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(54) Title: VISION ENHANCEMENT SYSTEMS AND METHODS

(57) Abstract: Vision enhancement systems and methods facilitate determining or estimating an optical alignment of a lens in relation to the visual axis of an eye and applying the optical alignment to an action or process of providing, facilitating, and/or presenting one or more ophthalmic assessments.

Vision Enhancement Systems and Methods

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the priority of U.S. provisional Application No. 61/635,825, filed on April 19, 2012, the full disclosure of which is incorporated herein by reference.

TECHNICAL FIELD

The invention relates generally to vision enhancement and, in particular, to systems and methods for providing, facilitating, and/or presenting one or more ophthalmic assessments.

BACKGROUND ART

Modern cataract surgery not only influences total eye astigmatism and serves to correct astigmatism from the cornea, but also has been confirmed to differentially affect higher order aberrations such as coma and trefoil depending on the incisional approach used. *See, e.g.*, Alió, J.L., et al., "Corneal Optical Quality Following Sub 1.8 mm Micro-Incision Cataract Surgery vs. 2.2 mm Mini-Incision Coaxial Phacoemulsification," *Middle East Afr J Ophthalmol*, Vol. 17, No. 1 (January 2010), pp. 94-99, which is hereby incorporated by reference. The ability to increase or decrease higher order aberrations with corneal incisions is important to predicting postoperative HOAs with respect to multifocal IOL candidacy, and potentially in creating incisional strategies to reduce or eliminate HOAs at the time of surgery. It would be useful to be able to provide a decision tool to assist surgeons with lens (e.g., IOL) selection and determining a treatment plan for each eye.

SUMMARY OF THE INVENTION

In an example embodiment, a method for enhancing vision includes: determining an estimated anatomical misalignment of a center of a lens following implantation of the lens in an eye, and applying the estimated anatomical misalignment to ocular information associated with the eye to control, generate, or provide a visual representation.

In an example embodiment, a method for enhancing vision includes: determining an estimated anatomical misalignment of a center of a lens following implantation of the lens in an eye, and applying the estimated anatomical misalignment to ocular information associated with the eye to facilitate, control, or initiate an action or process involving one or more of: controlling, generating, or providing a visual representation, comparing one or more vision enhancement procedures and/or products, selecting one or more vision enhancement procedures and/or products, identifying one or more candidate lens, selecting a lens and performing a surgical procedure involving the lens and the eye, selecting a surgical procedure and performing the surgical procedure on the eye, and inducing, simulating, estimating, or predicting a postoperative result in relation to one or more vision enhancement procedures and/or products.

In an example embodiment, a method for assessing potential candidates for lens implantation includes: using Angle Alpha and ocular anatomy information associated with one or more eyes to determine the location of the optical center for the one or more eyes; using the location of the corneal vertex and the location of the optical center to determine the visual axis for each of the one or more eyes; using a point along the visual axis and intersecting with a plane perpendicular to the lens axis to determine, for each of the one or more eyes, an optical alignment of the lens in relation to the visual axis; and applying the one or more optical alignments to ocular information associated with the one or more eyes to facilitate, control, or initiate an action or process of estimating outcomes for one or more lens implantation procedures.

In an example embodiment, a method for facilitating a vision enhancement procedure includes: accessing ophthalmic information for one or more eyes; and applying one or more criteria to the information to facilitate or initiate an action or process of controlling, generating, or providing a visual representation of one or more of a preoperative status associated with the one or more eyes, candidate vision enhancement procedures and/or products, estimated postoperative results for one or more vision enhancement procedures and/or products, a comparison of pre and postop corneal astigmatism, angle alpha associated with one or more of the eyes, an estimate of visual axis to lens deviation associated with one or more of the eyes, estimated image quality for one or more vision enhancement procedures and/or products, estimated surgeon specific surgically induced changes, an estimated postoperative assessment, a comparison of lenses that is one or more of surgeon-specific, lens style-specific, and surgical procedure-specific or approach-specific, one or more personalized parameters or determinations, and an indication of cases having desired outcomes.

In an example embodiment, a method for assessing surgically induced changes includes: measuring, determining, or estimating pre and postop corneal wavefront astigmatisms for an eye; and applying the pre and postop corneal wavefront astigmatisms in an action or process of controlling or utilizing one or more electronic devices and/or display devices to provide a visual representation of one or more surgically induced changes.

In an example embodiment, a method of selecting a vision enhancement procedure and/or product includes: for multiple subjects, utilizing pre and postoperative ophthalmic information including corneal topography and IOL centration relative to the corneal vertex to map surgeon-specific, IOL-specific surgically-related tendencies in relation to multiple different IOLs.

In an example embodiment, a method of selecting a vision enhancement procedure and/or product includes, for each of a series of subjects: obtaining corneal topography information for a preoperative eye, after implanting an IOL lens, determining IOL centration relative to the corneal vertex; after determining IOL centration, determining for all or a plurality of subjects of the series that have been postoperatively measured an aggregate or average estimated surgically induced change; and applying the aggregate or average estimated surgically induced change to control one or more electronic displays in relation to generating, updating, or providing a visual representation pertaining to one or more surgically induced changes.

In an example embodiment, a vision enhancement system includes: a computer-executable software application configured or programmed to receive or access ocular information associated with one or more eyes and to process the ocular information in relation to determining an optical center and a corneal vertex for an eye, using the optical center and corneal vertex to determine a visual axis for the eye, determining an intercept of the visual axis with a lens plane, and using the intercept to determine an optical alignment of the lens in relation to the visual axis.

In an example embodiment, a vision enhancement method includes: measuring an image location at the retina and an axial length of the eye to approximate a visual axis of the eye; using an optic diameter to determine the distance between the cornea and the lens; determining an intercept of the visual axis with a lens plane; using the intercept to determine an optical alignment of the lens in relation to the visual axis; and applying the optical alignment to an action or process of providing, facilitating, and/or presenting one or more ophthalmic assessments.

In an example embodiment, a vision enhancement system includes: a computer-executable software application configured or programmed to receive or access ocular information associated with one or more eyes and to process the ocular information in relation to measuring an image location at the retina and an axial length of the eye to approximate a visual axis of the eye, using an optic diameter to determine the distance between the cornea and the lens, determining an intercept of the visual axis with a lens plane, and using the intercept to determine an optical alignment of the lens in relation to the visual axis.

In an example embodiment, a vision enhancement method includes: utilizing estimated or a priori determined coordinates of the visual axis at the cornea to locate arcuate corneal incisions during femtosecond laser surgery of the eye.

In an example embodiment, a vision enhancement method includes: selecting and/or optimizing one or more vision correction modalities in consideration of foveal curvature.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows an example embodiment of a vision enhancement system;

FIG. 2 shows an example embodiment of a vision enhancement method;

FIGs. 3-5 illustrate the relation between Angle Alpha, the Corneal Vertex and Lens Alignment with the Visual Axis;

FIG. 6 is an example eye image showing the visual axis, pupil margin, pupil center, limbal center, and the 4th Purkinje image of the 4-point illumination pattern;

FIG. 7 shows an example visual representation of a “dashboard” for providing, facilitating, and/or presenting one or more ophthalmic assessments;

FIG. 8 shows an example group of visual representations pertaining to estimated image quality performance of advanced aspheric IOLs;

FIG. 9 shows an example “IOL Selection Overview” interface/visual representation;

FIG. 10 shows an example “Preoperative Assessment” interface/visual representation;

FIG. 11 shows an example “Multifocal IOL Summary” interface/visual representation;

FIG. 12 shows an example “Toric IOL Summary” interface/visual representation;

FIG. 13 shows an example “Monofocal IOL Summary” interface/visual representation;

FIGs. 14 and 15 show example visual schemes utilized to present to a user factors or determinations relevant to selecting a vision enhancement procedure and/or product;

FIG. 16 is a flow diagram representing alternative techniques for determining visual axis;

FIG. 17 shows an IOL during dilation of the eye;

FIG. 18 shows an example of a visual axis of the eye;

FIG. 19 shows an example of an approximated visual axis;

FIG. 20 shows an example of an anterior capsulotomy;

FIG. 21 shows centering of arcuate corneal incisions for the treatment of astigmatism;

FIGs. 22 and 23 show the impact of residual positive spherical aberration on retinal image curvature at the fovea;

FIGs. 24 and 25 show the impact of residual negative spherical aberration on retinal image curvature at the fovea;

FIG. 26 illustrates geometrically how the radius of curvature of image focus can be estimated by assuming that the image surface is part of a sphere; and

FIG. 27 illustrates geometrically how the radius of curvature of image focus can be determined in consideration of a curved (non-spherical) imaging surface.

DISCLOSURE OF INVENTION

Example embodiments described herein generally involve systems and methods for providing, facilitating, and/or presenting one or more ophthalmic assessments. An example methodology includes: determining or estimating an optical alignment of a lens in relation to the visual axis of an eye; and applying the optical alignment to an action or process of providing, facilitating, and/or presenting one or more ophthalmic assessments (e.g., in relation to one or more vision enhancement products and/or procedures).

Referring to FIG. 1, in an example embodiment, a vision enhancement system 100 includes biometry device(s) 102, corneal topography/integrated topo/aberrometry device(s) 104, processing module(s) 106 (e.g., computers, system applications, add-ins), database(s) 108, display(s) 110 (e.g., electronic and/or computer-controlled display, user interface), and (additional) user input mechanism(s) 112 configured as shown. The biometry device(s) 102 can include one or more systems, apparatuses, or devices such as the commercially-available products: IOLMaster 500 (Carl Zeiss International) and LENSTAR LS900® biometry product (Haag-Streit AG, Switzerland). The corneal topography/integrated topo/aberrometry device(s) 104 can include one or more systems, apparatuses, or devices such as the commercially-available products: OPD-Scan III Wavefront Aberrometer (NIDEK Inc., Fremont, CA), iTrace Wavefront Aberrometer/Topographer (Tracey Technologies, Houston, Texas), and ATLAS™ 9000 Corneal Topography System (Carl Zeiss International).

FIGs. 3-5 illustrate the relation between Angle Alpha, the Corneal Vertex and Lens Alignment with the Visual Axis. As can be seen in the right eye anterior/posterior section view (FIG. 3), the apex of the cornea, or corneal vertex, is rarely perfectly aligned with the lens. Rather the corneal vertex is shifted in most eyes giving rise to the visual axis as shown by the arrow (denoted “VA”) in FIG. 4. In the case shown in FIGs. 3 and 4, the cornea is shifted nasally, which allows incoming paraxial light to be focused near the fovea. This shifting of the corneal vertex also shifts the optical center of the eye, sometimes referred to as the “nodal point”, shown as the black point (denoted

"NP") in FIGs. 3 and 4. In doing so, the lens is then effectively misaligned from the visual axis as shown in FIG. 5.

Angle Alpha is shown in FIG. 5 as the angular measure of alignment between the corneal vertex and the lens center. The iTrace Wavefront Aberrometer/Topographer can be utilized to estimate the lens center using the limbal center. Angle Alpha measurements can be obtained utilizing the LENSTAR LS900® biometry product.

Angle Alpha estimates the relation between the corneal vertex and the lens center, but does not directly determine lens alignment relative to the visual axis, which is shown in FIG. 5 (denoted as "Anatomical Misalignment"). Systems and methods described herein facilitate determining the actual anatomical misalignment shown in FIG. 5 for a given Angle Alpha and ocular anatomy. This approach is generalizable to the case of pseudophakic eyes and IOLs.

The lens center may also be identified as described herein utilizing the 4th Purkinje image reflection. Referring to FIG. 6, the example eye image shows the visual axis, pupil margin, pupil center, and limbal center. The 4th Purkinje image (denoted "4PI") of the 4-point illumination pattern gives a more direct measure of the lens center.

For a great many ocular physiologies, Purkinje image reflections can be utilized to determine the lens center. In the case of a well aligned lens (of the eye), the 4th Purkinje image may be difficult to distinguish from the 1st Purkinje image. In IOL cases, a subset of anterior and posterior IOL curvatures could potentially lead to large reflection angles and images that are not within the visible aspect of the anterior chamber. Regardless, a light source or other device configured to generate or provide a Purkinje pattern is believed to be suitable in relation to reliably capturing images for the vast majority of eyes. *See also*, Dunne, M.C.M., et al., "Peripheral astigmatic asymmetry and angle alpha," *Ophthal. Physiol. Opt.*, 1993, Vol. 13 (July 1993), pp. 303-305 (hereafter, "Dunne"), which is hereby incorporated by reference.

In example embodiments, the light source includes one or more beams or rays. By way of example, infrared light rays directed (e.g., sequentially) along multiple different parallel paths can be utilized to assess lens alignment. The iTrace Wavefront Aberrometer/Topographer (Tracey Technologies, Houston, Texas) can be utilized to provide such a light source. In example embodiments, multiple lens alignment determinations made at different known light source (e.g., laser beam) locations are utilized to provide a lens alignment assessment for an eye. By way of example, multiple lens alignment determinations (e.g., associated with 256 paraxial laser beam locations, respectively) are averaged to provide a lens alignment assessment. One or more (e.g., groups) of the lens alignment determinations can also be weighted or adjusted depending, for example, on a quality or other metric associated with determinations made in association with different groups of the known light source locations.

Referring to FIG. 2, in an example embodiment, a vision enhancement method 200 includes, at 202, determining optical center and corneal vertex for an eye. At 204, the optical center and corneal vertex are used to determine visual axis for the eye (e.g., calculate 3D linear equation of the visual axis as described below). With the visual axis determined, at 206, the intercept (e.g., intercept point location: X_{IOL}, Y_{IOL}, Z_{IOL}) of the visual axis with the lens plane (e.g., IOL plane) is determined. At 208, the intercept is used to determine an optical alignment of the lens in relation to the visual axis (e.g., determine custom lens alignment factor, $r_o = \sqrt{(X_{IOL}\text{^}2 + Y_{IOL}\text{^}2)}$). At 210, the optical alignment is applied to an action or process of providing, facilitating, and/or presenting one or more ophthalmic assessments (e.g., in relation to one or more vision enhancement products and/or procedures).

In an example methodology, the location of the optical center of each eye is determined (e.g., calculated as described herein). The approach has been generalized to any pseudophakic eye to estimate optical alignment that would result from IOL implantation, which involves using:

- Approximate IOL parameters such as thickness, anterior/posterior power, postop location behind the cornea, and the index of refraction of the IOL material.
- Measured value of Angle Alpha
- The SRK II to estimate the IOL power needed given the corneal power, axial length and expected IOL position.
- Expected surgical change in corneal astigmatism

In this example methodology, once the location of the optical center (x, y, z) has been calculated for a particular eye a three dimensional linear equation is used to find the intersection of the visual axis and the plane perpendicular to the lens axis at its center point (denoted "A") in FIG. 5. The anatomical misalignment of the lens center from the visual axis can then be calculated (e.g., in mm) from the location of point A on the visual axis.

The following two sections describe example approaches to determining anatomical misalignment of the IOL center from the visual axis and estimating IOL power for each eye.

Determining Anatomical Misalignment of the IOL Center from the Visual Axis

Consider the astigmatic eye with a single-surface corneal power K_s @ θ_s & K_f @ θ_f, that is, the steep principal meridian lies at θ_s (°) and the flat principal meridian lies at θ_f (°) and the corresponding principal powers along them are K_s (D) and K_f (D), respectively. By definition $K_s \geq K_f$ and θ_s and θ_f are typically 90° apart. The lens has front and back surface powers LA_s (D) and LA_f (D) at meridia α_s (°) and α_f (°) and LP_s (D) and LP_f (D) at meridia β_s and β_f. The reduced distance between the cornea and the lens is ACD (mm) and between the lens and the retina PCD (mm). The lens has reduced thickness L (mm). We suppose further that all the refracting surfaces are centered on longitudinal lens axis Z except that the cornea is decentered $Alpha_x$ (mm), $Alpha_y$ (mm) from the corneal vertex. The index of the lens is n_L and the index of the rest of the eye is n_{aq}.

The length of the eye is then

$$z = n_{aq} \times ACD + n_L \times L + n_{aq} \times PCD.$$

Undecentered the cornea would have transference

$$\mathbf{T}_1 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ -(K_s - K_f) \times \sin\text{^}2(\theta_s) & 0 & 1 & 0 & 0 \\ 0 & -(K_s - K_f) \times \cos\text{^}2(\theta_s) & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}.$$

Decentration of $Alpha_x$ (mm), $Alpha_y$ (mm) is equivalent to displacing the longitudinal axis -$Alpha_x$ (mm), -$Alpha_y$ (mm). That is, from Equation 11, of Harris, W.F., "Optical Axes of Eyes and Other Optical Systems," *Optometry and Vision Science*, Vol. 86, No. 5 (May 2009), pp. 537–541 and *Appendix*, which are hereby incorporated by reference,

$$\mathbf{d}_{Z0}^{*} = \begin{pmatrix} -\mathrm{Alpha}_x \\ -\mathrm{Alpha}_y \\ 0 \\ 0 \end{pmatrix}.$$

From Equation 22 (of Harris)

$$\mathbf{P}_1 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -(K_s - K_f)\times \sin\text{^}2(\theta s) & 0 & 1-n_{aq} & 0 \\ 0 & -(K_s - K_f)\times \cos\text{^}2(\theta s) & 0 & 1-n_{aq} \end{pmatrix}$$

for the cornea. Thus, from Equation 21 (of Harris), the decentered cornea has

$$\delta_1 = \mathbf{P}_1 \mathbf{d}_{Z0}^{*} = \begin{pmatrix} 0 \\ 0 \\ (K_s - K_f)\times \sin\text{^}2(\theta s)\times Alpha_x \\ (K_s - K_f)\times \cos\text{^}2(\theta s)\times Alpha_y \end{pmatrix}$$

and, hence, transference

$$\mathbf{T}_1 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ -(K_s - K_f)\times \sin\text{^}2(\theta s) & 0 & 1 & 0 & (K_s - K_f)\times \sin\text{^}2(\theta s)\times Alpha_x \\ 0 & -(K_s - K_f)\times \cos\text{^}2(\theta s) & 0 & 1 & (K_s - K_f)\times \cos\text{^}2(\theta s)\times Alpha_x \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}.$$

The anterior chamber has transference

$$\mathbf{T}_2 = \begin{pmatrix} 1 & 0 & ACD & 0 & 0 \\ 0 & 1 & 0 & ACD & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}.$$

The transference of the first surface of the lens is

$$\mathbf{T}_3 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ -(LA_s - LA_f)\times \sin\text{^}2(\alpha_s) & (LA_s - LA_f)\times \sin(\alpha_s)\times \cos(\alpha_s) & 1 & 0 & 0 \\ (LA_s - LA_f)\times \sin(\alpha_s)\times \cos(\alpha_s) & -(LA_s - LA_f)\times \cos\text{^}2(\alpha_s) & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix},$$

the transference of the body of the lens is

$$\mathbf{T}_4 = \begin{pmatrix} 1 & 0 & L & 0 & 0 \\ 0 & 1 & 0 & L & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix},$$

and the transference of the second surface of the lens is

$$\mathbf{T}_5 = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ -(LP_s - LP_f)\times \sin\text{^}2(\beta_s) & (LP_s - LP_f)\times \sin(\beta_s)\times \cos(\beta_s) & 1 & 0 & 0 \\ (LP_s - LP_f)\times \sin(\beta_s)\times \cos(\beta_s) & -(LP_s - LP_f)\times \sin\text{^}2(\beta_s) & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}.$$

Finally the transference of the posterior portion of the eye is

$$\mathbf{T}_6 = \begin{pmatrix} 1 & 0 & PCD & 0 & 0 \\ 0 & 1 & 0 & PCD & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}.$$

It follows that the transference of the eye is, from Equation A6 (of Harris),

$$\mathbf{T} = \mathbf{T}_6\mathbf{T}_5\mathbf{T}_4\mathbf{T}_3\mathbf{T}_2\mathbf{T}_1\text{, or}$$

$$\mathbf{T} = \begin{pmatrix} \mathbf{A} & \mathbf{B} & \mathbf{e} \\ \mathbf{C} & \mathbf{D} & \boldsymbol{\pi} \\ \mathbf{0} & \mathbf{0} & \mathbf{1} \end{pmatrix} \textbf{ where } \boldsymbol{\delta} = \begin{pmatrix} \mathbf{e} \\ \boldsymbol{\pi} \end{pmatrix}$$

From Equation 22 (of Harris) we obtain

$$\mathbf{P} := \begin{pmatrix} \mathbf{A} - \mathbf{I} & \mathbf{nair} \times \mathbf{B} - \mathbf{z} \times \mathbf{I} \\ \mathbf{C} & \mathbf{nair} \times \mathbf{D} - \mathbf{naq} \times \mathbf{I} \end{pmatrix}$$

which has rank 4 and so is nonsingular. Hence $\mathbf{P}^{-} = \mathbf{P}^{-1}$.

Then the *incident nodal characteristic* is given by

$$\mathbf{No} := \mathbf{C}^{-1} \times (\mathbf{n}_{\mathbf{air}} \times \mathbf{D} - \mathbf{n}_{\mathbf{aq}} \times \mathbf{I}).$$

See, Harris, W.F., “Nodes and nodal points and lines in eyes and other optical systems,” *Ophthalmic and Physiological Opt*ics, Vol. 30, No. 1 (2010), pp. 24–42 (hererafter, “Harris, 2010”), which is hereby incorporated by reference.

Then one can define

$$N_{0I} = ½\,(n011 + n022).$$

The incident node is centered on

$$z_{N0m} = N_{0I},$$

the *incident mid nodal longitudinal position*. *See*, Harris, 2010.

Then the intersection of the optical axis with the incident mid nodal plane is given by the two dimensional vector (*See again*, Harris, 2010)

$$\mathbf{y}^*_{\mathbf{No}} := -(\mathbf{I} \quad \mathbf{N_{0I}}\,\mathbf{I}) \times \mathbf{P}^{-1}\boldsymbol{\delta}.$$

Then the emergent *incident nodal characteristic* is given by

$$\mathbf{N} := \mathbf{C}^{-T} \times (\mathbf{n_{air}} \times \mathbf{I} - \mathbf{n_{vit}} \times \mathbf{A}^{T})$$

The emergent node is center on

$$z_{Nm} = N_I = ½\,(n11 + n22)$$

the *emergent mid nodal longitudinal position*. Similarly, and with reference to Equations 106-110 (reproduced below) of Harris, 2010, the intersection of the optical axis with the emergent nodal plane is given by the vector

$$\mathbf{y}^*_{\mathrm{N}} = -(\mathbf{I} \quad (N_{\mathrm{I}} + z)\mathbf{I})\mathbf{P}^{-1}\delta. \qquad (106)$$

The point halfway between the incident and emergent nodal centers represents an approximation to an optical center of the optical system. It is the approximate optical center of the system. Relative to entrance plane its longitudinal position is

$$z^* := \tfrac{1}{2}(z_{\mathrm{N0m}} + z_{\mathrm{Nm}} + z) \qquad (107)$$

or, from Equations 34 and 69 (of Harris, 2010),

$$z^* = \tfrac{1}{2}(N_{01} + N_1 + z). \qquad (108)$$

For nodal centers represented by the two dimensional vectors $\mathbf{y}^*_{\mathbf{No}}$ and $\mathbf{y}^*_{\mathbf{N}}$ the transverse position of the approximate optical center is

$$\mathbf{y}^* := \tfrac{1}{2}(\mathbf{y}^*_{\mathrm{N0}} + \mathbf{y}^*_{\mathrm{N}}). \qquad (109)$$

From Equations 105 and 106 this can be expressed explicitly as a linear function of d:

$$\mathbf{y}^* = -(\mathbf{I} \quad z^*\mathbf{I})\mathbf{P}^{-1}\delta. \qquad (110)$$

Thus the location of the optical center of the eye in space is given by:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \mathrm{y} * 11 \\ \mathrm{y} * 21 \\ \mathrm{z} * \end{pmatrix}.$$

The three dimensional equation for the visual axis can be determined by the location of the corneal vertex and the optical center:

$$\begin{pmatrix} \mathrm{X}va \\ \mathrm{Y}va \\ \mathrm{Z}va \end{pmatrix} = \begin{pmatrix} \mathrm{y} * 11 \\ \mathrm{y} * 21 \\ \mathrm{z} * \end{pmatrix} + \begin{pmatrix} \mathrm{y} * 11 - \mathrm{ALPHA}x \\ \mathrm{y} * 21 - \mathrm{ALPHA}y \\ \mathrm{z} * - 0 \end{pmatrix} \times \begin{pmatrix} \mathrm{x} \\ \mathrm{y} \\ \mathrm{z} \end{pmatrix}.$$

In the case of a pseudophakic eye with an IOL with its center at (0,0, ACD+0.5*L) the intersection of the visual axis with the IOL plane is then:

$$\begin{pmatrix} X'va \\ Y'va \\ Z'va \end{pmatrix} = \begin{pmatrix} y*11 \\ y*21 \\ z* \end{pmatrix} + \begin{pmatrix} y*11 - \mathrm{ALPHA}x \\ y*21 - \mathrm{ALPHA}y \\ z* - 0 \end{pmatrix} \times \begin{pmatrix} 0 \\ 0 \\ \mathrm{ACD} + 0.5 * \mathrm{L} \end{pmatrix}.$$

The custom lens alignment factor, or anatomical misalignment of the IOL center from the visual axis, is then given by (X'_{va}, Y'_{va}), or

$$d = \sqrt{(X'^{2}_{va} + Y'^{2}_{va})}.$$

Estimating IOL Power for Each Eye

The SRK II has been used to simply estimate the IOL power needed for each eye. The SRK II formula is as follows:

$$P = A1\text{-}2.5 \times z\text{-}0.9 \times K$$

where P is the IOL power for emmetropia, A1 is the modified lens constant, A is the manufacturer recommended A constant for the specific IOL, and K is the average of K_s and K_f:

If z <20, A1=A+3.

If 20<=z <21, A1=A+2.

If 21<=z <22. A=A1+ 1.

If 22<=z <24.5 A1=A.

If L >24.5 A1=A-1.

Alternatively, the "ACD" constant for the IOL may be used where:

$$A = (ACD - Konst + 68.747) / 0.62467.$$

See, HAIGIS, "IOL calculation according to HAIGIS," http://www.augenklinik.uni-wuerzburg.de/uslab/ioltxt/haie.htm, which is hereby incorporated by reference.

In an example embodiment, a method for enhancing vision includes: determining an estimated anatomical misalignment of a center of a lens following implantation of the lens in an eye, and applying the estimated anatomical misalignment to ocular information associated with the eye to control, generate, or provide a visual representation (e.g., via an interactive interface).

In FIG. 7, an example visual representation 700 (which can be referred to as a "dashboard") includes an arrangement of windows, graphics, visual schema, and the like presented, for example, in light of each eye's custom lens alignment factor. In example embodiments, the visual representation 700 summarizes key data that may influence patient candidacy for various IOL choices. A workstation (such as in FIG. 1) can be configured, for example, to provide an estimation of the image quality associated with aspheric IOLs applying each eye's custom lens alignment factor to other ocular information associated with each eye, respectively. More generally, a workstation can be configured for providing, facilitating, and/or presenting one or more ophthalmic assessments.

Multifocal IOLS

Considerations for multifocal IOL candidacy are three-fold: Corneal astigmatism, corneal higher order aberrations, and lens alignment. These factors could contribute to increasing the overall higher order aberration burden on an eye implanted with a multifocal IOL. In FIG. 7, the color coding scheme presented for these parameters allows surgeons to tailor his or her patient selection process to their personal level of experience. For example, multifocal IOLs are not recommended in the presence of more than 0.75 D of corneal cylinder. Thus, if a surgeon has a plan to reduce corneal astigmatism below this level by using LRIs or LASIK then he or she may more aggressive approach baseline cylinder levels.

Higher levels of corneal aberrations have been reported to be associated with "20/20 unhappy" multifocal IOL results. *See*, Chang, D., "Evaluating Unhappy Multifocal IOL Patients With Wavefront Aberrometry," RHEM, January 2012, Maui, Hawaii, which is hereby incorporated by reference. Thus understanding patients' preexisting corneal aberration status may help prevent or minimize 20/20 unhappy results associated with multifocal implantation.

Lens misalignment can further increase the HOA burden of eye, especially one with the advanced aspheric multifocal IOLs available today. Thus consideration of the Custom Lens Alignment Factor, in conjunction with the corneal HOA and residual postop cylinder, can provide a more complete portrait of ideal candidates for multifocal implantation.

Toric IOLs

The case depicted in the FIG. 7 Dashboard is not likely to be an ideal multifocal IOL candidate, but does have considerable corneal cylinder that may be suitable for Toric IOL correction. Alcon, the manufacturer of the only Toric IOL available in the US, recommends using manual keratometry to determine Toric IOL eligibility. However, identifying the steep meridian and cylinder magnitude in eyes with asymmetrical astigmatism can be variable. Thus, corneal topography approaches may be more robust in selecting Toric IOL candidates and planning their correction.

The Astigmatism Assessment area of the example Dashboard in FIG. 7 provides four separate measures of this patient's astigmatism. The first is the Simulated Keratometry at 3 mm from the corneal topography measurement of the iTrace. The next is the Refractive Corneal Power assessment within the 3 mm zone. The next two measures represent the Regular portion of the corneal astigmatism from the wavefront assessment at the 3 mm zone and with consideration to the pupil size.

The color coded visual representation of the astigmatism assessment takes into account the patient's pupil size and compares the Regular Refractive Corneal Cylinder from wavefront at this larger zone to the Sim K Cyl at the 3 mm zone (FIG. 8). In this case there is very good agreement with identification of the steep merdian in all four measures, though the pupil based Regular Corneal Cylinder indicates that patients may have more astigmatism than the Sim K indicates. Deviations between the cylinder or meridian data across these measures could indicate asymmetrical astigmatism.

Advanced Aspheric Monofocal IOLs

If the cased depicted in the Dashboard of FIG. 7 was not a good candidate for a Toric IOL or simply opted out due to the cost of the procedure then the surgeon next considers which monofocal IOL may be best in this particular eye. In FIG. 7, the portion denoted “Advanced Aspheric Monofocal IOL Options” depicts the monofocal IOL selection capability of the Dashboard. By comparing the Custom Lens Alignment Factor to the expected MTF performance of today’s IOLs the surgeon can estimate which IOL choice may be best for this patient. In this case, with a very low level of lens misalignment (0.19 mm), the dashboard confirms that a traditional Negative Aspheric may provide better image quality as compared with the Optimized aspheric IOL.

In an example embodiment, a method for enhancing vision includes: determining an estimated anatomical misalignment of a center of a lens following implantation of the lens in an eye, and applying the estimated anatomical misalignment to ocular information associated with the eye to facilitate, control, or initiate an action or process involving one or more of: controlling, generating, or providing a visual representation (provided, for example, at an electronic and/or computer-controlled display), comparing one or more vision enhancement procedures and/or products, selecting one or more vision enhancement procedures and/or products, identifying (and testing) one or more candidate lens (or other vision enhancement products) (e.g., for a surgical procedure to be performed on the eye), selecting a lens (and/or one or more other vision enhancement products) and performing a surgical procedure involving the lens and the eye, selecting a surgical procedure (and/or a surgical procedure approach) and performing the surgical procedure on the eye, and inducing, simulating, estimating, or predicting a postoperative result in relation to one or more vision enhancement procedures and/or products (e.g., induced astigmatism results, or induced corneal astigmatism results).

In this method, determining an estimated anatomical misalignment include, for example: using an estimate of the relation between the corneal vertex and the lens center (e.g., a measured value of Angle Alpha to determine the location of the optical center (x, y, z) for the eye (e.g., in three dimensions, (Xo, Yo, Zo)); using the optical center and the location of the corneal vertex to determine the visual axis of the eye (e.g., solving 3D equation as described herein); and using the visual axis and a point along the visual axis that intersects a plane perpendicular to the lens axis to determine the distance of the lens center from the visual axis (which provides the estimated anatomical misalignment). The step of using an estimate of the relation between the corneal vertex and the lens center includes, for example, using 4th Purkinje image reflections to identify or determine the lens center. The step of using an estimate of the relation between the corneal vertex and the lens center includes, for example, determining the location of the optical center for the eye in three dimensions. The step of using the optical center and the location of the corneal vertex to determine the visual axis of the eye includes, for example, using a three dimensional linear equation to determine the intersection of the visual axis and the plane perpendicular to the lens axis at the lens center.

In an example embodiment, a method for assessing potential candidates for lens implantation includes: using Angle Alpha and ocular anatomy information associated with one or more eyes (in the case of multiple eyes, information associated with each eye, individually) to determine the location of the optical center for the one or more eyes; using the location of the corneal vertex and the location of the optical center to determine the visual axis for each of the one or more eyes; using a point along the visual axis and intersecting with a plane perpendicular to the lens axis to determine, for each of the one or more eyes, an optical alignment (e.g., a custom lens alignment factor) of the lens (e.g., lens center) in relation to the visual axis; and applying the one or more optical alignments to ocular information associated with the one or more eyes to facilitate, control, or initiate an action or process of estimating outcomes for one or more lens implantation procedures (e.g., for multifocal IOL implantation).

In this method, the one or more optical alignments can be applied to the ocular information in conjunction with corneal high order aberration (HOA) information associated with the one or more eyes. In this method, the one or more optical alignments can be applied to the ocular information in conjunction with residual post operative cylinder information associated with the one or more eyes. The action or process involves, for example, providing an assessment of image qualities associated with multiple different aspheric IOLs (or other lens, e.g., in consideration of each eye's custom lens alignment factor). By way of example, FIG. 9 shows an "IOL Selection Overview" interface/visual representation.

The action or process can involve controlling, generating, or providing a user interface pertaining to a preoperative status associated with the one or more eyes (e.g., in relation to one or more of: Keratometric Astigmatism (Sim K Cyl), Total Corneal Higher Order Aberrations (Total Corneal HOAs), Corneal Spherical Aberration, and Visual Axis – Lens Deviation). As an additional example, FIG. 10 shows a "Preoperative Assessment" interface/visual representation. In selecting the IOL best suited for each eye it is helpful to understand if and how each of these metrics changes due to surgery. For example, the surgically induced change in astigmatism following cataract surgery can be quantified using vector analysis of pre and postop keratometry measurements or pre and postop refractions. *See*, Thibos, L.N., et al., "Power vector analysis of the optical outcome of refractive surgery," *J Cataract Refract Surg*, Vol. 27 (January 2001), pp. 80-85, which is hereby incorporated by reference. Generally, the mean magnitude of the vector change has decreased over time as incision size has been reduced from 6 mm 20 years ago to 2 mm today. Yet, in general, each surgeon's approach is still associated with a surgically induced change in cylinder magnitude and axis and it is important to know this in order to optimize toric IOL correction. Use of the pre and postop corneal wavefront astigmatism to assess surgically induced changes may represent an improved approach over other methods.

The action or process can involve controlling, generating, or providing a user interface pertaining to candidate vision enhancement procedures and/or products (e.g., arranged such that one or more vision enhancement procedures and/or products that satisfy the one or more criteria or a subset thereof is prominently presented at the interface) In FIG. 8, for example, the display areas labeled "Complete Astigmatism Assessment" and "Negative Aspheric Toric" are presented while other portions of the dashboard fade to the background or minimize (e.g., temporarily until the user provides an input, or responds to a prompt acknowledging that he or she has considered the presented factor). Such a display, i.e., showing a subset of a complete dashboard, can be automatically generated or provided in response to a user input such as, for example, a voice command to present key decisional factors in order of importance or relevance in deciding whether to further consider (or eliminate from further consideration as candidates) particular vision enhancement products and/or procedures.

The action or process can involve controlling, generating, or providing a user interface pertaining to estimated postoperative results for one or more vision enhancement procedures and/or products (e.g., estimated postoperative results for multiple different IOLs) (e.g., for monofocal and/or multifocal candidates) (e.g., for negative aspheric candidates) (e.g., for negative aspheric multifocal candidates) (e.g., for negative aspheric toric candidates). See e.g., FIGs. 9-13. FIG. 11 shows an example "Multifocal IOL Summary" interface/visual representation. FIG. 12 shows an example "Toric IOL Summary" interface/visual representation. FIG. 13 shows an example "Monofocal IOL Summary" interface/visual representation.

The action or process can involve controlling, generating, or providing a user interface pertaining to a comparison of pre and postop corneal (wavefront) astigmatism (e.g., a measured preoperative corneal wavefront astigmatism and an estimated postoperative corneal wavefront astigmatism) (e.g., vector analysis of individual pre and postop HOAs, such as coma or trefoil, when combined with induced astigmatism results, or induced corneal astigmatism results). Vector analysis of individual pre and postop HOAs, such as coma or trefoil, when combined with induced astigmatism results, provides a complete picture of the impact of cataract surgery on corneal optical quality. Spherical aberrations, being radially symmetric, are generally not altered by traditional cataract surgery.

The action or process can involve controlling, generating, or providing a user interface pertaining to angle alpha associated with one or more of the eyes (e.g., determined from a corneal topography measurement/determination that provides Zernike lower- and higher-order aberrations (HOAs)).

The action or process can involve controlling, generating, or providing a user interface pertaining to an estimate of visual axis to lens deviation associated with one or more of the eyes. The visual axis to lens deviation can be estimated as described herein. The limbal center, for example, is used as a marker for the crystalline lens center. While this is a reasonable approximation of where the center of an implanted IOL may lie, IOLs have been reported to center differentially in a particular direction with respect to the limbal center. For example, the HOYA VA-60BB IOL has been reported to center at 0.3 mm from the limbal center at approximately 45 degrees supero-nasally from the horizontal. *See*, Kim, K.H., et al. , "Intraocular Lens Stability and Refractive Outcomes after Cataract Surgery Using Primary Posterior Continuous Curvilinear Capsulorrhexis," *Ophthalmology*, Vol. 117, No. 12 (December 2010, Epub: Jun 18, 2010), pp. 2278-2286, which is hereby incorporated by reference. This may be the result of the anatomy of the capsular bag, the specific lens design, surgeon factors such as capsulorrhexis centration or final positioning of the lens in the bag at the time of surgery, or any combination of these. Thus, measurement of the postoperative centration of IOLs relative to the limbal center using, for example, Purkinje images to personalize the visual axis to lens center deviation stands to greatly improve the predictive capability of the dashboard. Further, the actual center of the visual axis at the cornea, sometimes referred to as the corneal vertex, may also change as a result of the corneal incision for cataract surgery.

The action or process can involve controlling, generating, or providing a user interface pertaining to estimated image quality (e.g., in relation to percent aligned) for one or more vision enhancement procedures and/or products. By way of example, the visual representation can include a display area (or key) such as displays 1400 and 1500 (shown in FIGs. 14 and 15, respectively) in which different sections or portions of the display areas represent different percentage ranges. In this example, each of the different sections or portions is generated or provided as a visually distinguishable area (e.g., each area having a different fill color). In example embodiments, a visual (e.g., color) scheme (e.g., presented via an Image Quality display area or key) is utilized (e.g., to identify factors or determinations relevant to different estimated image qualities) in multiple different visual representation areas. A visual representation can include a color coded column such as in display 1400 (FIG. 14) and/or a color coded gauge (or dial) such as in display 1500 (FIG. 15) as in a vehicle dashboard or cockpit. In this manner and as described herein, the vision enhancement technologies described herein can help a user to more easily visualize and consider factors or determinations relevant (or important, critical, or dispositive) to identifying or selecting a vision enhancement procedure and/or product.

The action or process can involve controlling, generating, or providing a user interface pertaining to estimated surgeon-specific surgically induced changes such as, for example, surgeon-specific surgically induced astigmatism or induced corneal astigmatism. As another example, a visual representation can include visible indicia (e.g., positioned on a plot in relation to Nasal-Temporal and Inferior-Superior axes) representing one or more of a pupil center, a limbal center, and a visual axis center.

The action or process can involve controlling, generating, or providing a user interface pertaining to an estimated postoperative assessment.

The action or process can involve controlling, generating, or providing a user interface pertaining to a comparison of lenses (e.g., candidate IOLs) that is one or more of surgeon-specific, lens style-specific (or lens model-specific, lens design specific, lens size-specific, or lens batch-specific), and surgical procedure-specific or approach-specific (e.g., as to different surgical approaches, for example, approaching superiorly) For example, a visual representation can include one or more visual representation areas such as an IOL-specific comparison in relation to different Angle Alpha selections (e.g., a visual representation including an arrangement of multiple different areas or windows in which plots of image quality vs. Angle Alpha are shown for different Angle Alpha values).

The action or process can involve controlling, generating, or providing a user interface pertaining to one or more personalized parameters or determinations, A visual representation can include a personalized lens parameter such as a lens power constant (A constant). By way of example, a provisional A constant (e.g., specified by a lens manufacturer) is adjusted to provide, or is replaced with, a personalized A constant (e.g., IOL-specific), which can be part of a "Personalized Dashboard". Further with regard to personalizing a user interface, a dashboard represents a starting point for a surgeon utilizing a given workstation to gain greater insight into matching the best IOL option to each patient. Ideally, this approach will be "personalized" to each surgeon and can include an assessment of the each patient's postoperative results. This may be accomplished, for example, by collecting pre and one-month postop examination results on 250 pseudophakic eyes per center, with 125 eyes receiving an Optimized Aspheric IOL and 125 receiving the IOLs typically used at the practice. In this way, the results shown in FIG. 14 can be assessed for the surgeon and incorporated into his or her dashboard to continually improve the predictive capabilities of its use in screening.

The action or process can involve controlling, generating, or providing a user interface pertaining to an indication (e.g., a percentage, or other characterization or identification or description) of cases (e.g., IOL-specific) having a (range of) desired (or acceptable or superior) outcomes (e.g., % cases within 0.5 D of target).

In an example embodiment, a method for facilitating a vision enhancement procedure includes: accessing ophthalmic information (e.g., including measurements and calculations and/or determinations made utilizing the information) for one or more eyes; and applying one or more criteria (e.g., one or more vision enhancement and/or information presentation criteria) to the information to facilitate or initiate an action or process of controlling, generating, or providing a visual representation (e.g., via an interactive interface) of one or more of (as previously discussed) a preoperative status associated with the one or more eyes, candidate vision enhancement procedures and/or products, estimated postoperative results for one or more vision enhancement procedures and/or products, a comparison of pre and postop corneal astigmatism, angle alpha associated with one or more of the eyes, an estimate of visual axis to lens deviation associated with one or more of the eyes, estimated image quality for one or more vision enhancement procedures and/or products, estimated surgeon specific surgically induced changes, an estimated postoperative assessment, a comparison of lenses that is one or more of surgeon-specific, lens style-specific, and surgical procedure-specific or approach-specific, one or more personalized parameters or determinations, and an indication of cases having desired outcomes.

In example methods, the visual representation is controlled, generated, or provided via an interface that is generated utilizing a custom add-in or plug-in system application which functions as an extension and overlay to an existing third party system application or other platform that facilitates ophthalmic assessments.

The preoperative status is associated with the one or more eyes in relation to one or more of, for example: Keratometric Astigmatism (Sim K Cyl), Total Corneal Higher Order Aberrations (Total Corneal HOAs), Corneal Spherical Aberration, and Visual Axis and Lens Deviation.

The candidate vision enhancement procedures and/or products can be arranged such that one or more vision enhancement procedures and/or products that satisfy the one or more criteria or a subset thereof are prominently presented (e.g., in the visual representation and/or at another user interface).

The estimated postoperative results for one or more vision enhancement procedures and/or products involve one or more of, for example: estimated postoperative results for multiple different IOLs, monofocal and/or multifocal candidates, negative aspheric candidates, negative aspheric multifocal candidates, and negative aspheric toric candidates.

The comparison of pre and postop corneal astigmatism pertains, for example, to a measured preoperative corneal wavefront astigmatism and an estimated postoperative corneal wavefront astigmatism.

The comparison of pre and postop corneal astigmatism pertains, for example, to individual pre and postop HOAs (such as coma or trefoil) and induced astigmatism results.

The estimated image quality for one or more vision enhancement procedures and/or products can be presented in relation to a visual scheme correlating multiple different ranges of estimated image quality with different visually distinct representations, respectively (e.g., as previously discussed).

The estimated surgeon-specific surgically induced changes (such as, for example, surgeon-specific surgically induced astigmatism or induced corneal astigmatism) include visible indicia (e.g., positioned on a plot in relation to Nasal-Temporal and Inferior-Superior axes) representing one or more of a pupil center, a limbal center, and a visual axis center.

The comparison of lenses includes, for example, an IOL-specific comparison in relation to different Angle Alpha selections.

The one or more personalized parameters or determinations include, for example, one or more of a personalized A constant and an IOL-specific parameter or determination.

In an example embodiment, a method for assessing surgically induced changes includes: measuring, determining, or estimating pre and postop corneal wavefront astigmatisms for an eye; and applying the pre and postop corneal wavefront astigmatisms in an action or process of controlling or utilizing one or more electronic devices and/or display devices to provide a visual representation of one or more surgically induced changes. In an example embodiment, the method further includes: measuring, determining, or estimating a postoperative centration of IOLs relative to the limbal center and/or the corneal vertex; and using the location of the lens center to update or modify (e.g., personalize) a determination and/or a visual representation involving visual axis to lens center deviation.

The predictive utility of the dashboard can be significantly augmented by aggregating pre and postop data following IOL implantation in a series of subjects. In particular, corneal topography converted to Zernike coefficients and IOL centration as measured by, for example, Purkinje images relative to the corneal vertex could be used to map the surgeon-specific, IOL-specific surgically-related tendencies. For example, a quantification of these trends can then be incorporated into the estimated postoperative assessment provided by the dashboard to greatly improve its utility in selecting which IOL may be best suited for each eye.

Thus, in an example embodiment, a method of selecting a vision enhancement procedure and/or product includes: for multiple (e.g., a series of) subjects, utilizing pre and postoperative ophthalmic information including corneal topography (e.g., converted to Zernike coefficients) and IOL centration (e.g., determined utilizing Purkinje images relative to the corneal vertex) to map surgeon-specific, IOL-specific (or len style/type-specific) surgically-related tendencies in relation to multiple different IOLs (e.g., of different lens style or type). The term corneal topography includes, for example, corneal topography information and, in example embodiments, can include ocular wavefront information created or influenced by the cornea. In an example embodiment, the method further includes: identifying (e.g., quantifying) one or more trends associated with the pre and postoperative ophthalmic information; and utilizing the one or more trends to provide or modify an estimated postoperative assessment (for example, quantifications of one or more of the trends can be incorporated into an estimated postoperative assessment).

In an example embodiment, a method of selecting a vision enhancement procedure and/or product includes, for each of a series of subjects: obtaining corneal topography information for a preoperative eye (e.g., by measuring, or data from a previous preoperative measurement), after (selecting and) implanting an IOL lens, determining IOL centration (e.g., identifying the lens center using the 4th Purkinje image reflection) relative to the corneal vertex; after determining IOL centration, determining for all or a plurality of subjects of the series that have been postoperatively measured an aggregate or average estimated (surgeon-specific) surgically induced change (e.g., Expected Surgical Change in Cyl (D)); and applying the aggregate or average estimated (surgeon-specific) surgically induced change to control one or more electronic displays in relation to generating, updating, or providing a visual representation pertaining to one or more surgically induced changes. The visual representation pertains, for example, to one or more estimated or predicted tendencies in relation to surgically induced changes (e.g., surgeon-specific surgically induced changes). The visual representation pertains, for example, to surgeon-specific, IOL-specific surgically-related tendencies. The visual representation pertains, for example, to surgeon-specific, lens style-specific surgically-related tendencies. The surgically-related tendencies can also be lens type-specific, lens model-specific, lens design specific, lens size-specific, or lens batch-specific. The surgically-related tendencies can also be surgical procedure-specific or approach-specific (e.g., as to different surgical approaches, for example, approaching superiorly).

In an example embodiment, a vision enhancement system includes: a computer-executable software application configured or programmed to receive or access ocular information associated with one or more eyes and to process the ocular information in relation to determining an optical center and a corneal vertex for an eye, using the optical center and corneal vertex to determine a visual axis for the eye (e.g., calculate 3D linear equation of the visual axis), determining an intercept of the visual axis with a lens (e.g., IOL) plane (X_{IOL}, Y_{IOL}, Z_{IOL}), and using the intercept to determine an optical alignment of the lens in relation to the visual axis (e.g., determine custom lens alignment factor, $r_o = \sqrt{(X_{IOL}^2 + Y_{IOL}^2)}$).

The computer-executable software application is, for example, configured or programmed to apply the optical alignment to an action or process of providing or facilitating an ophthalmic assessment in relation to one or more vision enhancement products and/or procedures. The computer-executable software application is configured or programmed, for example, to apply the optical alignment to an action or process of controlling, generating, or providing a display and/or a user interface.

The computer-executable software application can be a custom add-in or plug-in system application which functions as an extension and overlay to an existing third party system application or other platform that facilitates ophthalmic assessments. In example embodiments, the computer-executable software application is at least partially cloud-based and/or accessible via a website or other electronic or communications platform (e.g., provided in the form of an application for a personal computing and/or communications device, such as a smartphone or tablet computer).

Referring to FIG. 16, the previously described method 1600 including a technique for calculation of the nodal point of the eye so that, when combined with the measured visual axis point at the cornea, we could describe a three dimensional equation for the visual axis (path A). Then knowing the equation of the visual axis in space, and measuring the position along the longitudinal axis of the IOL using methods such as ultrasound or a Scheimpflug techique, one could calculate the deviation of the IOL center from the visual axis in the plane of the IOL. Referring also to FIG. 16, an alternative technique (path B) for determining visual axis involves calculating the equation for the visual axis of the eye without assuming knowledge of the nodal point. At 1602, by measuring the coordinates of the visual axis point at the cornea (1) and the corresponding coordinates of a paraxial ray traveling through point (1) at the retina (4) one can calculate the three dimensional equation of the visual axis as before. The position of the IOL along the longitudinal axis of the eye, known as the "pseudophakic ACD", can be determined at 1604 using, for example, a photographic method in a dilated eye. Then, at 1606, the deviation of the IOL center from the visual axis can be determined as in path A.

Once the three dimensional equation of the visual axis is known it can be used to optimize the location of the anterior capsulorhexis using a femtosecond laser so as to shift the IOL center towards the visual axis upon capsular bag contraction. Also, the coordinates of the visual axis point at the cornea may prove to be the optimal point of centration for arcuate incisional procedures to treat astigmatism on the cornea using a femto second laser.

Knowledge of the deviation of the IOL center from the actual visual axis gives insight into the expected image quality with different types of optics, which may in turn allow for optimal selection of a specific optic for a given eye. Optics with varying degrees of spherical aberration, for example, are now available to match with the pre-existing corneal spherical aberration. Another consideration affecting image quality is the degree of image curvature produced by residual refractive errors, such as spherical aberration, at the retina, and whether the level of image curvature produced matches the curvature of the human fovea, a curved detector.

The methods disclosed herein can facilitate various approaches to guiding selection of IOL features so as to optimize image quality for each eye.

Referring to FIG.17, example embodiments involve a method to estimate the distance along the longitudinal axis to the plane of the IOL from a dilated photograph. Typically a portion of the IOL optic edge is made visible with dilation of the eye. This section of the optic edge can be used to guide the extrapolation of the complete circumference, which then gives an estimate of the diameter of the optic and its center. In the case shown here the diameter of a 6.0 mm optic actually measures 7.2 mm due to corneal magnification of the image.

Knowing the estimated optic diameter and the measured corneal power the "IOL ACD" can be calculated as above. In this case a 7.2 mm magnified optic corresponds to location of the IOL plane at 5.0 mm behind the anterior cornea.

– Corneal magnification of the optic image and the corneal power can be used to determine the distance of the IOL behind the anterior cornea

$$IOL\ ACD = \left(\frac{Actual\ IOL\ Diameter}{Apparent\ Diameter} - 1\right) \times \left(1000 * \frac{1.336}{Corneal\ Power}\right)$$

– Average of 10 measurements in an actual pseudophakic eye: **7.2 mm ± 0.2 mm**

– Corresponds to an IOL ACD of **5.0 mm** behind the anterior cornea

– Approach can be used to optimize IOL constants

Referring now to FIG. 18, in general the visual axis (1-3-4) of the eye is not coincident with the longitudinal axis of the eye (2-5). Points 1, 2 and 3 may or may not be collinear. Under fixation of an object the focal image must be positioned on the fovea (4) for optimal vision. The eye rotates so as to accomplish this and thus establishes a point of intersection between the visual axis and the cornea (1). This gives rise to the concepts of angle kappa and angle alpha. In general, this point is not the geometric center of the cornea nor is it the apex of the cornea. The coordinates of the visual axis point at the cornea can be assessed by any vision testing device with adequate fixation. (See mathematics above as to points 1 and 3, which can be utilized in relation to points 1 and 4.)

Referring to FIG. 19, previously, we described a method to calculate the nodal point of the eye (3) so that, knowing the location in space of point 1, a three dimensional equation for the visual axis as defined by points 1 and 3 could be determined. This allowed one to estimate the visual axis at the plane of the IOL to assess the misalignment of the IOL center relative to the visual axis.

Since the cornea and IOL are of very limited thickness relative to the length of the eye the visual axis can be approximately by the line defined by points 1 and 4 instead of the set of rays in the previous figure. Thus one can alternatively calculate the three dimensional equation of the visual axis by measuring points 1 and 4 under fixation, which can be accomplished with so called "ray trace" aberrometry devices such as the iTrace (Tracey Technologies, Houston, Texas) or the wide field laser ray tracing aberrometer described by Mazzaferri and Navarro. See e,g, Mazzaferri J, Navarro R: Wide two-dimensional field laser ray-tracing aberrometer. *J of Vision* (2012) 12(2):2, 1–14, incorporated herein by reference. Then one can use the methods described earlier to calculate the three dimensional equation of the visual axis using the locations of points 1 and 4 relative to the same reference point, such as the limbal center, and the axial length of the eye.

Referring to FIG. 20, once the equation of the visual axis is known one can then employ an eccentric or decentered anterior capsulotomy created precisely by the femto laser that may induce a shift in the optic center towards the visual axis.

Purposely decentered and/or eccentric laser anterior capsulotomies that may induce a shift in the IOL center towards the predetermined visual axis coordinates after capsular bag contraction. This effect can be modeled with finite element analysis of the capsular bag. Wang Y, Wang Z, Zhao L, et al.: Finite element analysis of neodymium: yttrium-aluminum-garnet incisions for the prevention of anterior capsule contraction syndrome *Chin Med J 2013;126 (4): 692-696.* An eccentric capsulotomy at the time of cataract surgery has been employed in order to intentionally decenter IOLs to correct vertical strabismus. Nishimoto H,Shimizu K, Ishikawa H, et al.: New approach for treating vertical strabismus: Decentered intraocular lenses *J Cataract Refract Surg* 2007; 33:993–998. Today, cataract surgeons try to typically center the capsulorhexis and the IOL within the pupil or aligned with the first Purkinje reflex while the patient attempts to fixate on the operating microscope light. In the case of centering the capsulorhexis on the first purkinje image this cannot be accomplished with a femto laser during applanation of the cornea with the patient-laser interface. Further, in the case of manually centering IOLs within the bag, no one has been able to show that postoperatively the center of the IOL corresponds to the surgeon’s best attempts to manually locate the IOL in the capsular bag at the time of surgery, i.e., does it stay where he or she have positioned it or does it move with capsular fibrosis? Further, these techniques for centering anterior capsulotomies and IOLs are very difficult to accomplish with great precision in the presence of a dilated pupil with fixation on the very bright operating microscope light. Dr. Ramesh Dorairajan has posted a very nice example of bilateral Alcon Restor IOLs perfectly centered within the pupil, but the visual axises pass through the periphery of the optic; the patient sees 20/20 in both eyes, but is very unhappy. Dorairajan, Ramesh, MD. "Centering the Alcon Restor with Purkinje

Reflexes." *YouTube*. YouTube, 19 July 2010. Web. 17 Apr. 2013. http://www.youtube.com/watch?v=So37mYstxMU

Other IOL designs potentially fixate to the anterior capsule through the capsulotomy (Stevens Patent). Stevens, Julian Douglas: Intraocular Implant. European Patent Application #10251497.3, Filed August 26, 2010. Or fixate to the anterior and posterior capsules through two capsulotomies (BIL IOL). Verbruggen KHM, Rozema JJ, Gobin L, et al.: Intraocular lens centration and visual outcomes after bag-in-the-lens implantation. *J Cataract Refract Surg* 2007; 33:1267–1272. These IOL concepts directly benefit from the centration of the capsulotomy(ies) on the visual axis coordinates.

Referring to FIG.21, corneal incisions to correct astigmatism are typically centered on the pupil or the 1st Purkinje image, the latter of which is used to estimate the location of the visual axis at the cornea. During cataract surgery, however, the pupil is always dilated so that centering the treatment on the pupil is not so precise. In the case of femtosecond laser surgery with corneal arcuate incisions for astigmatism using the first Purkinje reflex may not be possible due to applanation of the cornea with the patient-laser interface device. Thus, using the a priori determined coordinates of the visual axis at the cornea may be an ideal approach for centering arcuate incisional treatments during femtosecond laser cataract surgery with astigmatism correction.

<u>Overview of the Impact of Residual Positive or Negative Spherical Aberration on Retinal Image Curvature at the Fovea</u>

Referring to FIG. 22, depicted here is a simple ray trace diagram of the retinal image formed from a distant object (arrow ABCDE). The first principle rays are shown as dashed lines and, by definition, intersect the optical plane and the visual axis and are not refracted. The second principle rays represent the paraxial rays that enter the eye parallel to the visual axis and are refracted to a focal point or plane on or near the retina. The effect of positive residual spherical aberration on image formation has been estimated by considering the image plane formed by light entering the eye near the visual axis (Green) versus light entering the eye furthest from the visual axis (RED rays). By definition, positive spherical aberration will focus peripheral incoming rays anterior to the focal plane of central incoming rays. Note that no specific amount of spherical aberration is considered here nor is retinal image size to scale. Further, this example only considers residual positive spherical aberration and does not consider and sphero-cylindrical residual errors.

Referring to FIG. 23, the exploded view of the foveal image the EA image plane shows that the periphery of the arrow abject is focused anterior to the central region of the arrow image that is focus to image plane DB, which is assumed to be tuned to focus exactly at the fovea. What is evident is that residual positive spherical aberration of the eye creates curvature of the image plane that is similarly oriented to the curvature of the fovea. Since the fovea is not a planar image detector there could be an amount of positive residual spherical aberration that, for a given image size, produces retinal image curvature that exactly matches the foveal curvature of a given eye. In this scenario, image quality may be optimized. Further, if eyes have different foveal curvatures then it follows that perhaps retinal image quality may be optimized by producing a specific amount of residual positive spherical aberration of the eye that would result in image curvature that closely matches the eye's foveal curvature.

Referring to FIG. 24, depicted here is the potential impact of negative spherical aberration on foveal image curvature. With negative spherical aberration incoming peripheral rays are focused posteriorly to incoming central rays, which can be seen to create image curvature opposite to that of the fovea.

Referring to FIG. 25, while part of the image can be focused perfectly on the fovea, for example, points E and A representing the tips of the arrow object, it is clear that not all of the image can be in focus along the natural curvature of the fovea.

What then is the axial separation of the peripheral and central image planes that corresponds to spherical aberration of 0.75 D? This too can be estimated from the reduced eye model. If we assume that the central 60 D focuses a distant object on the fovea then the axial length is 22.17 mm. Peripheral incoming rays that see 60.75 D would be focused to an image plane at 21.89 mm or 0.28 mm anteriorly to the central image plane. This difference represents an estimate of the distance between the anterior EA and posterior DB image planes in the previous depictions.

Spherical Aberration & Axial Focus

– Assume central 60 D focuses distant object at the fovea

– Focal length is the axial length (AL) and using a reduced schematic eye:

- $A = 1.33/60 = 22.17$ mm

– Then the peripheral 60.75 D focuses distant objects 0.75 D in front of the retina:

- $A' = 1.33/60.75 = 21.89$ mm, or 0.28 mm in front of the retina

– This axial difference represents an estimate of the distance between the anterior (EA) and posterior (DS) image planes

Referring to FIG. 26,

- $r^2 = (h_i/2)^2 + (r-0.28)^2$
  - h_i = image size at retina
- $r = ((h_i / 2)^2 + 0.28^2) / (2*0.28)$
- Image size at the retina has been estimated to be as large as 1.6 mm following toric IOL implantation[10], which is comparable to the diameter of the fovea
- If h_i = 1.5 mm then
  - **r = 1.15 mm**

Referring to FIG. 27,

- $r^2 = (h_i/2)^2 + (r-0.28)^2$
  - h_i = image size at retina
- $r = ((h_i / 2)^2 + 0.28^2) / (2*0.28)$
- If h_i = 1.5 mm then
  - **r_{image} = 1.15 mm**
  - **r_{fovea} = 1 mm**

Is it possible that the increase in positive spherical aberration of the eye that occurs with age somehow compensates for the decreasing radius of curvature thought to occur with age? Is this a physiological mechanism to optimize image quality as we age?

This assessment represents a simple example of how positive and negative spherical aberration create different image curvature at the fovea. In this example, residual spherical error, astigmatism, and other higher order aberrations were assumed to be zero. These other aberrations can all interact to influence image curvature at the fovea. Only an individualized ray tracing calculation could predict the expected image curvature for each eye. Further, it may be useful clinically to measure the curvature of the fovea in each eye and then select vision correction parameters to optimize image curvature at the fovea.

Although the present invention has been described in terms of the example embodiments above, numerous modifications and/or additions to the above-described embodiments would be readily apparent to one skilled in the art. It is intended that the scope of the present invention extend to all such modifications and/or additions.

CLAIMS

What is claimed is:

1. A method for enhancing vision, the method comprising:

determining an estimated anatomical misalignment of a center of a lens following implantation of the lens in an eye, and

applying the estimated anatomical misalignment to ocular information associated with the eye to facilitate, control, or initiate an action or process involving one or more of

controlling, generating, or providing a visual representation,

comparing one or more vision enhancement procedures and/or products,

selecting one or more vision enhancement procedures and/or products,

identifying one or more candidate lens,

selecting a lens and performing a surgical procedure involving the lens and the eye,

selecting a surgical procedure and performing the surgical procedure on the eye, and

inducing, simulating, estimating, or predicting a postoperative result in relation to one or more vision enhancement procedures and/or products.

2. The method of claim 1, wherein determining an estimated anatomical misalignment includes

using an estimate of the relation between the corneal vertex and the lens center to determine the location of the optical center for the eye,

using the optical center and the location of the corneal vertex to determine the visual axis of the eye, and

using the visual axis and a point along the visual axis that intersects a plane perpendicular to the lens axis to determine the distance of the lens center from the visual axis.

3. The method of claim 2, wherein using an estimate of the relation between the corneal vertex and the lens center includes

using 4th Purkinje image reflections to identify or determine the lens center.

4. The method of claim 2, wherein using an estimate of the relation between the corneal vertex and the lens center includes

determining the location of the optical center for the eye in three dimensions.

5. The method of claim 2, wherein using the optical center and the location of the corneal vertex to determine the visual axis of the eye includes

using a three dimensional linear equation to determine the intersection of the visual axis and the plane perpendicular to the lens axis at the lens center.

6. A method for assessing potential candidates for lens implantation, the method comprising:

using angle alpha and ocular anatomy information associated with one or more eyes to determine the location of the optical center for the one or more eyes;

using the location of the corneal vertex and the location of the optical center to determine the visual axis for each of the one or more eyes;

using a point along the visual axis and intersecting with a plane perpendicular to the lens axis to determine, for each of the one or more eyes, an optical alignment of the lens in relation to the visual axis; and

applying the one or more optical alignments to ocular information associated with the one or more eyes to facilitate, control, or initiate an action or process of estimating outcomes for one or more lens implantation procedures.

7. The method of claim 6, wherein the one or more optical alignments are applied to the ocular information in conjunction with corneal high order aberration (HOA) information associated with the one or more eyes.

8. The method of claim 6, wherein the one or more optical alignments are applied to the ocular information in conjunction with residual post operative cylinder information associated with the one or more eyes.

9. The method of claim 6, wherein the action or process involves providing an assessment of image qualities associated with multiple different aspheric IOLs.

10. The method of claim 6, wherein the action or process involves controlling, generating, or providing a user interface pertaining to one or more of

a preoperative status associated with the one or more eyes,

candidate vision enhancement procedures and/or products,

estimated postoperative results for one or more vision enhancement procedures and/or products,

a comparison of pre and postop corneal astigmatism,

angle alpha associated with one or more of the eyes,

an estimate of visual axis to lens deviation associated with one or more of the eyes,

estimated image quality for one or more vision enhancement procedures and/or products,

estimated surgeon-specific surgically induced changes,

an estimated postoperative assessment,

a comparison of lenses that is one or more of surgeon-specific, lens style-specific, and surgical procedure-specific or approach-specific,

one or more personalized parameters or determinations, and

an indication of cases having desired outcomes.

11. A method for facilitating a vision enhancement procedure, the method comprising:

accessing ophthalmic information for one or more eyes; and

applying one or more criteria to the ophthalmic information to facilitate or initiate an action or process of controlling, generating, or providing a visual representation of one or more of

a preoperative status associated with the one or more eyes,

candidate vision enhancement procedures and/or products,

estimated postoperative results for one or more vision enhancement procedures and/or products, a comparison of pre and postop corneal astigmatism,

angle alpha associated with one or more of the eyes,

an estimate of visual axis to lens deviation associated with one or more of the eyes,

estimated image quality for one or more vision enhancement procedures and/or products,

estimated surgeon specific surgically induced changes,

an estimated postoperative assessment,

a comparison of lenses that is one or more of surgeon-specific, lens style-specific, and surgical procedure-specific or approach-specific,

one or more personalized parameters or determinations, and

an indication of cases having desired outcomes.

12. The method of claim 11, wherein the visual representation is controlled, generated, or provided via an interface that is generated utilizing a custom add-in or plug-in system application which functions as an extension and overlay to an existing third party system application or other platform that facilitates ophthalmic assessments.

13. The method of claim 11, wherein the preoperative status is associated with the one or more eyes in relation to one or more of

keratometric astigmatism,

total corneal higher order aberrations,

corneal spherical aberration, and

visual axis and lens deviation.

14. The method of claim 11, wherein the candidate vision enhancement procedures and/or products are arranged such that one or more vision enhancement procedures and/or products that satisfy the one or more criteria or a subset thereof are prominently presented.

15. The method of claim 11, wherein the estimated postoperative results for one or more vision enhancement procedures and/or products involve one or more of

estimated postoperative results for multiple different IOLs,
monofocal and/or multifocal candidates,
negative aspheric candidates,
negative aspheric multifocal candidates, and
negative aspheric toric candidates.

16. The method of claim 11, wherein the comparison of pre and postop corneal astigmatism pertains to a measured preoperative corneal wavefront astigmatism and an estimated postoperative corneal wavefront astigmatism.

17. The method of claim 11, wherein the comparison of pre and postop corneal astigmatism pertains to individual pre and postop HOAs and induced astigmatism results.

18. The method of claim 11, wherein the estimated image quality for one or more vision enhancement procedures and/or products is presented in relation to a visual scheme correlating multiple different ranges of estimated image quality with different visually distinct representations, respectively.

19. The method of claim 11, wherein the estimated surgeon-specific surgically induced changes includes visible indicia representing one or more of a pupil center, a limbal center, and a visual axis center.

20. The method of claim 11, wherein the comparison of lenses includes an IOL-specific comparison in relation to different angle alpha selections.

21. The method of claim 11, wherein the one or more personalized parameters or determinations include one or more of a personalized A constant and an IOL-specific parameter or determination.

22. A method for assessing surgically induced changes, the method comprising:

measuring, determining, or estimating pre and postop corneal wavefront astigmatisms for an eye; and

applying the pre and postop corneal wavefront astigmatisms in an action or process of controlling or utilizing one or more electronic devices and/or display devices to provide a visual representation of one or more surgically induced changes.

23. The method of claim 22, further comprising:

measuring, determining, or estimating a postoperative centration of IOLs relative to the limbal center and/or the corneal vertex; and

using the location of the lens center to update or modify a determination and/or a visual representation involving visual axis to lens center deviation.

24. A method of selecting a vision enhancement procedure and/or product, the method comprising:

for multiple subjects, utilizing pre and postoperative ophthalmic information including corneal topography and IOL centration relative to the corneal vertex to map surgeon-specific, IOL-specific surgically-related tendencies in relation to multiple different IOLs.

25. The method of claim 24, further comprising:

identifying one or more trends associated with the pre and postoperative ophthalmic information; and

utilizing the one or more trends to provide or modify an estimated postoperative assessment.

26. A method of selecting a vision enhancement procedure and/or product, the method comprising:

for each of a series of subjects

obtaining corneal topography information for a preoperative eye, after implanting an IOL lens, determining IOL centration relative to the corneal vertex,

after determining IOL centration, determining for all or a plurality of subjects of the series that have been postoperatively measured an aggregate or average estimated surgically induced change, and

applying the aggregate or average estimated surgically induced change to control one or more electronic displays in relation to generating, updating, or providing a visual representation pertaining to one or more surgically induced changes.

27. The method of claim 26, wherein the visual representation pertains to one or more estimated or predicted tendencies in relation to surgically induced changes.

28. The method of claim 26, wherein the visual representation pertains to one or more of

surgeon-specific surgically induced changes,

surgeon-specific, IOL-specific surgically-related tendencies,

surgeon-specific, lens style-specific surgically-related tendencies,

lens type-specific, lens model-specific, lens design specific, lens size-specific, or lens batch-specific surgically-related tendencies, and

surgical procedure-specific or approach-specific surgically-related tendencies.

29. A vision enhancement method, comprising:

determining an optical center and a corneal vertex for an eye;

using the optical center and corneal vertex to determine a visual axis for the eye;

determining an intercept of the visual axis with a lens plane;

using the intercept to determine an optical alignment of the lens in relation to the visual axis; and

applying the optical alignment to an action or process of providing, facilitating, and/or presenting one or more ophthalmic assessments.

30. A vision enhancement system, comprising:

a computer-executable software application configured or programmed to receive or access ocular information associated with one or more eyes and to process the ocular information in relation to

determining an optical center and a corneal vertex for an eye,

using the optical center and corneal vertex to determine a visual axis for the eye,

determining an intercept of the visual axis with a lens plane, and

using the intercept to determine an optical alignment of the lens in relation to the visual axis.

31. The vision enhancement system of claim 30, wherein the computer-executable software application is configured or programmed to apply the optical alignment to an action or process of providing or facilitating an ophthalmic assessment in relation to one or more vision enhancement products and/or procedures.

32. The vision enhancement system of claim 30, wherein the computer-executable software application is configured or programmed to apply the optical alignment to an action or process of controlling, generating, or providing a display and/or a user interface.

33. The vision enhancement system of claim 30, wherein the computer-executable software application is a custom add-in or plug-in system application which functions as an extension and overlay to an existing third party system application or other platform that facilitates ophthalmic assessments.

34. The vision enhancement system of claim 30, wherein the computer-executable software application is at least partially cloud-based and/or accessible via a website or other electronic or communications platform.

35. A vision enhancement method, comprising:

measuring an image location at the retina and an axial length of the eye to approximate a visual axis of the eye;

using an optic diameter to determine the distance between the cornea and the lens;

determining an intercept of the visual axis with a lens plane;

using the intercept to determine an optical alignment of the lens in relation to the visual axis; and

applying the optical alignment to an action or process of providing, facilitating, and/or presenting one or more ophthalmic assessments.

36. The vision enhancement method of claim 35, wherein a photographic technique is used to determine the optic diameter of the lens.

37. The vision enhancement method of claim 35, wherein the optic diameter is determined from a measured visible edge portion of the optic.

38. A vision enhancement system, comprising:

a computer-executable software application configured or programmed to receive or access ocular information associated with one or more eyes and to process the ocular information in relation to

measuring an image location at the retina and an axial length of the eye to approximate a visual axis of the eye,

using an optic diameter to determine the distance between the cornea and the lens,

determining an intercept of the visual axis with a lens plane, and

using the intercept to determine an optical alignment of the lens in relation to the visual axis.

39. The vision enhancement system of claim 38, wherein the computer-executable software application is configured or programmed to apply the optical alignment to an action or process of providing or facilitating an ophthalmic assessment in relation to one or more vision enhancement products and/or procedures.

40. The vision enhancement system of claim 38, wherein the computer-executable software application is configured or programmed to apply the optical alignment to an action or process of controlling, generating, or providing a display and/or a user interface.

41. The vision enhancement system of claim 38, wherein the computer-executable software application is a custom add-in or plug-in system application which functions as an extension and overlay to an existing third party system application or other platform that facilitates ophthalmic assessments.

42. The vision enhancement system of claim 38, wherein the computer-executable software application is at least partially cloud-based and/or accessible via a website or other electronic or communications platform.

43. A vision enhancement method, comprising:

utilizing estimated or a priori determined coordinates of the visual axis at the cornea to locate arcuate corneal incisions during femtosecond laser surgery of the eye.

44. The vision enhancement method of claim 43, wherein the surgery includes femtosecond laser cataract surgery with astigmatism correction.

45. A vision enhancement method, comprising:

selecting and/or optimizing one or more vision correction modalities in consideration of foveal curvature.

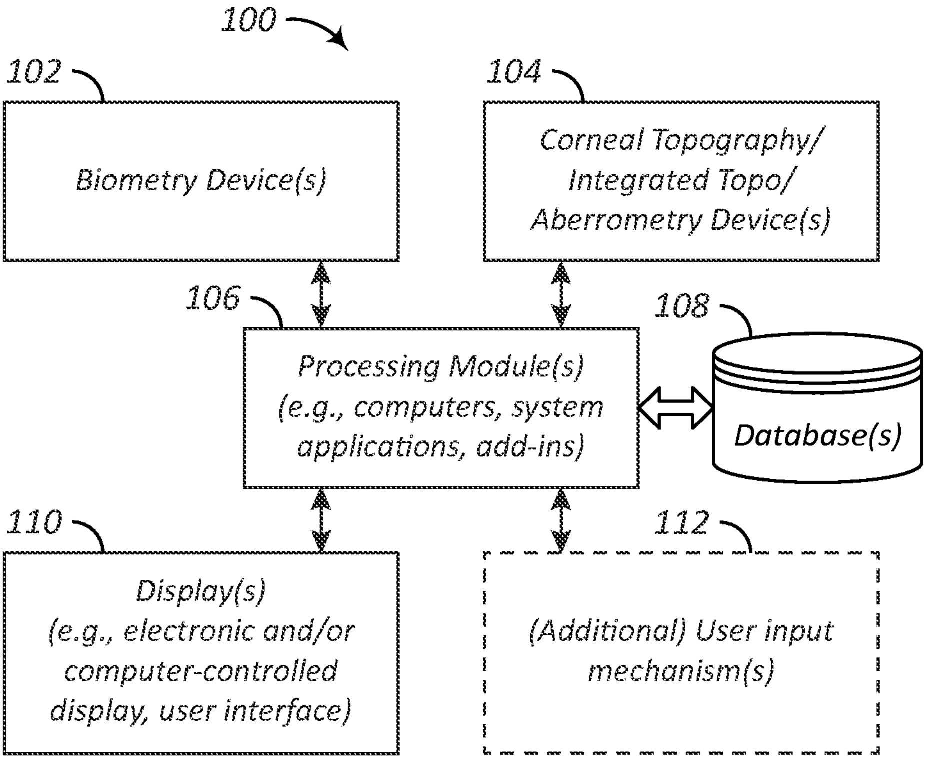

100
102
104
Biometry Device(s)
Corneal Topography/
Integrated Topo/
Aberrometry Device(s)
106
108
Processing Module(s)
(e.g., computers, system
applications, add-ins)
Database(s)
110
112
Display(s)
(e.g., electronic and/or
computer-controlled
display, user interface)
(Additional) User input
mechanism(s)

FIG. 1

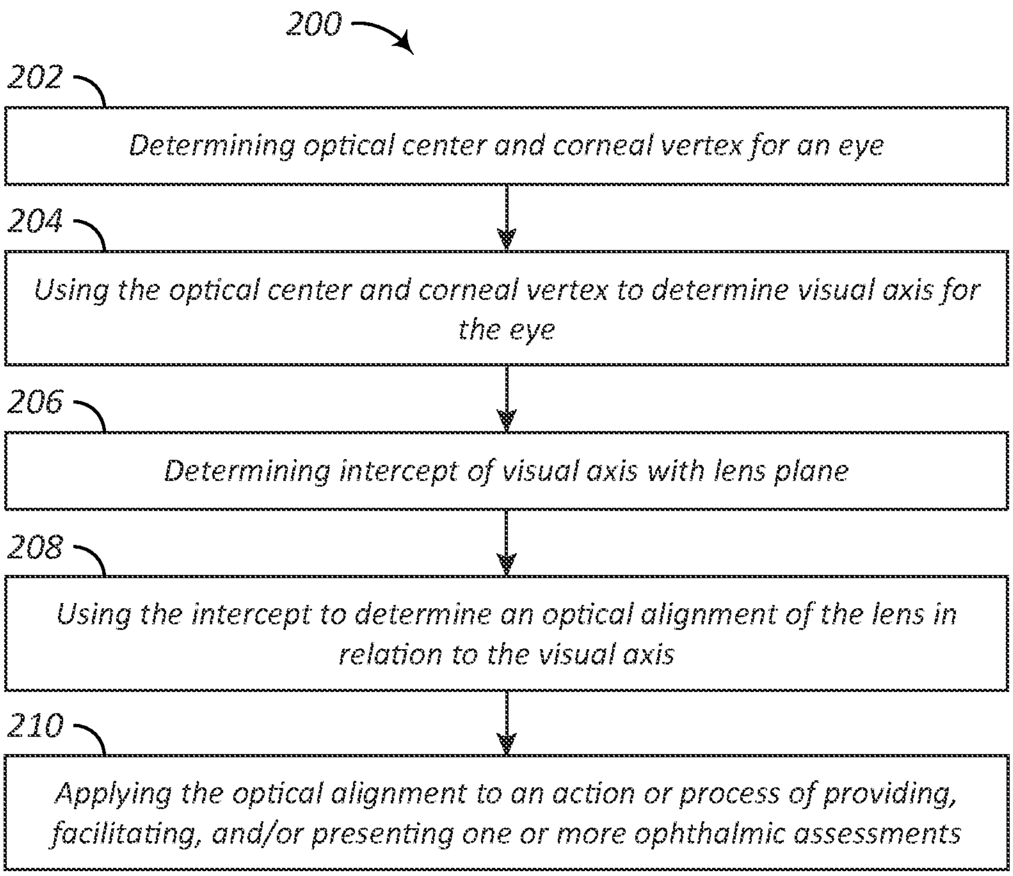

200
202
Determining optical center and corneal vertex for an eye
204
Using the optical center and corneal vertex to determine visual axis for the eye
206
Determining intercept of visual axis with lens plane
208
Using the intercept to determine an optical alignment of the lens in relation to the visual axis
210
Applying the optical alignment to an action or process of providing, facilitating, and/or presenting one or more ophthalmic assessments

FIG. 2

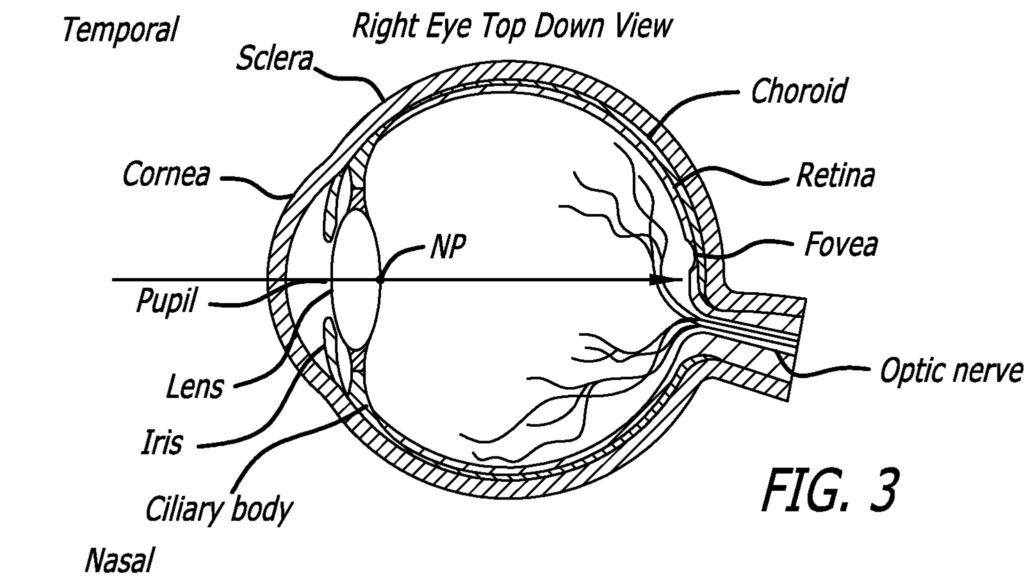


FIG. 3

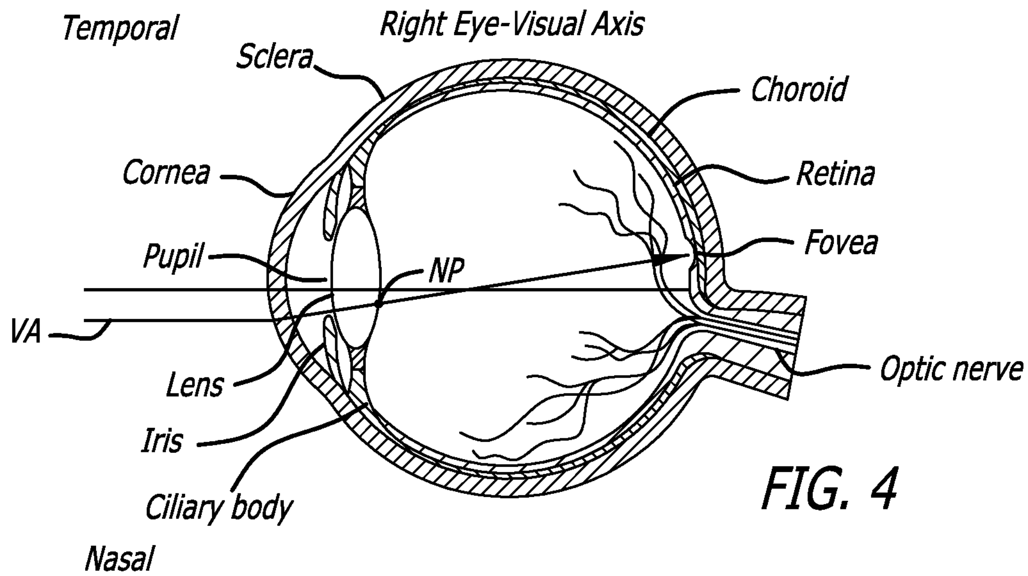


FIG. 4

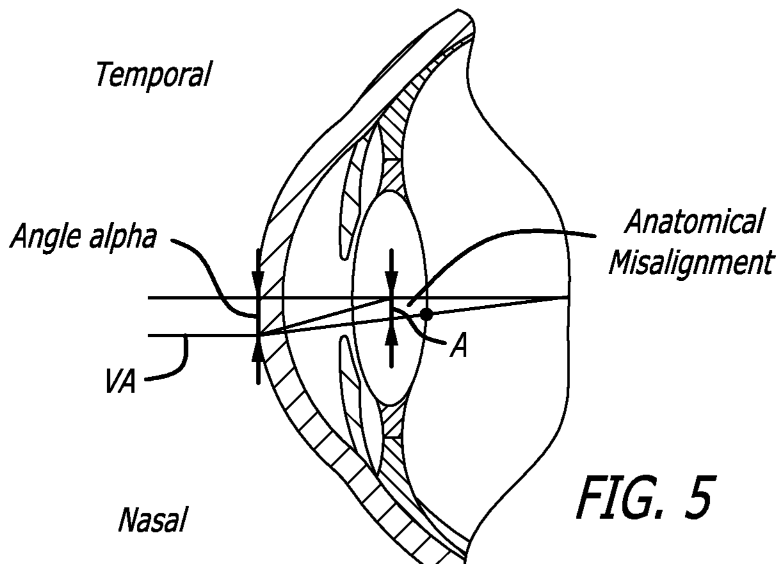


FIG. 5

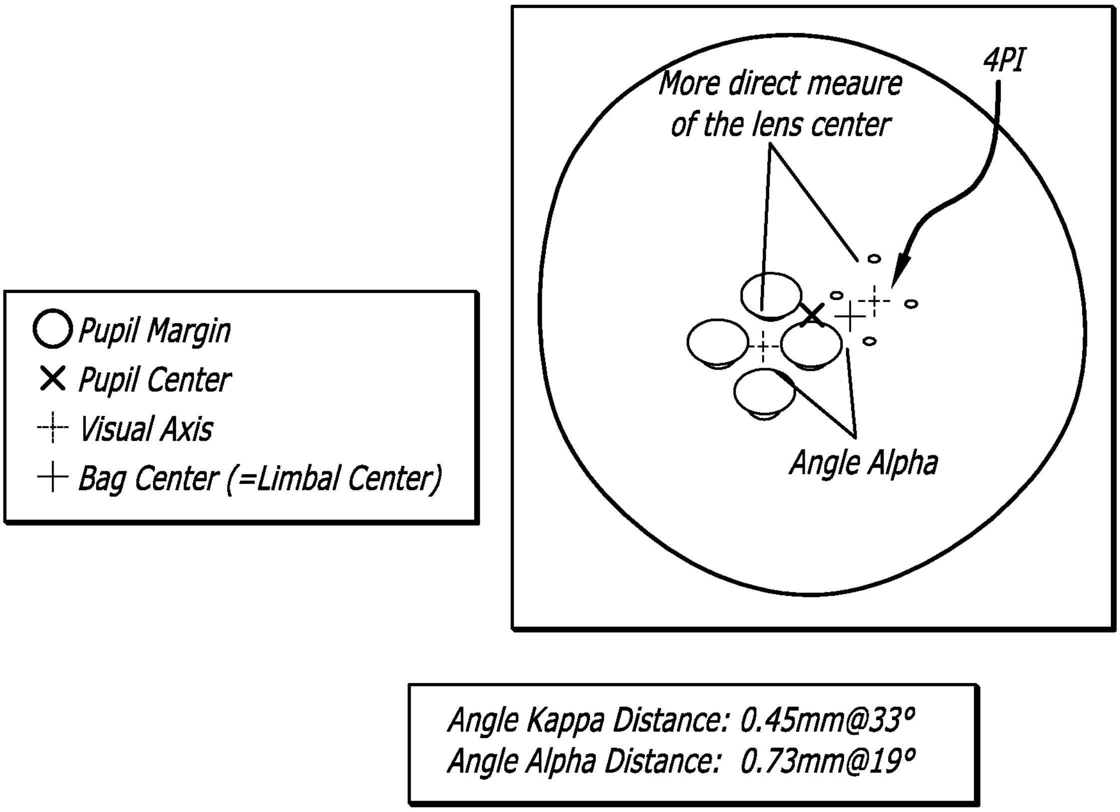

Pupil Margin
Pupil Center
Visual Axis
Bag Center (=Limbal Center)
More direct meaure of the lens center
4PI
Angle Alpha
Angle Kappa Distance: 0.45mm@33°
Angle Alpha Distance: 0.73mm@19°

FIG. 6

FIG. 7-1

Patient First Name	Jose
Patient Last Name	Puente
Pat ID	0
Eye	OD
Date Of Birth	5/9/1991
Gender	Male
Age (years)	206
Exam Date	12/6/2011
Pupil Size mm	6.91
Corneal HOA (mm)@	7.50
Sphere RMS	2.344
Astigmatism RMS	4.961
Axis	106
Total HOA RMS	1.116
Spherical Aberration RMS	0.472
Coma RMS	0.807
Coma Axis	104
Tre foil RMS	0.504
Tre foil Axis	104
Other RMS	0.421
Sph Aberration @ 6mm	0.26

First	Last	ID	Age	Center	ExamDate	Eye
Jose	Puente	0	20.5	0	11/6/2011	OD

PREOPERATIVE

Sim K Cyl	Patient	Corneal HOA Assessment Pupil+0.5mm	Patient	Anatomical Alignment Assessment	Patient
Diopters	0	Microns	0	mm	0
	3.02				
0.75			1.116		
0.70		0.50		0.70	
0.60		0.43		0.60	
0.50		0.36		0.50	
0.40		0.29		0.40	
0.30		0.21		0.30	
0.25		0.14		0.20	
0.20		0.07		0.10	0.194
0.10		0.00		0.00	
0.00					

*if optically aligned

Estimated POSTOPERATIVE

Premium IOL Options

Negative Aspheric Multifocal			Negative Aspheric Toric				Advanced Aspheric Monofocal IOL Options	
							HOYA Optimized	Negative Aspherics
Sim K Cyl D	Effective Corneal HOA Pupil+0.5mm Microns*	Mis align ment mm	Sim K Cyl D	REGULAR Refractive Corneal Cyl D	Difference in Steep Meridian Degrees	Image Quality	%	%
2.77			@3mm	@7.5mm	@7.5mm	HIGHER		
	1.042					100%		
						90%		
						80%		80
				3.46		70%	70	
						60%		
						50%		
			3.02		1	40%		
		0.194				30%		
						20%		
						10%		
						LOWER		

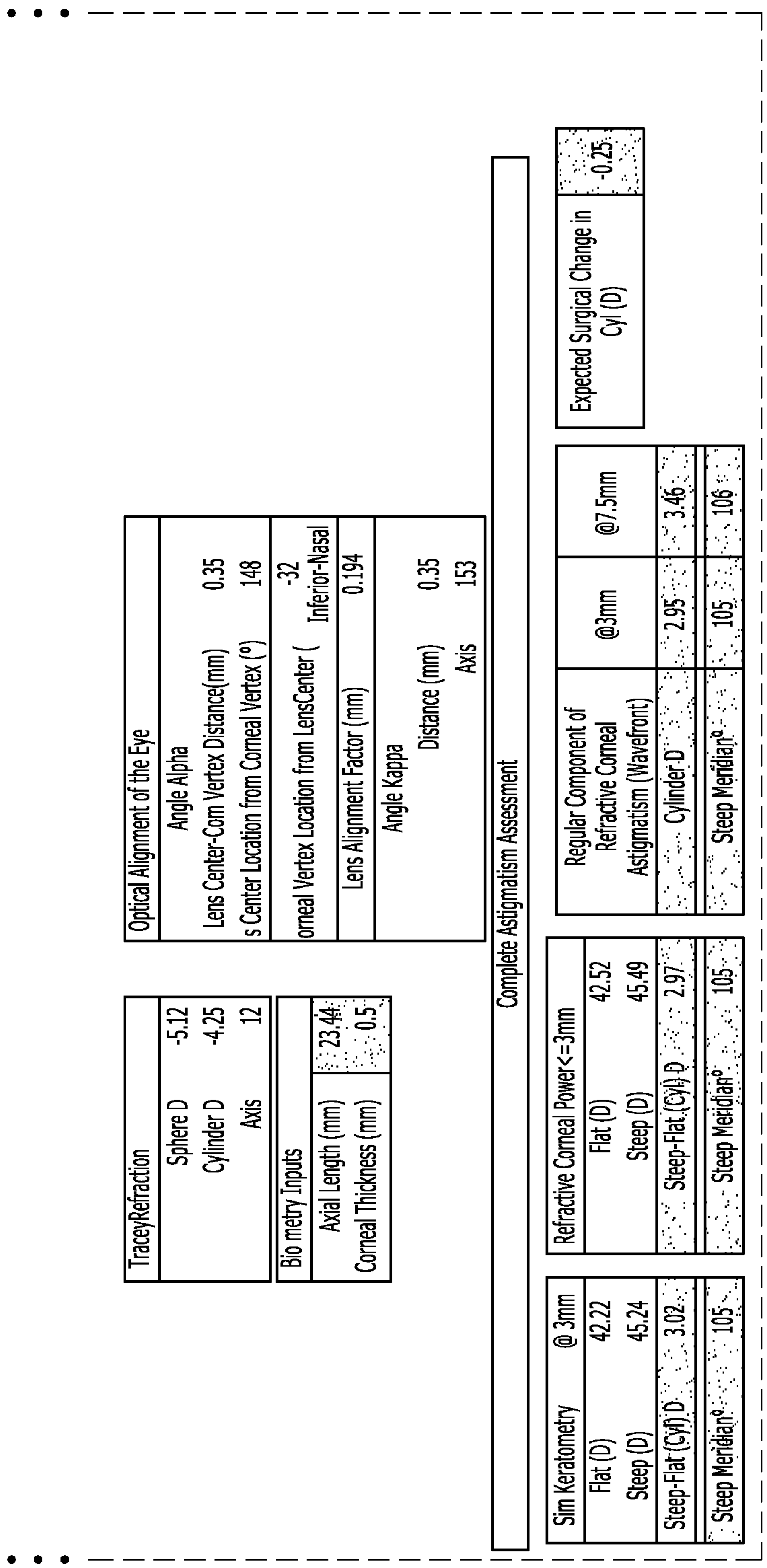

TraceyRefraction
Sphere D -5.12
Cylinder D -4.25
Axis 12
Bio metry Inputs
Axial Length (mm) 23.44
Corneal Thickness (mm) 0.5
Optical Alignment of the Eye
Angle Alpha
Lens Center-Com Vertex Distance(mm) 0.35
s Center Location from Corneal Vertex (°) 148
orneal Vertex Location from LensCenter (-32
Inferior-Nasal
Lens Alignment Factor (mm) 0.194
Angle Kappa
Distance (mm) 0.35
Axis 153
Complete Astigmatism Assessment
Sim Keratometry @ 3mm
Flat (D) 42.22
Steep (D) 45.24
Steep-Flat (Cyl) D 3.02
Steep Meridian° 105
Refractive Corneal Power<=3mm
Flat (D) 42.52
Steep (D) 45.49
Steep-Flat (Cyl) D 2.97
Steep Meridian° 105
Regular Component of Refractive Corneal Astigmatism (Wavefront) @3mm @7.5mm
Cylinder D 2.95 3.46
Steep Meridian° 105 106
Expected Surgical Change in Cyl (D) -0.25

FIG. 7-2

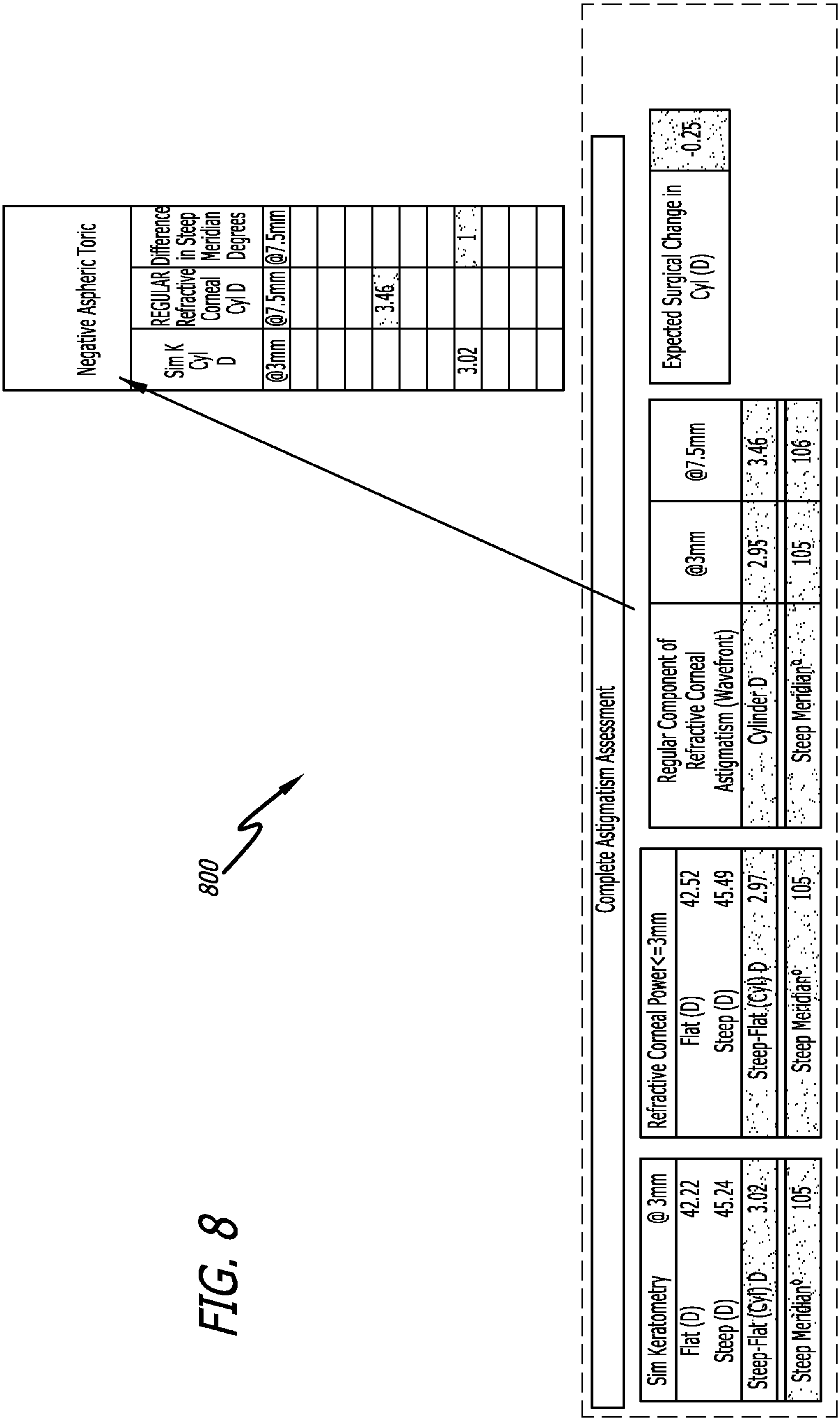
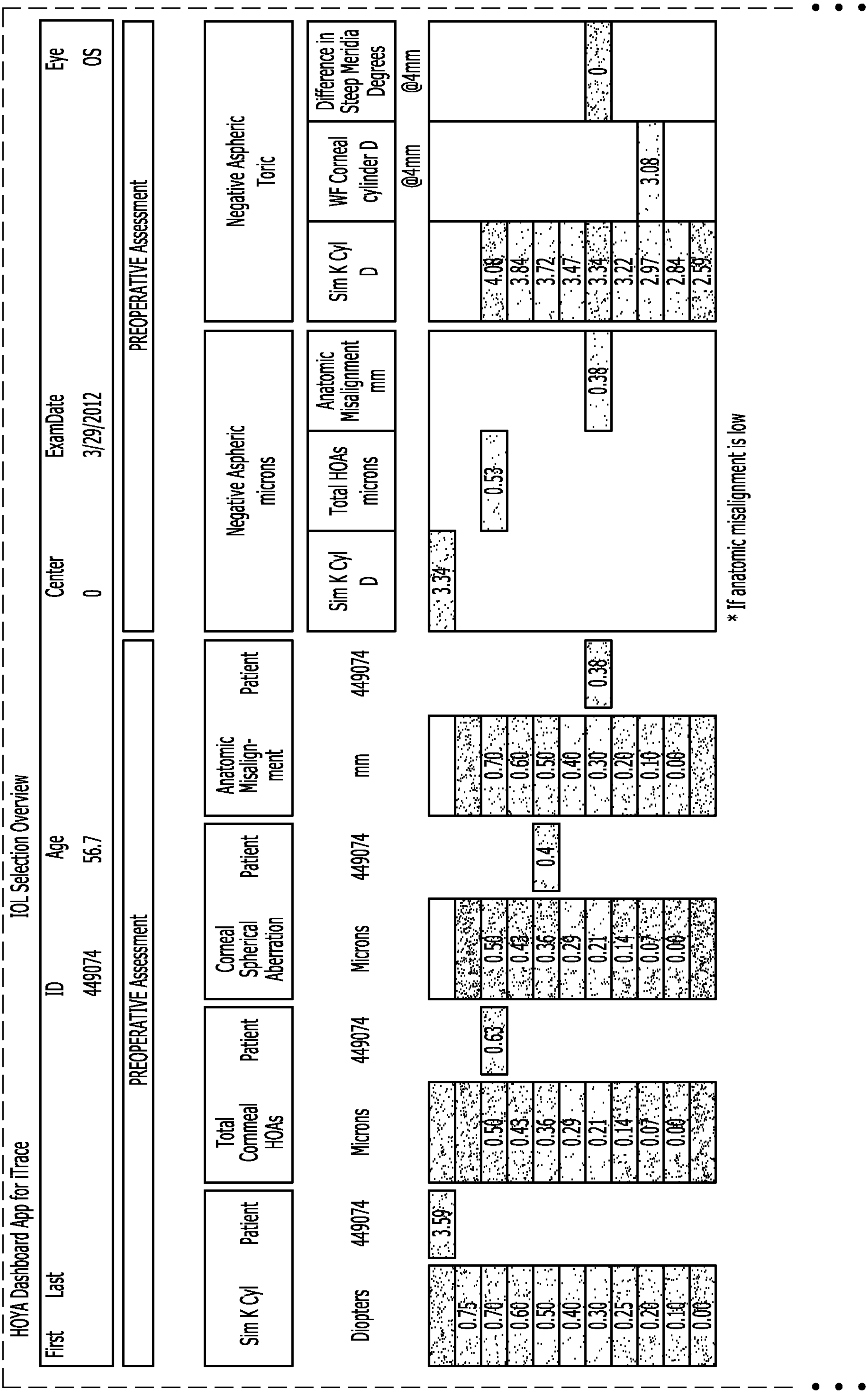

800
Negative Aspheric Toric
Sim K Cyl D
REGULAR Refractive Corneal Cyl D
Difference in Steep Meridian Degrees
@3mm
@7.5mm
@7.5mm
3.02
3.46
1
Complete Astigmatism Assessment
Sim Keratometry
@ 3mm
Flat (D)
42.22
Steep (D)
45.24
Steep-Flat (Cyl) D
3.02
Steep Meridian°
105
Refractive Corneal Power<=3mm
Flat (D)
42.52
Steep (D)
45.49
Steep-Flat (Cyl) D
2.97
Steep Meridian°
105
Regular Component of Refractive Corneal Astigmatism (Wavefront)
@3mm
@7.5mm
Cylinder D
2.95
3.46
Steep Meridian°
105
106
Expected Surgical Change in Cyl (D)
-0.25

FIG. 8

FIG. 9-1


HOYA Dashboard App for iTrace
IOL Selection Overview
First Last ID Age Center ExamDate Eye
449074 56.7 0 3/29/2012 OS
PREOPERATIVE Assessment
PREOPERATIVE Assessment
Sim K Cyl
Patient
Total Corneal HOAs
Patient
Corneal Spherical Aberration
Patient
Anatomic Misalign-ment
Patient
Negative Aspheric microns
Negative Aspheric Toric
Diopters 449074 Microns 449074 Microns 449074 mm 449074
Sim K Cyl D
Total HOAs microns
Anatomic Misalignment mm
Sim K Cyl D
WF Corneal cylinder D
Difference in Steep Meridia Degrees
@4mm @4mm
0.75 0.70 0.60 0.50 0.40 0.30 0.25 0.20 0.10 0.00
3.59
0.50 0.43 0.36 0.29 0.21 0.14 0.07 0.00
0.63
0.50 0.43 0.36 0.29 0.21 0.14 0.07 0.00
0.4
0.70 0.60 0.50 0.40 0.30 0.20 0.10 0.00
0.38
3.34
0.53
0.38
4.08 3.84 3.72 3.47 3.34 3.22 2.97 2.84 2.59
3.08
0
* If anatomic misalignment is low

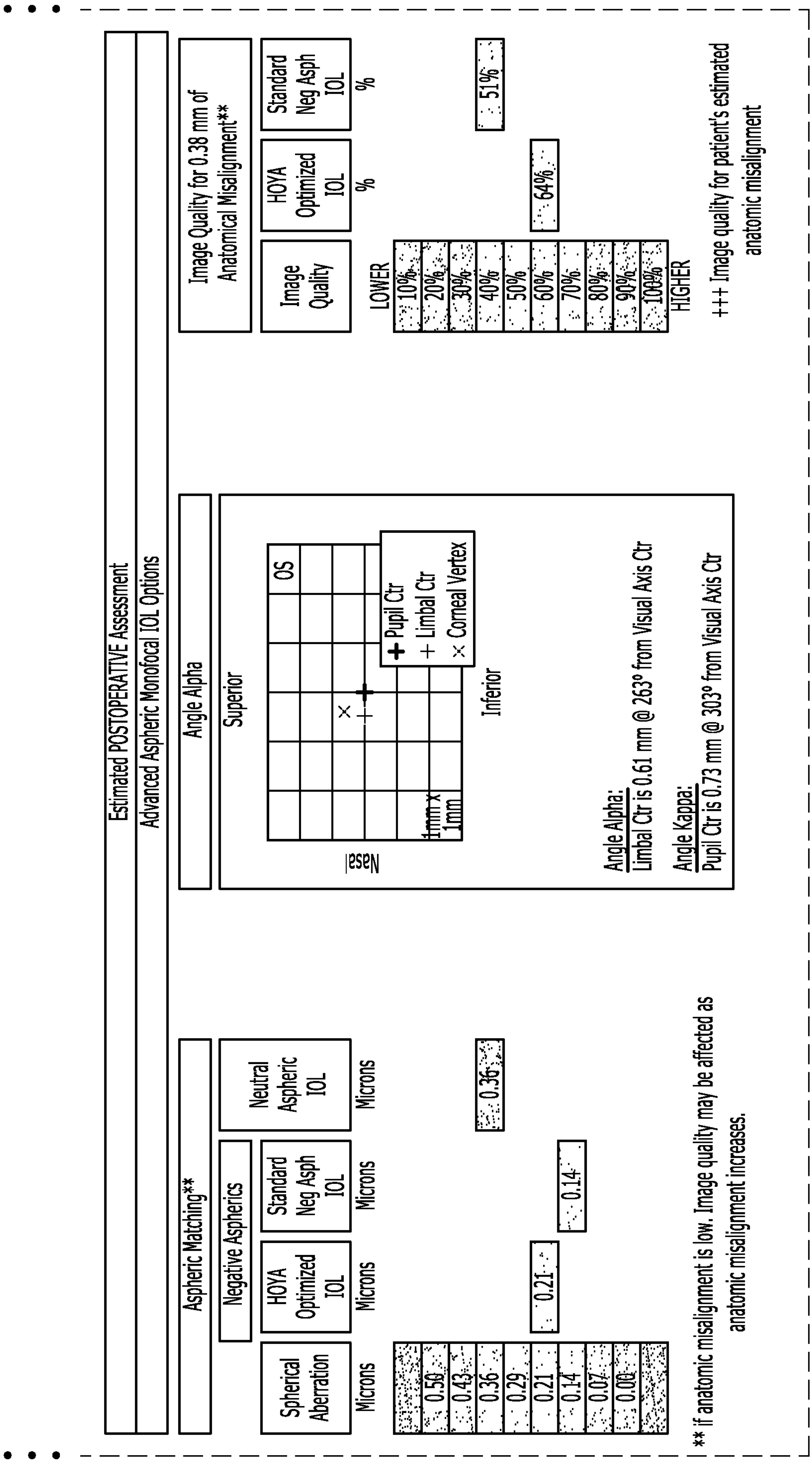

Estimated POSTOPERATIVE Assessment
Advanced Aspheric Monofocal IOL Options
Image Quality for 0.38 mm of Anatomical Misalignment**
Image Quality
HOYA Optimized IOL
%
Standard Neg Asph IOL
%
LOWER
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
HIGHER
64%
51%
+++ Image quality for patient's estimated anatomic misalignment
Angle Alpha
Superior
Inferior
Nasal
OS
1mm x 1mm
Pupil Ctr
Limbal Ctr
Corneal Vertex
Angle Alpha:
Limbal Ctr is 0.61 mm @ 263° from Visual Axis Ctr
Angle Kappa:
Pupil Ctr is 0.73 mm @ 303° from Visual Axis Ctr
Aspheric Matching**
Negative Aspherics
Spherical Aberration
Microns
HOYA Optimized IOL
Microns
Standard Neg Asph IOL
Microns
Neutral Aspheric IOL
Microns
0.50
0.43
0.36
0.29
0.21
0.14
0.07
0.00
0.21
0.14
0.36
** If anatomic misalignment is low, Image quality may be affected as anatomic misalignment increases.

FIG. 9-2

FIG. 10

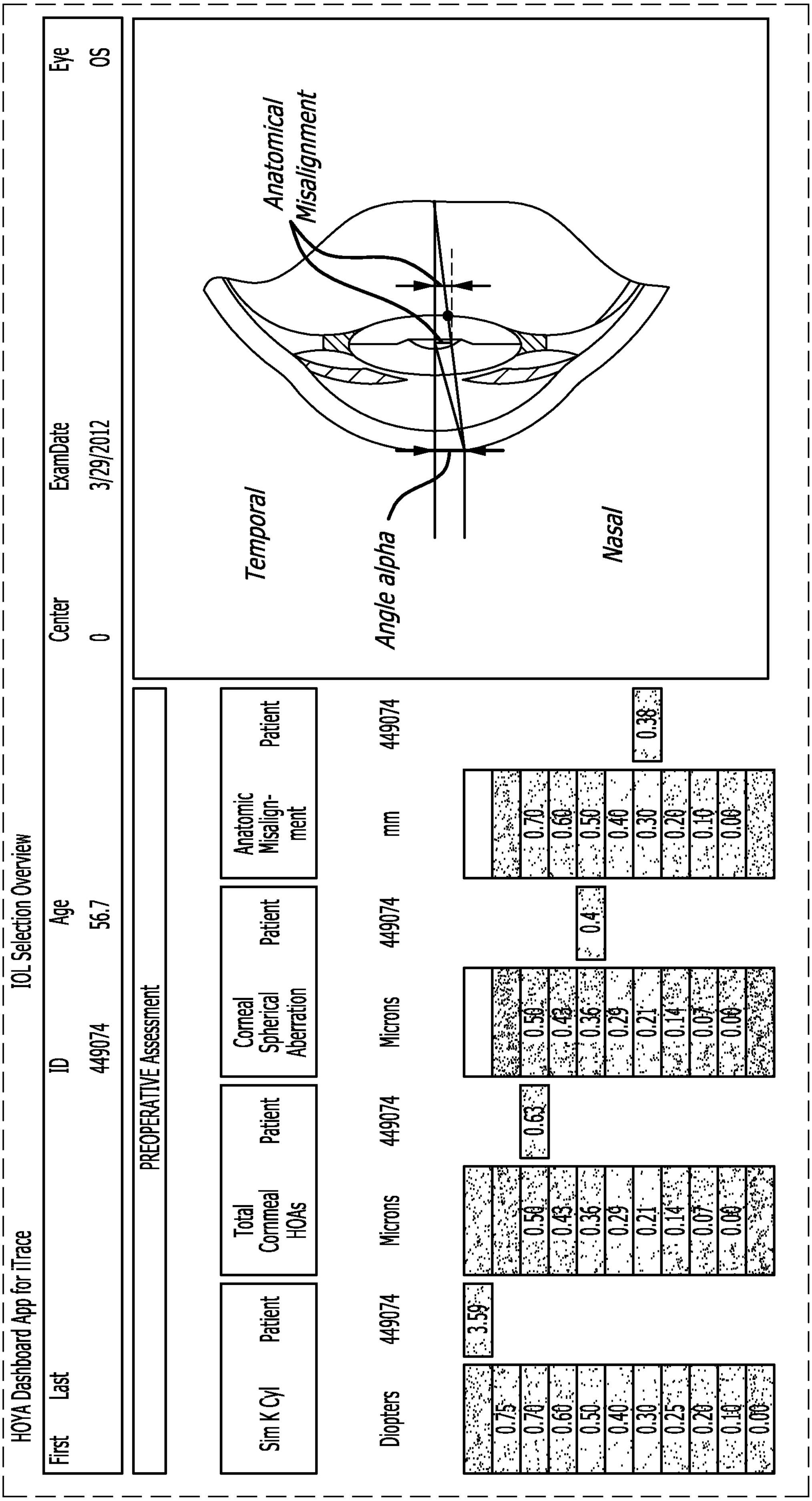

HOYA Dashboard App for iTrace
IOL Selection Overview
First
Last
ID
449074
Age
56.7
Center
0
ExamDate
3/29/2012
Eye
OS
PREOPERATIVE Assessment
Sim K Cyl
Patient
Total Cornmeal HOAs
Patient
Corneal Spherical Aberration
Patient
Anatomic Misalign-ment
Patient
Diopters
449074
Microns
449074
Microns
449074
mm
449074
0.75
0.70
0.60
0.50
0.40
0.30
0.25
0.20
0.10
0.00
3.59
0.50
0.43
0.36
0.29
0.21
0.14
0.07
0.00
0.63
0.50
0.42
0.36
0.29
0.21
0.14
0.07
0.00
0.4
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.38
Temporal
Nasal
Angle alpha
Anatomical Misalignment

FIG. 11

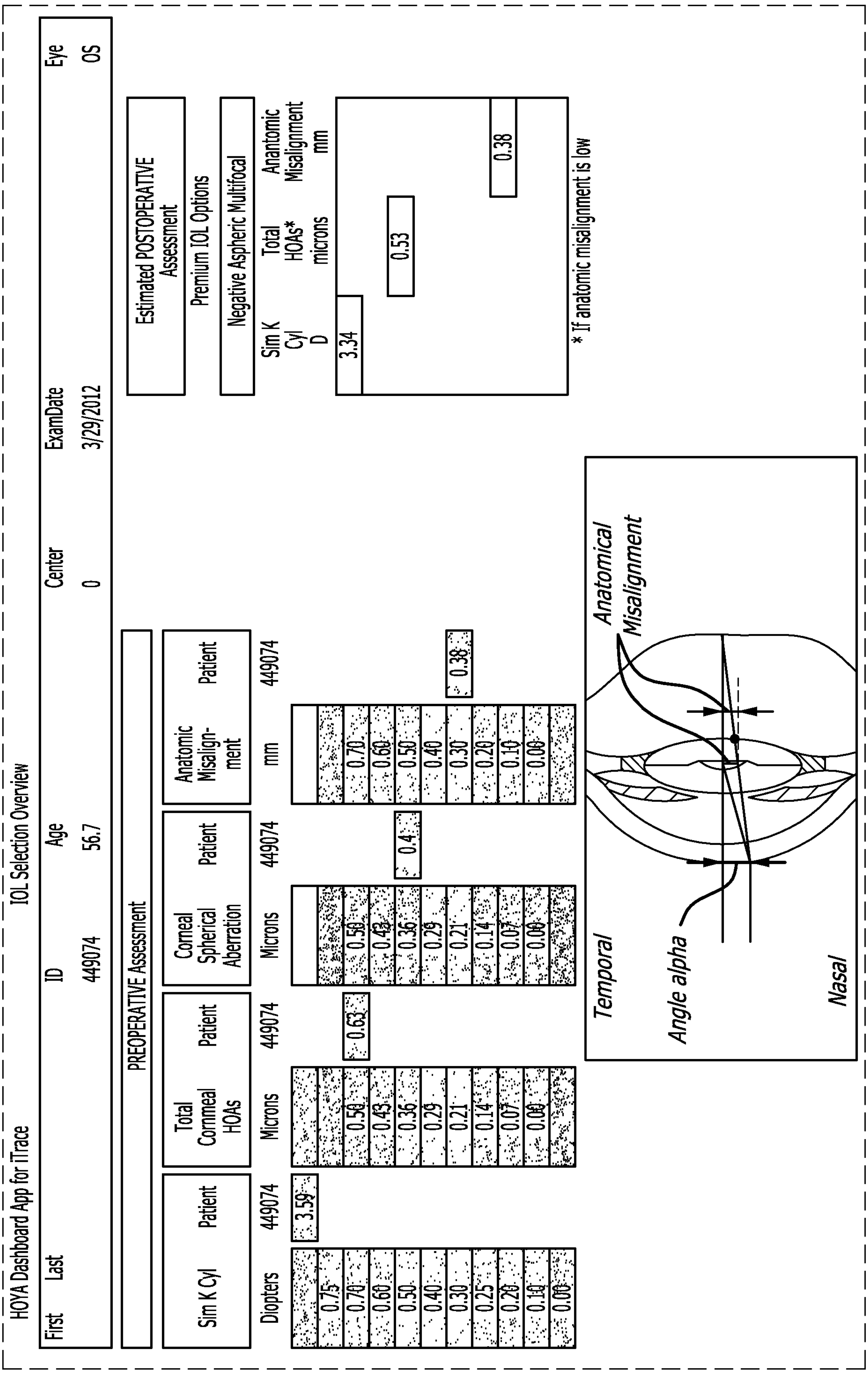

HOYA Dashboard App for iTrace
IOL Selection Overview
First
Last
ID
449074
Age
56.7
Center
0
ExamDate
3/29/2012
Eye
OS
PREOPERATIVE Assessment
Sim K Cyl
Patient
Diopters
449074
3.59
0.75
0.70
0.60
0.50
0.40
0.30
0.25
0.20
0.10
0.00
Total Cornmeal HOAs
Patient
Microns
449074
0.63
0.50
0.43
0.36
0.29
0.21
0.14
0.07
0.00
Corneal Spherical Aberration
Patient
Microns
449074
0.4
0.50
0.43
0.36
0.29
0.21
0.14
0.07
0.00
Anatomic Misalign-ment
Patient
mm
449074
0.38
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Estimated POSTOPERATIVE Assessment
Premium IOL Options
Negative Aspheric Multifocal
Sim K Cyl D
Total HOAs* microns
Anatomic Misalignment mm
3.34
0.53
0.38
* If anatomic misalignment is low
Anatomical Misalignment
Temporal
Angle alpha
Nasal

FIG. 12

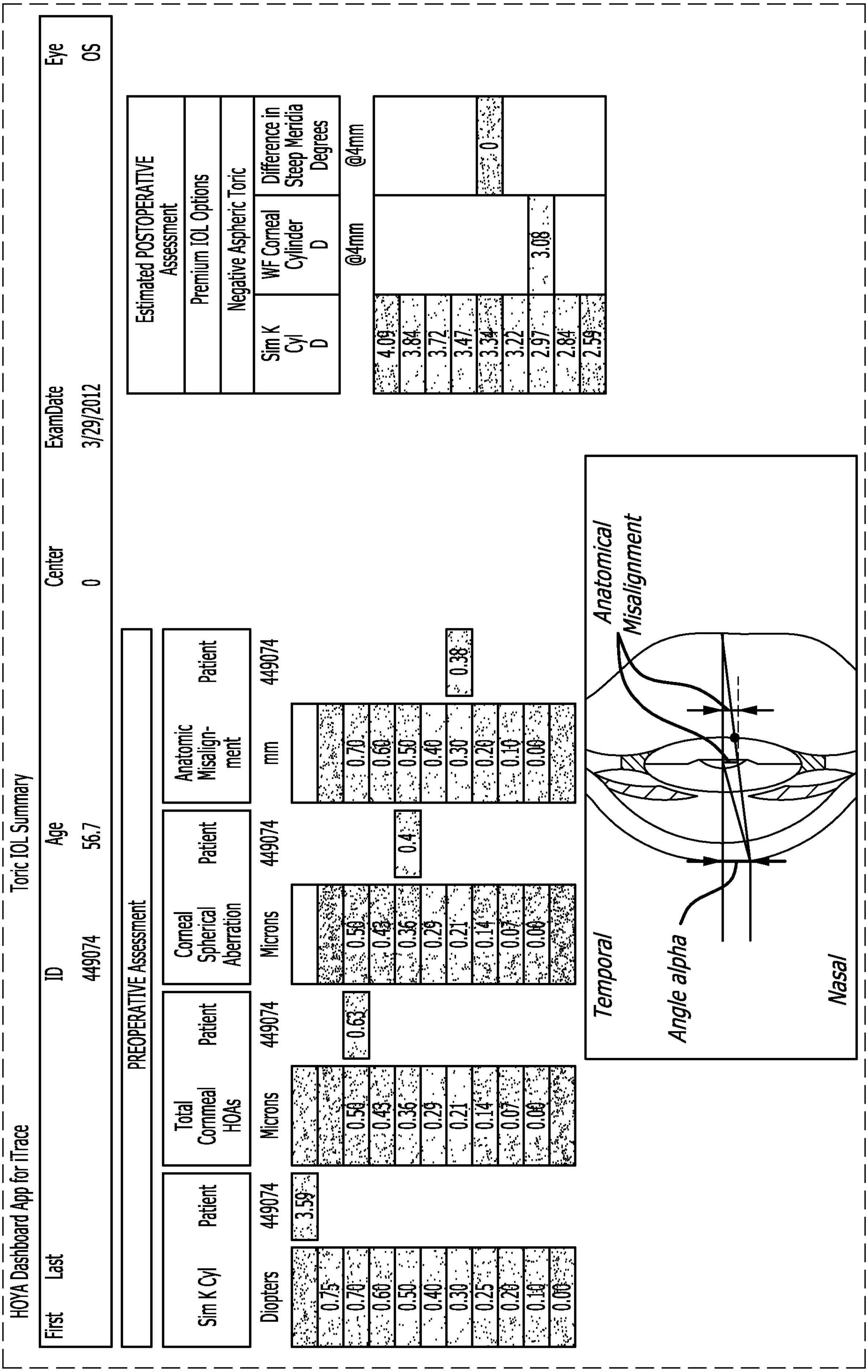
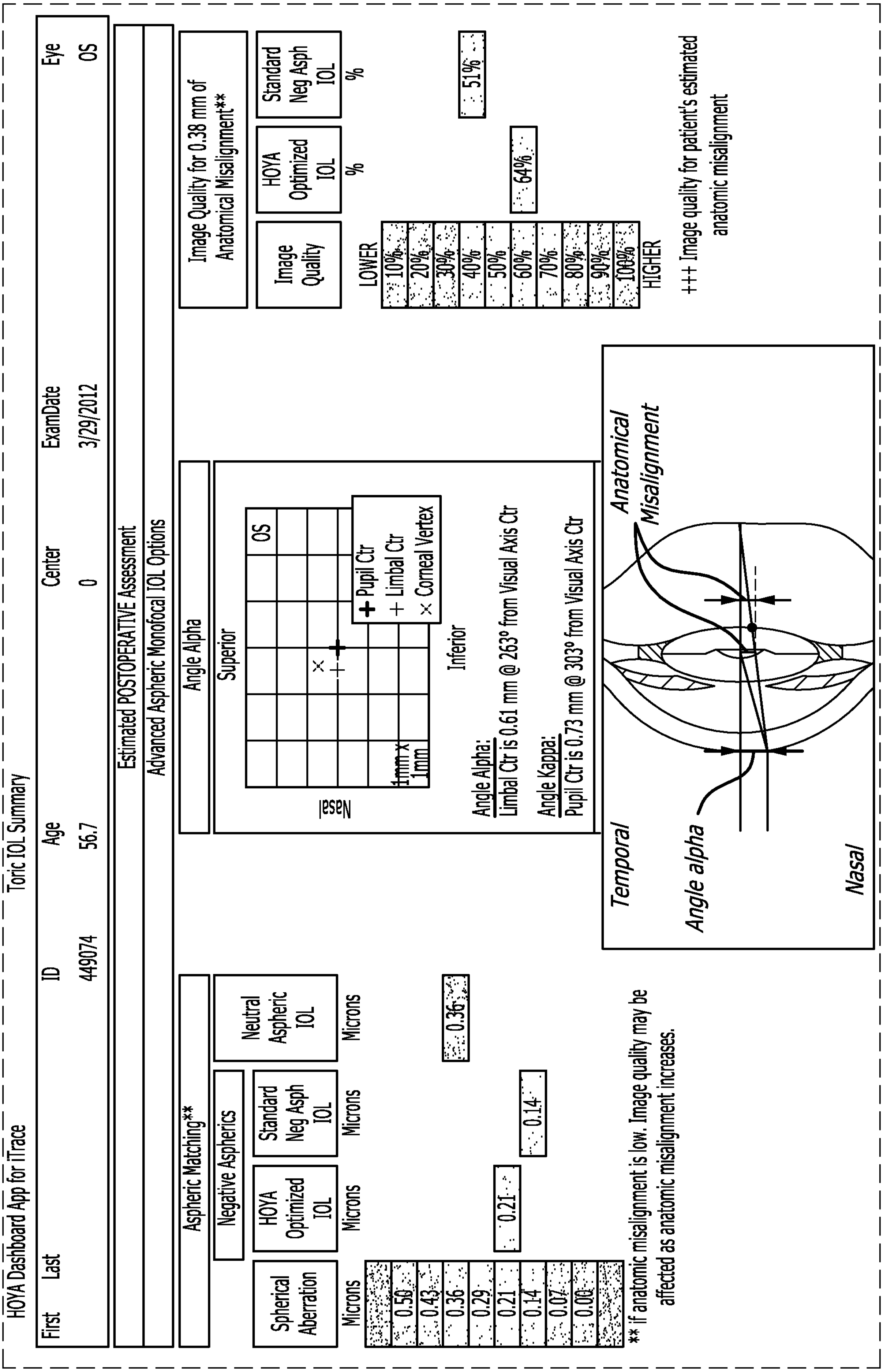

HOYA Dashboard App for iTrace
Toric IOL Summary
First
Last
ID
449074
Age
56.7
Center
0
ExamDate
3/29/2012
Eye
OS
PREOPERATIVE Assessment
Sim K Cyl
Patient
Diopters
449074
0.75
0.70
0.60
0.50
0.40
0.30
0.25
0.20
0.10
0.00
3.59
Total Corneal HOAs
Patient
Microns
449074
0.50
0.43
0.36
0.29
0.21
0.14
0.07
0.00
0.63
Corneal Spherical Aberration
Patient
Microns
449074
0.50
0.43
0.36
0.29
0.21
0.14
0.07
0.00
0.4
Anatomic Misalign-ment
Patient
mm
449074
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.38
Estimated POSTOPERATIVE Assessment
Premium IOL Options
Negative Aspheric Toric
Sim K Cyl D
WF Corneal Cylinder D
Difference in Steep Meridia Degrees
@4mm
@4mm
4.09
3.84
3.72
3.47
3.34
3.22
2.97
2.84
2.59
3.08
0
Anatomical Misalignment
Temporal
Angle alpha
Nasal

FIG. 13


HOYA Dashboard App for iTrace
Toric IOL Summary
First Last ID Age Center ExamDate Eye
449074 56.7 0 3/29/2012 OS
Estimated POSTOPERATIVE Assessment
Advanced Aspheric Monofocal IOL Options
Aspheric Matching**
Negative Aspherics
Spherical Aberration
HOYA Optimized IOL
Standard Neg Asph IOL
Neutral Aspheric IOL
Microns
0.50
0.43
0.36
0.29
0.21
0.14
0.07
0.00
0.21
0.14
0.36
** if anatomic misalignment is low. Image quality may be affected as anatomic misalignment increases.
Angle Alpha
Superior
Inferior
Nasal
OS
1mm x 1mm
Pupil Ctr
Limbal Ctr
Corneal Vertex
Angle Alpha:
Limbal Ctr is 0.61 mm @ 263° from Visual Axis Ctr
Angle Kappa:
Pupil Ctr is 0.73 mm @ 303° from Visual Axis Ctr
Anatomical Misalignment
Temporal
Angle alpha
Nasal
Image Quality for 0.38 mm of Anatomical Misalignment**
Image Quality
HOYA Optimized IOL
Standard Neg Asph IOL
%
LOWER
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
HIGHER
64%
51%
+++ Image quality for patient's estimated anatomic misalignment

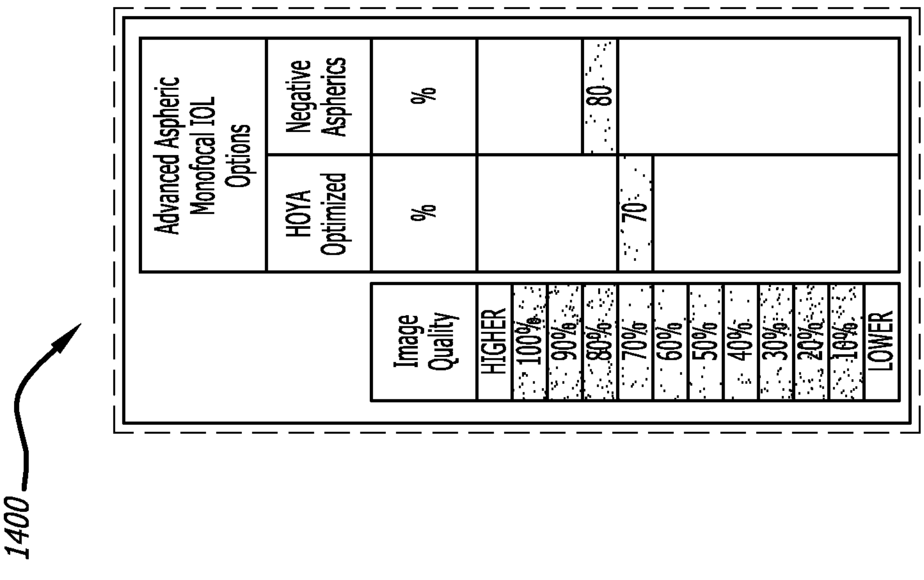

1400
Advanced Aspheric Monofocal IOL Options
HOYA Optimized
Negative Aspherics
%
%
70
80
Image Quality
HIGHER
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
LOWER

FIG. 14

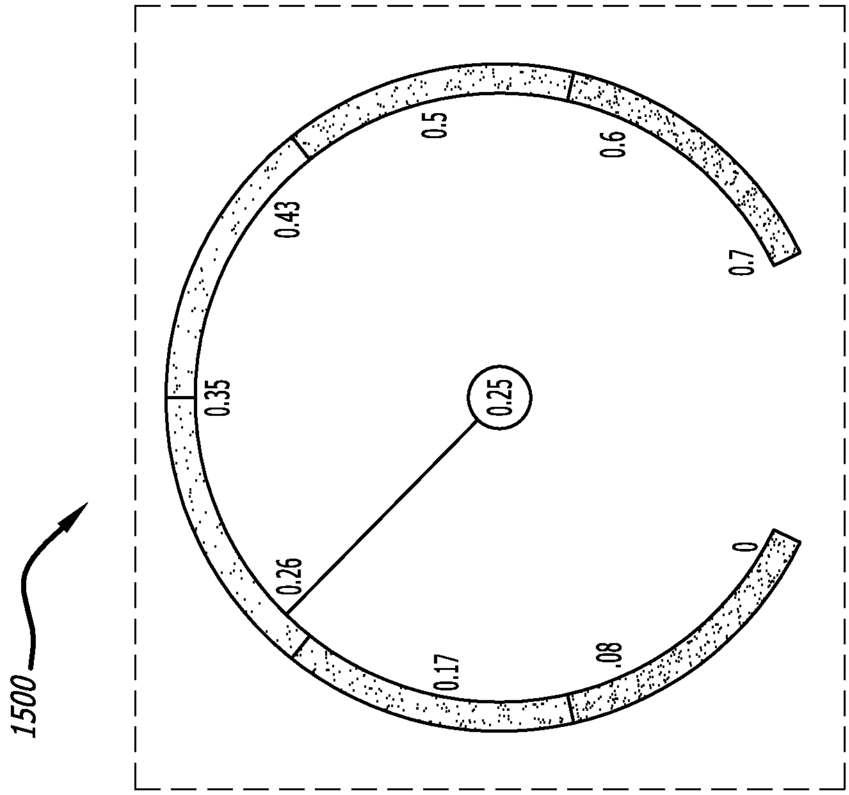

1500
0.25
0
.08
0.17
0.26
0.35
0.43
0.5
0.6
0.7

FIG. 15

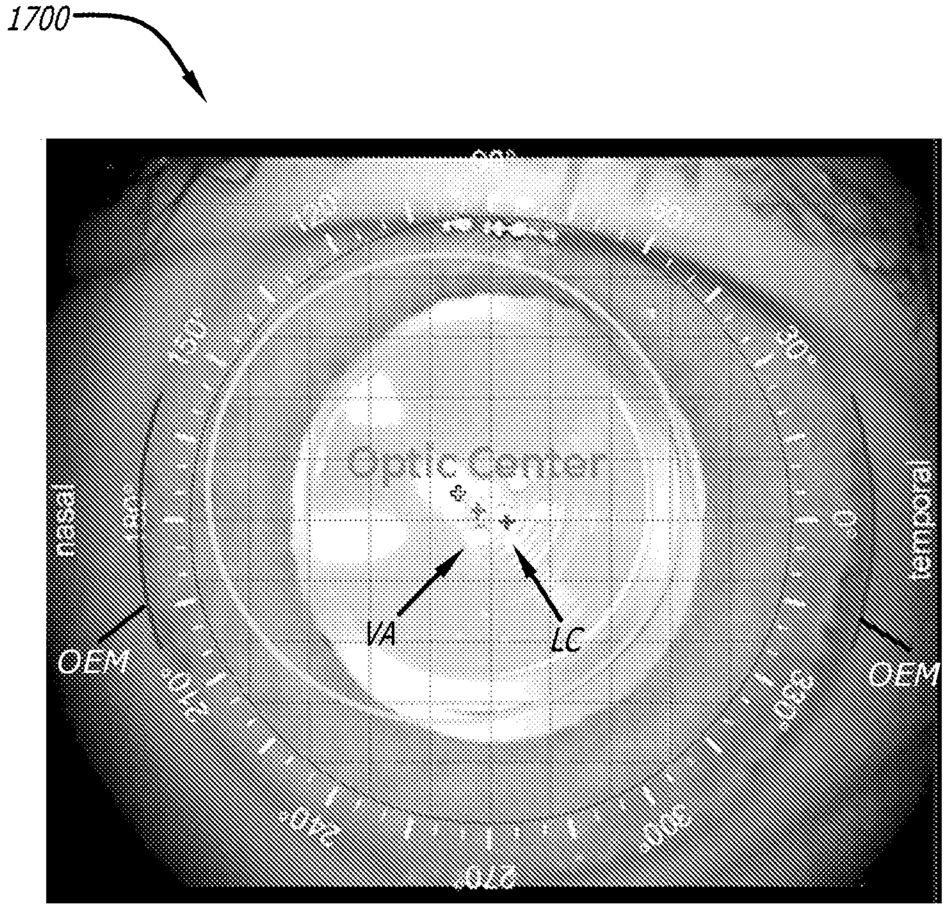

1700
Optic Center
nasal
temporal
VA
LC
OEM
OEM
120°
150°
30°
210°
240°
270°
300°
330°
0

FIG. 17

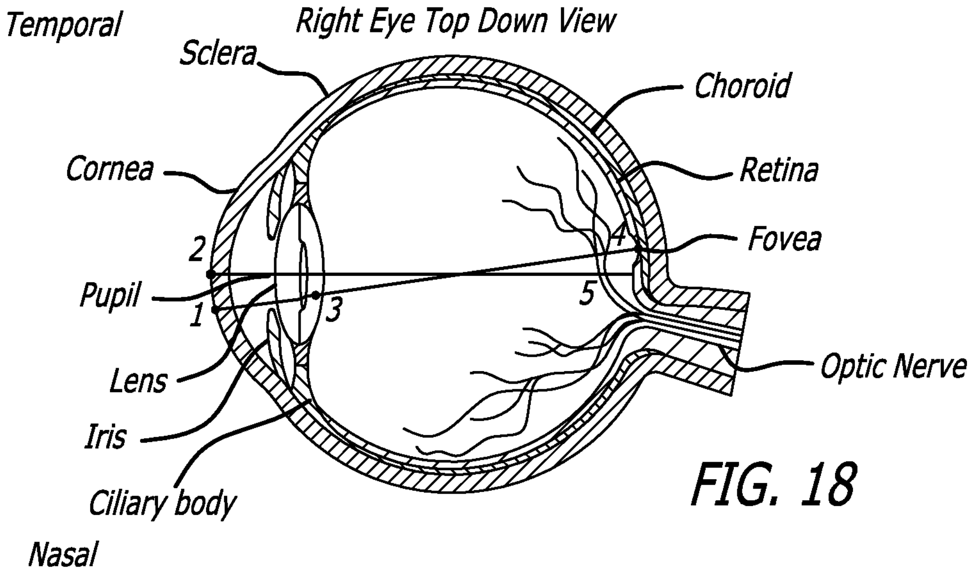


FIG. 18

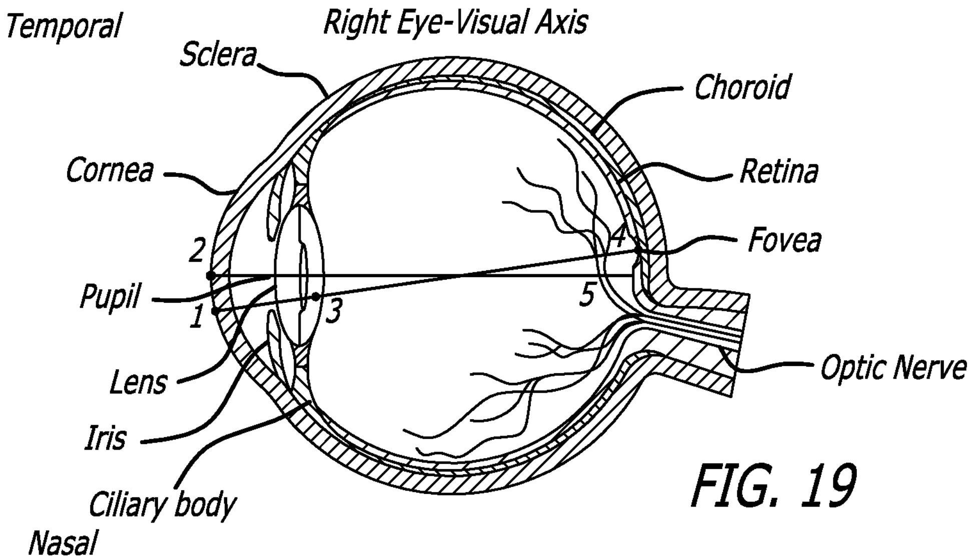


FIG. 19

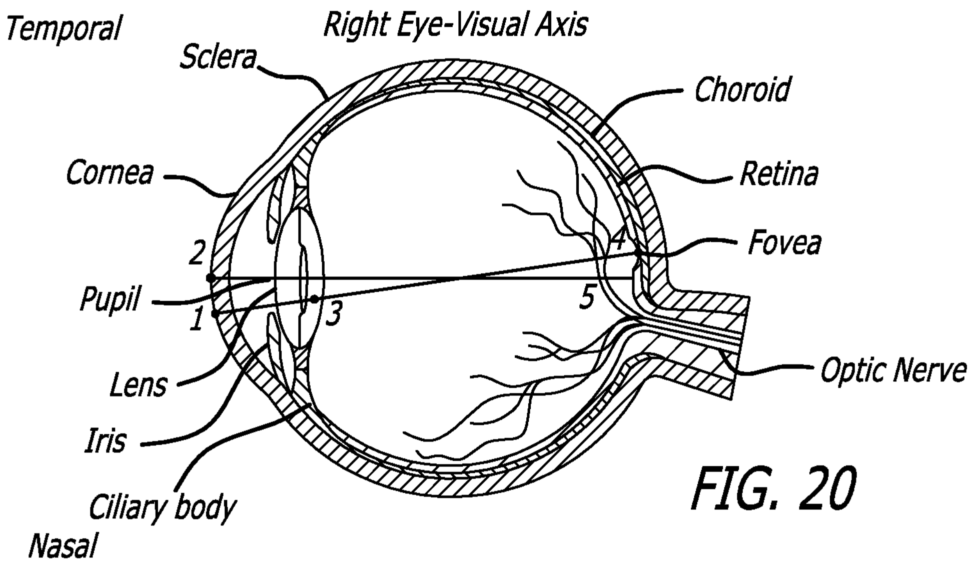


FIG. 20

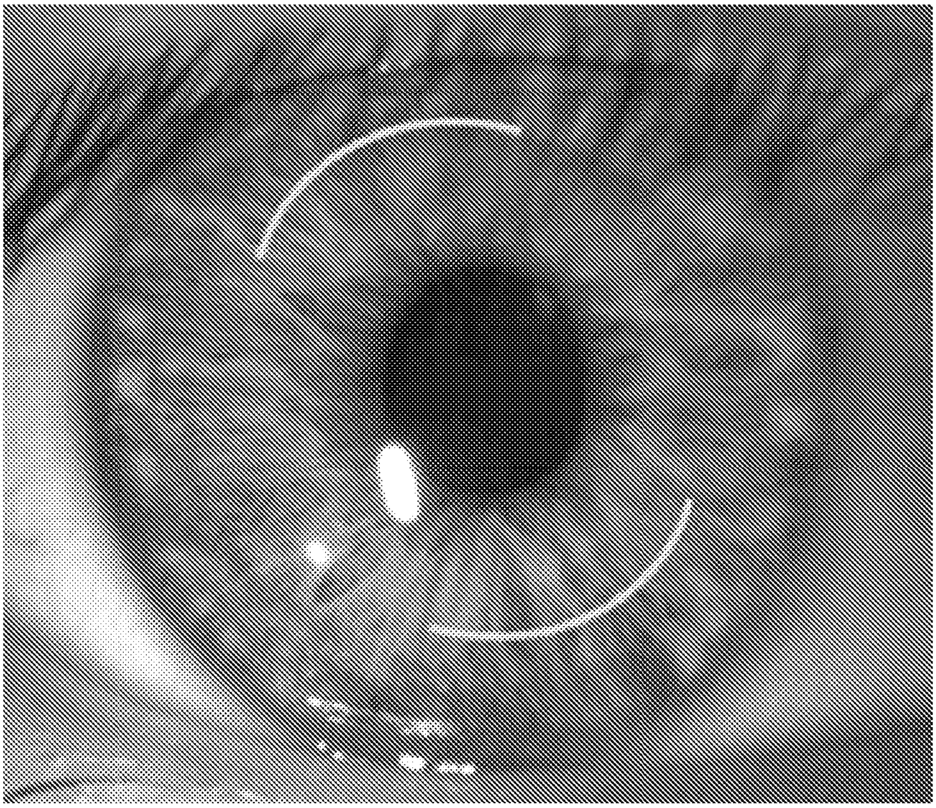


FIG. 21

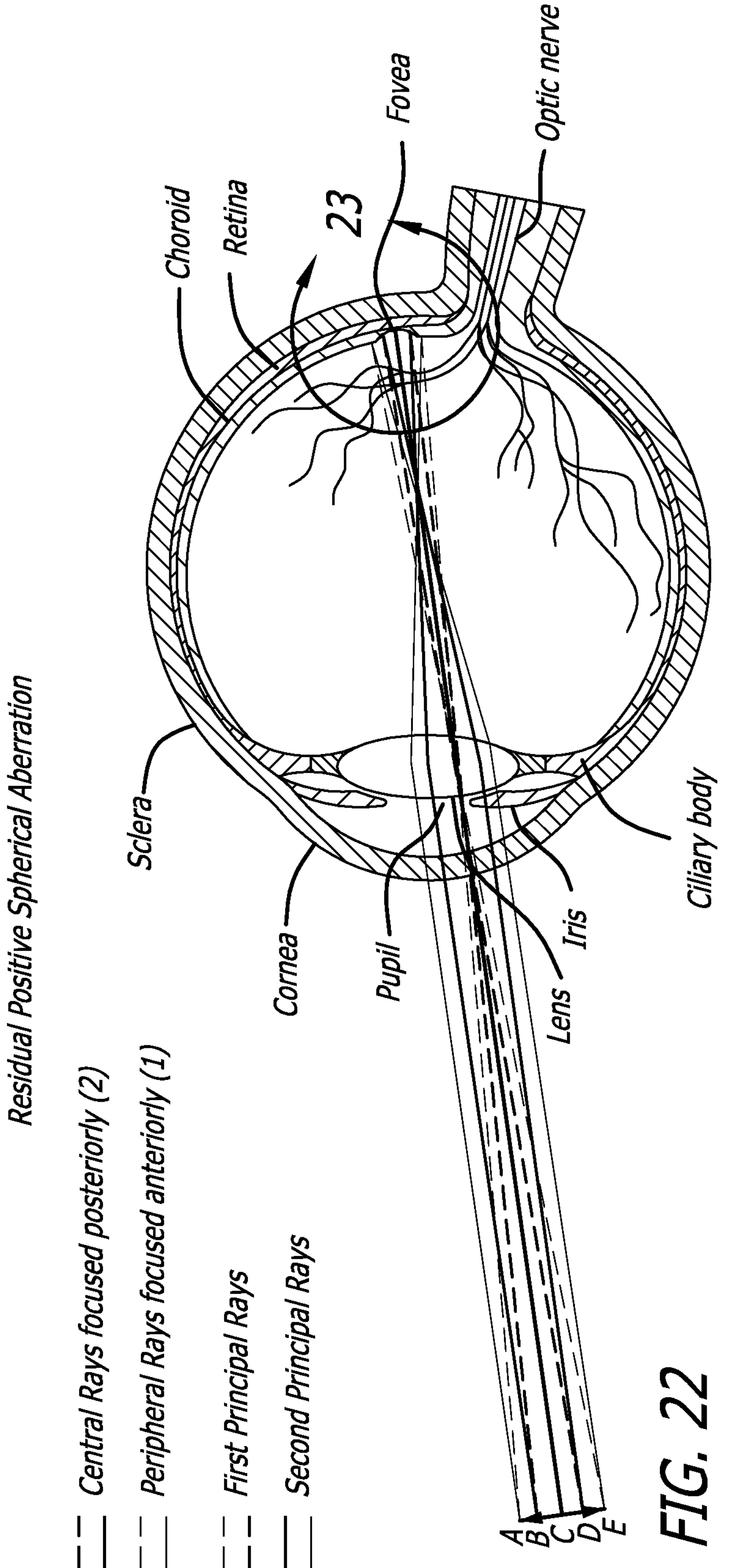

Residual Positive Spherical Aberration
Central Rays focused posteriorly (2)
Peripheral Rays focused anteriorly (1)
First Principal Rays
Second Principal Rays
Choroid
Retina
Fovea
Optic nerve
23
Sclera
Cornea
Pupil
Lens
Iris
Ciliary body
A
B
C
D
E

FIG. 22

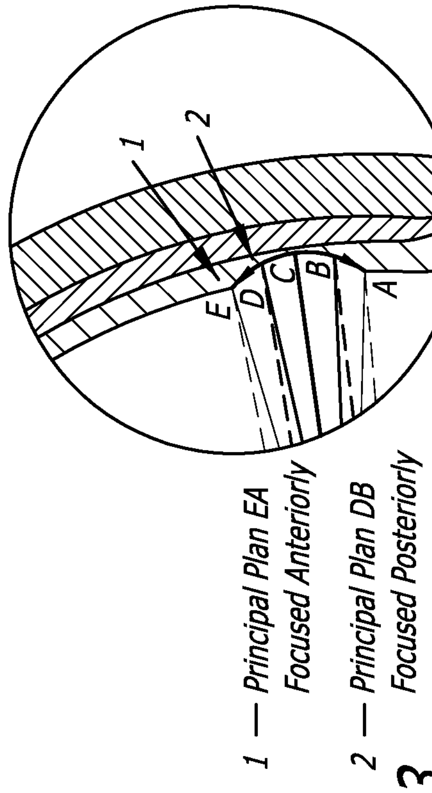

1
2
E
D
C
B
A
1 — Principal Plan EA Focused Anteriorly
2 — Principal Plan DB Focused Posteriorly

FIG. 23

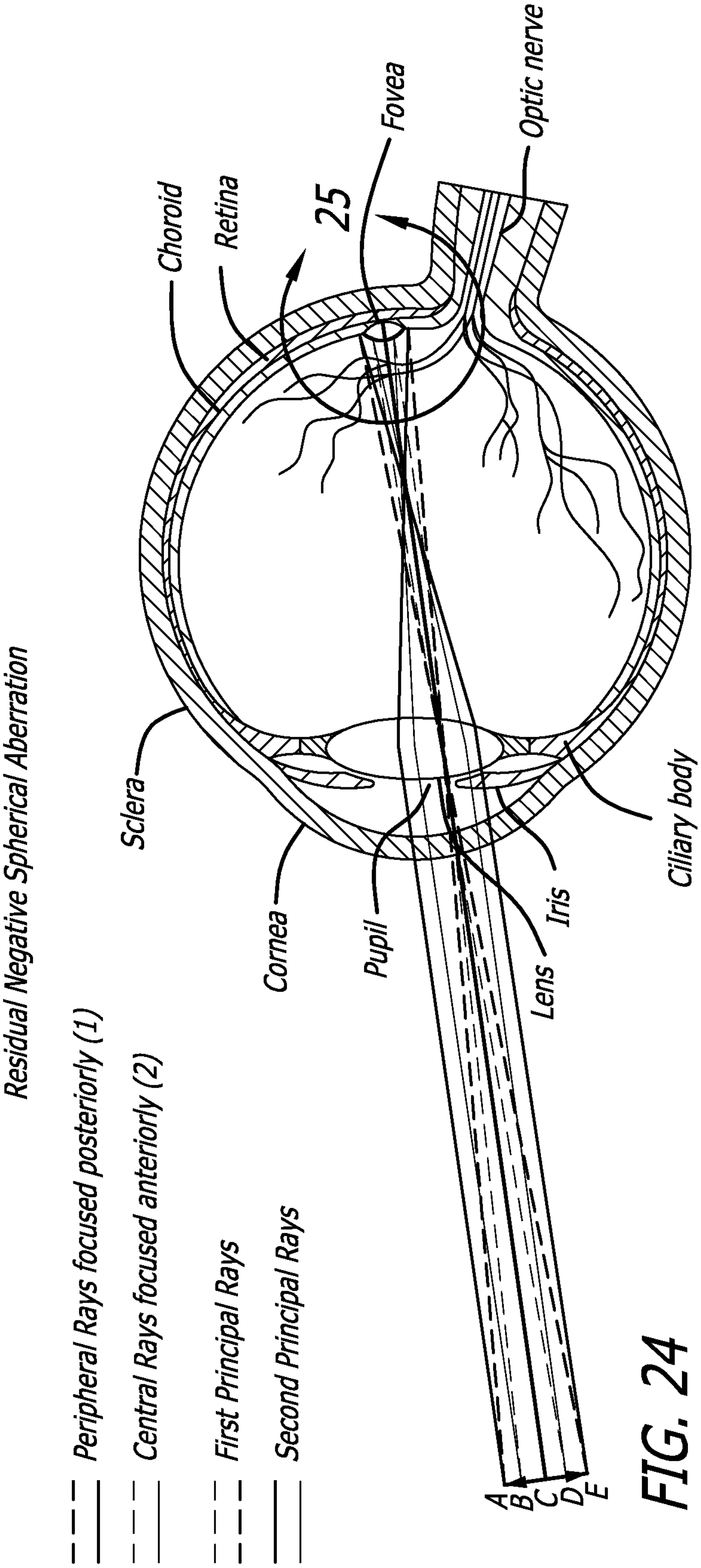

Residual Negative Spherical Aberration
Peripheral Rays focused posteriorly (1)
Central Rays focused anteriorly (2)
First Principal Rays
Second Principal Rays
Sclera
Cornea
Pupil
Lens
Iris
Ciliary body
Choroid
Retina
Fovea
Optic nerve
25
A
B
C
D
E

FIG. 24

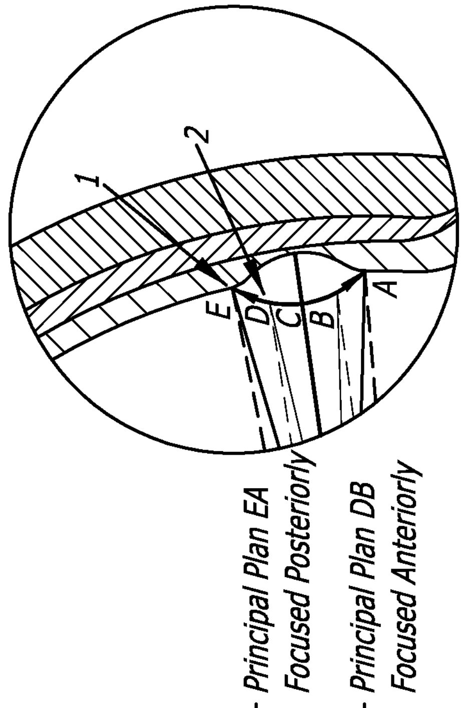

1
2
E
D
C
B
A
1 — Principal Plan EA Focused Posteriorly
2 — Principal Plan DB Focused Anteriorly

FIG. 25

FIG. 26

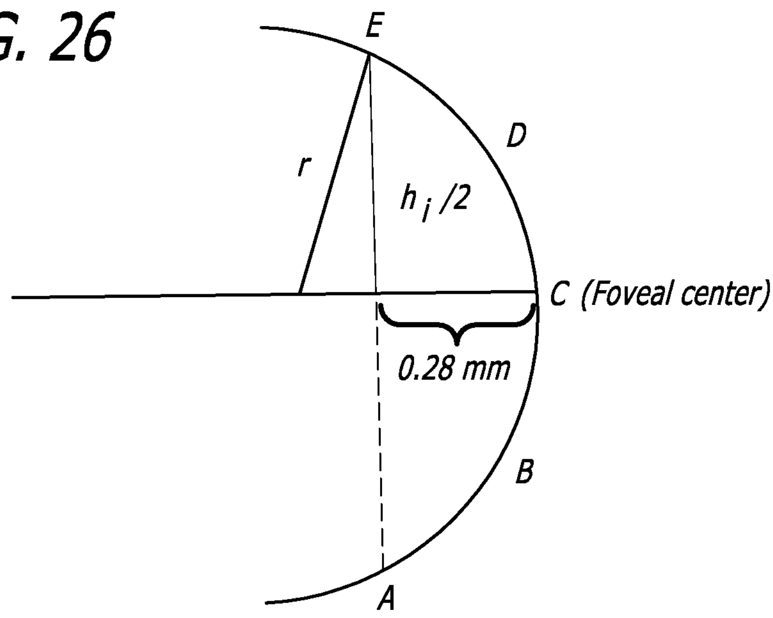
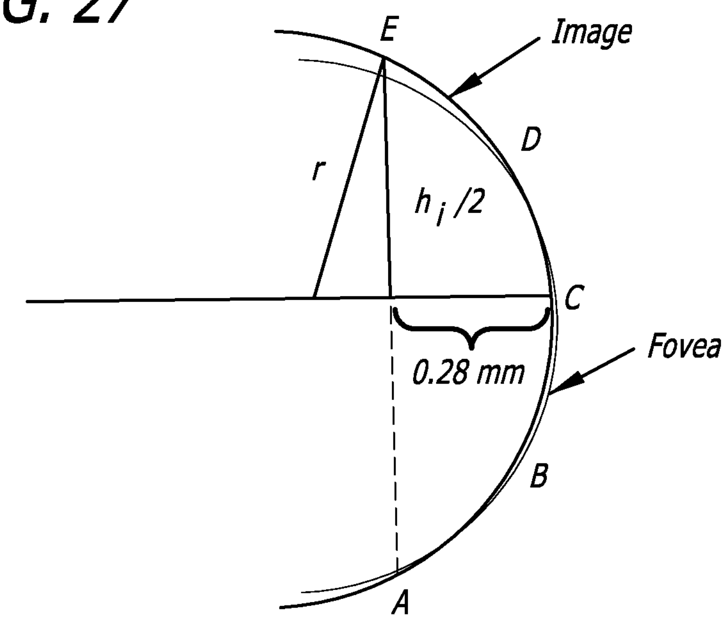

E
D
r
$h_i/2$
C (Foveal center)
0.28 mm
B
A

FIG. 27


E
Image
D
r
$h_i/2$
C
Fovea
0.28 mm
B
A