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Corneal Power Determination with Corneal Tomography after Refractive Surgery with Excimer Laser

Determinación del poder corneal con un tomógrafo corneal luego de cirugía refractiva con láser excimer

Determinação da potência corneana com uma topografia de córnea após cirurgia refrativa com excimer láser

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Abstract

Introduction. Corneal power determination after refractive surgery with excimer laser is complex. Different alternatives with the use of corneal tomography have been used for this measurement. **Objective.** To evaluate various methods of determination of corneal power in patients undergoing photorefractive surgery, including diagnostic tests with quantitative measurements. **Methodology.** This is a retrospective observational study. We included patients undergoing photorefractive surgery with refractive results and post-operative corneal tomography taken at least ten weeks after surgery. **Results.** In myopic eyes, significant differences were found in the value determined by the keratometry derived from the clinical history when compared with the average post-operative manual keratometry, the simulated

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keratometry and the Mean Pupil Power of the Sirius® tomograph. On another note, when averaging the mean post-operative manual keratometry with the post-operative Mean Pupil Power (value called $K_{pop\ average\ 1}$) and comparing it with the keratometry derived from the clinical history method, no statistically significant differences were observed in myopic patients. Likewise, when averaging the simulated post-operative keratometry of the Sirius® equipment with the post-operative Mean Pupil Power (value called "$K_{pop\ average\ 2}$") and comparing it with the keratometry derived by the method of the clinical history, no statistically significant differences were observed in myopic patients. On the other hand, in hyperopic eyes and those with mixed astigmatism, mean errors from post-operative Mean Pupil Power, in comparison to the keratometry derived by clinical history method, were not significantly different from the errors when comparing the "$K_{pop\ average\ 1}$" and the "$K_{pop\ average\ 2}$" with keratometry derived by the clinical history method. **Conclusions.** In myopic eyes the post-operative corneal power determinations with the "$K_{pop\ average\ 1}$" and "$K_{pop\ average\ 2}$" are closer to the keratometry derived by clinical history method than to measurements from the average post-operative manual keratometry, the post-operative simulated keratometry or the Mean Pupil Power of the Sirius® equipment. *[Jaramillo LC, Galvis V., Tello A., Camacho PA, Castillo A., Pareja LA. Corneal power determination with corneal tomography after refractive surgery with excimer laser. MedUNAB 2018;21(1):31-45. doi: 1029375/01237047.*2397*].*

Key words: Corneal Topography; Cornea; Photorefractive Keratectomy; Excimer Laser; Refractive Surgical Procedures; Refractive Errors

Resumen

Introducción. La determinación del poder corneal, después de la cirugía refractiva con láser excimer, es difícil. Diferentes alternativas con el uso de tomógrafos corneales se han utilizado para esta medición. **Objetivo**. Evaluar diversos métodos de determinación del poder corneal en pacientes operados de cirugía fotorrefractiva, incluyendo pruebas diagnósticas con medidas cuantitativas. **Metodología**. Estudio retrospectivo de pacientes operados de cirugía fotorrefractiva que tuvieran resultados refractivos y tomografía corneal post-operatoria al menos diez semanas luego de cirugía. **Resultados**. En los ojos miopes se encontraron diferencias significativas en el valor determinado por la queratometría derivada de la historia clínica al compararla con la queratometría manual promedio postoperatoria, la queratometría simulada y el Mean Pupil Power del tomógrafo Sirius®. Por otra parte, al promediar la queratometría manual promedio postoperatoria con el Mean Pupil Power postoperatorio (valor denominado $K_{pop\ promedio\ 1}$) y compararla con la queratometría derivada por el método de la historia clínica, no se observaron en los pacientes miopes diferencias estadísticamente significativas. Asimismo, al promediar la queratometría simulada postoperatoria del equipo Sirius® con el Mean Pupil Power postoperatorio (valor denominado $K_{pop\ promedio\ 2}$) y compararla con la queratometría derivada por el método de la historia clínica tampoco se observaron en los pacientes miopes diferencias estadísticamente significativas. Por otro lado, en los ojos hipermétropes y con astigmatismo mixto, los promedios de los errores del Mean Pupil Power postoperatorio, con respecto a la queratometría derivada por el método de la historia clínica, no fueron significativamente diferentes de los errores al comparar la $K_{pop\ promedio\ 1}$ y la $K_{pop\ promedio\ 2}$ con la queratometría derivada por el método de la historia clínica. **Conclusiones**. En ojos miopes las determinaciones del poder corneal postoperatorio con las $K_{pop\ promedio\ 1}$ y $K_{pop\ promedio\ 2}$ se aproximan más a la queratometría derivada por el método de la historia clínica que a las mediciones de la queratometría manual promedio postoperatoria, la queratometría simulada postoperatoria o el Mean Pupil Power del equipo Sirius®. *[Jaramillo LC, Galvis V, Tello A, Camacho PA, Castillo A, Pareja LA. Determinación del poder corneal con un tomógrafo corneal luego de cirugía refractiva con láser excimer. MedUNAB. 2018;21(1):16-30. doi:1029375/01237047.2397].*

Palabras clave: Topografía de la Córnea; Córnea; Queratectomía Fotorrefractiva; Láseres de Excímeros; Procedimientos Quirúrgicos Refractivos; Errores de Refracción.

Resumo

Introdução. A determinação da potência corneana, após a cirurgia refrativa com excimer láser, é difícil. Foram usadas diferentes alternativas com o uso de tomógrafos de córnea para esta medição. Objetivo. Avaliar vários métodos de determinação da potência corneana em pacientes submetidos à cirurgia fotorrefrativa, incluindo testes diagnósticos com medidas quantitativas. **Métodos**. Este é um estudo observacional retrospectivo. Foram incluídos pacientes submetidos à cirurgia fotorrefrativa com resultados refrativos e topografia corneana pós-operatória pelo menos um mês após a cirurgia. **Resultados**. Nos olhos míopes foram encontradas diferenças significativas no valor determinado pela ceratectomia derivada da história clínica, quando comparada com a média da ceratectomia manual pós-operátoria, a ceratectomia simulada e o Mean Pupil Power do tomógrafo Sirius®. Por outro lado, ao calcularmos a média da ceratectomia manual pós-operátoria com o Mean Pupil Power pós-operatório (valor denominado $K_{pop\ média\ 1}$) e compará-la com a ceratectomia pelo método da história clínica, não foram observadas diferenças estatisticamente significantes nos pacientes miopes. Da mesma forma, ao calcular a média da

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ceratectomia pós-operatória simulada do equipamento Sirius® com o Mean Pupil Power pós-operatório (valor denominado $K_{pop\ média\ 2}$) e compará-la com a ceratectomia derivada do método de história clínica, não foram observadas diferenças estatisticamente significantes nos pacientes miopes. Por outro lado, em olhos hipermetrópicos e com astigmatismo mixto, as médias de erros do Mean Pupil Power pós-operatório, em relação à ceratectomia derivada pelo método da história clínica, não foram significativamente diferentes dos erros na comparação do $K_{pop\ média\ 1}$ y la $K_{pop\ média\ 2}$ com a ceratectomia derivada pelo método da história clínica. **Conclusões**. Nos olhos míopes, as determinações de potência corneana pós-operatória com $K_{pop\ média\ 1}$ e $K_{pop\ média\ 2}$ estão mais próximas da ceratectomia derivada pelo método da história clínica do que das medidas de ceratectomia manual média pós-operatória, da ceratectomia simulada pós-operatória ou Mean Pupil Power do equipamento Sirius®. *[Jaramillo LC, Galvis V, Tello A, Camacho PA, Castillo A, Pareja LA. Determinação da potência corneana com uma topografia de córnea após cirurgia refrativa com excimer láser. MedUNAB. 2018;21(1):16-30. doi:1029375/01237047.2397]*.

Palavras-chave: Topografia da Córnea; Córnea; Ceratectomia Fotorrefrativa; Lasers de Excimer; Procedimentos Cirúrgicos Refrativos; Erros de Refração.

Introduction

In order to achieve an adequate intraocular lens power calculation, to be implanted during cataract extraction surgery, it is vital to know the power of the patient's cornea. Standard keratometry mathematically calculates it by using the keratometry index. This allows the approximate determination of total corneal power by measuring only the radius from the curvature of the anterior surface. Unfortunately, keratometric index is very imprecise in those cases in which there has been an alteration of the corneal surface, as, for example, after photorefractive laser surgery. Since the end of the 1990s, several studies have shown that this procedure generates overestimation of total corneal power in patients with past history of myopic correction and underestimation in those who have received hyperopic treatments (1, 2).

Additionally, manual keratometers and topographers (when analyzing the simulated keratometry value SimK of the latter), measure the radius of curvature based on the reflection of some mires in the cornea in an area of 3.00 mm of diameter on average, but do not directly take into account the pupil's smaller central area, were visual axis is located (which is less than approximately, 2.00 mm of diameter). Corneal paracentral's area measurement made by these systems has a diameter that may vary in between 2.00 mm and 4.00 mm, depending both on the equipment's characteristics and curvature characteristics from each cornea. This approach in a cornea with no past surgical history, where each meridian of the cornea in the central area is almost spherical, works quite well, since the difference is minimal between a measurement made at 3.00 mm and another made, for example, at 1.5 mm diameter. However, the change in sphericity caused by the ablation of the corneal surface in cases of refractive surgery, makes this approach less accurate, given the greater differences in central and paracentral curvatures (2-4).

Currently, the method introduced by Holladay in 1989, by which a corneal power derived from clinical history (K_{DHC}) is obtained, is the best way we have to estimate the real corneal power in a patient who underwent refractive surgery if, many years later, consults because he/she presents cataracts, and such data is required to calculate the power of the intraocular lens to be implanted (4, 5). The difficulty with this method is, that it is necessary to know refraction and keratometry values prior to refractive surgery, and also those of a recent post-operative refraction that must be prior to the appearance of the opacity of the lens (since the nuclear cataract can generate secondary myopia, altering the calculations). However, since these patients are usually undergoing refractive surgery between 20 and 40 years of age, the time span until the appearance of the cataract is usually more than 15 years (and may be much longer depending on the age of the patient) and very few patients return regularly to ophthalmological controls during this period of time.

Due to these reasons in most cases, there is no reliable data both preoperatively (before the refractive surgery with excimer laser) and post-operative (after the refractive surgery, but before the onset of cataract). These circumstances make that the clinical history method, although in theory is very precise, in practice it is frequently inapplicable or unpredictable due to the lack of availability of reliable data (2, 4).

A possible solution to this problem is to estimate corneal power directly in the cornea already operated, using the ray tracing technique based on Snell's law. Unlike traditional keratometry, the technique of ray tracing does not take as a basis the determination of the radius of curvature of the anterior surface of the cornea, nor the keratometric index, nor the measurement of paracentral areas. Instead, it uses the actual measurement of the radius of curvature of the anterior and posterior corneal surfaces and is based on the true refractive indices (air, cornea and aqueous humor) for the estimation of real refractive power (6).

According to our knowledge, there are no studies of this type in our country, and only a few published abroad. A study with this same approach, carried out by Savini and coauthors in Italy, found that the difference between the simulated keratometry values (SimK), calculated with Sirius® corneal tomograph (CSO-Costruzione Strumenti Oftalmici, Florence, Italy), before and after refractive surgery, underestimated the refractive change after the myopic correction and overestimated it after the correction of hyperopia. Such a result was expected, given the errors introduced by the paracentral measurement and the use of the keratometric index.

On the other hand, the difference on measures before and after the refractive surgery of the Mean Pupillary Power (MPP for Mean Pupil Power in English), calculated by the same Sirius® equipment with the ray tracing approach, showed an excellent correlation with the refractive change (6). However, although Savini and coauthors evaluated the difference of corneal power values versus refractive change, they did not calculate the post-operative corneal power by the still considered the gold standard method (the clinical history method, K_{DHC}), to be able to compare it with the one determined in the post-operative period by the MPP (4, 6). Other studies on the determination of corneal changes after corneal surgery with excimer laser have been carried out by Holladay and collaborators in the United States, using the Pentacam® tomograph (Oculus, Wetzlar, Germany) (7), by Sónego-Krone and collaborators in Brazil, with corneal tomograph Orbscan II® (Bausch & Lomb, Orbtek Inc., Salt Lake City, United States) (8), and by Gelender in the United States, also with the Orbscan II (9).

The objective of this study is to evaluate the concordance on MPP given by Sirius® equipment or a value derived from that measurement, together with other direct post-operative measurements of the corneal power, after refractive surgery with excimer laser, with the power calculated by the Holladay clinical history method (K_{DHC}), which until now is still considered to be the "gold standard" if reliable pre- and post-operative data are available (4, 5). This equipment is called a corneal tomograph because, in addition to capturing and analyzing information from the anterior surface of the cornea (by the reflection of Placido's discs), it also obtains data from the posterior surface (using a slit beam of light), unlike corneal topographers based solely on reflection, which only captures information from the anterior corneal surface. Now, the direct determination of the real corneal power after refractive surgery would be very useful to be applied in the future in other patients with this past history, but in who the information prior to the procedure with excimer laser is not known, which as commented, is a very frequent situation.

Methodology

This was a retrospective, observational study, which analyzed the correlation of various methods for the determination of corneal power after refractive surgery, including diagnostic tests with quantitative measurements. All patients with no history of another corneal surgery who underwent photorefractive surgery with excimer laser in the Virgilio Galvis Ophthalmological Center, and who achieved post-operative distance corrected visual acuity better than 20/40 and to whom corneal tomography with the Sirius® tomographer was performed at least ten weeks after the procedure, were included in the study. Exclusion criteria included the presentation of some intraoperative or post-operative complication, or some type of retinal comorbidity.

The pre- and post-operative spherical equivalent and the pre- and post-operative manual keratometry average (ophthalmometer OM-4, Topcon, Itabashi-Ku, Japan) were analyzed. Additionally, post-operative SimK and MPP measured with the Sirius® tomograph, were evaluated. These values were compared with the corneal power calculated by the Holladay clinical history method (K_{DHC}). This method consists on determining the refractive change generated by the surgery, adjusting it to the corneal apex and then subtracting (in case of eyes operated on for myopia), or adding (in case of hyperopic eyes) that change to the pre-operative corneal power, to obtain post-operative corneal power (4, 5).

To briefly explain this method, we will use an example. If a patient had a pre-operative refraction, measured in the standard manner (i.e., in the plane of the spectacles, approximately 12 mm from the corneal apex) of -5.25 Diopters (D), and after refractive surgery is found in emmetropia (that is, with an error of zero D), the method is applied in the following manner:

First the values of the refractions measured in the plane of the spectacles are determined and they are converted into the refraction measured at the apex of

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the cornea, with a simple formula (10):

$Rc = Rg/[1 - (g*Rg)]$

Where:

"Rc" is the refraction corrected to the plane of the cornea, considering the distance to the corneal apex.

"Rg" is the refraction measured in the plane of the spectacles (in the usual clinical examination).

"g" is the distance at which the refraction was measured with respect to the vertex of the cornea (in meters), known as "distance to the vertex", which corresponds to the distance from the cornea to which the lenses placed in the spectacles are located . This distance varies between 10 and 15 mm (that is, between 0.01 and 0.015 m), depending on the instrument that is used to place the test lenses in front of the patient's eye, although it is usually 12 mm (0.012 m).

In the example, the pre- and post-operative refractions corrected to the vertex of the cornea, applying the aforementioned formula, results:

Pre-operative refraction corrected to the corneal vertex: -4.94 D

Corneal vertex corrected post-operative refraction: 0 D

For the next step, in the method derived from clinical history, the difference in pre- and post-operative refraction in the plane of the cornea is then calculated. The pre-operative refractive value is subtracted from the post-operative refraction.

In our example: (-4.94 D) - (0) = -4.94 D.

This is the value at which, effectively, the power of the patient's cornea was decreased. Next, we take the corneal power measured by pre-operative keratometry, which, let´s suppose, was 45.00 D; to this value is added the refractive change and, in this way, the post-operative corneal power is calculated. In the case of myopia, a negative value will be added. Corneal power will be diminished, which is the actual effect of the surgery.

In our example:

$K_{DHC} = 45.00\ D + (-4.94\ D) = 40.06\ D$

This is the real post-operative corneal power of that eye. This value could be used to be introduced into a formula for calculating the power of an intraocular lens when the patient requires cataract surgery (as long as the post-operative refraction has been performed shortly before the onset of the cataract, a condition that, as mentioned above, is met in very few cases, because patients do not return regularly to annual controls).

In the group of patients from the present study, given that they had been operated a few months earlier, all had complete information to apply the method of the clinical history in order to determine the real post-operative corneal power. Of course, in none of them this data was required to calculate an intraocular lens, since they had no cataract, but it was made to be used as a reference in the evaluation of the accuracy of the direct method, or from values derived from that method, with the tomograph Sirius®. For this purpose, the averages of two different post-operative measurements were obtained (both including as one of the terms the MPP): Km_{pop} averaged with the MPP (value denominated in the present study $K_{pop\ average\ 1}$) and $SimK_{pop}$ averaged with the MPP (value denominated in the current study $K_{pop\ average\ 2}$). These two values were compared with the K_{DHC}.

The descriptive analysis was carried out according to frequency distribution. The qualitative variables were presented in absolute and relative frequencies. In the quantitative variables, normality was graphically and statistically evaluated, by means of the Shapiro Wilk test. The differences between measurements of the direct post-operative corneal power (Km_{pop}, $SimK_{pop}$) and the derivated by the clinical history method (K_{DHC}) were evaluated with the paired Student t test. The relationship between the $K_{pop\ average\ 1}$ and the $K_{pop\ average\ 2}$ with the K_{DHC} was evaluated with the Pearson correlation coefficient and this was calculated using a robust linear regression. The agreement between the K_{DHC} with each of these averages ($K_{pop\ average\ 1}$ and $K_{pop\ average\ 2}$) was evaluated by the Bland-Altman plot.

It is important to consider that two methods that measure the same biological variable must be concordant and interchangeable. It is expected that the mean difference between these, are not different from zero, and that 95% of the differences are within the 2.5 and 97.5 percentiles. Also, that these differences are not clinically important. The limits of agreement may have differences between the measurements, without reaching clinical significance and should ideally be defined in advance, in order to help interpret the comparison between different methods (11-14). For this study, limits of maximum acceptable differences, would be 1.00 D for the measurement of post-operative corneal power. The analysis was performed in the software STATA VE 11.2 and the level of significance was 5% (12, 13).

The research adhered to recommendations established in Helsinki's Declaration from October 2008 and all its updates and was approved by the Research Ethics Committee of the Fundación Oftalmológica de Santander (CEI - FOSCAL). Due to the nature and the retrospective observational design of the study, an informed consent from patients included, was not considered to be necessary, due that their identity was always kept as anonymous.

Results

92 eyes were analyzed (46 right and 46 left eyes) from 50 patients. All patients had undergone photorefractive surgery with excimer laser between December 2012 and August 2015. Demographic characteristics of the patients are shown in **table 1** 84.78% (78 eyes), underwent LASIK (abbreviation for laser-assisted in situ keratomileusis) and 15.22% (14 eyes) Trans-PRK (abbreviation for *Trans-epithelial Photorefractive Keratectomy*) with excimer laser.

Average follow-up was of 4.31 months and the range from 2.8 to 9.3 months. Myopic patients were divided into two groups: low myopic, with a spherical equivalent less negative than -5.00 D (39 eyes), and high myopic, with a spherical equivalent equal to or more negative than -5.00 D (14 eyes). The eyes were also analyzed separately with hyperopic errors (29 eyes) and with mixed astigmatism (10 eyes). In both myopic and hyperopic eyes, the average post-operative manual keratometry (Km_{pop}) underestimated the changes generated by refractive surgery (**Table 2**).

When comparing the keratometry derived by the clinical history method (K_{DHC}) with the average post-operative manual keratometry (Km_{pop}), a difference of just over half D was observed in the high myopia, being lower with K_{DHC} than with Km_{pop} (37.96 +/-0.98 D versus 38.59 +/-1.10 D, p = 0.0002). In the group of low myopic patients, this comparison showed a difference of somewhat less than half D in the same direction (K_{DHC}=40.94 +/-1.69 D versus Km_{pop}=41.43 +/-1.56 D, p<0.001). In hyperopes, the difference was somewhat more than half D, but K_{DHC} showed greater curvature than Km_{pop} (46.57 +/-2.13 D versus 46.01 +/-1.98 D, p = 0.001). In patients with mixed astigmatism, the difference was only about one sixth of a D (43.41 +/-1.85 D versus 43.58 +/-2.48, p = 0.687) (**Table 3**).

When comparing the K_{DHC} with the post-operative keratometry determined by the SimK of the Sirius® tomograph ($SimK_{pop}$), a difference of just over three quarters of D was observed in high myopic patients, with K_{DHC} being lower than $SimK_{pop}$ (37.96 +/-0.98 D versus 38.73 +/-0.78 D, p = 0.03). In the group of low myopic patients, this comparison showed a difference of somewhat less than average D in the same direction (K_{DHC} = 40.94 +/-1.69 D versus $SimK_{pop}$ = 41.38 +/-1.61 D, p=0.25). In hyperopic patients, the difference was somewhat less than average D, but K_{DHC} showed greater curvature than $SimK_{pop}$ (46.57 +/-2.13 D versus 46.10 +/-2.16 D, p=0.41). In patients with mixed astigmatism, the difference was close to zero (43.60 +/-1.86 D versus 43.58 +/-2.48, p = 0.98) (**Table 3**).

When comparing the K_{DHC} with the post-operative MPP in high myopic patients, an underestimation of the corneal power was observed by the MPP (37.45 +/-0.83 D versus 37.96 +/-0.98 D, p=0.0002), that is, a contrary tendency to the one observed when comparing the K_{DHC} with the Km_{pop} or with the $SimK_{pop}$. In the group of low myopic patients, a difference of more than one third of D was also found with underestimation by the MPP (40.56 +/-1.75 D versus 40.94 +/-1.69 D, p=0.001). In the group of hyperopic patients, a difference of less than one third of a diopter was found, with underestimation of power by the MPP (46.27 +/-2.33 D versus 46.57 +/2.13 D, p=0.033). In the mixed astigmatism group, the difference was a little less than one fifth of a D (43.58 +/-2.48 D versus 43.39 +/-2.18 D, p=0.465) (**Table 3**).

Table 4 shows the p values for the comparisons of the differences between the K_{DHC} and the Km_{pop}, with the differences of the K_{DHC} and the post-operative MMP; as well as the differences of the K_{DHC} versus the $SimK_{pop}$ for the four groups of eyes (high myopic, low myopic, hyperopic and eyes with mixed astigmatism). It was found that, both in hyperopic patients and in eyes with mixed astigmatism, there were no significant differences between the various magnitudes of differences between the other methods, in comparison to the clinical history, nor when comparing their arithmetic values (taking into account the signs) or

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Table 1. Demographic characteristics (50 individuals/92 eyes)

Characteristic	
Age	(17 - 55) years
[Average ± Standard Dev. (range)]	31.4 ± 10.26
Sex: Female, n (%)	36 (72%)
Original refractive error	
Myopic error	30 individuals/53 eyes (57.6%)
Hyperopic error	16 individuals*/29 eyes (31.5%)
Mixed astigmatism	7 individuals*/10 eyes (10.9%)

* Two patients had a hyperopic error in one eye and mixed astigmatism in the other; one of the patients had myopic error in one eye and mixed astigmatism in the other. For this reason, the number of individuals, when adding the three groups, results in 53, but it is 50. The units of analysis of each group were the results of each eye.

Table 2. Changes induced by surgery on the spherical equivalent and the average keratometry (measured with a manual keratometer)

Pre and Post-operative Measures. Refractive error	SE * Preoperative (corneal plane) Diopters	SE * Postoperative (corneal plane) Diopters	SE * Difference (corneal plane) Diopters	Average Preoperative Keratometry Diopters	Average Postoperative Keratometry Diopters	Difference in Average Keratometry. Diopters
Low myopic (n=39 eyes)	-2.93 ±0.92	0.07 ±0.42	-3.00 ±1.07**	43.94 ±1.21	41.43 ±1.56	-2.51 ±1.11**
High myopic (n=14 eyes)	2.64 ±1.66	-0.54 ±1.13	3.18 ±1.73**	43.39 ±1.44	46.01 ±1.98	2.62 ±1.63**
Hyperopic (n=29 eyes)	2.64 ±1.66	-0.54 ±1.13	3.18 ±1.73**	43.39 ±1.44	46.01 ±1.98	2.62 ±1.63**
Mixed Astigmatism (n=10 eyes)	0.01 ±1.09	-0.16 ±0.50	0.17 ±1.54	43.41 ±1.43	43.41 ±1.85	0.00 ±1.75

* SE: Spherical Equivalent.

** Paired Student t test, p <0.001

Table 3. Difference between the keratometry resulting from the clinical history method (K_{DHC}) and the post-operative manual keratometry (Km_{pop}), the simulated keratometry of the Sirius® equipment ($SimK_{pop}$) and the post-operative Mean Pupil Power (MPP), according to refractive error

	K_{DHC} vs. Km_{pop}		K_{DHC} vs. $SimK_{pop}$		K_{DHC} vs. MPP	
	Average ±SD	p**	Average ±SD	p**	Average ±SD	p**
Whole Myopic Group (n = 53 eyes)	-0.53 ±0.54	<0.001	-0.53 0.48	0.1619	+0.42 ±0.49	<0.001
High Myopic > -5.00 D (n = 14 eyes)	-0.63 ±0.46	0.0002	-0.77 ±0.42	0.03	+0.52 ±0.37	0.0002
Low myopic ≤ 5.00 D (n = 39 eyes)	-0.49 ±0.56	<0.001	-0.44 ±0.47	0.25	+0.38 ±0.52	0.001
Hyperopic (n = 29 eyes)	+0.56 ±0.73	0.001	+0.47 ±0.66	0.41	+0.30 ±0.73	0.033
Mixed Astigma-tism (n = 10 eyes)	+0.17 ±1.28	0.687	-0.02 ±0.91	0.98	+0.19 ±0.81	0.465

* Values in diopters

** Paired Student t test, p <0.005

DS = standard deviation

when comparing their absolute values.

Now, on another note, in myopic eyes significant we did find differences between values, when they were analyzed taking into account the signs, because while, compared to the value determined by the K_{DHC}, both the Km_{pop} and the $SimK_{pop}$ overestimated the post-operative corneal power in myopic eyes, the MPP underestimated it. This means, the error was presented in the opposite direction. However, when analyzing the absolute values of this error, in comparison to the K_{DHC}, no statistically significant difference was identified between the Km_{pop}, $SimK_{pop}$ and MPP. This suggested that the magnitude of the error was similar, but in the opposite direction (**Table 4**).

Taking into account this detail, we considered it possible that, when averaging the MPP with one of the other two post-operative measurements in myopic eyes, the errors will tend to be canceled. Therefore, as new possibilities to determine post-operative corneal power, we calculated the average of the post-operative MPP and Km_{pop} data, on the one hand (this average being called $K_{pop\ average\ 1}$), and of the post-operative MPP and $SimK_{pop}$, on the other hand (calling it $K_{pop\ average\ 2}$). In the high myopic group, the average of the $K_{pop\ average\ 1}$ was 38.02 +/-0.95 D, which was not statistically different from the value of 37.96 +/-0.98 D calculated by K_{DHC} (p = 0.871). The average of the $K_{pop\ average\ 2}$ was 38.09 +/-0.80 D, which

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Table 4. Comparative differences between power derived from the clinical history method (K_{DHC}) and the corneal power of manual keratometry, the SimK and the post-operative Mean Pupil Power (MPP), according to refractive error

Comparison of differences with respect to K_{DHC}	Arithmetic values of the differences* (values of p)**			Absolute values of the differences* (values of p)**		
	K_{DHC}/Km_{pop} vs. K_{DHC}/MPP	K_{DHC}/Km_{pop} vs. $K_{DHC}/SimK_{pop}$	K_{DHC}/MPP vs. $K_{DHC}/SimK_{pop}$	K_{DHC}/Km_{pop} vs. K_{DHC}/MPP	K_{DHC}/Km_{pop} vs. $K_{DHC}/SimK_{pop}$	K_{DHC}/MPP vs. $K_{DHC}/SimK_{pop}$
Whole Myopic Group (n = 53 eyes)	-0.53 vs. +0.42 (<0.0001)	-0.53 vs. -0.53 (1.00)	+0.42 vs. -0.53 (<0.0001)	0.53 vs. 0.42 (0.2746)	0.53 vs. 0.53 (1.00)	0.42 vs. 0.53 (0.246)
High myopic > -5.00 D (n = 14 eyes)	-0.63 vs. +0.52 (<0.0001)	-0.63 vs. -0.77 (0.408)	+0.52 vs. -0.77 (<0.0001)	0.63 vs. 0.52 (0.4919)	0.63 vs. 0.77 (0.408)	0.52 vs. 0.77 (0.107)
Low myopic ≤ 5.00 D (n = 39 eyes)	-0.49 vs. +0.38 (<0.0001)	-0.49 vs. -0.44 (0.674)	+0.38 vs. -0.44 (<0.0001)	0.49 vs. 0.38 (0.377)	0.49 vs. 0.44 (0.674)	0.38 vs. 0.44 (0.595)
Hyperopic (n = 29 eyes)	+0.56 vs. +0.30 (0.178)	+0.56 vs. +0.47 (0.621)	+0.30 vs. +0.47 (0.356)	0.56 vs. 0.30 (0.178)	0.56 vs. 0.47 (0.621)	0.30 vs. 0.47 (0.356)
Mixed Astigmatism (n = 10 eyes)	+0.17 vs. +0.19 (0.967)	+0.17 vs. -0.02 (0.707)	+0.19 vs. -0.02 (0.747)	0.17 vs. 0.19 (0.967)	0.17 vs. 0.02 (0.707)	0.19 vs. 0.02 (0.794)

* Values in diopters

** Paired Student t test, p <0.005

K_{DHC}: Clinical history method

Km_{pop}: Post-operative manual keratometry

MPP: Mean Pupil Power of the Sirius® tomograph

$SimK_{pop}$: Simulated keratometry of the post-operative Sirius® tomograph

was not statistically different from that calculated by the clinical history method (p = 0.704). In the low myopic group, the average of the $K_{pop\ average\ 1}$ was 41.00 +/-1.64 D, which was not statistically different from the value of 40.94 +/-1.69 D calculated by the K_{DHC} (p=0.874). The mean of the $K_{pop\ average\ 2}$ was 40.97 +/-1.68 D, which was not statistically different from the calculation by K_{DHC} (p=0.938), either. Magnitude differences of each of these two values ($K_{pop\ average\ 1}$ and $K_{pop\ average\ 2}$), compared to powers calculated by the K_{DHC}, are shown in **Table 5**. The average differences of the $K_{pop\ average\ 1}$ and $K_{pop\ average\ 2}$ compared with the

K_{DHC} versus the difference of MPP compared with the K_{DHC} are shown in **Table 6**. Regression formulas were obtained to calculate the K_{DHC} from the $K_{pop\ average\ 1}$ and the $K_{pop\ average\ 2}$ for the four groups of eyes (high myopic, low myopic, hyperopic and eyes with mixed astigmatism) (**Figures 1, 2**). For myopic eyes, the Bland and Altman plots were constructed for the $K_{pop\ average\ 1}$ and $K_{pop\ average\ 2}$ determinations compared to the corneal power calculated by the clinical history method (K_{DHC}) (**Figures 3, 4**). The limits of agreement of these differences were below the pre-established limit, as of clinical significance (**Figures 3, 4**).

Discussion

Determination of corneal power with a keratometer (or only the data from the anterior surface of the cornea obtained with a corneal topographer or tomographer) uses the keratometric index, which allows obtaining that approximate value without measuring the curvature of the posterior surface of the cornea, which constitutes an approach with results quite close to reality in virgin corneas. Furthermore, in patients who have undergone photorefractive surgery, the relationship between anterior and posterior corneal curvatures is significantly altered and, therefore, erroneous results are obtained when applying the keratometric index. In general, in eyes operated due to myopia, instruments that use this index tend to overestimate the value of corneal power. On the contrary, in case of hyperopic eyes, there is a tendency to underestimate the real value of corneal power. This introduces an additional error when using biometric formulas to calculate the power of intraocular lenses when these patients undergo cataract surgery (2, 3, 15).

An alternative offered by current technology is the determination of corneal power without having to

Table 5. Difference between K_{DHC} and $K_{pop\ average\ 1}$, and between K_{DHC} and $K_{pop\ average\ 2}$

	K_{DHC} vs $K_{pop\ average\ 1}$		K_{DHC} vs $K_{pop\ average\ 2}$	
	Average ±DS	**p***	**Average ±DS**	**p***
Whole Myopic Group (n = 53 eyes)	-0.06 ±0.44	0.878	-0.06 ±0.46	0.877
High Myopic > -5.00 D (n = 14 eyes)	-0.06 ±0.34	0.871	-0.13 ±0.38	0.704
Low myopic ≤ 5.00 D (n = 39 eyes)	-0.06 ± 0.47	0.874	-0.03 ± 0.48	0.937
Hyperopic (n = 29 eyes)	+0.43 ±0.6	0.444	+0.39 ±0.68	0.5
Mixed Astigmatism (n = 10 eyes)	+0.18 ±1.01	0.86	+0.09 ±0.85	0.93

* Paired Student t test, p <0.005

K_{DHC}: Corneal power derived by the method of clinical history

$K_{pop\ average\ 1} = (Km_{pop} + MMP)/2$

$K_{pop\ average\ 2} = (SimK_{pop} + MMP)/2$

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Table 6. Comparative differences between the power derived by the clinical history method (K_{DHC}) and the MPP compared with the differences between the power derived by the clinical history method (K_{DHC}) and the corneal power calculated by the $K_{pop\ average\ 1}$ and the $K_{pop\ average\ 2}$, according to refractive error

Comparison of differences with respect to K_{DHC}	Absolute values of the differences* (values of p)**		Absolute values of the differences* (values of p)**	
	K_{DHC}/MMP vs $K_{DHC}/K_{pop\ average\ 1}$	K_{DHC}/ MMP vs K_{DHC}/ $SimK_{pop\ average\ 2}$	K_{DHC}/MMP vs $K_{DHC}/K_{pop\ average\ 1}$	K_{DHC}/ MMP vs K_{DHC}/ $SimK_{pop\ average\ 2}$
Whole Myopic Group (n = 53 eyes)	+0.42 vs -0.06 (<0.0001)	+0.42 vs -0.06 (<0.0001)	0.42 vs 0.06 (<0.0001)	0.42 vs 0.06 (<0.0001)
High myopic > -5.00 D (n = 14 eyes)	+0.52 vs -0.06 (0.0002)	+0.52 vs -0.13 (0.001)	0.52 vs 0.06 (0.002)	0.52 vs 0.13 (0.01)
Low myopic ≤ 5.00 D (n = 39 eyes)	+0.38 vs -0.06 (0.0002)	+0.38 vs -0.03 (0.006)	0.38 vs 0.06 (0.006)	0.38 vs 0.03 (0.003)
Hyperopic (n = 29 eyes)	+0.30 vs +0.43 (0.462)	+0.30 vs +0.39 (0.629)	0.30 vs 0.43 (0.462)	0.30 vs 0.39 (0.629)
Mixed Astigmatism (n = 10 eyes)	+0.19 vs +0.18 (0.98)	+0.19 vs +0.09 (0.791)	0.19 vs 0.18 (0.98)	0.19 vs 0.09 (0.791)

* Values in diopters.

** Paired Student t test, p <0.005

K_{DHC}: Clinical history method

MPP: Mean Pupillary Power of the Sirius® tomograph

$K_{pop\ average\ 1} = (Km_{pop} + MMP)/2$

$K_{pop\ average\ 2} = (SimK_{pop} + MMP)/2$

assume values of the posterior corneal curvature, instead, measuring it directly with a corneal tomographer and performing the calculation of the real corneal power with a ray tracing approach, which is a quantitative diagnostic test. The Sirius® equipment calls this alternative *Mean Pupillary Power* (MPP). In order to determine the accuracy of this measure, it can be compared with the calculation of corneal power using the clinical history method, which is based on the subtraction of the refractive change measured in the corneal plane, according to the description by Holladay, previously explained in methodology (1, 2, 4, 5, 15).

Savini and colleagues, in their study published in 2014, included 72 eyes that underwent photorefractive surgery and found that the difference between the pre-operative and post-operative MPP had an excellent correlation with the refractive change induced by surgery. Although these authors compared the differences between the pre- and post-operative values of the simulated keratometry and the MPP, they did not determine the post-operative corneal power by the Holladay method (6). Our approach was a bit different: we evaluated the correlation between the post-operative MPP and the post-operative keratometry derived by the clinical history method, without the necessity of having the pre-operative MPP data. We found a correlation of this value with

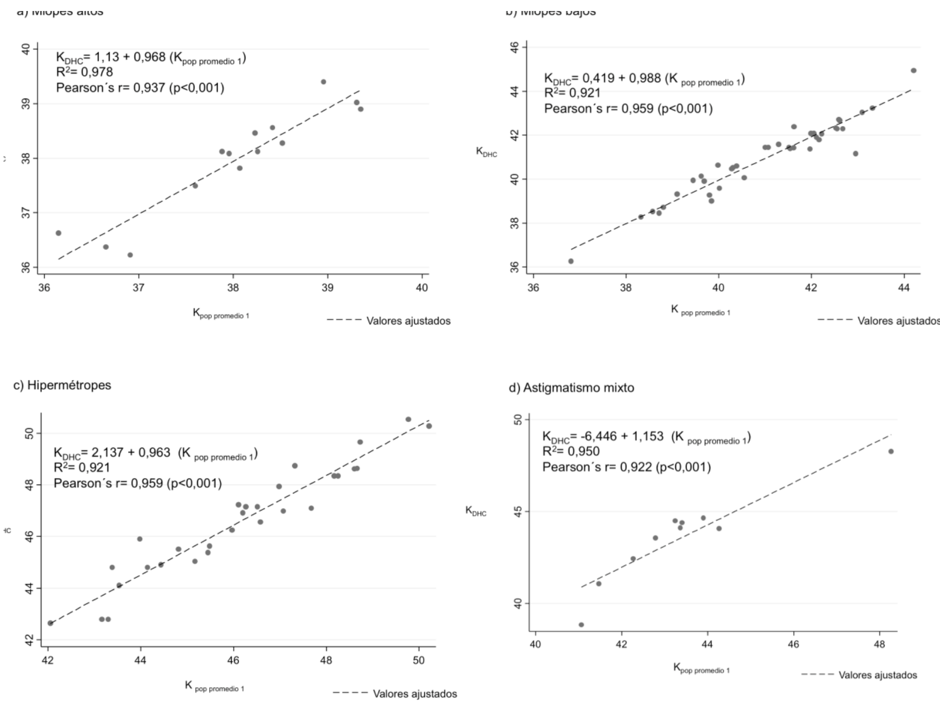

Figure 1. Correlation of $K_{pop\ average\ 1}$ and K_{DHC} in patients undergoing refractive surgery

a) High myopic; b) Low myopic; c) Hyperopic and d) Mixed astigmatism

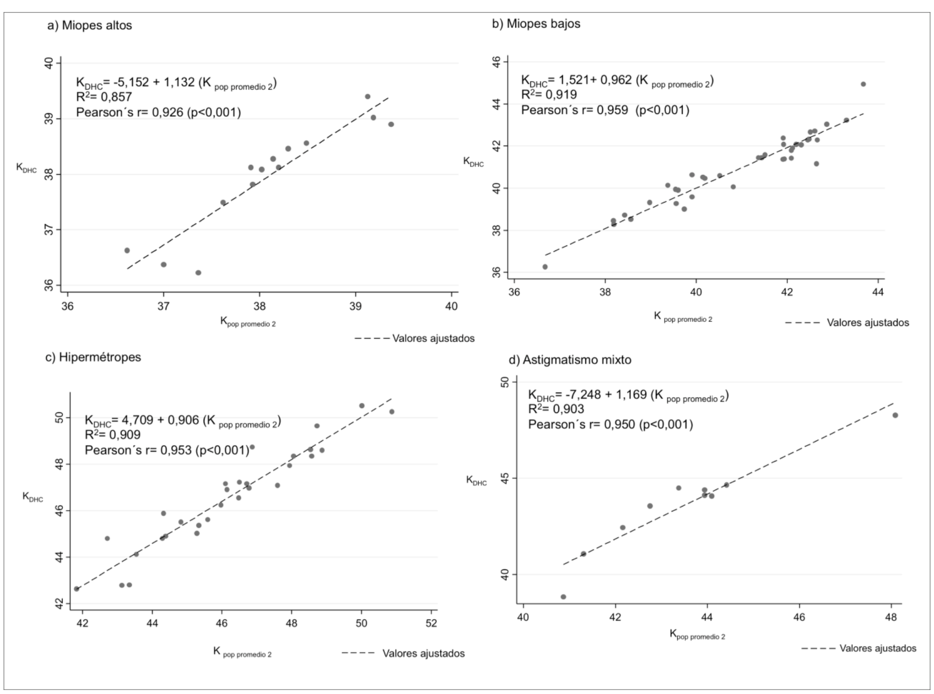

Figure 2. Correlation of $K_{pop\ average\ 2}$ and K_{DHC} in patients who underwent refractive surgery

a) High myopic; b) Low myopic; c) Hyperopic and d) Mixed astigmatism

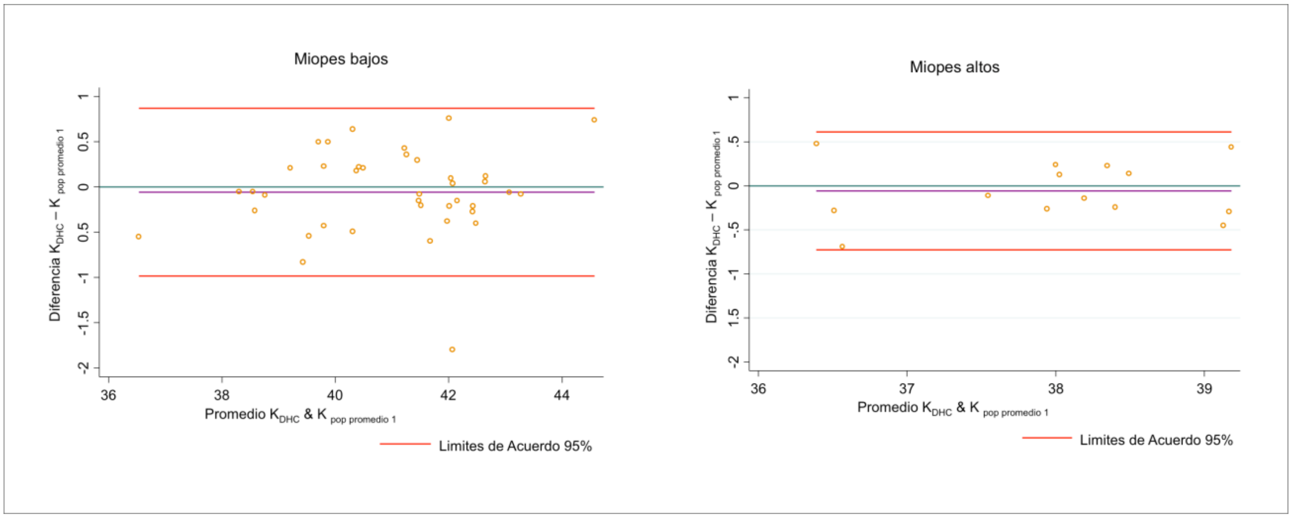

Figure 3. Bland and Altman graphics for the determination of $K_{pop\ average\ 1}$ compared with the corneal power calculated by the clinical history method (K_{DHC}) in myopic eyes

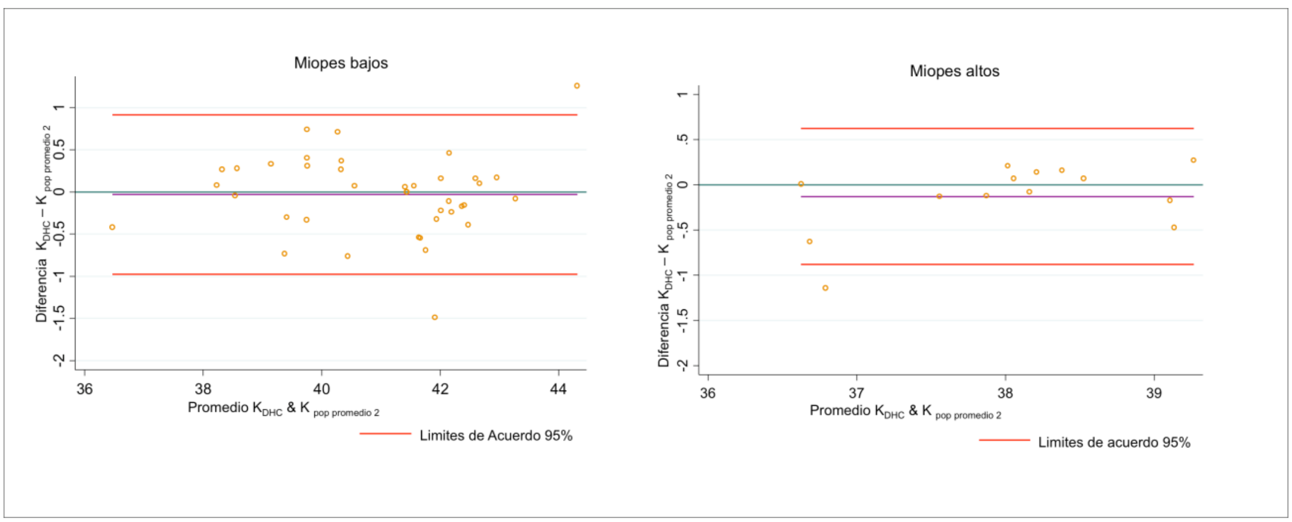

Figure 4. Bland and Altman graphics for the determinations of $K_{pop\ average\ 2}$ compared with the corneal power calculated by the clinical history method (K_{DHC}) in myopic eyes

that obtained by the derivative keratometry method according to the clinical history (K_{DHC}).

Initially, we obtained regression formulas for calculating the keratometry derived by the clinical history method from the MPP. However, we were struck by the fact that both the manual keratometry and the SimK post-operative with the Sirius® equipment in myopic eyes overestimated corneal power, when compared to the power derived by the method of clinical history; post-operative MPP with Sirius® underestimated it. The magnitude of the error was similar, but in opposite directions. Given this, we decided to calculate an average of the data of the post-operative manual keratometry and the post-operative MPP, on the one hand ($K_{pop\ average\ 1}$), and of the SimK$_{pop}$ and the post-operative MPP, on the other hand ($K_{pop\ average\ 2}$), and compare them with the power derived by the K_{DHC}, foreseeing that errors in contrary directions would be canceled. Effectively, values calculated by these two averages were very close to the corneal powers calculated by the clinical history method (K_{DHC}), without showing statistically significant differences with this.

The magnitude of the differences of these two values ($K_{pop\ average\ 1}$ and $K_{pop\ average\ 2}$), compared with the K_{DHC}, were very low (**Table 5**). The average differences of these magnitudes, compared with the corneal power calculated by the clinical history method (K_{DHC}), were significantly lower in myopic eyes than the differences of the isolated post-operative MPP, compared with the clinical history method (K_{DHC}) (**Table 6**). It did not happen in hyperopic eyes or with mixed astigmatism. We found a correlation of $K_{pop\ average\ 1}$ and $K_{pop\ average\ 2}$ with that obtained by K_{DHC}. We obtained regression formulas for calculating the K_{DHC} from the $K_{pop\ average\ 1}$ and $K_{pop\ average\ 2}$ (**Figures 1, 2**).

When comparing the $K_{pop\ average\ 1}$ and the $K_{pop\ average\ 2}$ with the K_{DHC}, using the Bland and Altman plots, the agreement limits for myopic eyes were below the pre-established limit as of clinical significance (**Figures 3, 4**). In the study conducted by Holladay et al., published in 2009 (7), the equivalent K-reading (EKR) of another corneal tomography equipment (Pentacam®, Oculus, Wetzlar, Germany) was used to measure the central corneal power, an average deviation of -0.06 ±0.56 D was obtained in 100 patients undergoing LASIK, but also with a wide range (-1.63 to +1.34 D).

Moreover, Sónego-Krone and collaborators, in a paper published in 2004, used multiple maps of corneal power obtained by the corneal tomograph Orbscan II® (Bausch & Lomb, Orbtek Inc., Salt Lake City, United States). They found in 26 eyes that the Total Mean Power in the area of 2 mm in diameter showed an average difference compared with the refractive change calculated to the corneal plane of 0.07 ±0.62 D; however, the range of this difference was not indicated (although they mentioned that one eye had a difference greater than 1.00 D). The Total-Optical Power performed a better evaluation of the corneal power at 4 mm of central diameter, with an average difference of -0.08 ±0.53 D. The range was not indicated and two eyes presented differences greater than 1.00 D (8).

In the study by Gelender, published in 2006, 59 eyes subjected to myopic LASIK were analyzed; from them, the corneal power was derived from the Mean Power Maps of the Orbscan II® and the central area of 1.5 and 2 mm was determined as the most accurate to perform this measurement. Subsequently, after applying this approach in 17 patients undergoing cataract surgery, they obtained an average deviation of post-operative refractive error of +0.05 ±0.59 D with a range of -0.75 to +0.90 D. This suggests that these determinations of corneal power in patients with previous refractive surgery, obtained by means of a corneal tomographer, could be applied accurately within the formulas used to perform the calculation of the intraocular lens when these patients require cataract surgery (9).

In our study, when combining two methods to establish the post-operative corneal power after refractive surgery (one from the measurement of the radius of curvature from the anterior surface, the manual keratometry (Km_{pop}), and another from the measurement of the MPP with Sirius® tomographer) in eyes with past history of myopic refractive errors, we found that the determined value was not statistically different from that calculated by the method of the clinical history (K_{DHC}) and obtained mean differences averages between -0.03 and -0.13 D. These mean errors were significantly lower than those found when comparing the MPP with the clinical history method in myopic eyes. Additionally, when using the Bland and Altman method, it was found that the agreement limits of the differences between these means and the K_{DHC} were below the pre-established level of clinical significance (which was 1.00 D). Therefore, we propose these two averages ($K_{pop\ average\ 1}$ and $K_{pop\ average\ 2}$) as a valid alternative to determine the post-operative corneal power in eyes with a past history of refractive surgery with excimer laser for myopia. To confirm the interchangeability of these values, a validation with a greater number of eyes is required and, in addition, in eyes with a history of refractive surgery with excimer lasers, that are submitted to surgery for cataract extraction by phacoemulsification.

In hyperopic eyes and with mixed astigmatism, the results were less conclusive, since no clear advantage was found when using the MPP_{pop} on the Km_{pop} or the $SimK_{pop}$ regarding their errors compared to the K_{DHC} (**Table 3**). No statistically significant differences were observed when using the derived values $K_{pop\ average\ 1}$ and $K_{pop\ average\ 2}$, neither in eyes with a previous hyperopic error, nor in eyes with a previous defect of mixed astigmatism (**Table 6**).

Limitations of the present study include its retrospective character, for which we had to exclude eyes to which post-operative Sirius® tomography was not performed. Therefore, the size of the sample is relatively small (92 eyes), which made that, by dividing them, there were subgroups with sample sizes of between 10 and 39 eyes. However, for the subgroups of high myopic (14 eyes), low myopic (39 eyes) and hyperopic (29 eyes), the power estimation

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of the pre- and post-operative comparisons was 100%. For the group of eyes with mixed astigmatism (10 eyes), it was only 10%.

Conclusions

The corneal power obtained by means of the Mean Pupil Power of the Sirius® tomographer (MPP), averaged with the post-operative values of the manual keratometry (Km_{pop}) or the $SimK_{pop}$ of the same Sirius® equipment, can be very similar to the value obtained for the keratometry resulting from the method of clinical history (K_{DHC}), in patients who have undergone photorefractive surgery with excimer laser for myopia. It is necessary to perform additional studies of interchangeability between testing methods that allow to establish, in the future, with a greater number of eyes, and its application to cases that require phacoemulsification surgery and intraocular lens implant.

Ethical considerations

Protection of people and animals. The authors declare that in this investigation no experiments have been conducted in humans or animals.

Confidentiality of the data. The authors declare that they have followed the protocols of their work center for patient data publication.

Right to privacy and informed consent. The authors declare that patient data does not appear in this article.

Conflict of interests

The authors declare no conflict of interests.

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