in rural China. Voluntary subjects who participated in the Handan eye study field were selected for this subgroup. Eligible participants underwent a comprehensive eye examination by two ophthalmologists and optometrists including distance habitual and best corrected LogMAR VA, and mesopic contrast sensitivity (CS) function (CSV-1000E, VectorVision, Greenville, OH, USA) for spatial frequencies 3, 6, 12, and 18 cycles per degree (c/d) under natural pupil sizes. Following instillation of 0.2 ml of 1% tropicamide, cataract was graded using a slit lamp and standard photos of the Lens Opacities Classification System III. All the assessments were done by the same ophthalmologist. Cataracts were classified into four groups of nuclear opacity (NO), nuclear color (NC), cortical opacity (C), and posterior subcapsular opacity (P) and were graded from 0.1 (early cataract) to 6.9 (mature cataract) for NC and NO and from 0.1 to 5.9 for C and P.

Subjects were screened based on inclusion and exclusion criteria. The inclusion criteria for the cataract group included nuclear cataract NO or NC ≥ 3.0, and/or cortical cataract C ≥ 2.0, and/or any posterior subcapsular cataract P ≥ 2.0. The inclusion criteria for the control group were ≤ 45 years, with corrected LogMAR VA of 0.0 or better, and lens opacity grading of NO ≤ 2.0, NC ≤ 2.0, C ≤ 1.0, and P ≤ 1.0. For each subject, the eye for examination was selected randomly. The exclusion criteria included non-lens anomalies impairing ocular transparency and a range of ocular pathologies.

Ray-tracing aberrometer
iTrace uses the principle of ray tracing, with 250 parallel infrared beams in concentric arrays that are projected sequentially onto the eye within one eighth of a second. This rapid sequence of beams avoids any data confusion enabling measurement of highly aberrated eyes on a point-by-point basis. The locations of the beams reflected from the retina are combined to reconstruct the wavefront using the standardized Zernike polynomials and to determine the MTFs.

Double-pass system
MTFs were derived by a clinical DP system, the OQAS. The image of a 780 nm laser diode is formed on the patient’s retina, and images captured after passage out of the eye. The DP system uses an unequal pupil configuration with an in-going diameter of 2 mm in the entrance pupil and a variable out-going diameter for the exit pupil. In this study, the diameter of the exit pupil was set as 6.0 mm. Defocus was corrected carefully with the instrument’s optometer and astigmatism was corrected with cylindrical lenses placed in front of the eye.

Experimental procedure
Measurements were performed after pupil dilation following a standardized procedure. The HOA-derived MTF and the RMS of HOAs (third- to sixth-order Zernike coefficients) were determined for a 6.0 mm pupil with the iTrace aberrometer. After determining the best objective focus, OQAS measurements were performed for a 6.0 mm exit pupil. For both instruments, participants fixated a near-infrared point light source during measurements. The room illumination was 42 lux (digital lux meter, LX-1010B).

MTFs were estimated for six spatial frequencies (5, 10, 15, 20, 25, and 30 c/d) from the iTrace and OQAS, and the MTFs calculated from both were radially averaged values. Areas under the MTF (AUMTF) were calculated with an in-going diameter of 2 mm in the entrance pupil and a variable out-going diameter for the exit pupil. In this study, the diameter of the exit pupil was set as 6.0 mm. Defocus was corrected carefully with the instrument’s optometer and astigmatism was corrected with cylindrical lenses placed in front of the eye.

We also conducted a calibrated test under the same procedure on a model eye using both systems.


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Statistical analysis
Statistical analysis was performed using SPSS 18.0 for Windows (SPSS Inc., Chicago, IL, USA). Normality of all data distributions was confirmed using the Kolmogorov-Smirnov test. Parametric statistical analysis was performed. Paired Student’s *t* test was used to compare the MTF determined by the iTrace and OQAS. Spearman correlation tests were used to determine the correlations between the two MTFs in the cataract group. Stepwise regression analysis was used to assess the factors that affected the difference in AUMTF between iTrace- and OQAS-derived MTFs. The factors considered included age, VA, spherical equivalent refraction, RMS of HOAs, and lenticular opacities grading. Bonferroni corrections were used to avoid family-wise errors.

RESULTS

Subjects
This study included 128 people (75 males and 53 females). The mean ages of the cataract group (*n*=67) and control group (*n*=61) were (59.8±6.7) years and (40.2±5.2) years, respectively. The cataract group included 52 nuclear, 6 cortical, and 9 mixed types. The mean grades for NO, NC, C, and P were 3.0±0.3 (range 2.5–4.0), 3.0±0.3 (2.5–4.0), 0.7±1.1 (0.1–3.5), and 0.3±0.6 (0.1–3.0), respectively. Best corrected VAs in LogMAR were −0.01±0.02 (−0.10 to 0.00) in the control group and 0.07±0.14 (−0.06 to +0.66) in the cataract group.

The mean log CSs at 3, 6, 12, and 18 c/d were significantly lower in the cataract group than in the control group by approximately 0.18 (all *P* <0.01; Table 1). Differences between the two groups were significant at all spatial frequencies (*P* <0.05; Figure 1). For all spatial frequencies the iTrace-derived MTFs were significantly higher than the OQAS-derived values (all *P* <0.01; Figures 2 and 3). The modulation transfer differences between the two instruments were higher in the cataract group than in the control group (Table 1), and the iTrace AUMTFs were significantly higher than the OQAS AUMTFs in both the cataract group (*r* =−8.02, *P* <0.01; Figure 2) and control group (*r* =−5.58, *P* <0.01; Figure 3). Figure 4 shows the plots for a model eye that does not suffer from scatter. For all spatial frequencies, the iTrace-derived modulation transfers were considerably higher than the OQAS-derived values.

Table 2 summarizes the correlations between the iTrace and OQAS-derived AUMTFs for the cataract group. Stepwise multiple regression analysis showed the difference between iTrace and OQAS-derived AUMTFs was significantly associated with the RMS of HOAs and age (adjusted *R*²=0.38, *F*=38.8, *P* <0.01; Figure 5).

DISCUSSION
The evaluation of retinal image quality in cataract eyes has gained importance because of phacoemulsification and intraocular lens implantation. At present, there is no gold standard for clinical MTF assessment. We compared the MTF results derived from iTrace and OQAS in groups of early cataract, healthy control eyes, and a model eye. The iTrace-derived MTFs were higher than the OQAS MTFs.

Table 1. iTrace- and OQAS-derived AUMTFs and the contrast sensitivity function in cataract and control groups (means ± standard deviations (SD))

<table>
<thead>
<tr>
<th>Groups</th>
<th>iTrace</th>
<th>OQAS</th>
<th><em>P</em> values</th>
<th>3</th>
<th>6</th>
<th>12</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cataract</td>
<td>6.08±1.78</td>
<td>4.21±1.05</td>
<td>0.001</td>
<td>1.34±0.23</td>
<td>1.60±0.30</td>
<td>1.24±0.32</td>
<td>0.79±0.36</td>
</tr>
<tr>
<td>Control</td>
<td>6.27±1.77</td>
<td>4.93±1.25</td>
<td>0.002</td>
<td>1.51±0.16</td>
<td>1.76±0.18</td>
<td>1.43±0.20</td>
<td>1.00±0.21</td>
</tr>
<tr>
<td><em>P</em> values</td>
<td>0.554</td>
<td>0.004</td>
<td>—</td>
<td>0.003</td>
<td>0.002</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

Figure 1. Log CS at 3, 6, 12, and 18 c/d. Gray line and symbols represent the cataract group, and black line and symbols represent the control group. Error bars are standard deviations.

Figure 2. Modulation transfer at 5, 10, 15, 20, 25, and 30 c/d in cataractous eyes. Gray line and symbols represent the iTrace-derived modulation transfer, and black line and symbols represent the OQAS-derived modulation transfer. Error bars are standard deviations.

Figure 3. Modulation transfer at 5, 10, 15, 20, 25, and 30 c/d in normal eyes. Gray line and symbols represent the iTrace-derived modulation transfer, and black line and symbols represent the OQAS-derived modulation transfer. Error bars are standard deviations.
Relative to the control group, the cataract group demonstrated significant impairments in CS function at all spatial frequencies. OQAS-derived AUMTF correlated of DP images contained more of the energy for 780 nm than for green wavelengths.

However, we found different MTFs between the two devices in healthy subjects with relatively lower lens opacities, which suggested the scattering effect was not the only factor that led to the difference. Liang and Williams also found different MTF results between aberrometer and DP measures in healthy subjects. Lee et al reported that MTF values determined using OQAS were significantly lesser than those determined by iTrace in patients after refractive surgery. On the contrary, two other studies reported similar MTF in healthy subjects between aberrometer and DP techniques. In the calibrated test, we observed a larger MTF difference for the model eye than for the control group, indicating the differences were not only in the eyes but also from the instruments. Model eyes do not always behave like real eyes, particularly when it comes to the intensity of reflection from the "retina", but how this affects especially the DP results is unknown.

Although refractive errors were carefully corrected by an optometer and trial lens, the DP MTF would still be influenced by residual second-order errors. The iTrace MTFs were calculated from the HOA terms only. Although we did not obtain residual second-order error during OQAS measurement, it is a potential factor that could influence the results. In addition, a 2 mm pupil is used for OQAS as the entrance beam in order to minimize blur of the spot on the retina. Therefore, the final image is not "doubly degraded" by the DP system. To the extent that the image on the retina is not a perfect point image, this could contribute to the differences between the iTrace and the OQAS results.

for all spatial frequencies in both early cataract and control groups, with the differences being greater in the former group.

We attribute the MTF differences between the two instruments partly to overestimation of image quality by aberrometers, which do not take into account intraocular scatter. Analysis of data from wavefront sensors takes no account of the quality of individual spots. Multiple regression analysis shows that HOAs contribute more than age to the difference. The largest differences between the instruments for the cataractous group occurred when aberrations were low and hence their influence on the OQAS-derived AUMTF should be low compared with the scattering effects of cataract.

In addition to the overestimated image quality by aberrometers, it is possible that the OQAS using a 780 nm IR light underestimates image quality in visible light because of the additional scatter within the deep retinal layers and choroid. Williams et al demonstrated better DP estimates of retinal image quality for 543 nm than in 632 nm light, and Lopez-Gil and Artal found that the tails of DP images contained more of the energy for 780 nm than for green wavelengths.

Table 2. Correlations of iTrace- and OQAS-derived areas under MTF (AUMTF) for the cataract group (n=67)

<table>
<thead>
<tr>
<th>Items</th>
<th>iTrace</th>
<th>OQAS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>P values</td>
</tr>
<tr>
<td>Best corrected visual acuity</td>
<td>-0.12</td>
<td>0.35</td>
</tr>
<tr>
<td>Area under contrast sensitivity function</td>
<td>0.25</td>
<td>0.04*</td>
</tr>
<tr>
<td>Spherical equivalent refraction</td>
<td>-0.34</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>RMS higher-order aberrations</td>
<td>-0.90</td>
<td>&lt;0.01*</td>
</tr>
<tr>
<td>Age (years)</td>
<td>-0.27</td>
<td>0.03*</td>
</tr>
<tr>
<td>Nuclear opacity</td>
<td>-0.24</td>
<td>0.05</td>
</tr>
<tr>
<td>Nuclear color</td>
<td>-0.24</td>
<td>0.05</td>
</tr>
<tr>
<td>Cortical opacity</td>
<td>-0.05</td>
<td>0.69</td>
</tr>
<tr>
<td>Posterior subcapsular opacity</td>
<td>-0.05</td>
<td>0.67</td>
</tr>
</tbody>
</table>

R is the Spearman correlation coefficient. P values showed significant correlations.

Figure 4. Modulation transfer at 5, 10, 15, 20, 25, and 30 c/d in a model eye. Gray line and symbols represent the iTrace-derived modulation transfer, and black line and symbols represent the OQAS-derived modulation transfer.

Figure 5. Partial regression plot of RMS of higher-order aberrations and the differences between iTrace- and OQAS-derived AUMTF for all participants. The regression equation is: iTrace AUMTF-OQAS AUMTF=1.93-3.3±(0.38) x age, where the numbers in brackets are the standard errors of constants. Partial regression shows the HOAs (standardized beta coefficient=-0.63, R^2=0.37).

Figure 6. Partial regression plot of age and the differences between iTrace- and OQAS-derived AUMTF for all participants. The regression equation is: iTrace AUMTF-OQAS AUMTF=1.93-3.3±(0.38) x age, where the numbers in brackets are the standard errors of constants. Partial regression shows the age (standardized beta coefficient=0.26, R^2=0.09).
significantly with best corrected VA; both the iTrace- and OQAS-derived AUMTFs had significant correlations with the area under the CSF, which was much higher for the OQAS than for the iTrace. These findings indicate that OQAS-derived MTF may be an useful indicator of visual performance in early cataract eyes.

In this study, we provide clinical data for comparison with two commercially available devices that allow clinicians to compare the MTF measurements given by these devices. MTFs determined from a iTrace and a DP system (OQAS) differ significantly in early cataractous and normal subjects. Correlations with visual performance were higher for the DP system. OQAS-derived MTF may be an useful indicator of visual performance in early cataract eyes.

REFERENCES


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