ORIGINAL ARTICLE

Errors Associated to Keratoconus Grading using Systems based on Corneal Power

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ABSTRACT

Purpose: To analyze and define the possible errors that may be introduced in keratoconus classification when the keratometric corneal power is used in such classification.

Materials and methods: Retrospective study including a total of 44 keratoconus eyes. A comprehensive ophthalmologic examination was performed in all cases, which included a corneal analysis with the Pentacam system (Oculus). Classical keratometric corneal power (P_k), Gaussian corneal power (P_c^{Gauss}), True Net Power (TNP) (Gaussian power neglecting the corneal thickness effect), and an adjusted keratometric corneal power (P_{kadj}) (keratometric power considering a variable keratometric index) were calculated. All cases included in the study were classified according to five different classification systems: Alió-Shabayek, Amsler-Krumeich, Rabinowitz-McDonnell, collaborative longitudinal evaluation of keratoconus (CLEK), and McMahon.

Results: When P_k and P_{kadj} were compared, differences in the type of grading of keratoconus cases was found in 13.6% of eyes when the Alió-Shabayek or the Amsler-Krumeich systems were used. Likewise, grading differences were observed in 22.7% of eyes with the Rabinowitz-McDonnell and McMahon classification systems and in 31.8% of eyes with the CLEK classification system. All reclassified cases using P_{kadj} were done in a less severe stage, indicating that the use of P_k may lead to the classification of a cornea as keratoconus, being normal. In general, the results obtained using P_{kadj}, P_c^{Gauss} or the TNP were equivalent. Differences between P_{kadj} and P_c^{Gauss} were within ± 0.7D.

Conclusion: The use of classical keratometric corneal power may lead to incorrect grading of the severity of keratoconus, with a trend to a more severe grading.

Keywords: Corneal topography, Keratoconus, Pentacam.

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INTRODUCTION

In a previous paper of our research group, theoretical and clinical errors associated to the calculation of central corneal power in keratoconus eyes considering a unique keratometric index (n_k) and the anterior corneal radius (r_{1c}) (keratometric corneal power, P_k) were analyzed and compared, using as a reference the Gaussian corneal power (P_c^{Gauss}), which is calculated considering both anterior (r_{1c}) and posterior (r_{2c}) corneal radii. In the theoretical simulations, an overestimation of P_k was observed in most of cases, with differences among the Gaussian and keratometric approaches ($\Delta P_c = P_k - P_c^{Gauss}$) ranging from –0.1 to 4.3 D, depending on r_{1c} and r_{2c} combinations and the theoretical eye model considered. Clinically, P_k was always found to overestimate the P_c^{Gauss} provided by the topography system in a range between 0.5 and 2.5 D (p < 0.01), with a mean clinical difference (ΔP_c) of 1.48 D. According to all these findings, we concluded that the use of a single value of n_k for the calculation of corneal power was imprecise in keratoconus and could lead to significant theoretical and clinical errors.[1] These errors could be reduced to clinically acceptable levels by using an adjusted keratometric index (n_{kadj}), with values ranging from 1.3153 to 1.3396, and derived from a linear expression depending on the r_{1c} value.[2]

Current classification and detection tools for keratoconus are based on different criteria, but most of them still consider the optical power of the cornea as one of the most relevant parameters to consider.[3] As there is no uniform classification for the severity of keratoconus to date, different approaches have been reported in the literature using a combination of objective and subjective parameters.[4-6] Likewise, several indices, algorithms, and even neural network approaches based on geometrical and optical properties of the anterior corneal surface have been developed for keratoconus diagnosis and detection.[5-7] Specifically, indexes and parameters, such as corneal irregularity measurement (CIM), mean toric keratometry (MTK), surface regularity index (SRI), predicted corneal acuity (PCA), surface asymmetry index (SAI), central keratometry (CK) value or the I-S index have been shown to be valuable tools for the diagnosis and even classification of keratoconus.[4,5,8-11]

The aim of the current study was to analyze and define the possible errors that may be introduced in keratoconus classification when the keratometric corneal power is used in such classification. Specifically, this analysis was performed using several different types of keratoconus classification systems that are still currently accepted and widely used in clinical practice.[6,7,12-14]

MATERIALS AND METHODS

Retrospective study including a total of 44 keratoconus eyes revised at the department of ophthalmology (Oftalmar) of the Medimar International Hospital (Alicante, Spain). The inclusion criterion for the study was the presence of keratoconus using the standard criteria for the diagnosis of this corneal condition: corneal topography revealing an asymmetric bowtie pattern with or without skewed axes and at least one keratoconus sign on slit-lamp examination, such as stromal thinning, conical protrusion of the cornea at the apex, Fleischer ring, Vogt striae or anterior stromal scar.[15] Exclusion criteria were previous ocular surgery and other active ocular disease. Consent to include clinical information in scientific studies was taken from all patients, following the tenets of the Helsinki declaration. In addition, local ethics committee approval was obtained for this investigation.

A comprehensive ophthalmologic examination was performed in all cases, which included refraction, corrected distance visual acuity (CDVA), slit lamp biomicroscopy, Goldman tonometry, fundus evaluation, and the analysis of the corneal structure by means of a scheimpflug photography-based tomographer, the pentacam system (Oculus Optikgeräte GmbH, Germany, software version 1.14r01). Specifically, the following parameters were recorded and analyzed: anterior (r_{1c}) and posterior corneal radius (r_{2c}) in the central 3 mm corneal area, anterior (ACA) and posterior corneal astigmatism (PCA) in the central 3 mm corneal area, anterior and posterior corneal asphericity (QA and QP), and minimum

(e_{cmin}) and central corneal thickness ($e_{ccentral}$). Keratometric corneal power (P_k) using $n_k = 1.33751$ and Gaussian corneal power (P_c^{Gauss}) based on Gaussian optics in paraxial approximation[1] were calculated. The True Net Power was also obtained, which is the Pentacam system corneal power calculated by using the Gaussian equation (P_c^{Gauss}) with the Gullstrand eye model neglecting the corneal thickness (e_c).

An adjusted keratometric index of refraction (n_{kadj}) was considered for the calculation of an adjusted keratometric corneal power (P_{kadj}) as follows:[2]

$$P_{kadj} = (n_{kadj}-1)/r_{1c} \quad (1)$$

This n_{kadj} allows the estimation of corneal power using the keratometric approach (the cornea as an only optical surface) but minimizing the errors associated to this approach. The most appropriate value of n_{kadj} to use in a specific keratoconus cornea should be calculated using a mathematical linear relationship dependent on r_{1c}, as shown in Table 1.[2] Eight different linear expressions have been defined and validated for different interval of curvature of the anterior corneal surface (Table 1).[2]

Besides the calculation of P_{kadj}, all cases included in the study were classified according to five different classification systems: Alió-Shabayek,[6] Amsler-Krumeich,[6] Rabinowitz-McDonnell,[7] collaborative longitudinal evaluation of keratoconus (CLEK),[12] and McMahon[13] classification systems (Table 2). The specific details of such classification or grading systems for keratoconus are summarized in Table 2.

Differences in the results of such classifications using P_k, P_c^{Gauss} and P_{kadj} were analyzed and discussed in detail.

RESULTS

This study comprised 44 eyes of 27 patients with keratoconus [12 women (44.4%) and 15 men (55.6%) with a mean age of 40.8 years ± 12.8, range from 14 to 73 years]. The sample comprised 24 left eyes (54.5%) and 20 right eyes (45.5%).

Table 1: n_{kadj} algorithms developed using the Gullstrand eye model for different r_{1c} and/or k intervals. Likewise, the corresponding theoretical ranges for n_{kadj}, P_{kadj}, P_c^{Gauss} and differences (ΔP_c) between P_{kadj} and P_c^{Gauss} are also shown. Minimum and maximum n_{kadj}, P_{kadj} and P_c^{Gauss} values are bolded in the table

r_{1c} (mm)	[k_{min}, k_{max}]	n_{kadj} Algorithm	n_{kadj}	P_c^{Gauss} (D)	P_{kadj} (D)	ΔP_c (D)
[4.2, 4.7]	[1.20, 1.52]	$-0.01217_{r1c} + 1.3777$	[1.3205, 1.3266]	[67.5, **78.5**]	[68.2, **77.8**]	[−0.7, 0.7]
[4.8, 5.6]	[1.17, 1.56]	$-0.01043_{r1c} + 1.3774$	[**1.3190**, 1.3273]	[56.3, 68.6]	[57.0, 68,2]	[−0.7, 0.7]
[5.7, 6.2]	[1.21, 1.55]	$-0.00926_{r1c} + 1.3773$	[1.3199, 1.3245]	[50.9, 57,7]	[51.6, 56.9]	[−0.7, 0.7]
[6.3, 6.4]	[1.05, 1.31]	$-0.00741_{r1c} + 1.3770$	[1.3296, 1.3303]	[50.8, 53.2]	[51.5, 52.4]	[−0.7, 0.7]
[6.5, 6.8]	[1.14, 1.45]	$-0.00792_{r1c} + 1.3771$	[1.3243, 1.3266]	[47.0, 51.0]	[47.4, 50.2]	[−0.7, 0.7]
[6.9, 7.5]	[1.03, 1.39]	$-0.00669_{r1c} + 1.3767$	[1.3266, 1.3306]	[42.9, 48.6]	[43.8, 47.9]	[−0.7, 0.7]
[7.6, 7.8]	[1.09, 1.39]	$-0.00643_{r1c} + 1.3767$	[1.3266, 1.3279]	[41.2, 43.9]	[41,9, 43,1]	[−0.7, 0.7]
[7.9, 8.5]	[0.96, 1.35]	$-0.00561_{r1c} + 1.3768$	[1.3291, **1.3324**]	[**38.0**, 42,8]	[**38.7**, 42.1]	[−0.7, 0.7]

Table 2: Keratoconus classification or grading systems used

Classification	Stage I	Stage II	Stage III	Stage IV
Alio-Shabayek[6]	$P_k < 48D$ RMS (1.5 to 2.5) µm	$P_k > 48D$ to $\leq 53D$ RMS > 2.5 to ≤ 3.5 µm $e_{cmin} > 400$ µm	$P_k > 53D$ to $\leq 55D$ RMS > 3.5 to ≤ 4.5µm e_{cmin} (300 to 400) µm	$P_k > 55D$ RMS > 4.5 µm $e_{cmin} < 200$ µm
Amsler-Krumeich[6]	Myopia and Astig. < 5D $P_k < 48D$	Myopia and Astig. from 5D to 8D $P_k < 53D$ $e_{cmin} > 400$ µm	Myopia and Astig. from 8D to 10D $P_k > 53D$ e_{cmin} (300 to 400) µm	$P_k > 55D$ $e_{cmin} < 200$ µm
Rabinowitz-McDonnell[7]	No KC Sim K $\leq 47.2D$ I-S < 1.4	KC suspect Sim K (47.2 to 48.7) D I-S [1.4 to 1.9]	KC Sim K > 48.7D I-S > 1.9	
CLEK[12]	Mild KC $P_k < 45$ D	Moderate KC $P_k \geq 45$ to ≤ 52 D	Severe KC $P_k > 52$ D	
McMahon[13]	KC Atypical 47.75D < $P_k \leq 48D$ suspect KC 48D < $P_k \leq 49D$	Mild KC 49 D < $P_k \leq 52D$	Moderate KC 52 D < $P_k \leq 56D$	Severe KC $P_k > 56.01D$

Astig: astigmatism; P_k: central corneal power; e_{cmin}: minimum central corneal thickness; RMS: Root mean square; KC: keratoconus; Sim K: simulated keratometry

Alio-Shabayek and Amsler-Krumeich Grading Systems

Alio-Shabayek and Amsler-Krumeich grading systems consider similar P_k range values for keratoconus classification. Besides this, these classifications consider other parameters, such as the root mean square (RMS) value for coma-like aberrations, the myopic refractive error, the magnitude of astigmatism or corneal thickness. Considering only the corneal power value, 29 keratoconus eyes of our sample were classified in stage I if $P_{k(1.3375)}$ was used, whereas 31 keratoconus were classified in stage I if P_{kadj} was used, with an overestimation of $P_{k(1.3375)}$ between 0.60 and 1.40 D (Table 3). Concerning stage II, 11 keratoconus cases were included in it if $P_{k(1.3375)}$ was used and 12 if P_{kadj} was considered. This difference in the number of eyes graded as stage II was due to an overestimation of corneal power in some cases with the classical keratometric approach (between 1.10 and 1.90 D). In one case, an overestimation of 2.30 D was found when $P_{k(1.3375)}$ and P_c^{Gauss} were compared. However, with both corneal power values, $P_{k(1.3375)}$ and P_c^{Gauss}, this case was classified as stage II (Table 3).

There were three keratoconus eyes graded as Stage III when $P_{k(1.3375)}$ was used, but all of them were included

in stage II when P_{kadj} was considered (Table 3). This was due to an overestimation in these 3 cases of corneal power with the classical keratometric approach of 1.1 D. Only 1 keratoconus eye was classified as stage IV with both $P_{k(1.3375)}$ and P_{kadj} in spite of the presence of an overestimation of 2.3 D of corneal power when the classical keratometric approach was used (Table 3). It should be remarked that the same results were obtained using P_{kadj}, True Net Power or P_c^{Gauss}.

Rabinowitz-McDonnell Classification System

The main parameters of this classification system are topographic, I-S and Sim K values. Considering only the corneal power calculation, we found in our series 27 cases classified as normal if $P_{k(1.3375)}$ was used and 31 cases if P_{kadj} was used, with an overestimation of corneal power with $P_{k(1.3375)}$ between 0.60 and 1.40 D (Table 4). Likewise, in our series, 4 cases of keratoconus suspect were found if $P_{k(1.3375)}$ was used. In contrast, if P_{kadj} was considered, these 4 cases were reclassified as normal cases (Table 4). This difference was due to an overestimation of corneal power with $P_{k(1.3375)}$ in these four cases that ranged between 1.10 and 1.20 D. Finally, a total 13 eyes were classified as keratoconus if $P_{k(1.3375)}$ was used and 8 if P_{kadj} was considered. A total of 5 cases (38.5%) were

Table 3: Patients classified in different keratoconus stages following the Alio-Shabayek classification method and considering the adjusted and classical keratometric corneal power

	$n_1 P_{k(1.3375)}$	%	$n_2 P_{kadj}$	%
Stage I	29	65.9	31	70.5
Stage II	11	25	12	27.3
Stage III	3	6.8	0	0
Stage IV	1	2.3	1	2.3

n_1: KC cases using $P_{k(1.3375)}$; %: total percentage of KC cases in each stage; n_2: KC cases using P_{kadj}

Table 4: Patients classified in different keratoconus stages following the Rabinowitz-McDonnell classification method

	n_1 $P_{k(1.3375)}$	%	n_2 P_{kadj}	%
Normal	27	61.4	31	70.4
Suspect	4	9.1	5	11.4
Keratoconus	13	29.5	8	18.2

n_1: KC cases using $P_{k(1.3375)}$; %: total percentage of KC cases in each stage; n_2: KC cases using P_{kadj}

reclassified as keratoconus suspect when P_{kadj} was used due to an overestimation in these five cases of corneal power with $P_{k(1.3375)}$ (between 1.10 and 2.30 D, Table 4).

If P_c^{Gauss} was used, one case initially classified as normal was reclassified as keratoconus suspect, although the difference between P_c^{Gauss} and P_{kadj} was only of -0.10 D. Likewise, 2 keratoconus suspect eyes were reclassified as keratoconus if True Net Power or P_c^{Gauss} were used. It should be considered that differences between P_{kadj} and P_c^{Gauss} were not clinically significant, with P_{kadj} underestimating P_c^{Gauss} between 0.30 and 0.50 D. In contrast, differences between P_{kadj} and True Net Power were clinically significant, with an overestimation between 0.50 and 0.60 D.

Collaborative Longitudinal Evaluation of Keratoconus Grading System

With the CLEK classification, 17 keratoconus were classified as mild KC if $P_{k(1.3375)}$ was used, and 24 if P_{kadj} was considered. This difference in grading was due to the overestimation of corneal power by $P_{k(1.3375)}$ in a range between 0.60 and 1.30 D (Table 5). A total of 23 eyes were classified as Moderate KC if $P_{k(1.3375)}$ was used and 16 if P_{kadj} was considered, with 7 cases (30.4 %) being reclassified as mild KC. This difference in grading was also due to the overestimation of corneal power by $P_{k(1.3375)}$ that in these 7 cases ranged between 1.40 and 1.80 D (Table 5). Four cases were classified as severe KC using $P_{k(1.3375)}$ and P_{kadj}, in spite of the overestimation in such cases of corneal power by the classical keratometric approach that ranged between 1.10 and 2.30 D (Table 5). All these results were the same compared with P_{kadj} if True Net Power was used. However, when P_c^{Gauss} was used, 2 mild KC cases were reclassified as moderate KC compared to P_{kadj}, although differences between corneal power estimations were not clinically relevant (0.1–0.2 D).

McMahon Grading System

McMahon grading system is based on the combined analysis of topographic patterns, best spectacle corrected acuity, steepening and flat keratometry reading and clinical keratoconus corneal signs. Considering the value of corneal power, 29 cases were classified as normal

Table 5: Patients classified in different keratoconus stages following CLEK classification method

	n_1 $P_{k(1.3375)}$	%	n_2 P_{kadj}	%
Mild	17	38.6	24	54.5
Moderate	23	52.3	16	36.4
Severe	4	9.1	4	9.1

n_1: KC cases using $P_{k(1.3375)}$; %: total percentage of KC cases in each stage, n_2: KC cases using P_{kadj}

Table 6: Patients classified in different keratoconus stages following the McMahon classification method

	n_1 $P_{k(1.3375)}$	%	n_2 P_{kadj}	%
Normal	29	65.9	31	70.5
Suspect	2	4.5	5	11.3
Mild	9	20.5	4	9.1
Moderate	3	6.8	3	6.8
Severe	1	2.3	1	2.3

n_1: KC cases using $P_{k(1.3375)}$; %: total percentage of KC cases in each stage; n_2: KC cases using P_{kadj}

if $P_{k(1.3375)}$ or P_{kadj} were used indistinctly, even though $P_{k(1.3375)}$ overestimated P_{kadj} between 0.60 and 1.40 D. A total of two suspect KC were found if $P_{k(1.3375)}$ was used, while if P_{kadj} was considered these two cases were considered as normal due to the overestimation of corneal power by $P_{k(1.3375)}$ in theses two cases of 1.1 D (Table 6). Nine cases were classified as mild KC if $P_{k(1.3375)}$ was used and five if P_{kadj} was considered. This difference in grading was due to an overestimation of corneal power by the classical keratometric approach between 1.7 and 1.9 D (Table 6). Moderate KC were observed in 3 cases and severe KC in 1 case using $P_{k(1.3375)}$ and P_{kadj}, although the overestimation of corneal power by $P_{k(1.3375)}$ in these three moderate cases was of 1.10 D and in the severe case was of 2.3 D (Table 6).

If P_c^{Gauss} was used, two cases classified as suspect were reclassified as mild, with a difference between P_c^{Gauss} and P_{kadj} ranging from -0.50 to -0.6 D. Also, one mild KC eye was reclassified as suspect, with 0.6 D of difference between P_c^{Gauss} and P_{kadj}. Finally, three moderate KC were reclassified as mild grade, with differences between the Gaussian and the adjusted keratometric approach ranging from 0.40 to 0.70 D. If True Net Power was used and compared with P_{kadj}, one suspect KC was classified as mild (-0.50 D of difference between P_{kadj} and True Net Power), and one mild KC was classified as suspect (0.70 D of difference between P_{kadj} and True Net Power). Finally, three moderate KC were classified as mild if True Net Power was used, with differences between the adjusted keratometric approach and True Net Power ranging from 0.6 to 0.9 D.

DISCUSSION

In the current study, we have tried to confirm if the use of the adjusted keratometric corneal power (P_{kadj}), a concept developed by our research group in previous studies,[1,2] could affect significantly the grading of keratoconus severity using classification systems based on the use of corneal power. For such purpose, we have compared the result obtained with the adjusted keratometric approach with that obtained using the classical keratometric

readings ($P_{k(1.3375)}$). It should be considered that the exact corneal power calculation in paraxial optics can only be obtained by calculating P_c^{Gauss} and using the curvature of both corneal surfaces (r_{1c} and r_{2c}). However, devices providing curvature measurements of both corneal surfaces are not always available in clinical practice, and the keratometric corneal power (P_k) is used as an estimation of corneal power.

Our results show that with the use of P_{kadj} several keratoconus cases would be reclassified. Specifically, 6 keratoconus (13.6 %) cases would be reclassified using P_{kadj} and the Alió-Shabayek or the Amsler-Krumeich grading systems, with the same reclassifications if the True Net Power or P_c^{Gauss} were considered. With the Rabinowitz-McDonnell grading system, 10 keratoconus (22.7 %) were reclassified using P_{kadj}, with only differences in three and two cases when a reclassification was done using P_c^{Gauss} and True Net Power, respectively. Although differences between P_{kadj} and P_c^{Gauss} in those cases were not clinically relevant (0.1, 0.3 and 0.5 D), differences between P_{kadj} and True Net Power were considerable (0.5 and 0.6 D). Concerning the CLEK grading system, 14 keratoconus (31.8 %) cases were reclassified using P_{kadj}, with only two cases differing if P_c^{Gauss} was used, although differences between P_{kadj} and P_c^{Gauss} were not clinically relevant (0.1 and 0.2 D). Finally, 10 keratoconus cases (22.7%) were reclassified using the McMahon classification system if P_{kadj} was used and compared with $P_{k(1.3375)}$. If P_c^{Gauss} was used, six cases differed from the use of P_{kadj}, with differences between −0.6 and 0.7 D, and five if the True Net Power was used, with differences between −0.5 and 0.9 D.

As demonstrated in previous studies,[1,2] if a limit value of $P_{k(1.3375)}$ ss< 48 D is considered as a criterion for defining an incipient keratoconus, an error is being assumed that may range between −0.1 and 2.10 D depending on r_{1c} and r_{2c} combinations, when we compared $P_{k(1.3375)}$ with P_c^{Gauss}. To consider $P_{k(1.3375)}$ limits for moderate keratoconus classification between 48 and 55 D may lead to overestimations of real corneal power between 0.3 and 3.5 D.[1,2] Likewise, the use of a $P_{k(1.3375)}$ value higher than 55 D as a limit for defining a severe keratoconus would be associated to potential overestimations between 1.8 and 4.0 D.[1,2] These errors in using the classical keratometric powers as valid estimators of corneal power in keratoconus are the reasons for the findings of the current study. When $P_{k(1.3375)}$ and P_{kadj} were compared, differences up to 13.6% in the type of grading of keratoconus cases was found when the Alió-Shabayek or the Amsler-Krumeich grading systems were used. With the Rabinowitz-McDonnell and McMahon classification systems differences up to 22.7% were obtained in the type of grading

of our keratoconus cases, and up to 31.8% when the CLEK classification system was used. As may be expected, errors in classification were more frequent when corneal power values approached to the limits established by each author between grades, being the most common errors those associated to the grading between moderate and severe keratoconus. A relevant finding that should be remarked is that 100% of reclassified cases using P_{kadj} were done in a less severe stage, indicating that the use of classical keratometry may lead to the classification of a cornea as keratoconus, being a normal case. In general, the results obtained using P_{kadj}, P_c^{Gauss} or the True Net Power were equivalent. Differences between P_{kadj} and P_c^{Gauss} never exceeded ± 0.7 D as predicted in our previous articles,[1,2] with only one case showing a difference of 0.9 D between P_{kadj} and True Net Power.

CONCLUSION

The use of classical keratometric corneal power may lead to incorrect grading of the severity of keratoconus, with a trend to more severe grading. The use of an adjusted keratometric corneal power calculated using a variable refractive index dependent on r_{1c} seems to be a useful method to minimize this error when a device measuring both corneal surfaces is not available in clinical practice. If it is available, grading of keratoconus should be performed considering P_c^{Gauss} or True Net Power.

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