ASSESSMENT OF TOPOGRAPHIC SEMI-MERIDIAN PARAMETERS FOR CORNEAL ASTIGMATISM ANALYSIS AND VECTOR PLANNING TREATMENT

Cross-references to Related Applications

This application claims the benefit of U.S. Provisional Application No. 61/260,556 filed on November 12, 2009, which is incorporated herein by reference.

Field Of The Invention

The invention relates to the determination of astigmatism parameters to represent each semi-meridian of the cornea derived from the keratometric view of topography for use in vector analysis and planning of treatment. These two semi-meridian values (for the superior and inferior semi-meridians) can then together determine a single corneal topography value for magnitude and meridian as an alternative to simulated keratometry as well as quantifying the irregularity of the cornea.

The invention further relates to a vector planning modality to simultaneously reduce and regularize naturally occurring irregular corneal astigmatism achieved by applying different laser ablation profiles to each of the two semi-meridians of the cornea. This treatment plan combines both topographic and refractive (wavefront) parameters and can be used as an algorithm for excimer laser technology applications to reduce ocular aberrations and improve visual performance.

Summary Of The Invention

According to the invention, a keratometric map is obtained by computer assisted videokeratography and vector summation is employed to determine two semi-meridian parameters to quantify astigmatism for the separate halves of the cornea. These astigmatism magnitudes can be weighted for 3mm, 5mm and 7mm concentric zones subscribed from the central axis of the cornea so that corneal astigmatism and irregularity can then be quantified. Namely, there are two factors which influence the weighting to

be assigned to the 3mm, 5mm and 7mm zones. These are 1) proximity to the central axis of the cornea and 2) the area subscribed by the respective zones. Based on these factors I have found that suitable theoretical weighting coefficients for the 3mm zone is 1.2, for the 5mm zone is 1.0 and for the 7mm zone 0.8. In an evaluation of 100 patients post surgically, it has been found that weighting values for the 3mm, 5mm and 7mm zones are equal, namely 1.0, 1.0, and 1.0 respectively. Subjective evaluation by the surgeon of each individual patient can influence him or her to assign weighting values between these two ranges. Hereafter we will proceed with illustration using the theoretical weighting coefficients 1.2, 1.0, and 0.8 for the 3mm, 5mm and 7mm zones respectively.

The two semi-meridian values calculated using weighting coefficients for the 3mm, 5mm and 7mm zones from topography allow for a more representative determinant of the corneal astigmatism. This provides parameters for the purpose of vector planning treatment and the reliable determination of corneal topographic astigmatism as well as a standard for corneal irregularity. These values can also be used pre and post operatively to gauge the success of astigmatic outcomes in patients undergoing refractive surgery.

In accordance with the invention, there is provided a method for determining parameter of magnitude and axis representing corneal astigmatism for use in vector analysis for diagnostic and surgical treatment, comprising producing a keratometric map of topographic measurements of each of two semi-meridians of the cornea of an eye, assigning weighting values to the topographic measurements in each of a plurality of zones in each semi-meridian, and vectorially combining the weighted values of the topographic measurements to obtain a vector parameter in each semi-meridian representing magnitude and axis of topographic irregularity which is adapted for use in diagnostic and surgical treatment.

In further accordance with the invention, the technique of vector planning combines corneal (topography) and refractive (wavefront) parameters to both reduce and regularize astigmatism in a single treatment step. The treatment is determined by first employing ocular residual astigmatism (ORA) to optimally reduce the astigmatic

magnitude, followed by the regularization of the now reduced corneal astigmatism using a common refractive target for the two separate semi-meridians.

The calculated treatments are presented as a single asymmetric treatment application. In this way any astigmatism that cannot be eliminated from the optical system of the eye due to the prevailing ORA is both minimized and regularized.

The advanced vector planning technique of the invention can be used to treat naturally occurring irregular astigmatism by applying the treatment independently to each semi-meridian of the cornea. As a result the remaining astigmatism is optimally minimized and regularized leading to a reduction in ocular aberrations and subsequent potential for improvement in the best corrected visual activity.

Thus, in further accordance with the invention, there is provided a method for reducing and regularizing measured values of astigmatism in an eye of a patient to obtain target values for diagnosis and treatment of the patient, said method comprising the steps of: considering the cornea of an eye of a patient to be divided into superior and inferior semi-meridians; measuring corneal and refractive astigmatism values in each of the semi-meridians; determining topographic treatment parameters in each semi-meridian to maximally reduce the topographic astigmatism values in each of the semi-meridians based on minimizing ocular residual astigmatism in each semi-meridian and regularizing the thus reduced topographic treatment parameters using a common refractive parameter for the two separate semi-meridians to obtain in one step from said determining step to said regularizing step, final treatment target values for the two semi-meridians.

In still further accordance with the invention, there is provided apparatus for carrying out the method of the invention for obtaining surgical parameters comprising: means for obtaining target parameters representing topography of an eye in superior and inferior semi-meridians, means for obtaining a target parameter representing a refractive parameter for each semi-meridian, and a computer means for carrying out the steps of: determining target induced astigmatism vector parameters (TIA) for treating each semi-meridian by vectorially combining the topographic target parameters with the

refractive parameter to obtain treatment vectors TIA in the two meridians which are equal and regularized.

Brief Description Of The Drawing

Figure 1 is a topographic illustration of a cornea showing the flat and steep keratometry parameters in the 3mm, 5mm and 7mm zones of the semi-meridians.

Figure 2a is a Polar diagram showing the superior and inferior semi-meridian astigmatism values.

Figure 2b is a double angle vector diagram in which astigmatism meridian is doubled while magnitude remains the same and vectorial difference represents topographic disparity (TD).

Figure 2c is a Polar diagram in which the TD axis for the 3mm zone is divided in half to display the direction as it would appear on the eye.

Figure 3a is a Polar diagram showing the astigmatism parameters for each of the 3mm, 5mm and 7mm semi-meridians in the corresponding superior half of the cornea.

Figure 3b is a Polar diagram showing the astigmatism parameters for each of the 3mm, 5mm and 7mm semi-meridians in the corresponding inferior half of the cornea.

Figure 4a is a double angle vector diagram showing head to tail summation of the 3mm, 5mm and 7mm astigmatism parameters which are doubled in angle to calculate the average superior astigmatism parameter.

Figure 4b is a double angle vector diagram showing head to tail summation of the 3mm, 5mm and 7mm astigmatism parameters which are doubled in angle to calculate the average inferior astigmatism parameter.

Figure 5a is a Polar diagram showing the average superior and inferior semi-meridian astigmatism values.

Figure 5b is a double angle vector diagram showing the average superior and inferior astigmatism values being summated vectorially to a brain their own average value which represents the CorT parameter.

Figure 5c is a Polar diagram showing the superior and inferior average semi-meridian astigmatism values together with CorT displayed on both semi-meridians orthogonally.

Figure 6a is a double angle vector diagram showing the vector difference between the superior and inferior average astigmatism values which represents topographic disparity (TD).

Figure 6b is a Polar diagram showing the superior and inferior average astigmatism values in their corresponding corneal semi-meridians wherein TD is displayed at 0.56D at its axis of 108 degrees.

Figure 6c is a tabular illustration showing the comparative effect of weighted and unadjusted astigmatisms for each zone of the superior and inferior semi-meridians.

Figure 6d is a tabular illustration showing comparison between CorT and Sim K parameters.

Figure 7a is a polar diagram showing refractive and topographic parameters for the superior and inferior semi-meridians of an eye.

Figure 7b is a double angle vector diagram showing the parameters of Figure 7 as vectors.

Figure 8 is a polar diagram illustrating the treatment of astigmatism and the values of various components.

Figure 9a is a double angle vector diagram showing the component in Figure 8 with their magnitudes and axis.

Figure 9b is a double angle vector diagram after treatment of the components along with respective magnitudes and axes.

Figure 10 is a double angle vector diagram showing treatment of the vectors together with magnitudes and axes thereof.

Figure 11a is a vector diagram illustrating regularization of non-orthogonal astigmatism together with values of magnitude and axes.

Figure 12a is a double angle vector diagram showing the refractive targets after regularization together with magnitudes and axes of the components therein.

Figure 13 is a DAVD showing optimal treatment vectors after regularization.

Figure 14 is a polar diagram showing refractive and topographic treatment of astigmatism together with magnitude and axes of the components thereof.

Figure 15 is a DAVD showing the treatment of the preoperative parameters to reduce magnitude and regularize corneal treatment in a single step.

Figure 16 is a polar diagram showing preoperative topography and with refractive and topographical targets after maximum treatment of astigmatism and regularization in a single surgical step.

Figure 17 is a diagrammatic illustration of vector planning apparatus for evaluating and obtaining surgical parameters for treatment of astigmatism in an eye of a patient.

Detailed Description of the Invention

Advances in computer assisted videokeratography (CAVK) have assisted the surgeon by providing detailed information regarding corneal shape. The keratometric view provided by topographers (Figure 1) displays the corneal power and radius of curvature for different concentric zones of the cornea and provides more information than currently necessary for lasers that provide symmetric refractive corneal treatments. The keratometric view also customarily provides a Simulated Keratometry (Sim K) value that is a quantitative descriptor of corneal astigmatism at the 3mm zone as an attempt to gain equivalence of corneal keratometry at the time of the introduction of the CAVK technology in the 1980's.

One commonly encountered difficulty with the Sim K value is that the algorithm that selects the meridian can on occasions be erratic where the bow tie demonstrates non-orthogonal characteristics. The topography device may be inconsistent in its choice of meridian ranging from either of the bow tie meridian or somewhere in between. The technique herein provides relevance and consistency in the corneal topography astigmatism value (CorT) by obtaining a vector summated mean magnitude and meridian from the keratometric view at three (inner, middle and peripheral) zones.

Currently no consistent values are offered by topographers that usefully represent the two semi-meridians of the cornea. Nor is there one astigmatism value that represents the whole cornea other than just the paracentral 3mm region utilized by the Sim K magnitude and meridian value. These two vector semi-meridian values are necessary and useful parameters to derive this single value quantifying the astigmatism of the whole cornea. They are also essential for the vector planning of the asymmetric treatment process, to gauge irregularity and quantify the success of astigmatic outcomes by corneal parameters. The invention seeks to derive these values from the data currently available from corneal topographer maps as seen in Figure 1.

Using the keratometric parameters from the 3mm, 5mm and 7mm zones circumscribed from the central axis of the cornea (i.e., the area from 0-3mm, from 3-5mm and from 5-7mm respectively), the semi-meridian values can be refined to more reliably

identify the meridian and magnitude of the corneal topographical astigmatism by the process of vector summation.

The topographic map in Figure 1 displays two flat and two steep keratometric magnitudes together with their respective meridians for each of the three zones. The most applicable topographic reading for planning treatment and assessing potential astigmatic outcome is that of the 3mm zone, as this is what predominantly coincides with the pupil and visual axis. Pairing up the most appropriate keratometric parameters for the 3mm zone is determined by establishing the minimum magnitude of corneal irregularity or TD of the two pairs. That is, using one combination of flat/steep to determine the TD and comparing this in magnitude to the other combination of flat/steep to find the minimum of the two choices (Figures 2a, b and c).

Once the appropriate pairing is established for the 3mm zone, the corresponding steep meridian in the 5mm zone is determined by calculating the smallest angular difference between each of the steep meridians in the 5mm zone relative to the 3mm steep meridian determined from step 1 above. This is then repeated for the 7mm zone, comparing the angular difference to the parameters of the 5mm zone. The same process is then applied for the flat meridian. The magnitude of astigmatism for each zone is determined by the arithmetic difference between the flat and steep parameters for that zone, and its orientation is that of the steepest meridian.

The result is three astigmatism values for the superior semi-meridian of the cornea (3, 5 and 7mm zones) and three for the inferior semi-meridian of the cornea (3, 5 and 7mm zones). Based on the significance of the 3mm, 5mm and 7mm zones in any surgical treatment paradigm, a weighting can be given to each zone, suitably increased for the inner and reduced for the outer with the middle unchanged: x1.2 for the 3mm (most applicable), x1.0 for the 5mm and x 0.8 for the 7mm zone (least applicable) (Figures 3a and 4a).

The polar diagram in Figure 5a displays the two summated vector means as they would appear on an eye- one astigmatism in the superior semi-meridian and another

in the inferior semi-meridian. These topographic astigmatism values will be used in vector planning as will be described later.

To determine the irregularity of the whole cornea, factoring in the weightings for the 3, 5 and 7mm zones discussed above, the vectorial difference between these two astigmatisms is calculated by again doubling the axis on to a DAVD (Figure 5b). The final meridian of the TD is determined by joining the resultant vector originating from the superior average astigmatism and terminating at the inferior average astigmatism on the DAVD and then being returned to the origin and halved to determine its actual direction. The corneal irregularity quantified in this way is termed Topographic Disparity (TD) and is expressed in diopters and degrees. This provides the value as it would appear on an eye (Figure 5c).

To determine the total corneal topography astigmatism (CorT) as a representation of the whole cornea, a vector summated mean is calculated using the T_{SUP} and T_{INF} weighted values (Figures 6a and 6b). This describes the whole cornea as quantified by corneal topography with appropriate weightings to the 3, 5 and 7mm zones such as presented in the example. This is preferential to the simulated keratometry value (Sim K) which is derived entirely from the 3mm zone with variability and inconsistent bias sometimes demonstrated in the meridian selected.

The concentric corneal zones provided by the topography map (i.e. at 3mm, 5mm and 7mm) are used to achieve two semi-meridian values, each representing one half of the cornea, and to weight the relevance of each zone and then determine corneal irregularity. This technique assesses the topographic disparity (TD) - a vectorial measure of irregular astigmatism, calculated as the dioptric distance between the displays of superior and inferior values on a 720 degree double-angle vector diagram (DAVD). A direct proportional relationship between increasing TD and ocular residual astigmatism (ORA) has been observed.

The ORA which quantifies the internal aberrations of the eye is calculated as the vectorial difference between corneal and refractive astigmatism parameters, and has a magnitude expressed in diopters and an orientation in degrees.

The relationship between TD and ORA has been shown to be significant in a group of 100 healthy astigmatic corneas prior to surgery. ORA and TD magnitudes of 0.75D or less are considered to be normal with no impediment to achieving good astigmatic outcomes. Whereas magnitudes above 1.00D might display a significant concern for the excess degree of internal aberrations or corneal irregularity with potential adverse outcomes, so that refractive laser or incisional surgery to correct astigmatism may be limited in the outcome achievable in correcting astigmatism. For this reason the surgeon may decide not to treat or to use vector planning as a treatment paradigm to optimize and reduce the resultant amount of corneal astigmatism remaining in such cases.

Figure 6c displays the importance of the weighted summated vector means ($T_{SUP\ av}$ and $T_{INF\ av}$). The 7mm zone unadjusted astigmatism magnitude is comparatively large at 1.74D for the inferior semi-meridian, relative to the corresponding 1.06D for the superior semi-meridian. In both the superior and inferior semi-meridian the 7mm astigmatism values are larger than the 3mm and 5mm ones for the unadjusted parameters. The importance of a summated average vector is highlighted by the 'dampening' down of 0.06D for the inferior semi-meridian, but only 0.01D for the superior semi-meridian.

The summated vector mean of the two weighted semi-meridian values $T_{SUP\ av}$ and $T_{INF\ av}$ can be determined (Figure 6d) to calculate an effective total corneal topography astigmatism described here as the CorT value (0.91D @ 91). Examining the relationship of the Sim K (0.88D @ 102) to the Cor T value reveals similar magnitudes (both less than the arithmetic mean) this is likely a similar effect estimating the corneal topography astigmatism as a result of the steep meridian of the three zones not being inline. The meridian of the CorT value however aligns closer to the T sup (85 degrees) and T_{INF} (275 degrees) in a clockwise direction and as a result is likely more representative of the total corneal astigmatism meridian by factoring in the influence of the 7mm zone orientation. This difference of almost 10 degrees (CorT meridian of 91

degrees compared to Sim K meridian of 102 degrees) would be a significant amount to factor in during surgical incision or laser planning.

It is important to note that the greater the lack of linearity of each of the individual components in the three zones, the less the effective regular astigmatism represented by Sim K or CorT. The values of 20% increase and decrease from unity for the inner and outer zones respectively is an example which is empirically estimated at this stage and could be modified in the future according to experience and population studies. The sum of the three weighted zone values of 3.0D is equal to the sum of the three unadjusted unity values so that no net increase or decrease of astigmatism results from this adjustment process.

The closeness of the Sim K magnitude and weighted CorT magnitudes also demonstrates the parallel effect of this non linear phenomenon, and how effectively the CorT represents the whole cornea. Of particular benefit of CorT is accuracy and consistency in identifying the most relevant meridian by employing the vectorial sum and mean of the T_{SUP} and T_{INF} semi-meridian components.

The technique provides additional safety where corneal parameters are included in the refractive treatment plan using vector planning. Vector averaging of multiple values reduces the effect of any measurement artefact or actual outliers that may occur in an automated measurement process such as CAVK.

This method of calculating semi-meridian values to quantify corneal astigmatism incorporates the keratometric magnitudes and meridian of each of the 3mm, 5mm and 7mm zones from both halves of the cornea. These two semi-meridian values can in turn undergo vector summation to provide a corneal topography astigmatism value – the CorT that quantifies the overall corneal astigmatism of the eye as determined by corneal topography. This value may have benefits over Sim K values currently employed. The semi-meridian values calculated can also provide a vectorial value for corneal irregularity – the topographic disparity. This together with the ORA value, can be used in the consulting suite as fundamental preoperative parameters to determine patient

suitability and potential for good visual outcomes when planning refractive surgery to correct for astigmatism.

The technique described also allows for adjusted weighting to be given to values closer to or further from the visual axis, by providing a factor to apportion greater or lesser relevance to their magnitudes at the measured meridian. The derived semi-meridian values, each representing one half of the cornea, can be incorporated as treatment parameters to accurately quantify the corneal astigmatism required to resolve with refractive parameters in the vector planning treatment process. Combining corneal and refractive parameters in the vector planning process for the concurrent treatment of idiopathic irregular astigmatism using these semi-meridian values, can potentially lead to greater consistency in corneal astigmatism outcomes, providing the opportunity for further refinement of overall visual outcome quality in the routine laser vision correction process.

Using the parameters in Figure 1:

Step 1. Determine the appropriate pairing of flat and steep meridian.

(i) To determine the appropriate pairing of flat and steep parameters calculate the minimum TD magnitude from the values in the 3mm zone.

First pairing (Figures 2a, 2b and 2c) -

40.46/41.23 @ 90 (0.77D @ 90) superior semi-meridian

40.68/41.54 @ 294 (0.86D @ 294) inferior semi-meridian

TD = 0.67D

Alternative pairing –

40.68/41.23 @ 90 (0.55D @ 90) superior semi-meridian

40.46/41.54 @ 294 (1.08D @ 294) inferior semi-meridian

TD = 0.82D

The first pairing has the lower irregularity value so is selected to provide adjusted astigmatism values for zones.

Step 2. Apply the appropriate weightings to the flat/steep parameters selected from (i). (Figures 3a and 4a)

3mm zone:

0.77D @ 90 (superior semi-meridian) x 1.2 (weighting for 3mm zone) = 0.92D @ 90

0.86D @ 294 (inferior semi-meridian) x 1.2 (weighting for 3mm zone) = 1.03D @ 294

Step 3. Match up the corresponding steep and flat keratometry readings in the 5mm zone by selecting the ones closest by angular separation to that in the 3mm zone.

5mm zone:

41.13/41.87 @ 100 (0.74D @ 100) superior semi-meridian

0.74D @ 100 x 1.0 (weighting for 5mm zone) = 0.74D @ 100

41.17/42.45 @ 276 (1.28D @ 276) inferior semi-meridian

1.28D @ 276 x 1.0 (weighting for 5mm zone) = 1.28D @ 276

Step 4. Again match up the corresponding steep and flat keratometry readings for the 7mm zone by selecting the ones closest by angular separation to that in the 5mm zone.

7mm zone:

42.18/43.24 @ 66 (1.06D @ 66) superior semi-meridian

1.06D @ 66 x 0.80 (weighting for 7mm zone) = 0.85D @ 66

42.30/44.04 @ 260 (1.74 @ 260) inferior semi-meridian

1.74D @ 260 x 0.80 (weighting for 7mm zone) = 1.39D @ 260

Step 5. Head-to-tail summation is used to calculate the resultant superior and inferior semi-meridian average astigmatism (Figures 3b and 4b).

Summated vector mean superior astigmatism = 0.74D @ 85 $T_{SUP\ av}$

Summated vector mean inferior astigmatism = 1.10D @ 275 $T_{INF\ av}$

(Figure 5a).

Step 6. Vectorial difference T_{SUP} and T_{INF}.

Doubling the meridian of the average superior and inferior vector mean astigmatism ($T_{SUP\ av}$ and $T_{INF\ av}$ and determining the vectorial difference on a DAVD provide the corneal irregularity or TD in diopters and degrees.

TD = 0.48D Ax 111 (Figures 5b and 6).

Step 7. Vectorial addition T_{SUP} and T_{INF} for CorT value.

Head to tail summation of superior and inferior astigmatism values to derive a corneal topography astigmatism value (CorT) which is represented on both semi meridian with equal magnitudes and 180 apart.

0.91D @91

0.91D @271

Significant ocular aberrations can reduce the quality and quantity of vision resulting in symptoms of glare, haloes, star bursting of light at night and an overall reduction in best corrected visual acuity. These commonly occur in cases of irregular astigmatism and can be measured in quantified by aberrometry. An accurate gauge of aberrations can also be calculated by vectorial differences in corneal and refractive astigmatic values to quantify the internal (non-corneal) aberrations.

The technique of vector planning is a systematic paradigm that enables the combination of corneal parameters with refractive parameters for the optimized treatment of astigmatism.

Advanced vector planning allows for treatment of naturally occurring irregular astigmatism using LASIK or PARK for each semi-meridian of the cornea. The process provides potential for improvement in visual outcomes over the exclusive use of either topographic or wavefront refractive values.

There is commonly a difference between corneal and refractive astigmatism magnitudes and/or axes. In such cases this is quantified by the ocular residual astigmatism (ORA). The ORA is a calculated vectorial value that quantifies intraocular aberrations due to differences between topographical and second order aberrometry astigmatism. Higher amounts of ORA are directly proportional to larger amounts of topographic disparity (TD) as previously shown as a calculated vectorial value to quantify corneal irregularity. Reducing ocular aberrations by minimizing the resultant ORA using vector planning can improve the visual performance of an eye.

The technique of applying vector planning independently to each semi-meridian of the cornea is described hereafter.

To further improve current astigmatic and visual outcomes in excimer laser surgery two treatment principles are paramount. Firstly, the total sum astigmatism as examined both topographically and refractively is maximally reduced (which will be a minimum value quantified by the ORA). Secondly, the minimum astigmatism remaining

on the cornea is preferentially left in a regular state. These two principles have heretofore been separately detailed for naturally occurring regular and irregular astigmatism.

Vector planning enables maximum reduction of astigmatism in such a way that the sum of the resultant topographic and refractive astigmatic targets (i.e. the ORA) is at a minimum for that individual eye's unique parameters. This remaining astigmatism is best apportioned between the topographic and refractive modalities in an optimized manner. The net effect is to leave less astigmatism remaining on the cornea and potentially achieve a better visual outcome with reduced lower and higher order optical aberrations.

Naturally occurring irregular astigmatism is widely prevalent in the population presenting for laser surgery and can be quantified using the TD evaluation. This vectorial value has a magnitude and axis, and is expressed in diopters as previously explained with 43% of eyes in a previous study having a value of greater than 1.00D. It is calculated as the separation between the two opposite semi-meridian astigmatic values representing each half of the topography map on a 720 degree double angle vector diagram (DAVD) (Figures 1 a, b and c). Note the relevant direct relationship observed that the higher the irregularity (TD) of a cornea the greater is the ORA.

To maximally reduce the astigmatism, one common value for refractive astigmatism (manifest or wavefront) can be resolved separately with two differing topographic astigmatism values; one for each semi-meridian of the cornea as shown, for example, in Figure 6. Current modes of practice using wavefront or manifest refraction only ascertain a single refractive cylinder value for the entire eye including the cornea. The additional step of regularization of the resultant reduced but still irregular corneal astigmatism is beneficial to achieve an orthogonal and symmetrical cornea and hence achieve the best visual potential for an eye.

The treatment process, according to the invention, sequentially combines the two fundamental treatment steps into one. Firstly, maximally and optimally reducing the astigmatism (step from A to B) employing both topographic and wavefront

parameters in an optimized manner, followed secondly by the regularization of the remaining corneal astigmatism (step from B to C); these two separate steps can be merged into a single step treatment process, calculated at the final orthogonal symmetrical targets C from the preoperative astigmatism state of A.

Treatment Paradigm For Naturally Occurring Irregular Astigmatism

1. The optimal reduction of astigmatism (step A to B).

Figure 7a displays a 360 degree polar (not vector) diagram of astigmatism parameters as measured by topography and refraction, in which the two pre-operative measurements do not correspond with each other in magnitude or orientation. The corneal astigmatism is irregular as the superior topographic semi meridian value (T_{SUP}) differs from the inferior topographic semi meridian value (T_{INF}) both in magnitude and orientation as shown in Figure 6, hence making it both asymmetrical and non-orthogonal. The refractive astigmatism (R), using wavefront (second order Zernike 3 and 5 cylindrical astigmatism) or manifest parameters, is displayed as a common symmetrical orthogonal value for the superior and inferior corneal semi-meridians.

Calculation Of The ORA

The first parameter that requires calculation to maximally reduce the existing astigmatism is the ORA – this is the vectorial difference between the refractive and corneal astigmatism at the corneal plane.

The existing astigmatism can be quantified by the simple arithmetic sum of the refractive and topographic components. This quantifies the sum total astigmatism to be corrected, and what proportion is uncorrected as quantified by the ORA. In the presence of corneal irregularity, the ORA can be calculated separately for each of the two semi meridians as shown in Figure 7a. The neutralization of the ORA must occur either on the cornea or in the spectacles, or in this case where operative parameters are optimized, a combination of the two (Figure 8 displays the corresponding treatment vectors). The emphasis chosen here for apportioning correction of the ORA is 40%

topographic and 60% refractive – this has previously been calculated as an average and used in a vector planning study.

The apportioning of each can vary from case to case and is dependent on the proportional theoretical topographic and refractive targets the surgeon is aiming to achieve. Where possible these targets should aim at reducing the corneal astigmatism to 0.75D and the spectacle refraction cylinder to 0.50DC or less. In cases where this is not achievable because the ORA is greater than 1.25D then another emphasis option as previously may be appropriate. Regardless of the emphasis placed on how to optimally deal with the ORA, the maximum amount of astigmatism is being treated in the optical system of any eye when the sum of the topography and refractive astigmatism targets equal the ORA. Calculating the ORA prior to surgery allows the maximum amount of astigmatism to be treated and the amount left on the cornea minimized to more acceptable levels.

Calculation Of Treatment (TIA) To Optimally Reduce Astigmatism With Minimum ORA Remaining

The target induced astigmatism vector (TIA) for astigmatic treatment for each semi- meridian is a steepening effect and hence is aligned with the axis that is being maximally ablated. The TIA is the vectorial difference, or the treatment required between the preoperative astigmatism and the target which it identifies. This treatment vector can be applied separately, to each semi-meridian ($TIA_{SUP\ AB}$ and $TIA_{INF\ AB}$), differing both in magnitude and meridian due to the differing topographic values T representing each semi-meridian . This can be represented on a DAVD - that is, the TIA vectors are doubled in axes with no change in magnitude and then applied to their corresponding preoperative topography values (on the DAVD at two times their steep meridian). This results in topographic targets (Target $T_{SUP\ B}$ and Target $T_{INF\ B}$) of the astigmatic reduction from A to B which still remain asymmetrical and non-orthogonal (Figure 8a). The same process can be applied to the common refractive astigmatism using the treatment vectors $TIA_{SUP\ AB}$ and $TIA_{INF\ AB}$ to achieve two refractive targets (Figure 8b) – one for each semi-meridian - although in practice only one refractive target is utilized.

To determine the symmetric *refractive* cylinder target (Target R_B) the net overall treatment effect (TIA $_{NET\ AB\ x2}$) is calculated by summating the applied TIA $_{INF\ AB}$ and the TIA $_{SUP\ AB}$ in a head to tail manner on a DAVD (Figure 9). The TIA $_{NET\ AB\ x1}$ (halving the magnitude since two parameters are summated) is then applied to each of the semi meridional displays of the preoperative cylindrical refraction (Figure 10a displays the orthogonal and symmetrical 'superior' and 'inferior' refractions as a pair – which overlie one another on a DAVD as they are 360° apart) resulting in the one common refractive target (Target R_B). This together with the resultant refractive and topographic targets together with the superior and inferior ORA are displayed in Figure 10b.

This optimized outcome is for the minimum amount of astigmatism to remain – this is equal to the ocular residual astigmatism (ORA) normally addressing the internal aberrations of the whole eye and in this case calculated separately for each semi-meridian.

Regularization Step (Step B To C) With Minimum Remaining ORA.

A second treatment ($TIA_{SUP\ BC}$ and $TIA_{INF\ BC}$) can then be applied to each corresponding corneal target achieved from the optimal reduction of astigmatism above (Target $T_{SUP\ B}$ and Target $T_{INF\ B}$) to achieve a symmetrical and orthogonal corneal astigmatism outcome This is done by targeting the refractive cylinder target (Target R_B) achieved from the first step (step A to B) as shown in Figure 12a. The resultant refractive targets for the superior and inferior semi meridians are displayed in Figure 12b. The final symmetrical refractive cylinder target (Target R_C) from the second step (B to C) of regularization is calculated by again averaging the superior and inferior TIA $_{BC}$ in a head to tail manner and adding this value (TIA $_{NET\ BCx1}$) to Target R_B (Figures 13a and 13b) resulting in the common refractive cylinder and the topography being aligned as displayed in Figure 14.

This refractive change from B to C by the treatment TIA $_{NET\ BCx1}$ to each of the Target R $_{B's}$ effectively quantifies each of the separate ORAs (ORA $_C$)to be the minimum possible defined in the same step as regularizing the cornea (Figure 14).

Maximum Optimized Reduction And Regularization In One Step (A To C)

The semi meridian treatments required to achieve in one step the maximum optimized reduction of astigmatism together with a symmetrical, orthogonal cornea (TIA $_{SUP\ AC}$ for superior semi meridian and TIA $_{INF\ AC}$ for inferior semi meridian) is calculated by targeting the target refraction from step A to B (Target R_B) achieved from the first process of maximally and optimally reducing the existing corneal irregular astigmatism. These treatments are then applied to both the preoperative corneal values (T $_{SUP\ A}$ and T $_{INF\ A}$) as displayed in Figure 15 to achieve the goal in one surgical treatment step of reduction and regularization. Figure 16 displays the superior and inferior treatments together with the refractive and topographic targets after maximum treatment of astigmatism and regularization in a single surgical step.

The function of a transparent cornea can be compared to the properties of a clear window pane. Just as warpage in a flat pane of glass causes distortion of transmitted contours for the observer when looking through it, so too does irregularity of the cornea reduce the equally spaced arrangement of parallel light rays that pass through it. The distortion experienced when looking through an irregular cornea can be displayed on an aberrometer using a point spread function of an image of light passing through the cornea with existing elevated high order astigmatisms (HOAs}.

In the commonly practised symmetrical treatment of corneal astigmatism, whether the astigmatism is regular or irregular, differences commonly exist between corneal and refractive astigmatism values. Conventional treatment by refractive values alone leaves all the non-corneal astigmatism (quantified by the ORA) remaining on the cornea to neutralize the internal aberrations of the eye. This can amount to more than one diopter in more than 30% of eyes treated by laser vision correction for myopia and astigmatism and more than the preoperative existing corneal astigmatism in 7% causing an overall increase in astigmatism as a result of the surgery.

Similarly the net effect of treatment by wavefront parameters alone is an excess of astigmatism left on the corneal surface than is otherwise necessary. A second

undesirable effect of aberrometric treatment of HOAs is the necessity to create irregularities on the corneal surface to neutralize those that lie behind it on the light's optical pathway to the retina without specifically attempting to regularize the cornea.

There is no question that wavefront aberrometry is an important and useful diagnostic modality to create an aspheric cornea and improve the spherical visual outcome in patients with large pupils and significant HOAs . However, an inherent disadvantage of the technology is that the aberrations measured and permanently neutralized on the corneal surface may be lenticular or perceptive, and so create a permanent change based on variables that are not stable over time.

The significance of these higher level disorders may be visual cortex and/or occipital perceptions of astigmatism at the visual cortex that influence the manifest refraction is substantially unmeasured and excluded from treatment using aberrometry alone. These non optical astigmatic influences can have a significant effect on the treatment applied to the cornea and its resultant shape when the manifest refraction is the exclusive guiding paradigm. In conventional refractive treatments these are not moderated by any topographic input at all.

There are major theoretical and practical obstacles to the dependence upon wavefront values being used alone as a treatment modality which has also been recognized by other authors. The key benefit of vector planning in the treatment process is the ability to combine preoperative corneal astigmatism parameters with those for refractive wavefront astigmatism in a systematic manner. In this way, the cornea can be protected against astigmatism considered to be unfavorable (such as against-the-rule or oblique), and so avoid excess astigmatism remaining in such cases and its consequent higher order aberrations such as coma or trefoil. Using the technique described, any unavoidable ORA that does remain neutralized on the cornea can be left in an orthogonal symmetric (regular) state, resulting in reduced distortion of parallel light rays as they pass through the cornea. In this manner an optimal visual outcome is possible with both reduced and regularized corneal astigmatism and potentially reduced aberrations.

Figures 8 and 9 display the maximum reduction of astigmatism. Targeting less corneal astigmatism theoretically shifts a proportion of the remaining astigmatism to the refractive level. In practice this has been shown to be less than expected when actual post operative manifest refractions are measured and evaluated. The vector planning technique employing asymmetrical corneal astigmatism treatments (Figure 8) attempts to minimize the non-corneal astigmatism, quantified by ORA, hence gaining the maximum correspondence between corneal and refractive values and potentially improve the optical quality of the perceived image. The best possible equivalence between these two is likely to minimize both lower and higher order optical aberrations within the eye.

It is envisaged that wavefront measurements are likely in future to make it possible to better match two differing refractive values, one for each semi-meridian, with the two separate topographic values on the cornea, hence employing a separate refractive and topographic measurement for each corneal semi-meridian. This combined treatment paradigm has a greater potential for improving the best corrected vector analysis (BCVA) than using wavefront or topography parameters alone. The ideal ablation shape to effectively correct irregular astigmatism will be determined by an ellipse that has modified dimensions for each semi-meridian. The ellipses may be angularly displaced to achieve the non-orthogonal and asymmetrical treatment requirements.

The treatment changes necessary to address these asymmetrical and non-orthogonal values of the cornea are achieved by creating gradual and undulating variations in contour between the principal meridian of the cornea. Smooth continual rather than rough abrupt changes have a greater prospect for being sustained to combat the natural forces of epithelial healing that over time are likely to smooth out any localised applied unevenness.

The method of vector planning can be expanded upon to refine outcomes in cases of irregular astigmatism. Utilizing asymmetrical vector planning with a separate astigmatism treatment plan for each separate semi-meridian of the cornea would likely result in less overall astigmatism and a more regular corneal profile at the completion of a single corneal surgery correcting sphere and irregular cylinder. Incorporation of these

algorithms into future excimer laser technology would potentially improve the outcomes currently achieved by the treatment of spherocylinder in laser vision correction.

Calculation Of Treatment For Maximum Reduction Of Astigmatism And Regularization Of Cornea

The first step in the process is the maximum reduction of astigmatism and has been referred to as step A to B (AB) and the second step the regularization of the cornea as step B to C (BC).

Preoperative parameters are displayed in Figure 7a.

Superior topography 2.60D @ 130

Inferior topography 1.90D @ 278

Wavefront refraction -3.24DS / -1.80DC x 18 (BVD = 12.5mm)

The separate semi meridian astigmatic treatments ($TIA_{SUP\ AB}$ and $TIA_{INF\ AB}$) are displayed in Figure 8 and are calculated based on emphasis of 40% sphericizing the cornea / 60% sphericizing the refractive cylinder with an existing ORA of 1.82D Ax 59 for the superior semi- meridian. The inferior semi-meridian treatment is also based on 40% sphericizing the cornea/ 60% sphericizing the refractive cylinder applied to an existing ORA of 0.67D Ax 340. Irrespective of the emphasis chosen for the ORA, the maximum amount of astigmatism is being treated in each semi meridian of the cornea.

The vectorial difference between the preoperative topography and the target topography, as determined by the emphasis on neutralizing the ORA, is equal to the astigmatic treatment (TIA) for each semi-meridian. The topography targets (Target $T_{INF\ B}$ and Target $T_{SUP\ B}$) are displayed in Figure 9.

When the TIA between the two semi-meridians differs, a summation of the TIA's ($TIA_{NET\ AB}$) or average needs to be calculated (Figure 10) to determine the combined effect on refractive astigmatism. The average of the treatment vectors, the TIA

$_{NET\ AB}$, is calculated using a head to tail summation of the TIA $_{SUP\ AB}$ and TIA $_{INF\ AB}$ which is then divided by 2 because there are 2 values involved in the summation calculation:

1.87D Ax 29 + 1.71D Ax 194 = 1.73D Ax 22

The average treatment vector TIA $_{NET\ AB}$ is added to each of the common pair of refractive values of +1.63 Ax 108 for the 2 semi-meridians (then the axis subsequently is halved to convert to a polar diagram as it would appear on the eye) to obtain a refractive cylinder target (R_B) displayed in Figure 11:

1.63 Ax 108 + [+1.73 Ax 22] = +0.25 Ax 53 (R_B)

To regularize the cornea, the topography targets after the first process of the maximum optimized reduction of astigmatism (Target T $_{INF\ B}$ and Target T $_{SUP\ B}$) (step AB) have a second treatment added (TIA $_{SUP\ BC}$ and TIA $_{INF\ BC}$) to target the initial refractive cylinder result (Target R_B) of +0.25D Ax 53 (axis 106 on DAVD displayed in Figure 12).

In this example the resultant topography (Target T $_{INF\ C}$ and Target T $_{SUP\ C}$) and the final refraction (Target R_C), which again is calculated by vectorially adding the 2 treatments TIA $_{SUP\ BC}$ and TIA $_{INF\ BC,}$ are aligned (Figure 14) resulting in minimum remaining ORA when Target R_B shifts to Target R_C from the resultant net refractive change.

The remaining ORA i.e. the vectorial difference between the final topography and refractive cylinder targets is at a minimum. The topography targets equal 0.25D @ 53 and result from the maximum reduction of astigmatism and regularization and the effect of the second treatments to regularize the cornea (TIA $_{SUP\ BC}$ and TIA $_{INF\ BC}$). These regularization changes of the second process (BC), affect the refractive target (Target R_B) → Target R_C = 0.87D Ax 53 by shifting an amount equal to the resulting final ORA of 0.62D Ax 53.

One Step Treatment For Maximum Reduction And Regularization Of Irregular Astigmatism (Step A to C).

The treatment required to maximally reduce (AB) and regularize the astigmatism (BC) in one step begins with the 2 preoperative corneal values (T_{SUP} and T_{INF}) targeting the refractive target (Target R_B) that is calculated from step AB. The single step treatment here (TIA $_{SUP\ AC}$ and TIA $_{INF\ AC}$ in figure 15) is the addition of the TIA superior and TIA inferior treatment vectors calculated in step AB (Figure 9) and step BC (Figure 12).

Preoperative parameters

Superior topography 2.60D @ 130

Inferior topography 1.90D @ 278

Treatment

Superior TIA $_{AC}$= 2.82D Ax 131 (TIA SUP AB + BC)

Inferior TIA $_{AC}$= 1.91D Ax 102 (TIA INF AB + BC)

Targets

Superior topography 0.25D @ 53

Inferior topography 0.25D @ 233

Refractive target (Target R_C) +0.87D Ax 53

Symmetrical And Orthogonal Outcome Is Thus Obtained.

Figure 17 is a diagrammatic illustration of apparatus for carrying out the methods hereto described.

Therein can be seen a topographer 50 for producing a map of the cornea from which corneal values can be obtained in the 3mm, 5mm, and 7 mm zones. Figure 17 also shows a refractive measuring device which can determine the refractive condition of the eye of a patient. The parameters obtained from the topographer 51 and the refractive measuring device 52 are supplied to computer 53 which carries out the operations heretofore described to produce the topography parameters T sup and T inf as well as TD and CorT and the parameters for TIA sup and TIA inf for the semi-meridians which will provide maximum topographic reduction and minimal ORA.

WHAT IS CLAIMED IS:

1. A method for determining parameter of magnitude and meridian axis representing corneal astigmatism for use in vector analysis for diagnostic and surgical treatment, comprising the steps of:

producing a keratometric map of topographic measurements of each of two semi-meridians of the cornea of an eye,

assigning weighting values to the topographic measurements in each of a plurality of zones in each semi-meridian, and

vectorially combining the weighted values of the topographic measurements to obtain a vector parameter in each semi-meridian representing magnitude and axis of topographic irregularity which is adapted for use in diagnostic and surgical treatment.

2. The method as claimed in claim 1, wherein said plurality of zones are formed as concentric circular zones.

3. The method as claimed in claim 2, comprising selecting in each said zone a parameter of steepest magnitude and a parameter of flattest magnitude and combining these parameters to obtain a single parameter of magnitude and meridian in each said zone, and vectorially combining the single parameters in said zones to obtain a single topographic parameter of magnitude and meridian for each respective semi-meridian.

4. The method as claimed in claim 3, comprising combining the parameters of magnitude and meridian in each semi-meridian to obtain a single topographic parameter of magnitude and meridian for each semi-meridian of the cornea.

5. The method as claimed in claim 4, comprising adding the topographic parameters of the semi-meridians to obtain a single topographic value for the entire cornea representing corneal topography astigmatism (CorT).

6. The method as claimed in claim 4, comprising subtracting the topographic parameters in the semi-meridians from one another to obtain a topographic parameter representing topographic disparity (TD) between the semi-meridians.

7. The method as claimed in claim 2, wherein each semi-meridian is formed with three said successive zones.

8. The method as claimed in claim 7, wherein the successive zones in each semi-meridian are at 3mm, 5mm and 7mm.

9. The method as claimed in claim 7, wherein the parameters of magnitude in each of the respective zones is multiplied by the respective weighting factors to produce the weighted values of magnitude in the zones.

10. The method as claimed in claim 9, wherein the parameters of magnitude and meridian are combined by vectorially averaging these parameters on a double angle vector diagram.

11. The method as claimed in claim 1 wherein a value of ocular residual astigmatism (ORA) is obtained by determining the vectorial difference between the corneal and refractive astigmatism values.

12. The method as claimed in claim 7 comprising reducing the parameters of magnitude in each of said semi-meridians to obtain maximum values of topographic parameters by leaving minimum values of ocular residual astigmatism in each semi-meridian that are equal in magnitude but are asymmetrical, and regularizing the thus obtained values of topography in said semi-meridians to obtain topography parameters which are symmetrical and orthogonal in one step.

13. The method as claimed in claim 12 wherein the symmetrical topographic parameters are regularized by vectorially combining each thereof with a common refractive astigmatism value.

14. The method as claimed in claim 13 wherein said common refractive astigmatism value is obtained by reducing a measured refractive parameter by reducing said measured vectorial parameter by a proportional amount of said ocular residual astigmatism.

15. A method for reducing and regularizing measured values of astigmatism in an eye of a patient to obtain target values for diagnosis and treatment of the patient, said method comprising the steps of:

considering the cornea of an eye of a patient to be divided into superior and inferior semi-meridians;

measuring corneal and refractive astigmatism values in each of the semi-meridians;

determining topographic treatment parameters in each semi-meridian to maximally reduce the topographic astigmatism values in each of the semi-meridians based on minimizing ocular residual astigmatism remaining in each semi-meridian; and

regularizing the thus reduced topographic treatment parameters using a common refractive parameter for the two separate semi-meridians to obtain in one step from said determining step to said regularizing step, final treatment target values for the two semi-meridians.

16. The method as claimed in claim 15, wherein said topographic treatment parameters (Target T) for each of the semi-meridians is vectorially combined with a common refractive target value R to obtain treatment parameters (TIA) for each semi-meridian in which targets T are regularized.

17. The method as claimed in claim 16, wherein the determined topographic values T are maximally reduced to leave a minimum value of ORA to be neutralised on the cornea .

18. The method as claimed in claim 17, wherein the TIA parameters for each semi-meridian is determined by first applying emphasis factors on each topography and refractive parameter to obtain topographic targets T and refractive target R for each semi-meridian, then obtaining an average target T for the two semi-meridians whereafter the average value of target T is vectorially combined with target R for each semi-meridian.

19. Apparatus for carrying out the method as claimed in claim 15 comprising:

a keratometer for measuring the cornea of the eye of a patient to obtain topographic parameters thereof in each semi-meridian of the cornea,

a device for refractive measurement of the eye to obtain a refractive parameter for both semi-meridians, and

a computer receiving the topographic and refractive parameters including means for reducing the topographic parameters to a minimum value of ORA to obtain maximum treatment to the minimum topographic target parameters T and refractive target R for each semi-meridian, and means for vectorially combining the topographic parameters T and the refractive parameter R to obtain target induced astigmatism parameters (TIA) which produce said topographic targets T which are regularized.

20. Vector planning apparatus for obtaining target parameters for surgical use comprising:

means for obtaining parameters representing topography of an eye in superior and inferior semi-meridians of the cornea,

means for obtaining a parameter representing a refractive value for each semi-meridian, and

a computer means for carrying out the steps of:

a) determining a target topographic vector for each semi-meridian from the obtained topography parameters and

b) vectorially combining said target topographic vector with the refractive value to obtain treatment vectors for the semi-meridians which are equal and regularized.