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Objective Assessment of Visual Quality and Ocular Scattering Based on Double-pass Retinal Images in Refractive-surgery Patients and Emmetropes

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This study was performed to evaluate objective visual quality and ocular scattering in myopic refractive-surgery patients, compared to emmetropes. Optical vision-quality parameters (modulation transfer function (MTF) cutoff and Strehl ratio) and objective scattering index (OSI) were measured using an optical quality analysis system (OQAS II) based on the double-pass technique. In all subjects, the higher the MTF cutoff and Strehl ratio, the lower the OSI and ocular higher-order aberrations (HOAs). The MTF cutoff and Strehl ratio for the laser-assisted subepithelial keratectomy (LASEK) group were lower than those for the emmetropia group, while the OSI, ocular HOAs, and spherical aberration (SA) for the LASEK group were higher than those for emmetropia group. Ocular scattering would be one of the important factors in regard to visual quality. Therefore, the quality of the retinal image in the LASEK patients has been shown to reduce the quality of vision more than in the emmetropes.

Keywords : Refractive surgery, Ocular scattering, Visual quality
OCIS codes : (330.7335) Visual optics, refractive surgery; (330.7327) Visual optics, ophthalmic instrumentation

I. INTRODUCTION

Laser refractive surgery, as a method to correct refractive errors, has been extensively practiced because of its advantage to maintain good vision with the naked eye, compared to optical correction using glasses or contact lenses. In Korea, which has a high incidence of myopia, refractive-surgical procedures for myopic correction have developed rapidly over the past 20 years, and laser *in situ* keratomileusis (LASIK) and laser-assisted subepithelial keratectomy (LASEK) surgical techniques have been widely used for myopia patients.

After corneal refractive surgery, patients are highly satisfied with daytime life. On the other hand, in a modern lifestyle in which city night life increases, it is also true that quality of vision under low lighting conditions is deteriorated, due to decrease of contrast sensitivity, glare, and light blurring (Fig. 1) [1]. These phenomena in the human eye are related to intraocular scattering and optical aberrations, resulting in the degradation of optical quality in visual function [2, 3].

FIG. 1. Simulation of night vision related to glare complaints caused by significant amounts of ocular scattering (source: Pinero *et al*., 2010) [1].

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The advent of the Hartmann-Shack wavefront sensor and the double-pass system as a method to evaluate the quality of the retinal image has enabled many researchers to study the effects of higher-order aberrations (HOAs) and intraocular scattering on visual performance, and has provided an opportunity to better understand our visual system. It has been known that the double-pass technique (Fig. 2) [4], which is based on the optical pathway that carries the image on the retina after passage through the ocular media and retinal reflection [5, 6], can provide more accurate estimates or information about retinal image quality [6], as well as being useful for the objective assessment of ocular optical quality [7-9]. The Optical Quality Analysis System (OQAS) is the only instrument with the double-pass technique [6, 10] and is widely used to estimate the quality of the retinal image in clinical practices.

Previous studies have only analyzed ocular scattering to assess optical quality after corneal refractive surgery, or to evaluate visual quality between refractive-surgical techniques, such as LASIK, LASEK, or photorefractive keratectomy (PRK). Since the goal of corneal refractive surgery is to attain emmetropia, comparing the degree of ocular scattering in refractive-surgery patients to that in emmetropes may be helpful in understanding the postoperative ocular optical system, but few studies have been conducted. Therefore, the aim of this study was to compare objective visual quality and ocular scattering based on double-pass retinal images, for myopic refractive-surgery patients who have undergone LASEK and emmetropes.

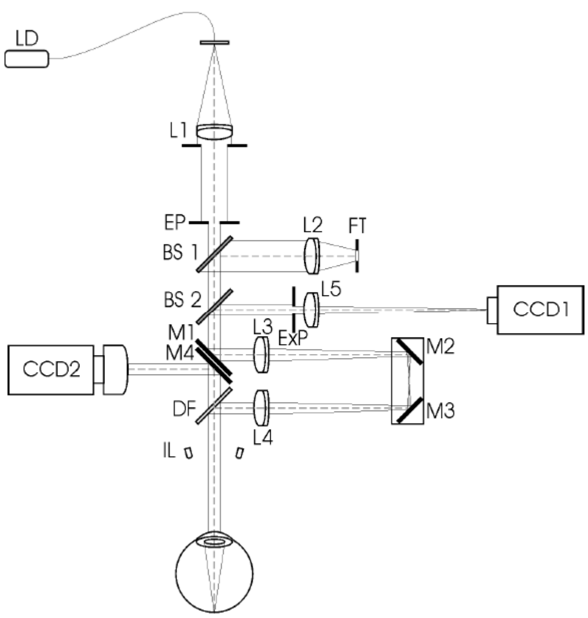


FIG. 2. Schematic diagram of the double-pass system (LD: laser diode, L1-L5: lenses, EP: entrance pupil, ExP: exit pupil, BS1, BS2: beam splitters, FT: fixation test, CCD1 and CCD2: CCD cameras, M1-M4: mirrors, DF: dichroic filter, IL: infrared LED) (source: Vilaseca *et al.*, 2012) [4].

II. METHODS

2.1. Subjects

Subjects were recruited from patients who underwent conventional myopic LASEK, and from emmetropes as a control group. The subjects who met the criterion of best unaided monocular visual acuity of 0.9 (including no more than 0.50D of astigmatic refractive errors) or better in both groups were selected for this study. None of the subjects had any systemic or ophthalmic diseases. This study was approved by the Institutional Review Board (IRB) of Eulji University. All subjects provided written informed consent, following a detailed explanation of the study's procedures.

2.2. Measurement of Biometric Data

Measurement of uncorrected distance visual acuity (UCDVA) was made under photopic conditions (340 Lx), using high-contrast (100%) ETDRS acuity charts at a distance of 4 m. VA was recorded in logMAR units. In addition, measurement of refractive error was performed by autorefractor (KR-8100P, Topcon, Japan) and phoropter (VT-SE, Topcon, Japan). The testing was carried out monocularly. Corneal thickness was measured by pachymetry function, which is included in the Pentacam Oculyzer topography-measuring system (Oculus Inc., Germany). The natural pupil diameter was taken under scotopic conditions using a digital variable pupillometer (VIP^{TM}- 200, Neuroptics, USA). The pupil diameter can be measured under varying light levels (scotopic, low mesopic, and high mesopic) in one sequence. Measurement was performed three times alternately between right and left eyes.

2.3. Measurement of Optical Parameters

Ocular higher-order aberrations (HOAs) for a 4-mm pupil were analyzed by a wavefront analyzer (KR-1W, Topcon, Japan) with Hartmann-Shack aberrometry, and calculated as the root mean square (RMS) values of the third- and fourth-order Zernike coefficients.

For the quality of the retinal image, optical vision-quality parameters were taken using an optical quality analysis system (OQAS II, Visiometrics, Terrassa, Spain) based on the double-pass technique. The system acquires an image from a point-source object reflecting on the retina, and then directly calculates the modulation transfer function (MTF) from the received double-pass retinal image through Fourier transformation [5]. The MTF represents the contrast loss produced by the ocular optics as a function of spatial frequency, which provides information on the overall ocular optical performance [11].

The OQAS II provides several parameters related to optical quality, including MTF cutoff, Strehl ratio, OQAS values (OVs), and objective scattering index (OSI). The MTF cutoff is the spatial frequency that reaches a value of 0.01 for MTF [9]; the larger the MTF cutoff value, the better the ocular optical quality. The Strehl ratio represents the ratio of peak focal intensity in an aberrated image corresponding to the ideal point-spread function (PSF). The Strehl ratio has a value between 0 and 1.0, with 1.0 indicating an unaberrated, perfect optical system. Therefore, the higher the value of the Strehl ratio, the better the ocular optical quality. Also, the greater the effect of ocular aberrations and scattering, the lower the measured quality of the retinal image [7, 12]. The OVs with 100%, 20%, and 9% contrast levels are standardized values for each spatial frequency corresponding to 0.01, 0.05, and 0.1 MTF values [11, 13]. The higher the OV values, the better the ocular optical quality, and an OV value above 1.0 is associated with higher optical quality [14]. In the case of OVs measured with three contrast levels (100%, 20%, and 9%), $OV_{100\%}$ normally has the same value as $VA_{100\%}$ (visual acuity), and the values of $VA_{20\%}$ and $VA_{9\%}$ simulated for $OV_{20\%}$ and $OV_{9\%}$ were indicated as decimal visual acuity, to express the objective contrast visual quality corresponding to each OQAS value (OV) in the present study. The OSI as an objective parameter is a numerical value obtained by quantifying the degree of intraocular scattered light [9]; the higher the OSI value, the greater the ocular scattering [15, 16].

During the measurements with OQAS II, any spherical refractive error was automatically corrected by the instrument, and cylindrical errors ≥ 0.50 D were corrected with an external trial lens. All measurements were conducted for a 4-mm artificial pupil in mesopic lighting conditions (1 Lx), and were carried out monocularly with an undilated pupil. In addition to this, to minimize the influence of corneal drying, sufficient blinking of the eye was conducted to allow tears to spread sufficiently on the cornea before measurement with OQAS II.

2.4. Experimental Procedure

This study involved three visits, with the following procedures conducted at each visit. In the first visit, all subjects underwent an initial optometric examination and were checked according to the inclusion criterion. Also, they received full explanations of the procedures of the study. In the second visit, preoperative biometric data of the subjects were taken. Measurement for biometric data was performed, and followed by that for ocular aberrations. After that, each subject visited another eye hospital for the final measurements using the Pentacam and the OQAS II equipment.

2.5. Statistical Analysis

For optical quality parameters, comparisons between the two groups were analyzed by the independent *t*-test. The results were expressed as mean ± standard deviation (SD). The Pearson correlation test and simple linear regression analysis were used for relationships among the optical quality and ocular scattering parameters, in the LASEK group or the emmetropes. All data analyses were performed using SPSS/window programs, version 21.0 (SPSS, Chicago, IL, USA). A p value less than 0.05 was regarded as indicating statistically significant differences.

III. RESULTS AND DISCUSSION

Subjects were the 88 eyes of 44 patients who underwent conventional myopic LASEK, but not wavefront-guided refractive surgery, and the 40 eyes of 20 emmetropes. The mean uncorrected distance visual acuity (UCDVA) of the subjects was -0.02 ± 0.06 and -0.03 ± 0.05 for LASEK patients and emmetropes respectively. In terms of UCDVA and refractive error (spherical equivalent), there was no

TABLE 1. Demographics and biometric data of the study's subjects

Parameters	LASEK	Emmetrope	*p* value
Number of eyes (*n*)	88	40	
Age (years)	23.41 ± 2.63[1)]	22.50 ± 1.74	
Sex (M, F)	34, 54	22, 18	
UCDVA (logMAR)	-0.02 ± 0.06	-0.03 ± 0.05	0.510
Refractive error (SE) (D)	-0.18 ± 0.26	-0.20 ± 0.22	0.581
Flat K-reading (D)	38.01 ± 1.58	42.30 ± 0.95	0.000
Steep K-reading (D)	38.82 ± 1.67	43.38 ± 0.94	0.000
Corneal Thickness (μm)	463.41 ± 32.01	549.68 ± 30.99	0.000
Mesopic pupil size (mm)	6.54 ± 0.58	6.49 ± 0.55	0.687
SE of achieved refractive correction (D)	-5.45 ± 1.73		
Duration of post-op (months)	24.17 ± 17.31		

[1)]Mean ± standard deviation; UCDVA, uncorrected distance visual acuity; logMAR, log of the minimum angle of resolution; K, keratometry; SE, spherical equivalent.

statistically significant difference between the two groups. The mean period after refractive surgery was 24.17 ± 17.31 months. The demographics and biometric data of the subjects in the LASEK and emmetropia groups are outlined in Table 1.

The results for optical quality parameters and OSI in the LASEK and emmetropia groups are compared in Table 2. The means for MTF cutoff and Strehl ratio were significantly lower for LASEK (38.377 ± 10.022 and 0.212 ± 0.059 respectively) than those for emmetropes (43.094 ± 8.399 and 0.256 ± 0.058); there were statistically significant differences in MTF cutoff and Strehl ratio between the two groups (p = 0.007 and p = 0.000 respectively). In terms of OSI, the mean value for LASEK (0.727 ± 0.431) was significantly greater than for emmetropes (0.368 ± 0.158); there was a statistically significant difference in the OSI between the two groups (p = 0.000). Ocular HOAs and SA in the two groups were also analyzed. The mean magnitudes of ocular HOAs and SA for the LASEK group (0.160 ± 0.068 μm and 0.048 ± 0.038 μm respectively) were significantly higher than those for the emmetropia group (0.131 ± 0.059 μm and 0.030 ± 0.028 μm); there were statistically significant differences in ocular HOAs and SA between the two groups (p = 0.016 and p = 0.004 respectively).

Previous studies performed to compare changes in visual performance outcomes before and after refractive surgery have shown that visual quality was influenced by the increase of ocular HOAs and ocular scattering in corneal-refractive-surgery patients [17-19]. After laser corneal refractive surgery, the main causes of degradation of optical quality are related to increased ocular aberrations [20, 21] and scattering [22-24]. In fact, it is well-known that altered corneal shape and irregular corneal surface due to laser ablation cause these optical defects [25-27].

In the present study, it has been clearly shown that values of OSI and ocular HOAs for the LASEK group were greater than those for the emmetropia group. The results concerning increased ocular HOAs and ocular scattering after refractive surgery were similar to those of previous studies. Additionally, in the emmetropia group the mean values of MTF cutoff, Strehl ratio, and OSI for this study somewhat correspond to those of a previous study, which assessed them for use as reference values for clinical diagnosis in healthy young adults (18 to 30 years) [15]. Thus, the findings imply that the quality of the retinal image for the LASEK group is lower than that for the emmetropes. Meanwhile, the importance of correlations between OSI and achieved refractive correction in LASEK patients have been reported; the results were related to increased ocular scattering by the ablation procedure of refractive surgery [19]. Moreover, Miao *et al.* suggested that high myopia was more affected by ocular scattering than were moderate and low myopia in adults [11]. Given that the values of OSI according to the degree of refractive error have significant individual variations, the values of OSI may be helpful for predicting postoperative prognosis in regard to ocular scattering.

This study also analyzed the correlations between the optical quality parameters (MTF cutoff, Strehl ratio, ocular HOAs, and SA) and objective scatter index (OSI). In the LASEK group, the correlations of MTF cutoff frequency and Strehl ratio with OSI were compared to those of emmetropes (Fig. 3).

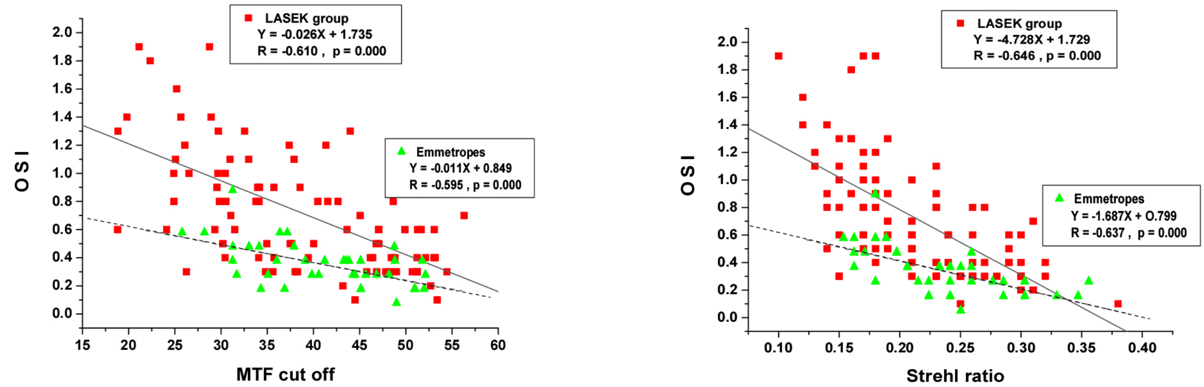
The correlations between OSI and MTF cutoff showed a significant negative relationship in both groups: the higher the OSI, the lower the MTF cutoff. The OSI was statistically correlated with MTF cutoff in both groups (p = 0.000 and p = 0.000 respectively). The correlation coefficient in the LASEK group (r = -0.610) showed higher correlation than that in the emmetropes (r = -0.595). Similar to the relationship between OSI and MTF cutoff in the two groups, the correlations between OSI and Strehl ratio were strong, negative relationships in both groups (p = 0.000 and p = 0.000 respectively). The correlation coefficients in the LASEK and emmetropia groups were r = -0.646 and r = -0.637 respectively. Accordingly, these results indicate that the MTF cutoff and Strehl ratio, as parameters of optical quality, are closely related to the OSI. The correlations between ocular HOAs and SA with OSI, for a 4-mm pupil in LASEK and emmetropia groups, are shown in Fig. 4.

In the LASEK group there was statistical correlation between OSI and ocular HOAs (r = 0.278, p = 0.007), but not in the emmetropes (r = 0.111, p = 0.494). The OSI was statistically correlated with ocular SA in the LASEK group

TABLE 2. The mean values of optical quality and ocular scattering parameters for a 4-mm artificial pupil, for the LASEK and emmetropia groups

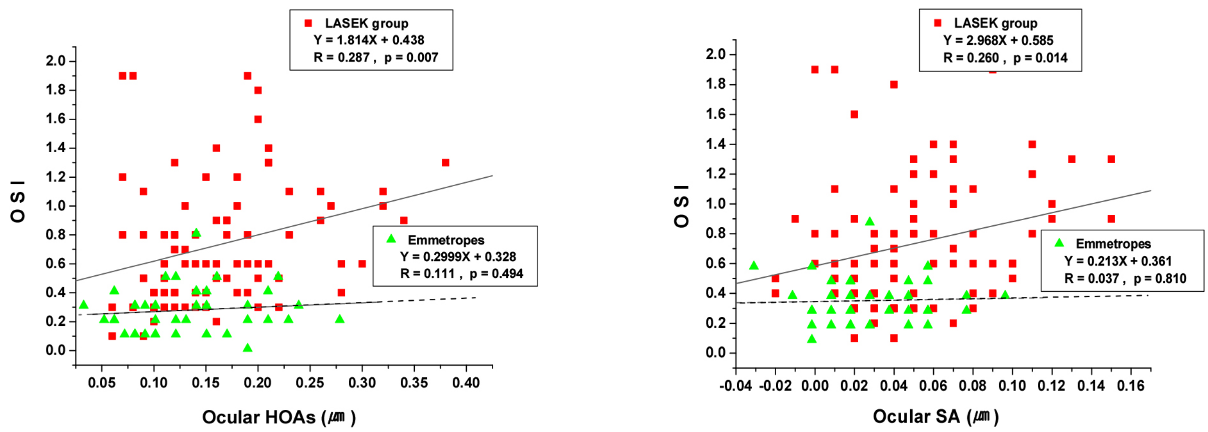
4-mm artificial pupil	LASEK	Emmetrope	p value
OSI	0.727 ± 0.431	0.368 ± 0.158	0.000*
MTF cutoff (cpd)	38.377 ± 10.022	43.094 ± 8.399	0.007*
Strehl ratio	0.212 ± 0.059	0.256 ± 0.058	0.000*
Ocular HOAs (RMS) (μm)	0.160 ± 0.068	0.131 ± 0.059	0.016*
Ocular SA (μm)	0.048 ± 0.038	0.030 ± 0.028	0.004*

OSI, objective scatter index; MTF, modulation transfer function; cpd, cycle per degree; RMS, root mean square; HOA, higher order aberrations; SA, spherical aberration; p value* < 0.05.



(a) (b)

FIG. 3. Scatter plots showing the correlations between (a) MTF cutoff and (b) Srehl ratio, as associated parameters of the optical quality of the eye, with objective scatter index (OSI), for a 4-mm artificial pupil, in the LASEK (squares, solid line) and emmetropia (triangles, dashed line) groups respectively.



(a) (b)

FIG. 4. Scatter plots showing the correlations between (a) ocular higher-order aberrations (HOAs) and (b) ocular spherical aberration (SA), as associated parameters of the optical quality of the eye, with objective scatter index (OSI), for a 4-mm artificial pupil, in the LASEK (squares, solid line) and emmetropia (triangles, dashed line) groups respectively.

($r = 0.260$, $p = 0.014$); however, there was no statistically significant correlation between OSI and ocular SA in the emmetropes ($r = 0.037$, $p = 0.810$). As a result, it was found that ocular scattering is closely related to the parameters of MTF cutoff and Strehl ratio, whereas it is less directly related to ocular higher-order aberrations, especially in the emmetropia group.

As mentioned above, the OVs measured with three contrast levels (100%, 20%, and 9%) were expressed as decimal visual acuity (VA) to objectively compare visual quality between the two groups. The mean values of objective contrast VA with three contrast levels are shown in Table 3. For the LASEK group, the means of $VA_{100\%}$, $VA_{20\%}$, and $VA_{9\%}$ were 1.279 ± 0.334, 0.929 ± 0.282, and 0.557 ± 0.176 respectively. For the emmetropia group, the means of $VA_{100\%}$, $VA_{20\%}$, and $VA_{9\%}$ were 1.434 ± 0.273, 1.095 ± 0.275, and 0.674 ± 0.169 respectively. As expected, as the contrast decreased, so did the objective visual acuity, in both groups. It was also found that there were statistically significant differences in $VA_{100\%}$, $VA_{20\%}$, and $VA_{9\%}$ between the two groups ($p = 0.007$, $p = 0.003$, and $p = 0.001$ respectively). As confirmed by the results of this

TABLE 3. The mean values of objective contrast visual acuity corresponding to each OQAS value (Ovs), with contrast levels of 100%, 20%, and 9%, for a 4-mm artificial pupil, in the LASEK and emmetropia groups

4-mm artificial pupil	LASEK	Emmetrope	*p* value
$VA_{100\%}$	1.279 ± 0.334	1.434 ± 0.273	0.007*
$VA_{20\%}$	0.929 ± 0.282	1.095 ± 0.275	0.003*
$VA_{9\%}$	0.557 ± 0.176	0.674 ± 0.169	0.001*

VA 100, 20, and 9%, visual acuity at 100, 20, and 9 percent contrast; p value* < 0.05.

study, all of the VAs for the three contrast levels in the emmetropia group were better than those of the LASEK group.

The visual acuities of simulated letters “E”, corresponding to retinal images according to values of MTF cutoff and Strehl ratio for the subjects for this study, are shown in Fig. 5. The MTF cutoff values are computed from double-pass retinal images acquired through the ocular media and retinal reflection after point-source object reflection on the retina.

The negative effect of ocular scattering on visual quality has long been studied [24, 28, 29]. Ocular scattering, which significantly deteriorates the quality of the retinal image, is closely related to the point-spread function (PSF; Strehl ratio) as one of the parameters for evaluating optical quality [30]. The PSF represents the distribution of light on the retinal image corresponding to a point source [1]; the greater the distribution of light scattering, the lower the optical quality of the eye. In the present study, the

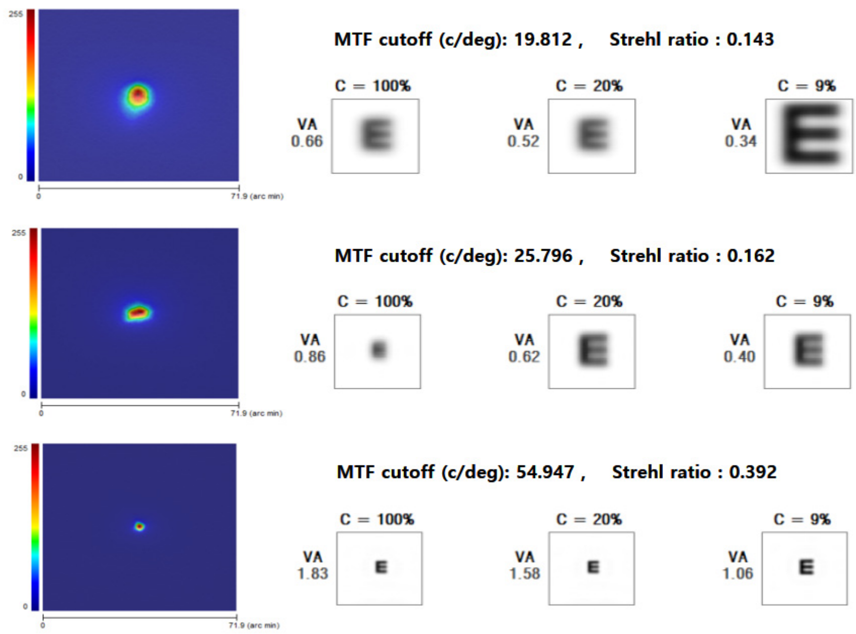


FIG. 5. Simulations of retinal images, according to values for MTF cutoff, Strehl ratio, and the visual acuities at different contrast levels (100%, 20%, and 9%) obtained by the OQAS system based on the double-pass technique, for this study’s subjects.

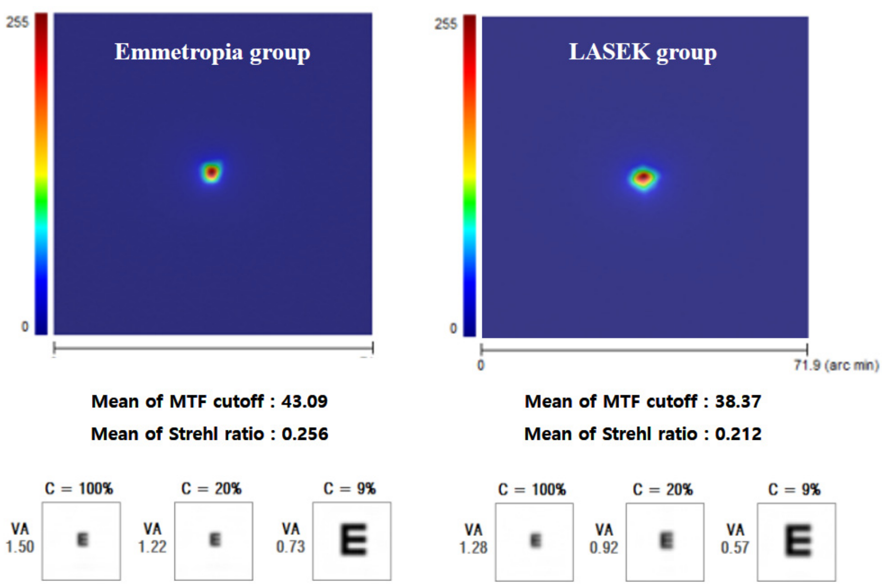


FIG. 6. Simulated double-pass retinal images and visual acuities at different contrast levels, corresponding to the means of MTF cutoff and Strehl ratio obtained by the OQAS system, for the emmetropia and LASEK groups.

results present examples of different contrast visual acuities according to double-pass images corresponding to the value of MTF cutoff and Strehl ratio in the study groups. As can be seen, the higher the value of MTF cutoff and Strehl ratio, the sharper the image, with less effect of scattering on the retinal image. VAs for three contrast levels and double-pass retinal images corresponding to the means of MTF cutoff and Strehl ratio, in the LASEK group compared to the emmetropia group, are presented in Fig. 6.

It is now accepted as fact that reduction of visual quality after corneal refractive surgery has not been observed when measured using high-contrast visual acuity under photopic conditions. In recent years, low-contrast visual acuity or contrast sensitivity has been commonly used to evaluate the quality of vision after corneal refractive surgery or cataract surgery [31, 32]. Furthermore, it has become possible to explain the loss of contrast caused by deficiency of the ocular optics or contrast sensitivity through a MTF value as a function of spatial frequency [33].

In a normal eye, an MTF cutoff frequency of 30 cpd is considered to be 1.0 in Snellen visual acuity [34]. In this study, it was found that the mean MTF cutoff value was higher than 30 cpd for both groups. Although VA with contrast 100, which could be deemed the maximum visual quality during the day, was greater than 1.0 in both groups, $VA_{100\%}$ for the emmetropia group was better than that for the LASEK group. In addition, $VA_{20\%}$ and $VA_{9\%}$, which could monitor the degree of loss of visual quality during the night, were also greater than those of the LASEK group. The difference between the two groups was higher in $VA_{9\%}$. These results suggest that the reduction of optical quality in the LASEK group would be more affected than in the emmetropia group, especially under low-contrast conditions.

Ocular scattering should be considered an important factor when evaluating visual quality in refractive-surgery patients. Increased ocular scattering is related to glare, which may cause problems such as difficulty in night driving and photophobia [29, 35]. In particular, it may be difficult to accurately recognize objects under low-illumination conditions [1]. Vilaseca *et al.* [14], who evaluated optical quality after refractive surgery, reported that optical quality before surgery affected postoperative optical quality. Accordingly, even considering that the maximum visual quality of the eye has considerably individual variation, it could be expected that an objective assessment of the optical quality of vision by the OQAS II may provide realistic information regarding the prognosis for refractive surgery. Meanwhile, this study did not consider the physiological factors, including dryness, that may affect the quality of vision when assessing optical quality between LASEK and emmetropia groups. Further studies would be needed to evaluate whether corneal dryness affects visual quality after corneal refractive surgery.

IV. CONCLUSION

Ocular scattering is one of the important factors related to visual quality. In all subjects, the higher the MTF cutoff and Strehl ratio, the lower the OSI, ocular HOAs, and SA. For the LASEK group, the MTF cutoff and Strehl ratio were lower than those for the emmetropia group, while the OSI, ocular HOAs, and SA were higher than those for emmetropes. Thus the quality of the retinal image in the LASEK group has been shown to reduce the quality of vision more than in the emmetropia group. In addition, most researchers have compared changes in ocular aberrations and ocular scattering before and after refractive surgery. Thus, comparing visual quality between refractive surgery patients and emmetropes would be helpful for understanding visual performance after refractive surgery, especially at night.

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