ARTICLE

Optical quality after myopic photorefractive keratectomy and laser in situ keratomileusis: Comparison using a double-pass system

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PURPOSE: To use a double-pass system to compare the optical quality after photorefractive keratectomy (PRK) and laser in situ keratomileusis (LASIK) for mild to moderate myopia.

SETTING: Universitat Politècnica de Catalunya, Terrassa, Barcelona Institute of Ocular Microsurgery, Barcelona, Spain.

DESIGN: Comparative case series.

METHODS: Optical quality was assessed with a clinical double-pass system preoperatively and 3 months after PRK or LASIK. The modulation transfer function (MTF), retinal image quality parameters (MTF cutoff frequency, Strehl ratio), and intraocular scattering (objective scatter index [OSI]) were calculated.

RESULTS: This study evaluated 34 eyes that had PRK and 55 eyes that had LASIK. Both PRK and LASIK had a statistically significant impact on retinal image quality, although no significant differences between the techniques were observed. The MTF at 30 cycles per degree decreased by a factor of 1.50 in the PRK group and by a factor of 1.32 in the LASIK group. The MTF cutoff frequency decreased by a factor of 1.04 in the PRK group and by a factor of 1.06 in the LASIK group. The Strehl ratio decreased by a factor of 1.10 and 1.07, respectively. Photorefractive keratectomy and LASIK increased the objective scatter index by factors of 1.48 and 1.57, respectively. Significant correlations between the preoperative refraction and the OSI were found.

CONCLUSIONS: Retinal image quality was similarly reduced with PRK and LASIK, with no significant differences between the 2 methods. Some PRK patients had a residual refractive error that might have been related to corneal-wound healing still present 3 months postoperatively.

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Laser in situ keratomileusis (LASIK)[1,2] is currently the most widely used refractive surgical technique and the first option for patients with low to moderate myopic refractive errors. In the early postoperative period, LASIK is more painless and the recovery faster than after some other refracture procedures; also, the wound-healing response is less because the central corneal epithelium remains intact.[3] Thus, surgeons prefer it to other laser techniques with surface ablation. However, other surgical procedures are still being used in refractive surgery.[4,5] One is photorefractive keratectomy (PRK),[6] which is mainly performed when LASIK is contraindicated, as in eyes with thin or irregular corneas.[7,8] Photorefractive keratectomy is also useful for patients with specific ocular conditions, such as epithelial basement membrane dystrophy, superficial corneal scars, recurrent erosions,[9] and previous radial keratotomy, because surface ablation may give better outcomes.[5] Furthermore, PRK avoids some of the possible complications of LASIK, including corneal ectasia,[10,11] and can be an alternative for patients who are reluctant to have incisional surgery because they are at risk for eye trauma (eg, those involved in the martial arts or in the military).

In recent years, several studies[12–14] have compared the refractive and visual outcomes after LASIK and

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PRK. Some studies suggest there is little difference between flap-based and PRK-based procedures for correcting myopia and found both techniques to be similarly effective, predictable, and stable and to be reasonably safe. However, other studies found differences in the refractive and visual performance with the 2 surgical techniques. In 1 study,[15] PRK provided slightly better visual outcomes than LASIK. Another long-term follow-up study[16] showed that LASIK had higher short-term efficacy than PRK. However, this trend was not observed some years later, when a myopic shift and a decline in uncorrected visual acuity occurred. The results in a study comparing the effects of PRK and LASIK on the contrast sensitivity function[17] found that PRK had a more significant effect than LASIK on mesopic contrast sensitivity. However, another study[18] found similar contrast sensitivity outcomes after PRK and LASIK.

An alternative way to compare the 2 surgical procedures is to use clinical instruments to objectively assess the visual quality achieved by patients.[19] One method is to use wavefront aberrometers, which have become common in daily clinical practice because their use has been linked to custom wavefront-guided LASIK.[20,21] Wavefront aberrometers, which are usually based on the Hartmann-Shack principle,[22,23] assess the eye's optical quality by objectively determining ocular higher-order aberrations (HOAs). In general, these devices consist of a microlens array conjugated with the eye's pupil and a camera placed at its focal plane. If a plane wavefront reaches the microlens array, the image recorded with the camera is a perfectly regular mosaic of spots. However, if a distorted (ie, aberrated) wavefront reaches the sensor, the pattern of spots is irregular. The displacement of each spot is proportional to the derivative of the wavefront over each microlens area. The wavefront aberration can be computed from the images of the spots, and the modulation transfer function (MTF), which represents the loss of contrast produced by the eye's optics as a function of spatial frequency, can be calculated by Fourier transformation. There have been several attempts to assess aberrations in eyes that have had PRK and LASIK using this technique. In general, the results showed significantly more HOAs after PRK and LASIK,[14,24–33] although in general, no significant differences between the techniques were observed.[14,25]

Retinal image quality can also be clinically assessed with instruments based on the double-pass technique.[34] The double-pass technique—in which the image of a point-source object is directly recorded after reflection on the retina and a double pass through the ocular media—has been shown to accurately estimate the eye's optical quality. In contrast to wavefront aberrometry, the MTF of the eye in a double-pass system is directly computed by Fourier transformation from the acquired double-pass retinal image. Because of the differences between the 2 technologies, recent studies suggest that wavefront aberrometers may overestimate the optical quality in eyes with very high ocular aberrations because the aberrometers smooth the interpretation of them. Moreover, they might overestimate the optical quality in eyes in which scattered light is prominent[35] because they cannot detect it. In contrast, the double-pass technique can characterize retinal image quality, including the effect of HOAs and intraocular scattering, which may be prominent in eyes with cataract or those treated with refractive surgery. One commercially available double-pass device is the Optical Quality Analysis System (Visiometrics S.L.).[36] This system has been used to assess retinal image quality in patients with keratitis,[37] patients having refractive surgery such as LASIK[38,39] and PRK,[40] and patients with intraocular lenses (IOLs).[39,41,42] This technique has also been used to evaluate presbyopia after PRK[43] and the in vitro optical quality of foldable monofocal IOLs.[44]

In this study, we used the double-pass technique to assess retinal image quality in patients who had PRK or LASIK. We believe this is the first comparative clinical study to use this technique. The increase in intraocular scattering after the 2 surgical techniques was also analyzed.

PATIENTS AND METHODS

This observational prospective cross-sectional consecutive case series study compared the retinal image quality in eyes having PRK and eyes having LASIK for mild to moderate myopia (≤ -6.75 diopters). All patients were treated at Instituto de Microcirugía Ocular de Barcelona, Barcelona, Spain, between June 1, 2008, and June 30, 2009. An ethics committee approved the study, and all patients signed an informed consent form before surgery and before additional

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examinations. The tenets of the 1975 Declaration of Helsinki (revised in Tokyo, 2004) were followed throughout the study.

The inclusion criteria were availability of preoperative and postoperative data, a stable refractive error for at least 1 year before surgery, a preoperative corrected distance visual acuity (CDVA) better than 0.2 logMAR, and normal preoperative optical quality values. Eyes with anterior segment disease, abnormal corneal topography, or abnormal posterior pole evaluation during the preoperative or postoperative stages were excluded, as were eyes that had preoperative intraocular pressure higher than 21 mm Hg.

The same surgeon (J.L.G.) performed all PRK and LASIK procedures. The PRK treatment was performed using an MEL 80 excimer laser system (Carl Zeiss Meditec AG) with aberration smart ablation optimized profile treatment, a 6.2 mm optical zone, and a standard 8.2 mm transition zone. This profile corresponds to a wavefront-optimized treatment that mainly takes into account final asphericity to reduce the induction of spherical aberration. It is mostly applied in myopic treatments. The same profile was used in all eyes. A standard corneal epithelial scraper (Alcon 681.01) was used to expose Bowman membrane in a central area 8.0 mm in diameter. Immediately after surgery, a bandage contact lens was applied. A broad-spectrum antibiotic agent was administered 3 times a day, and artificial tears were prescribed every hour. Three days later, the bandage contact lens was removed and standard treatment with fluorometholone (FML Forte) was prescribed 3 times a day and then tapered over the next 12 weeks. Artificial tears were prescribed for at least 5 times a day for 4 months.

Laser in situ keratomileusis was also performed using the MEL 80 excimer laser system with the same profile treatment, a 6.2 mm optical zone, and a standard 8.2 mm transition zone; the same profile was used in all eyes. An Amadeus microkeratome (Ziemer Group AG) with a 140 μm plate and 9.0 mm diameter was used to create the flap. Postoperative medication comprised tobramycin–dexamethasone (Tobradex) 4 times a day for 8 days and artificial tears at least 5 times a day for 2 months.

Patient examinations were performed preoperatively and 3 months postoperatively. The comparison between the PRK group and the LASIK group was performed at 3 months (routine patient visit) under the assumption that subsequent changes in optical quality would be relatively minor.[16,45,46] The follow-up clinical examination included manifest refraction, CDVA, uncorrected distance visual acuity (UDVA), and retinal image quality. The measurements took approximately 45 minutes. Visual acuity was measured using a standard logMAR acuity chart at 2 m. The acuity measurements were then transformed into decimal notation for calculation of the safety and efficacy indices.

The double-pass technique allows the assessment of the retinal image quality only with a specific pupil diameter per measurement; an additional measurement is required for other desired pupil sizes. Therefore, in this study, retinal image quality measures were assessed with a 4.0 mm pupil only; this is a standard size that is often used to analyze ocular aberrations and more closely simulates visual acuity measurement performed with an undilated pupil.[31] Artificial tears were instilled before each double-pass measurement because it has been suggested that retinal image quality is influenced by tear-film quality.[A] During the measurements, the patient's spherical refractive error was automatically corrected by the double-pass system, while the cylindrical error was corrected with an external lens. The aim was to achieve the best possible optical quality to compare the 2 surgical techniques in the retinal image quality affected by only HOAs and intraocular scattered light. Optical quality strongly depends on uncorrected refractive error because this factor directly affects the retinal image. Moreover, the optical quality of an external lens is much higher than the eye's optical quality. Therefore, assessment of the eye's retinal image quality is not affected.

The double-pass system was used to obtain preoperative and postoperative double-pass retinal images of the eye and the preoperative and postoperative MTFs. The double-pass image describes the response of the eye to a point-source object and is often expressed as a profile of variation in intensity with angle. The MTF represents the loss of contrast produced by the eye's optics as a function of the spatial frequency, as described above. The intensity profile as a function of the angle and MTF are 2-dimensional functions, although averaged profiles corresponding to all radial directions were used in this study to describe the optical quality of the eye. To simplify the data and facilitate the comparison of retinal image quality between the PRK group and the LASIK group, other standard parameters related to the MTF that can be measured with the double-pass system (ie, the MTF cutoff frequency [MTF cutoff] and the Strehl ratio) were also analyzed. Normal values for these parameters in a healthy young population, a post-refractive surgery group, and a cataract group have been reported.[47–49]

The MTF cutoff corresponds to a 0.01 MTF value in the double-pass instrument because there is background noise in the MTF profile from the real recorded double-pass image. This parameter is directly related to the patient's visual acuity, although it is not affected by retinal and neural factors.[50] It is normally assumed that a cutoff frequency of 30 cycles per degree (cpd) in the contrast sensitivity function, which includes the contrast degradation imposed by the optics and posterior visual processing, corresponds to a decimal visual acuity of 1.0.[51]

In the visual optics field, the Strehl ratio is often computed in the frequency domain as the ratio between the volume under the MTF curve of the measured eye and that of the aberration-free eye.[52,53] This provides general information on the eye's optical quality. The double-pass system computes the Strehl ratio in 2 dimensions as the ratio between the area under the MTF curve of the measured eye and that of the aberration-free eye, as discussed in the literature.[54] A Strehl ratio of 1 is related to a perfect optical system that is limited by diffraction only.

The system also uses an objective scatter index (OSI) to quantify intraocular scattered light.[40,47–49,55] From the image obtained by the double-pass system, the OSI is computed as the ratio between the amount of light recorded inside an annular area between 12 minutes of arc (arcmin) and 20 arcmin and that recorded closer to the peak, specifically in a circular area of a 1 arcmin radius from the central peak (Figure 1). Although such aberrations and scattered light are distributed through the retinal image,[56,57] the OSI calculation is based on the concept that ocular aberrations mainly modify the intensity distribution closer to the peak and that the effect of ocular scattering occurs farther from the center.[58] The choice of the angles from which the OSI is computed in the Optical Quality Analysis System is based on results in previous studies,[B–D] in which authors found a maximum correlation between OSI values and a standard cataract gradation (Lens Opacities Classification System III).[59] These studies

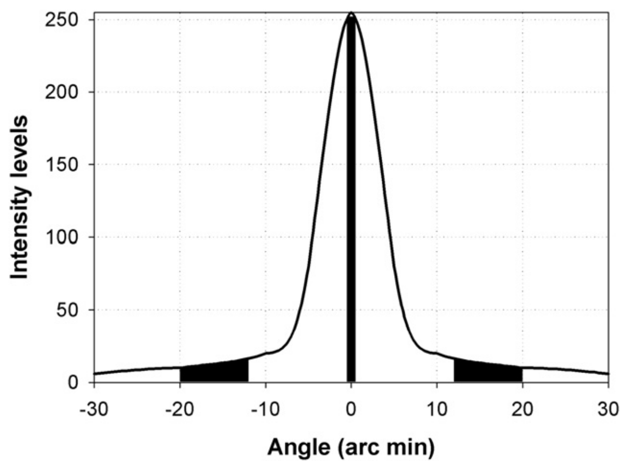

Figure 1. Computation of the OSI from the double-pass image acquired. Black areas correspond to the amount of light within an annular area of 12 arcmin and 20 arcmin and that recorded within 1 arcmin of the peak (arc min = minutes of arc).

concluded that, in general, OSI values around 1 are usually recorded in eyes with low scattering, values from 1 to 7 in eyes with moderate diffused light, and values above 7 in eyes with very high scattering, such as eyes with mature cataract.

Statistical analysis of the data was performed using SPSS for Windows software (version 17.0, SPSS Inc.). First, the *t* test was used to statistically compare the preoperative refractive error, CDVA, retinal image quality parameters (MTF cutoff and Strehl ratio), and OSI between PRK and LASIK. Second, the postoperative outcomes in both groups were compared using the same procedure. The paired-sample *t* test was used to statistically compare the CDVA and retinal image quality parameters obtained preoperatively and postoperatively for each surgical technique independently. In all cases, a *P* value less than 0.05 was considered statistically significant.

RESULTS

The study comprised 34 eyes (18 patients) that had PRK and 55 eyes (30 patients) that had LASIK (Table 1). There were no postoperative complications.

Refractive Error

Table 1 shows the preoperative manifest refraction sphere, cylinder, and spherical equivalent (SE) by group. There were no statistically significant difference in any of the parameters between the PRK group and the LASIK group ($P = .317$ [sphere], $P = .135$ [cylinder], $P = .185$ [SE]; *t* test). Therefore, the preoperative refractive error in the 2 groups was comparable.

Table 2 shows the postoperative refractive errors by group. There were no statistically significant differences in sphere ($P = .159$, *t* test) and in SE ($P = .916$, *t* test) between the 2 groups. However, there was a significant difference in cylinder ($P = .010$, *t* test), with some PRK patients having low residual astigmatism 3 months after surgery.

Table 1. Patient demographics and preoperative refractive error.

Parameter	PRK Group	LASIK Group
Age (y)		
Mean ± SD	31.1 ± 7.7	30.7 ± 8.9
Range	22, 45	20, 45
Sex (n)		
Male	8	10
Female	10	20
Sphere (D)		
Mean ± SD	−3.16 ± 1.39	−3.23 ± 1.74
Range	−5.50, −0.25	−6.75, 0.00
Cylinder (D)		
Mean ± SD	−0.72 ± 0.78	−1.06 ± 1.14
Range	−2.75, 0.00	−3.75, 0.00
SE (D)		
Mean ± SD	−3.46 ± 1.38	−3.69 ± 1.62
Range	−5.75, 0.00	−6.75, 0.00

LASIK = laser in situ keratomileusis; PRK = photorefractive keratectomy; SE = spherical equivalent

Visual Acuity

Table 3 shows the preoperative and postoperative logMAR CDVA and UDVA by group. It also shows the postoperative variation in visual acuity, represented by the ratio between the CDVA 3 months after surgery and the corresponding preoperative CDVA (ie, safety index) and the ratio between the postoperative UDVA and the preoperative CDVA (ie, the efficacy index).

The *t* test found no statistically significant difference in the preoperative CDVA between the 2 groups ($P = .920$), which suggests that the preoperative visual acuity was comparable. After 3 months, the CDVA and UDVA were better than 0.2 in all patients in

Table 2. Postoperative refractive error.

Parameter	PRK Group	LASIK Group
Sphere (D)		
Mean ± SD	0.05 ± 0.53	0.05 ± 0.18
Range	−1.00, 1.50	−0.25, 0.75
Cylinder (D)		
Mean ± SD	−0.33 ± 0.41	−0.12 ± 0.29
Range	−1.50, 0.00	−1.25, 0.00
SE (D)		
Mean ± SD	−0.12 ± 0.48	−0.01 ± 0.13
Range	−1.25, 1.25	−0.38, 0.38

LASIK = laser in situ keratomileusis; PRK = photorefractive keratectomy; SE = spherical equivalent

Table 3. Preoperative and postoperative CDVA, UDVA, safety index, and efficacy index.

Group/Exam	CDVA (LogMAR)	UDVA (LogMAR)	Safety Index	Efficacy Index
PRK				
Preop				
Mean ± SD	0.00 ± 0.06	<0.10	—	—
Range	0.15, −0.08	—	—	—
Postop				
Mean ± SD	0.00 ± 0.04	0.06 ± 0.11	1.00 ± 0.14	0.89 ± 0.16
Range	0.10, −0.10	0.18, −0.10	0.83, 1.32	0.62, 1.32
LASIK				
Preop				
Mean ± SD	0.01 ± 0.06	<0.10	—	—
Range	0.16, −0.10	—	—	—
Postop				
Mean ± SD	0.00 ± 0.07	0.00 ± 0.07	1.02 ± 0.14	1.01 ± 0.14
Range	0.14, −0.14	0.14, −0.14	0.58, 1.23	0.58, 1.23

CDVA = corrected distance visual acuity; LASIK = laser in situ keratomileusis; PRK = photorefractive keratectomy; UDVA = uncorrected distance visual acuity

both groups. There were no statistically significant differences in CDVA between the PRK group and the LASIK group ($P=.931$). However, there was a statistically significant difference in the postoperative UDVA between the 2 groups ($P<.001$) as a result of the residual cylindrical error in some PRK patients.

There were no significant within-group differences (ie, preoperatively and postoperatively) in CDVA ($P=.789$ [PRK], $P=.564$ [LASIK]).

Retinal Image Quality and Intraocular Scattering

Figure 2 shows the double-pass images and corresponding intensity profile with angle and MTF curve in an eye that had PRK surgery. The figure also shows the preoperative and postoperative CDVA, UDVA, and retinal image quality parameters (MTF cutoff, Strehl, and OSI) associated with each measurement. Figure 3 shows a representative LASIK case. Both the PRK eye and the LASIK eye had an increase in the postoperative intensity values at angles farther from the center. The MTF curve, MTF cutoff, and Strehl ratio decreased after surgery, which suggests worsening of the retinal image quality. The postoperative OSI was higher in both eyes as a direct consequence of the increase in intensity at broader angles measured postoperatively, which means that the intraocular scattered light was higher after both procedures.

Figure 4 shows the averaged profile of intensity as a function of the angle measured preoperatively and postoperatively. In both PRK cases and LASIK cases, broadening of the curve was observed, which means that image quality was worse after surgery. Similarly, Figure 5 shows the averaged preoperative and postoperative MTF as a function of the spatial frequency in all eyes. Figure 6 shows the corresponding mean MTF ratio (postoperative to preoperative) in the PRK group and the LASIK group. Loss of retinal contrast occurred postoperatively, especially at medium-high spatial frequencies.

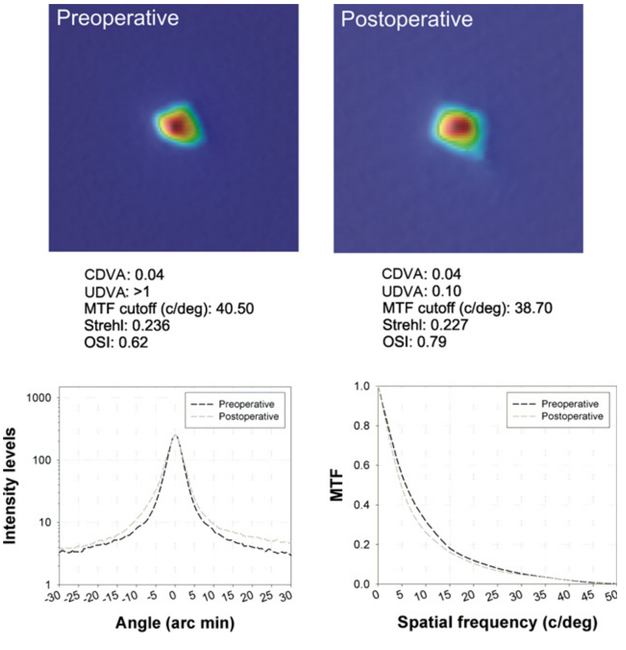

Figure 2. Preoperative and postoperative double-pass images, intensity profile as a function of the angle (logarithmic scale), and MTF, logMAR CDVA, UDVA, and retinal image quality parameters (MTF cutoff, Strehl ratio, and OSI) in an eye that had PRK (arc min = minutes of arc; c/deg = cycles per degree CDVA = corrected distance visual acuity; MTF = modulation transfer function; OSI = objective scatter index; UDVA = uncorrected distance visual acuity).

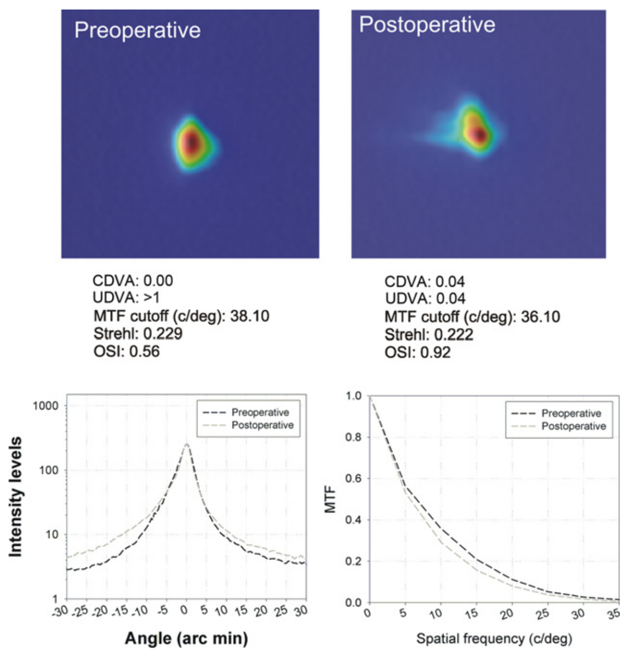

Figure 3. Preoperative and postoperative double-pass images, intensity profile as a function of the angle (logarithmic scale), and MTF, logMAR CDVA, UDVA, and retinal image quality parameters (MTF cutoff, Strehl ratio, and OSI) in an eye that had LASIK (arc min = minutes of arc; c/deg = cycles per degree CDVA = corrected distance visual acuity; MTF = modulation transfer function; OSI = objective scatter index; UDVA = uncorrected distance visual acuity).

Table 4 shows the preoperative and postoperative retinal image quality parameters (MTF cutoff, Strehl ratio, and OSI) for all patients and the ratios between the postoperative values and preoperative values for these parameters. The *t* test analysis showed no statistically significant differences in preoperative values between the PRK group and the LASIK group (P=.171 [MTF cutoff], P=.191 [Strehl ratio], P=.732 [OSI]). There were also no statistically significantly differences between the 2 groups postoperatively (P=.173 [MTF cutoff], P=.594 [Strehl ratio], P=.646 [OSI]).

The paired *t* test for the preoperative and postoperative PRK data showed that in general, the variations between the 2 stages were statistically significant or fell just within the limit of statistical significance (P=.050 [MTF cutoff], P=.022 [Strehl ratio], P=.010 [OSI]). This was also true for LASIK (P=.010 [MTF cutoff], P=.031 [Strehl ratio], P=.010 [OSI]).

Figure 7 shows the correlations between the achieved refractive correction in terms of SE and the postoperative retinal image quality parameters (MTF cutoff, Strehl ratio, and OSI) in all eyes. The retinal image quality and intraocular scattering worsened in proportion to the preoperative refraction in both

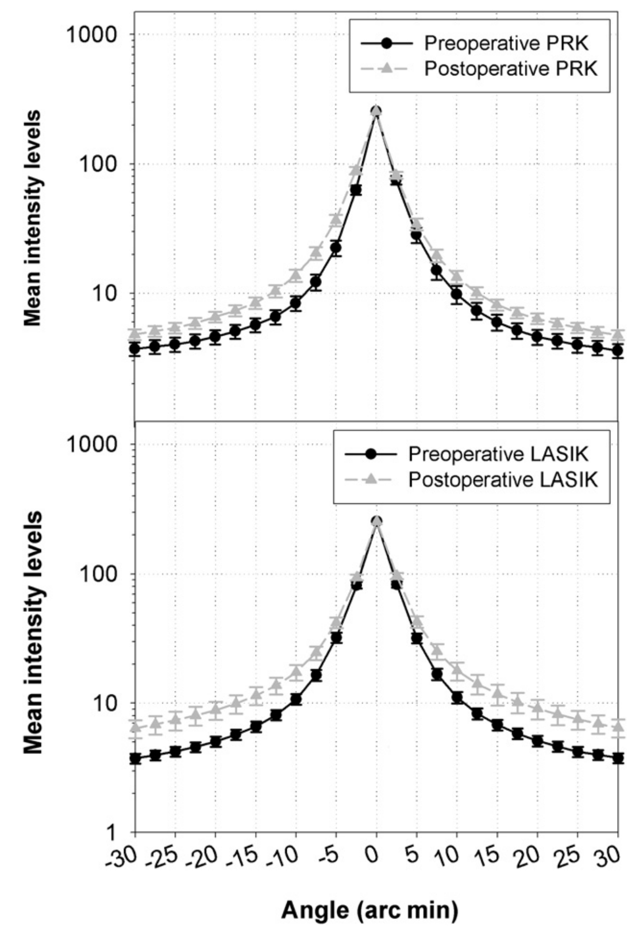

Figure 4. Mean preoperative intensity profile as a function of the angle of all eyes that had PRK or LASIK and the mean profile corresponding to the postoperative stage (logarithmic scale). Error bars represent the standard error of the mean (arcmin = minutes of arc; LASIK = laser in situ keratomileusis; PRK = photorefractive keratectomy).

groups. However, significant relationships were found only between the achieved refractive correction and the OSI in the PRK group and LASIK group (r = .448, P=.011 [PRK]; r = .369, P=.005 [LASIK]) and between the achieved refractive correction and the Strehl ratio in the LASIK group (r = .274, P=.043).

DISCUSSION

In this study, we analyzed the optical quality of patients who had PRK or LASIK; all surgeries were performed using the same ablation optical zone and transition area. We measured optical quality using the Optical Quality Analysis System clinical double-pass device, taking into account that in other similar studies, optical quality was assessed using wavefront examinations. Our results provide useful information on the optical quality 3 months after PRK and LASIK. Although these results might be considered early

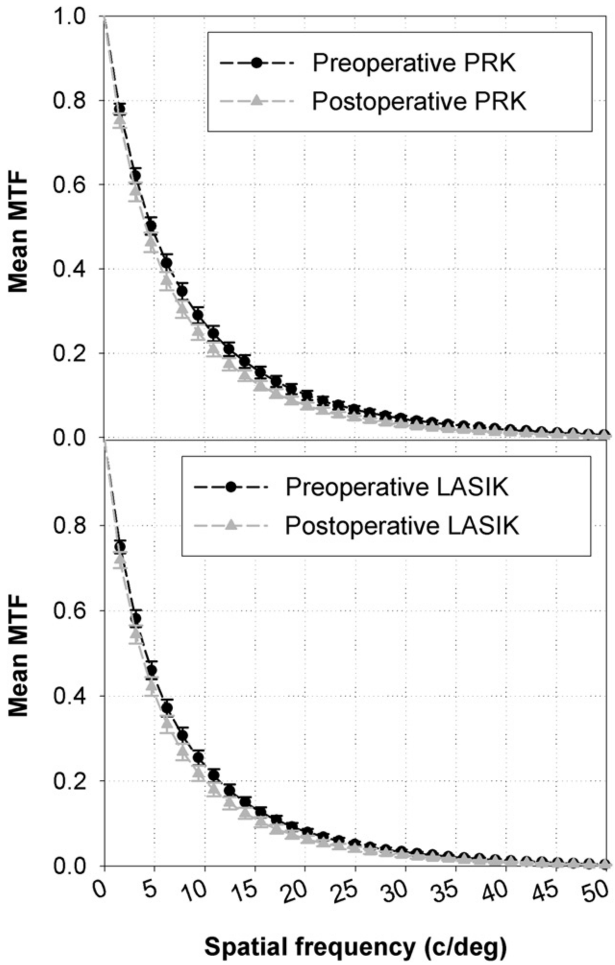

Figure 5. Mean preoperative MTF of all eyes that had PRK or LASIK and the mean MTF profile corresponding to the postoperative stage. Error bars represent the standard error of the mean (c/deg = cycles per degree; LASIK = laser in situ keratomileusis; MTF = modulation transfer function; PRK = photorefractive keratectomy).

because the optical properties of the eye may continue to evolve over time, many previous studies based on wavefront aberrometry were also performed at an early stage.

In our study, PRK and LASIK corrected most of the refractive error of patients with mild to moderate myopia. However, 3 months after surgery, some PRK patients had a low residual refractive error, which was mainly cylindrical. Patients in the PRK group and patients in the LASIK group had a similar CDVA 3 months postoperatively. However, the postoperative UDVA values were worse in the PRK group than in the LASIK group, probably because of the residual astigmatism. Furthermore, both techniques were safe (safety score 1.00 in PRK group and 1.02 in LASIK group). The efficacy index was 0.89 and 1.01, respectively. Therefore, LASIK and PRK gave similarly good visual outcomes in terms of safety and efficacy.

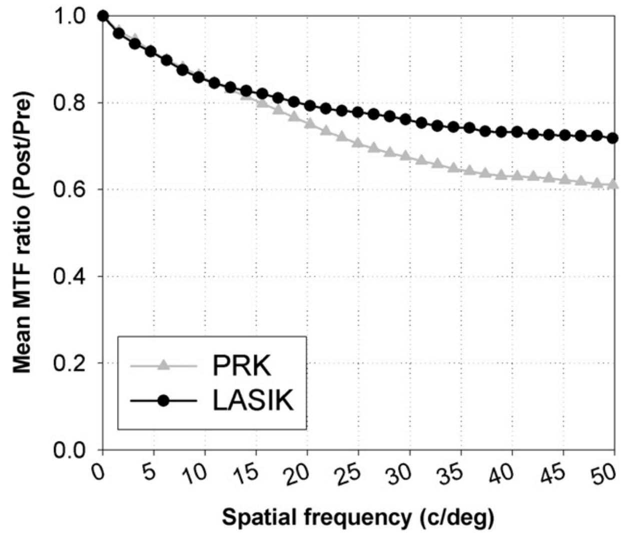

Figure 6. Mean MTF ratio (postoperative/preoperative) of all eyes that had PRK and LASIK surgery (c/deg = cycles per degree; LASIK = laser in situ keratomileusis; MTF = modulation transfer function; PRK = photorefractive keratectomy).

Some authors have concluded that refractive stability occurs during the first postoperative month with both techniques,[46] although most clinical studies

Table 4. Preoperative and postoperative retinal image-quality results and the corresponding ratios (postoperative to preoperative).

Group/Exam	MTF Cutoff (cpd)	Strehl Ratio	OSI
PRK			
Preop			
Mean ± SD	41.43 ± 11.16	0.248 ± 0.079	0.78 ± 0.43
Range	16.80, 51.6	0.099, 0.463	0.34, 2.45
Postop			
Mean ± SD	38.18 ± 10.24	0.213 ± 0.070	1.00 ± 0.46
Range	18.00, 54.30	0.094, 0.334	0.48, 2.13
Ratio			
Mean ± SD	0.96 ± 0.36	0.906 ± 0.317	1.48 ± 1.06
Range	0.36, 2.02	0.203, 1.798	0.59, 6.25
LASIK			
Preop			
Mean ± SD	37.88 ± 11.13	0.224 ± 0.075	0.78 ± 0.47
Range	16.20, 56.10	0.104, 0.446	0.18, 2.70
Postop			
Mean ± SD	33.43 ± 11.10	0.201 ± 0.071	1.07 ± 0.58
Range	18.70, 54.90	0.085, 0.448	0.22, 2.51
Ratio			
Mean ± SD	0.94 ± 0.34	0.935 ± 0.344	1.57 ± 0.90
Range	0.23, 1.81	0.293, 1.865	0.42, 4.19

cpd = cycles per degree; LASIK = laser in situ keratomileusis; MTF = modulation transfer function; OSI = objective scatter index; PRK = photorefractive keratectomy

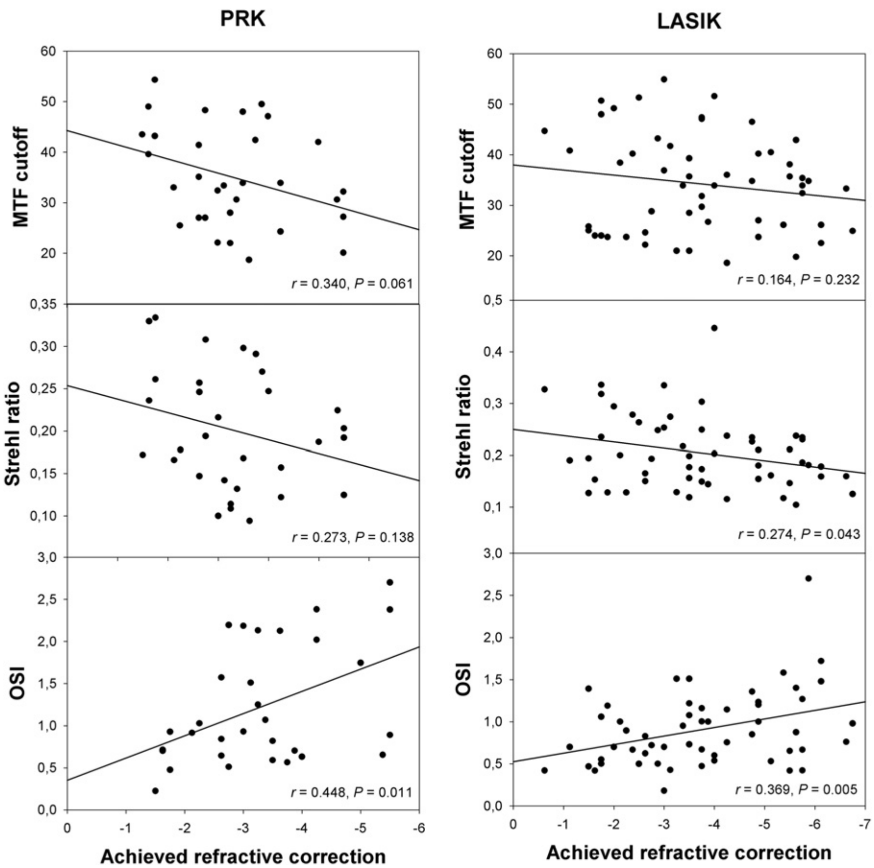

Figure 7. Correlation between the achieved refractive correction and postoperative retinal image quality parameters (LASIK = laser in situ keratomileusis; MTF = modulation transfer function; OSI = objective scatter index; *P* = statistical significance corresponding to *r*; PRK = photorefractive keratectomy; *r* = Pearson correlation coefficient).

emphasize that earlier refractive stability and visual recovery can be achieved with LASIK than with PRK.[3,16,A] One study[60] reports a slight decrease in the mean topographic cylinder over a 10-year period after PRK, which could be the cause of the cylindrical error found in our study. Despite the better short-term efficacy of LASIK, some studies suggest that this benefit is not retained after some years because a myopic shift and a decline in UDVA have been observed in LASIK patients.[16,61] Therefore, in general, the efficacy outcomes for the 2 procedures are similar.[62,63]

When the retinal image quality obtained using the double-pass system is taken into account, we can approach the visual outcomes of PRK and LASIK techniques in a new way. The analysis of the preoperative and postoperative averaged intensity profiles as a function of the angle suggested worsening of retinal image quality 3 months after both procedures. We also found that the mean MTF decreased after PRK and LASIK. The mean MTF ratio (postoperative to preoperative) indicated that the contrast degradation imposed by the optics of the eye was especially significant at medium-high spatial frequencies. Photorefractive keratectomy seemed to have had a greater impact on the MTF. For example, the MTF at 30 cpd decreased by a factor of 1.50 on average after PRK and by a factor of 1.32 after LASIK. The slightly greater decrease in optical quality after PRK was likely because the wound was still healing 3 months after surgery. Similar conclusions could be reached by analyzing specific retinal image quality parameters (ie, MTF cutoff and Strehl ratio), which decreased significantly after PRK and after LASIK. However, the postoperative statistical analysis of the data obtained using the double-pass system indicates that there were no significant differences between the 2 techniques. Specifically, the MTF cutoff and the Strehl ratio decreased on average by factors of 1.04 and 1.10, respectively, in the PRK group and 1.06 and 1.07, respectively, in the LASIK group. Furthermore, the only significant correlation was between the achieved refractive correction and the Strehl ratio in the LASIK group. This indicates that even though there was a slight tendency for the postoperative retinal image quality to worsen by increasing the attempted refractive correction, as other authors have suggested,[14] we established no significant relationships using the double-pass data.

Other authors also report a loss of contrast in terms of MTF after laser refractive surgery. Moreno-Barriuso et al.[27] and Marcos[31] found that MTF decreased on average by a factor of 2 after LASIK at a frequency of 30 cpd using a 3.0 mm pupil and laser ray tracing;

patients were evaluated before surgery and between 1 month and 3 months after surgery. The slightly lower decrease in our study using the double-pass technique could be a result of the longer postoperative period, which was at least 3 months in all cases. Sarver et al.[28] used a Hartmann-Shack aberrometer to compare the retinal image quality in eyes that had LASIK or phakic IOL (pIOL) implantation. They also found that the contrast transfer deteriorated significantly after LASIK; however, after pIOL implantation, the retinal image quality recovered totally, and the preoperative and postoperative MTF functions were similar. Hong and Thibos[30] found a loss of retinal contrast in a 35-year-old female LASIK patient using a wavefront aberrometer and a 6.0 mm pupil; however, the image quality with a 4.5 mm pupil was almost normal after 8 weeks of recovery. Our results differ and in general suggest that PRK and LASIK have a greater impact on the optical quality of the eye.

The Strehl ratio parameter is obtained in the double-pass system as the ratio between the area under the MTF curve of the measured eye and that of the aberration-free eye. Marcos[31] found that the area under the MTF curve for a 3.0 mm pupil decreased by a factor of 1.38 after LASIK (patients examined preoperatively and 1 to 3 months postoperatively). This change was greater than in our study, in which the Strehl ratio decreased by a factor of 1.10 in the PRK group and 1.07 in the LASIK group; this could be attributed to the shorter postoperative period in the study by Marcos. Sakata et al.[33] also found that PRK significantly reduced the area under the contrast sensitivity function by a factor of 1.07 on average, which fairly correlates with the MTF findings in our study.

A complete analysis of the impact of PRK and LASIK requires a separate analysis of the OSI parameter, which accounts for intraocular scattering. The effect of optical aberrations could be summarized as blurring of the retinal image, which in general reduces the patient's visual acuity, and intraocular scattering, which reduces the contrast of the retinal image and produces a darker perception of a scene.[64] Several approaches to psychophysically evaluate intraocular scattering have been proposed; these include measurement of the contrast sensitivity function with and without a glare source, which allows a light-scattering factor to be computed,[65,66] and visual acuity assessment using a brightness acuity tester.[67] Another study[68] attempted to evaluate scatter using a compensation-comparison method and a flickering glare ring that adds a veil to a central bipartite test (C-Quant system, Oculus GmbH); the result is an indicator of the stray light produced by the flickering glare ring. However, a general consensus has not been reached on how the scattering can be evaluated objectively. Artal et al.[55] recently proposed a new approach that used the OSI, which is computed based on the idea that ocular aberrations mainly modify the intensity distribution of the double-pass image closer to the peak and that the effect of ocular scattering is produced farther from the center.[58] A similar approach was proposed by Westheimer and Liang,[70] who measured an index of diffusion, which had a strong tendency to increase with age.

In the present study, we found a statistically significant increase in the OSI after PRK and LASIK that was a direct consequence of the increasing intensity values at broader angles. In the PRK group, the OSI increased by a factor of 1.48 on average. In LASIK patients, this factor rose to 1.57. However, even though the increase in the LASIK group was higher than in the PRK group, the difference between the groups was not statistically significant. Although the values suggest a significant change, the postoperative OSI was still similar to 1 on average, which is within the normal range for this parameter.[49] Furthermore, it should be kept in mind that the OSI is associated with large coefficients of repeatability (percentages higher than 30%) because this parameter has a mean absolute value closer to zero.[47,48] This could partly explain the large variability found in our study and why there were no statistically significant differences between PRK and LASIK.

Our scattered light results are similar to those in some previous studies, which also found a moderate increase in corneal haze using confocal microscopy and slitlamp biomicroscopy[70,71]; the haze intensity peaked at 3 months and gradually declined 1 year after PRK as a result of anterior keratocyte loss. Furthermore, Mohan et al.[72] found that haze formation was correlated with the level of PRK correction for myopia, which might be related to corneal wound healing. A straylight meter also detected a correlation between diminished anterior keratocyte density and increased intraocular straylight after LASIK.[73] This may explain the significant correlation between the intraocular scattering in terms of the OSI and the achieved refractive correction in our study.

In contrast, straylight values calculated using a straylight meter increased transiently after PRK, although in many cases they returned to preoperative levels after the initial rise.[74,75] Harrison et al.[76] also reported no significant changes in forward light scatter 1 month after PRK. The differences in the findings between these studies, which assessed intraocular scattering with a straylight meter, and studies using other techniques are probably a result of the relative contribution of backward scattering, which may be more important in the double-pass technique.[77]

In conclusion, the double-pass technique was a powerful tool for clinically evaluating the optical quality of the eye after laser refractive surgery. Photorefractive keratectomy and LASIK had a similar impact on the retinal image quality in eyes with low to moderate myopia. Both techniques led to a postoperative decrease in the MTF function and a worsening in retinal image quality parameters after 3 months. Moreover, both techniques increased intraocular scattering assessed using the OSI parameter, particularly in eyes with higher myopia. However, despite the changes caused by the 2 techniques, the postoperative optical quality of patients can be considered high in absolute terms. Modulation transfer function cutoff values above 30 cpd and Strehl ratios similar to 0.2 have been correlated with good optical quality.[49,78] Therefore, the optical quality achieved by both surgical techniques was acceptable, and this may explain why patients were not dissatisfied with the final visual results.

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