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ORIGINAL ARTICLE

Estimating Variability in Placido-Based Topographic Systems

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ABSTRACT

Purpose. To describe a new software tool for the detailed presentation of corneal topography measurements variability by means of color-coded maps.

Methods. Software was developed in Visual Basic to analyze and process a series of 10 consecutive measurements obtained by a topographic system on calibration spheres, and individuals with emmetropic, low, high, and irregular astigmatic corneas. Corneal surface was segmented into 1200 segments and the coefficient of variance of each segment's keratometric dioptric power was used as the measure of variability. The results were presented graphically in color-coded maps (Variability Maps). Two topographic systems, the TechnoMed C-Scan and the TOMEY Topographic Modeling System (TMS-2N), were examined to demonstrate our method.

Results. Graphic representation of coefficient of variance offered a detailed representation of examination variability both in calibration surfaces and human corneas. It was easy to recognize an increase in variability, as the irregularity of examination surfaces increased. In individuals with high and irregular astigmatism, a variability pattern correlated with the pattern of corneal topography: steeper corneal areas possessed higher variability values compared with flatter areas of the same cornea. Numerical data permitted direct comparisons and statistical analysis.

Conclusions. We propose a method that permits a detailed evaluation of the variability of corneal topography measurements. The representation of the results both graphically and quantitatively improves interpretability and facilitates a spatial correlation of variability maps with original topography maps. Given the popularity of topography based custom refractive ablations of the cornea, it is possible that variability maps may assist clinicians in the evaluation of corneal topography maps of patients with very irregular corneas, before custom ablation procedures.

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Key Words: corneal topography, variability, variance, color-coded maps

The anterior cornea is the major refractive surface of the eye responsible for over two-third of its total dioptric power. Very small changes in corneal shape may have a significant effect in the clarity with which an image is focused on the retina.[1–3]

Corneal topography is being performed with computer videokeratoscopy systems, which represent the entire corneal surface curvature or dioptric power, by measuring and analyzing thousands of points, whereas color-coded maps are being used for the depiction of the results.[4]

Therefore, corneal topography has a role, which is of great importance in every aspect. The variability of the measurements of topographic systems, which are being used in the every day routine, is still a very important area of research.[5–7] Several studies have been carried out to verify the repeatability and accuracy of various commercially available topographic systems. In general, these systems tend to be accurate for spherical surfaces but when surfaces under evaluation are aspheric, as in human eyes, there are limitations, especially in evaluating the contour of the very center and the periphery of the cornea.[8–11]

The main purpose of this study was to develop a simple and easily interpretable presentation of topographic measurements variability results, similar to the color-coded topographic maps. For the evaluation of our methodology, we used two commercially available corneal topographic systems (CTSs) performing several repeated measurements on calibration spheres and individuals.

METHODS

Topographic Systems, Calibration Spheres, and Individuals

We used two CTSs, the TechnoMed C-Scan-Color Ellipsoid Topometer (TechnoMed Technology, Germany), and the TOMEY Topographer TMS-2N v.2.4.2.j (TOMEY Corporation, USA), which were available in our institution while this study was conducted. TechnoMed C-Scan has a small placido cone of 30 rings and a measuring capability of up to 10,800 points with 360 measurements per each ring. TOMEY topographer system has a small placido cone with 28 measurement rings and a measuring capability of up to 7168 with 256 measurements per each ring (one measurement every 1.40625 degrees). Focusing and alignment are performed manually in both systems.

Using both topographic systems, we performed 10 consecutive measurements on 5 PMMA calibration spheres (6.5, 7, 8, 9, and 10 mm radius of curvature) and on 8 patients (4 for each CTS), belonging in the following examination categories: (1) emmetropia, (2) low astigmatism, (3) high astigmatism, (4) irregular astigmatism.

All measurements were performed by the same examiner. Individuals were asked to blink before each measurement, ensuring the best lacrimal film quality. They were also asked to reposition their head and re-fixate their gaze before each measurement. Every patient was asked to recognize the luminous fixation target and follow it during the measurement procedure. Patients who had even minor problems in recognizing the fixation target, because of high myopic or astigmatic errors, were excluded from the study.

Data Acquisition and Statistics

Each single examination provided a set of data comprising several hundreds pairs of values depended on the total number of the placido rings and on the number of measurements per ring. All data sets were exported in ASCII form after each single examination. Each pair of values consisted of (a) distance of each measured point from the reflected center of the placido disc over the cornea (center) and (b) calculated dioptric power for this particular point.

In this manner, each point was clearly distinguished by its polar coordinate (angle at which the point was measured over a specific placido ring and distance from the center as well as its dioptric power.

Custom computer software was developed in Microsoft Visual Basic 6.0 (1987–2000 Microsoft Corp.) to perform the statistical calculations of the exported ASCII data, from the 10 consecutive measurements of each case. Initially, the software segmented the imaginary corneal plane created by the corneal topography measurements. This segmentation procedure was essential to perform statistics in specific locations over the cornea (segments). To accomplish the segmentation procedure, the software functioned in three steps as follows:

a. The maximum and minimum distances from the center were determined for all 10 measurements. Subsequently, the mean values were calculated for the above distances.
b. Then, 11 concentrated rings were created on the imaginary corneal plane. The central ring had radius equal to the mean minimum distance. The remaining 10 rings had the same width equal to the one-tenth of the difference between the mean minimum and maximum distances.
c. Finally, arcs of 3 degrees width were created over the corneal plane, thus creating 120 angular segments.

Therefore, 1320 segments were created in total, with only 1200 participating in the grouping procedure, as the central 120 segments depicted an area where the topographic system did not obtain measurements.

Selection of the points to be included in a particular segment was based on comparison of each point's polar coordinates with the corresponding coordinates of the particular segment. Finally, when all 10 consecutive measurements where processed, each segment could contain 10 to 120 points. When a point was included in a specific segment, its dioptric power was added to the existing total of this segment.

The statistical parameters that were calculated for each segment to evaluate the topographic systems as concerning the variability were the mean dioptric power, the standard deviation of the mean dioptric power, and the coefficient of variation (CV). The CV expresses the standard deviation as a percentage of the mean value. Its formula is given by

$$CV = \frac{sd}{\bar{x}} * 100$$

CV is very useful as a measure of variation within a given set of data and also a very useful parameter when someone desires to compare the dispersion in two sets of data, which might have different mean values. Presentation of the CV statistical parameter as a single percentage quantity facilitates direct comparison between results without the use of complicated statistical tests. For these reasons, we used this parameter as measure of the variability for our study instead of standard deviation.

Graphical Presentation of Results

The software had the ability to represent three color-coded maps similar to those of a topographic system. The first map was a presentation of the topographic data in diopters exported from the mean values of the 10 consecutive measurements (Fig. 1b). This map was used to compare directly the true topographic map (Fig. 1a) with the one exported from the processed data. A similar color-coded graphical presentation was used for the two statistical parameters. For the depiction of mean values, the purple color was assigned to the minimum dioptric power values, whereas red was assigned to the maximum dioptric power values, as in the topographic color-coded maps (Fig. 1c). For the depiction of standard deviation and CV values, a reverse order of colors was used to utilize the warm colors for illustrating areas with increased values of variability. The scale of standard deviation was ranging from 0.1 to 1.5 D. The scale of CV was ranging from 0% to 1.2%. CV of 1.2% of CV for a normal value of corneal dioptric power at 42.2 D means approximately 0.51 D of standard deviation. Maps of CV were appointed variability maps (Fig. 1d).

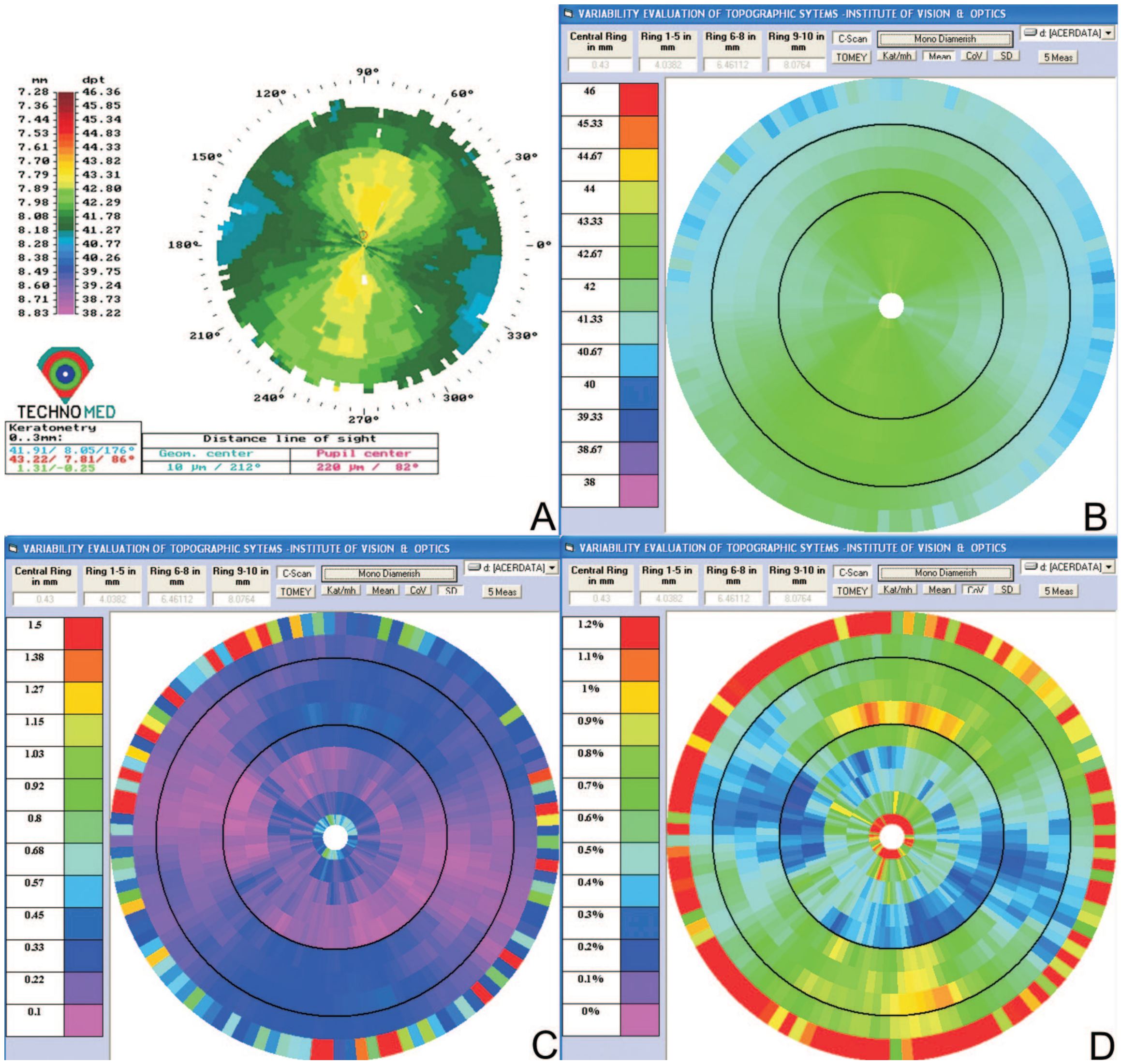

FIGURE 1.

Graphical representation of the calculated values from one individual with keratometic astigmatism of 1.31 D. (a) Actual corneal topographic map, (b) Map of mean values from 10 consecutive measurements, (c) Map of standard deviations from 10 consecutive measurements, (d) Map of coefficient of variance(CV) from 10 consecutive measurements (Variability Map).

All color-coded maps were divided in three zones: central, paracentral, and peripheral depicted in the maps as three concentric black circles. Each one of these zones was extended approximately up to 4.5, 7.0, and 9.0 mm, respectively. A central white disc was created for every Mean, SD, or CV map with radius ranging from 0.3 to 0.5 mm. This disc included the central 120 segments created by the segmentation procedure and denoted the area in which the topographic systems did not obtain measurements due to the position of the CCD camera, which was used for the capture procedure of the reflected image of the placido disc over the cornea.

To provide numerical results concerning the variability maps, which often give more concise information complementary to that provided by the color maps, the software also calculated the percentage of segments in every zone with a CV scores over a prespecified cutoff level (0.50%, 0.75%, 1.00%, and 1.25%) (Tables 1 and 2). In this study, we used the preset value of 0.50% as the limit for direct comparisons between surfaces, and thus, higher percentage of segments over this preset value presented higher variability results, which means generally worst outcome. When necessary, these data may be used for statistical comparisons between different subject or calibration objects by the use of contingency tables and χ^2 test, given the fixed number of segments per each examined zone.

RESULTS

Our software performed adequately in all cases with both topographic systems. In calibration spheres, a difference between the two systems was noted with TOMEY CTS appearing to perform better. Both systems performed better on the paracentral zone for all spheres (Fig. 2a, b). Specifically, for the measurements on calibration spheres the TOMEY CTS presented scores of CV below 0.50%, which signified SD values ranging from 0.26 D in the steepest spheres to less that 0.17 D in the flattest ones.

The C-Scan system had the lowest variability in the 8.0-mm sphere; when the radius of curvature increased toward 10.0 mm or

TABLE 1.
The amount of segments from the five calibration spheres, for each one of the three zones, with a CV score over a prespecified cutoff level (0.50%, 0.75%, 1.00%, and 1.25%) expressed as percent value[a]

	Spheres	C-Scan CTS				TOMEY CTS			
		>0.50%	>0.75%	>1.00%	>1.25%	>0.50%	>0.75%	>1.00%	>1.25%
Central zone	10.0 mm	78	53	35	14	0	0	0	0
	9.0 mm	44	11	1	0	0	0	0	0
	8.0 mm	28	13	7	4	7	1	0	0
	7.0 mm	27	10	3	1	4	2	0	0
	6.5 mm	37	16	7	4	8	2	0	0
Paracentral zone	10.0 mm	23	0	0	0	0	0	0	0
	9.0 mm	14	0	0	0	0	0	0	0
	8.0 mm	0	0	0	0	0	0	0	0
	7.0 mm	14	0	0	0	0	0	0	0
	6.5 mm	18	0	0	0	0	0	0	0
Peripheral zone	10.0 mm	68	29	28	26	4	0	0	0
	9.0 mm	49	46	44	41	0	0	0	0
	8.0 mm	45	42	35	29	0	0	0	0
	7.0 mm	52	41	33	25	0	0	0	0
	6.5 mm	59	43	27	22	1	0	0	0

[a]The three zones contained a total of 600, 360, and 240 segments respectively.

TABLE 2.
The amount of segments on the four categories for the individuals, for each one of the three zones, with a CV score over a prespecified cutoff level (0.50%, 0.75%, 1.00%, and 1.25%) expressed as percent value[a]

	Individuals	C-Scan CTS				TOMEY CTS			
		>0.50%	>0.75%	>1.00%	>1.25%	>0.50%	>0.75%	>1.00%	>1.25%
Central zone	Emmetropic	27	8	2	0	2	0	0	0
	Low Ast	36	18	8	4	29	10	2	0
	High Ast	56	20	12	6	52	20	5	2
	Irreg. Ast	100	93	77	50	92	76	58	42
Paracentral zone	Emmetropic	6	0	0	0	0	0	0	0
	Low Ast	4	0	0	0	6	1	0	0
	High Ast	67	19	6	1	44	19	8	6
	Irreg. Ast	87	64	34	12	59	27	18	12
Peripheral zone	Emmetropic	42	31	22	19	12	2	2	1
	Low Ast	67	40	31	23	50	35	25	17
	High Ast	59	33	20	13	88	79	55	46
	Irreg. Ast	79	58	30	19	52	41	27	17

[a]The three zones contained a total of 600, 360, and 240 segments respectively.

decreased toward 6.5 mm, the variability increased. For example, in the central zone the 10.0-mm sphere had a higher percentage of segments with CV more than 0.5% compared with the 9.0-mm sphere indicating a increased variability ($\chi^2 = 144$, $p < 0.001$). The CV for most of the segments in all spheres did not exceed 1.5%, with exception in the peripheral zone (Table 1).

As concerning the individuals, variability was increased as the corneal irregularity was increasing from low astigmatism to irregular astigmatism (Table 2). The paracentral zone showed the best results with the lowest variability score in both spheres and individuals (Fig. 2c to i, k). Both topographic systems performed similarly concerning the examined individuals as well as the specific zones.

On individuals, the least variability was derived in the paracentral zone of emmetropic and low astigmatic cases with both systems. For example, when comparing the variability at 0.50% cutoff level between the emmetropic and high-astigmatic individuals on the paracentral zone, there is statistical significant lower variability for the emmetropic ($\chi^2 = 286$, $p < 0.001$). The central and peripheral zone had relatively high scores of CV in all cases with both topographic systems, with a significant number of segments over 0.75%. The variability was increased for both systems when cases under evaluation where high and irregular astigmatic (Table 2).

A noticeable observation could be derived by examining the detailed patterns on the CV for cases with high and irregular astigmatism in both topographic systems (Fig. 2g, h). The CV increased on the variability maps in areas that corresponded to the steepest cornea in the actual topographic maps, whereas areas with flattest surface had lower scores of CV and thus less variability. This CV pattern was more obvious in cases with irregular astigmatism (Fig. 2i, k).

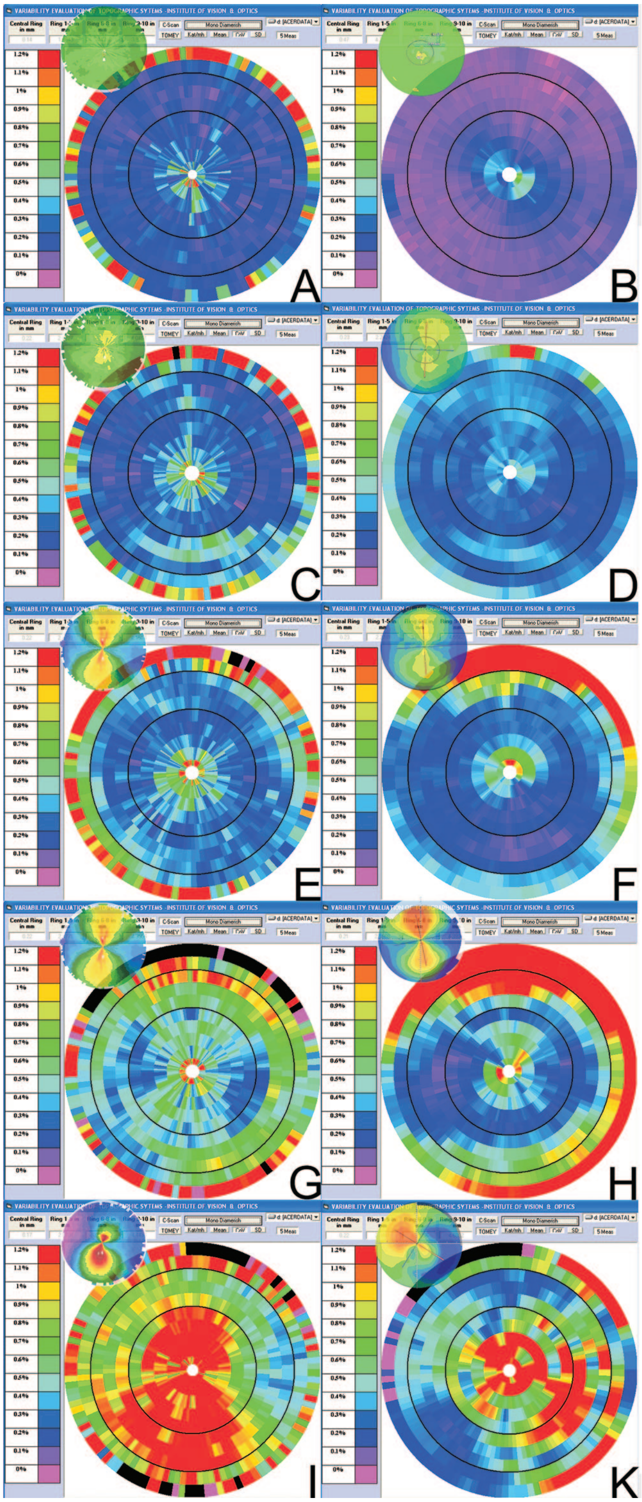

FIGURE 2.

Variability maps obtained with the two topographic systems. C-Scan CTS maps are exposed on the left; TOMEY CTS maps on the right. In the upper left corner of each map, there is the respective topographic map. Each row represents a specific category of examination surface: (a) and (b) are calibration spheres with 8.0 mm radius of curvature; (c) and (d) are corneas of emmetropic individuals; (e) and (f) are corneas of individuals with low astigmatism (keratometric astigmatism 2.00 and 1.58 D respectively); (g) and (h) are corneas of individuals with high astigmatism (keratometric astigmatism 3.59 and 4.19 D, respectively); (i) and (k) are corneas with irregular astigmatism (keratometric astigmatism 7.79 and 6.41 D, respectively).

DISCUSSION

Corneal topography has evolved along with the development of refractive surgery in all its aspects. As several new surgical techniques have been established and new technologies have been implemented in the laser industry, e.g., corneal topography guided customized ablations, the need for a detailed representation of the corneal surface has been very imperative. Several studies have been performed to evaluate parameters that characterize topographic systems such as measurement variance, repeatability, and especially accuracy compared with spherical and aspherical test surfaces.[12–15]

Most videokeratoscopic systems have been shown to measure the power of spherical test objects very accurately. However, other studies have found a decrease in variability (measurements variance) when dealing with very flat (<38 D) or very steep (>46 D) surfaces, or with sudden transitions[16] or else with irregular aspheric surfaces.[17] Factors that might affect the variability of topographic measurements include the quality of the automatic digitization, the total number of measurements over each ring, and the interpolation routines involved in the final representation of the results,[16,18] as well as the paraxial dioptric power approximation, which might give wrong results for the peripheral corneal areas because of the elliptic shaped eye.[11]

Regardless to their apparent differences, all currently available topographic systems use the same alignment principle by means of a luminous fixation point, which is located on the optical axis of each CTS and in the center of the placido disc.[19] The patient must follow this fixation point while the examiner carries out alignment and focusing procedures.[20] The fixation process may also contribute to some extend in increased variability in measurements.

In this work, we developed a method for the evaluation of variation in measurements with placido topography systems. We elaborated a process that involved the division of the corneal field in several sectors and the presentation of the results in color-coded maps. The aim of our effort was to develop a tool that would be easily interpretable and useful in clinical praxis. Topography systems are used today for the guidance of detailed surface ablations of the corneal surface[7,21,22]; as a result, even if the overall performance of these systems is within acceptable limits, very often it is necessary to know the repeatability and the accuracy of the systems over very localized areas of the cornea. Several authors have used a methodology similar to ours to examine the accuracy and the repeatability of various topography systems. However, in most cases, the methods that were used evaluated the repeatability in a very course way, using either small segmentation or a small number of examination repetitions.[23–25] In our method, the segmentation to 1200 segments and the big number of repetitions lead to a detailed topographical evaluation of the measurement variation over the corneal surface; this adds significant information not offered by the previous methods that may be useful for refractive surgeons. Only Buehren et al. use a segmentation method and a repetition number comparable to ours.[26] These authors, however, evaluated the contribution of tear film in topography variability in normal corneas; this way the value of the method for corneas with abnormal topography was not demonstrated. In our work, it becomes obvious that areas of the cornea with abnormal topography, which very often represent targets for custom ablations, demonstrate high variability. This information is also of significant clinical value.[5,6,27]

For the analysis of our data, we used the CV instead of standard deviation usually used in other studies.[24–26] CV is more suitable for the depiction of data having the contour of viedokeratographic data, especially when they are derived from irregular corneas. The CV is often used when discussing data with significantly different mean values, as well as when discussing the normal distribution for positive mean values with the standard deviation significantly less than the mean. These are often the case in the data obtained from irregular corneas. Standard Deviation variability maps should be examined in respect to their corresponsive mean values map for the best evaluation of the given results. Moreover, the use of the CV is common in spatial statistics. The CV is being used as an estimator of variability in sciences such as geography and hydrology, where topographical data are processed.[28]

We applied the variability method in the two devices that were used in our department during the period of our study. The devices were used mainly to demonstrate the principle of our method. Although some conclusions are drawn concerning the devices on the basis of our variability results, these conclusions should be considered as indicative only, because this study was not designed for a head-to-head comparison of the two systems. Although CTSs are "trained" to translate the measured slopes over the cornea into radius of curvature and moreover into dioptric power, based on spherical biased surfaces, they do not manage to represent well the surfaces of calibration spheres when they have an exaggerating radius of curvature.[9,11,17] Our study found differences in variability between the two evaluated systems when examining spheres, but did not find any differences when examining individuals. Variability was also found to be different in different corneal zones. Very steep and very flat calibration spheres presented high variability especially in the central and peripheral zone with both topographic systems.

The measurements on individuals had greater variability compared to calibration spheres. Variability increased as the corneal irregularity was increasing from emmetropic corneas to corneas with irregular astigmatism. Most placido based systems are spherically biased and designed to minimize errors when testing curvatures that approximate the normal cornea. This represents a major weakness when looking at abnormal corneas.[4,10] Even a topographic system such as C-Scan, which has the ability to measure over 10,000 points in each examination (about 33% more points than the TOMEY), presented considerable variability when the corneal irregularity increased considerably.

An important observation in this study that deserves further investigation was the correlation between variability and topographic patterns in the cases with high and irregular astigmatism. In these cases, steeper corneal areas seemed to have highest variability compared to flatter areas of the astigmatic bowtie. This effect was more obvious in the central zone and less in the paracentral. This observation was obvious only in the CV color maps. Most topographic systems have difficulties in the reproduction of areas with sudden transitions. Nevertheless, our method could depict with accuracy the corneal areas were topographic data should be interpreted with caution. This information may be useful for surgeons when they evaluate patients for a custom topography guided ablation procedure.

In summary, we presented a method that evaluates the variability of topographic systems in a comprehensive manner after a number of consecutive measurements. This method provided both numerical and very detailed graphical results and can be applied to every placido-based topographic system. Corneas with extreme curvatures tend to give the highest variability results, especially in the steeper region of the cornea. Given the popularity of topography-based custom ablations during the last years, it seems that variability maps can assist in the evaluation of corneal topographic maps in patients with very irregular cornea, before custom ablation procedures.

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