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(54) Title: CONTRAST-ENHANCING ASPHERIC INTRAOCULAR LENS

(57) **Abstract:** The present inventions provides an intraocular lens (IOL) having an optic with a posterior and an anterior refractive surfaces, at least one of which has an aspherical profile, typically characterized by a non-zero conic constant, for controlling the aberrations of a patient's eye in which the IOL is implanted. Preferably, the IOL's asphericity, together with the aberrations of the patient's eye, cooperate to provide an image contrast characterized by a calculated modulation transfer function (MTF) of at least about o.25 and a depth of field of at least about o.75 diopters.

CONTRAST-ENHANCING ASPHERIC INTRAOCULAR LENS

This application claims priority under 35 U.S.C. §120, to co-pending U.S. Application No. 11/000,728, filed December 1, 2004, the entire contents of which are incorporated herein by reference.

TECHNICAL FIELD OF THE INVENTION

The present invention generally relates to intraocular lenses (IOL) and, more particularly, to such lenses that provide enhanced vision for large pupil sizes.

An Intraocular lens is routinely implanted in a patient's eye during cataract surgery to compensate for the lost optical power when the natural lens is removed. In other applications, an intraocular lens can be implanted in a patient's eye, which retains its natural lens, so as to provide an optical power for correcting a refractive error of the natural eye. The aberrations of the eye, and in particular those of the cornea, are typically ignored in designing conventional intraocular lenses. Hence, patients having such lenses can suffer from a degraded image quality, especially at low light levels and large pupil sizes.

Intraocular lenses that compensate for corneal aberrations are also known. Typically, such aspheric intraocular lenses are designed to counteract the asphericity of the patient's cornea by greatly reducing, or eliminating all together, the overall aberrations of the eye. Although intraocular lenses fabricated based on these techniques may provide a better image contrast, they generally result in a decrease in a patient's depth of field.

BRIEF SUMMARY OF THE INVENTION

The present invention is generally directed to intraocular lenses that can provide a balance between image contrast and depth of field, upon implantation in a patient's eye, so as to afford the patient improved vision, especially under conditions where the pupil of the eye is large. More particularly, an intraocular lens of the invention can exhibit a selected degree of asphericity at one or more refractive surfaces such that the aberrations of the lens combine with those of the eye in a manner that would provide the patient not only with a useful image contrast, but also with a depth of field within an acceptable range, especially for large pupil sizes.

In one aspect, the present invention provides an intraocular lens (IOL) that includes an optic having an anterior refractive surface and a posterior refractive surface, which cooperatively provide a selected optical power, e.g., an optical power in a range of about zero to about 40 Diopters (D) or more, typically in a range of about 18 to about 26 Diopters. One or both of these surfaces are characterized by an aspheric profile for controlling the aberrations of an eye in which the IOL is implanted so as to provide the patient with an image contrast, as characterized by a peak modulation transfer function (MTF), of at least about 0.25 at a spatial frequency of about 50 line pairs per millimeter (lp/mm) and a depth of field of at least about 0.75 Diopters (D). For example, the implanted lens can provide the patient with an MTF in a range of about 0.25 to about 0.4 and a depth of field in a range of about 0.75 to about 1.5 Diopters. The aspherical lenses of the present invention can control the aberrations of the eye of a pseudophakic patient, i.e., a patient having the IOL as a replacement for a natural lens. Alternatively, such lenses can control the aberrations of the eye of a phakic patient, i.e., a patient having the IOL in addition to the natural lens.

As is known to those skilled in the ophthalmic art, a modulation transfer function (MTF) provides a quantitative measure of image contrast exhibited by an optical system, e.g., a system formed of an IOL and the cornea or an optical system formed of an IOL, the cornea and the natural lens, as discussed in more detail below. Further, the terms "depth of field" and "depth of focus," which are herein used interchangeably, are well known in the context of a lens and readily understood by those skilled in the art. To the extent that a quantitative measurement is needed to describe the present invention, the term "depth of field" or "depth of focus" as used herein, can be calculated and/or measured by an amount of defocus associated with the optical system at which a through-focus modulation transfer function (MTF) of the system calculated and/or measured with an aperture, e.g., a pupil size, of about 4.5 mm and monochromatic green light, e.g., light having a wavelength of about 550 nm, exhibits a contrast of at least about 0.05 at a spatial frequency of about 50 line pairs per millimeter (lp/mm).

In a related aspect, the aspheric profile of the anterior surface or the posterior surface, or both, can control the aberrations of an eye in which the IOL is implanted such that the combined lens and cornea would exhibit a peak modulation transfer function contrast of at least about 0.25 at a spatial frequency of about 50 lp/mm and a depth of field of at least about 0.75 Diopters for pupil diameters in a range of about 4.5 mm to about 5 mm and for monochromatic light at a wavelength of about 550 nm.

For example, the peak modulation transfer function can be calculated in a model eye, as discussed in more detail below.

An IOL according to this invention can be fabricated preferably by employing a deformable biocompatible material, such as acrylic, silicone, or hydrogel polymeric materials and the like that allow the lens body to be folded for insertion into the eye. For example, the optic can be formed of a copolymer of acrylate and methacrylate. For illustrative examples of such copolymer compositions, see for example, U.S. Patent No. 5,922,821 entitled "Ophthalmic Lens Polymers" issued to Lebouef *et al.* on July 13, 1999 and U.S. Patent No. 6,353,069 entitled "High Refractive Index Ophthalmic Device Materials" issued to Freeman *et al.* on March 5, 2002, the teachings of both of which are hereby incorporated by reference. In other embodiments, rigid biocompatible materials, such as polymethyl methacrylate (PMMA) can be employed.

In some embodiments, the aspherical profile of one of the surfaces can exhibit a selected deviation from a putative spherical profile having a radius of curvature of R_1 that substantially coincides with the aspherical profile at small radial distance from an optical axis of the lens, while the other surface can have a spherical profile having a radius of curvature R_2. Alternatively, the other surface can also have an aspherical profile exhibiting deviations from a respective putative spherical profile having a radius of curvature of R_2. The radii R_1 and R_2 are selected such that the lens would exhibit a desired optical power. In addition, if needed, R_1 and R_2 can be chosen to impart a selected shape factor (X) to the lens, which is generally defined by the following relation:

$$X = \frac{R_2 + R_1}{R_2 - R_1}.$$

In a related aspect, at least one refractive surface of the IOL has an aspheric portion for controlling average aberrations exhibited by the eyes of a selected patient group such that upon implantation of the lens in a patient's eye the combined lens and cornea would exhibit a peak modulation transfer function (MTF) contrast of at least about 0.25 for monochromatic light having a wavelength of 550 nm and depth of field of at least about 0.75 Diopters. The MTF and the depth of field can be calculated or measured, for example, for a spatial frequency of about 50 line pairs per millimeter and for a pupil size of about 4.5 mm.

In another aspect, the profile of the aspheric surface can be characterized by the following relation:

$$z = \frac{CR^2}{1+\sqrt{1-(1+Q)C^2R^2}} + AR^4 + BR^6 + \text{ higher order terms},$$

wherein

z denotes a sag of the surface parallel to an axis (z) perpendicular to the surface,

C denotes a curvature at the vertex of the surface,

Q denotes a conic coefficient,

R denotes a radial position on the surface,

A denotes a fourth order deformation coefficient, and

B denotes a sixth order deformation coefficient. Distance units are given herein in millimeters. For example, the curvature constant is given in units of inverse millimeter, while A is given in units of $\frac{1}{(\text{mm})^3}$ and B is given in units of $\frac{1}{(\text{mm})^5}$.

The curvature constant C can be chosen based on a desired optical power of the lens, and the aspherical coefficients Q, A, and B, as well as the higher order terms where applicable, can be chosen so as to impart a selected degree of asphericity to the surface. As discussed in more detail below, the choice of the aspherical coefficients can generally depend on the material from which the lens is fabricated, the shape factor of the lens, and the aberrations of the eye for which the lens is intended. For example, the conic constant for a biconvex lens of average power (e.g., 21 Diopters) formed of an acrylic polymer can be in a range of about 0 (zero) to about –100 (minus 100), or in a range of – 10 to about –50, or in a range of about –15 to about –25 and the higher order deformation coefficients A and B can be, respectively, in a range of about -1×10^{-3} (minus 0.001) to about 1×10^{-3} (plus 0.001) and in a range of about -1×10^{-4} (minus 0.0001) to about 1×10^{-4} (plus 0.0001). Further, in many embodiments, the curvature coefficient (C) can be in a range of about 0.0125 to about 0.12, or in a range of about 0.025 to about 0.1 (the curvature can be positive or negative corresponding to convex or concave surfaces, respectively).

In another aspect, the invention provides a method of designing an intraocular lens having an anterior and a posterior refractive surface that includes deriving a model average of aberrations of the eye based on wavefront measurements of aberrations exhibited by the eyes of a selected patient population (alternatively the aberrations of an individual patient for whom the lens is intended can be employed), and adjusting asphericity of at least one of the refractive surfaces for controlling the average aberrations such that a patient in which the lens is implanted would exhibit an image contrast characterized by a peak modulation transfer function (MTF) contrast of at least about 0.25 and a depth of field of at least about 0.75 D.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

FIGURE 1A schematically depicts an intraocular lens according to one embodiment of the invention having an anterior surface exhibiting an aspherical profile;

FIGURE 1B schematically illustrates a sag profile of the aspherical anterior surface of the IOL of FIGURE 1A exhibiting a selected deviation from a putative spherical profile;

FIGURE 1C schematically illustrates a sag profile of the spherical posterior surface of the IOL of FIGURE 1A;

FIGURE 2 schematically depicts a phakic eye having an IOL according to one embodiment of the invention in addition to the natural lens;

FIGURE 3A is a graph illustrating a theoretical modulation transfer function (MTF) calculated for the combined system of an eye having a spherical cornea and an IOL having spherical refractive surfaces;

FIGURE 3B is a graph illustrating a theoretical modulation transfer function (MTF) calculated for the combined system of an eye having a spherical cornea and an IOL according to one embodiment of the invention having an aspherical surface;

FIGURE 4A is graph illustrating a theoretical modulation transfer function (MTF) calculated for the combined system of an eye exhibiting corneal spherical aberration and an IOL having a spherical profile;

FIGURE 4B is a graph illustrating a theoretical modulation transfer function (MTF) calculated for the combined system of an eye exhibiting severe corneal flattening and an IOL according to one embodiment of the invention having an aspherical surface for controlling aberrations caused by the cornea;

FIGURE 5 is a graph illustrating a theoretical modulation transfer function (MTF) calculated for the combined system of an eye exhibiting an average corneal aberration and an IOL having spherical surfaces;

FIGURE 6 depicts three graphs depicting theoretically calculated peak modulation transfer function contrasts and depth of fields for various eye conditions with spherical IOLs and aspherical IOLs according to the teachings of the invention;

FIGURE 7A schematically depicts an exaggerated aspherical profile along one surface direction of a toric surface of an IOL according to one embodiment of the invention relative to a putative spherical profile, and

FIGURE 7B schematically depicts an exaggerated aspherical profile along another direction of the toric surface associated with the profile shown in FIGURE 7A relative to a putative spherical profile.

DETAILED DESCRIPTION OF THE INVENTION

FIGURE 1A schematically depicts a monofocal intraocular lens 10 according to one embodiment of the invention having an optic 12 preferably formed of a soft biocompatible material, such as soft acrylic polymer, silicone, or hydrogel. The exemplary lens 10 further includes radially extending fixation members or haptics 14 for its placement in a patient's eye. The fixation members 14 can be made of suitable polymeric materials, such as polypropylene, polymethyl methacrylate and the like as known to those having ordinary skill in the art. In some embodiments, the optic and the fixation members are formed from the same material as a single -piece lens. The optic 12 includes an anterior refractive surface 16 and a posterior refractive surface 18 that are shaped so as to cooperatively provide the lens with a nominal optical power in a range of zero to about 40 Diopters and, more preferably, in a range of about 18 to about 26 Diopters. In this exemplary embodiment, the refractive surfaces 16 and 18 are generally symmetric about an optical axis 20 of the lens, although in other embodiments either surface can be asymmetric about this axis. Further, although the refractive surfaces 16 and 18 are depicted as being generally convex, either surface can have a generally concave shape. Alternatively, the surfaces 16 and 18 can be selected to generate a plano-convex or a plano-concave lens. Hence, a lens according to the teachings of the invention can have a positive or a negative nominal power. In some embodiments, the lens can have a negative power, e.g., in a range of about –20 D to about –10 D, or –15 D to about –10 D. Such lenses can be employed in phakic patients. More generally, a lens of the invention can have a power in a range of about –20 D to about +10 D.

FIGURE 1B schematically illustrates a base profile 22a of the anterior refractive surface 16 as a function of radial distance (r) relative to an intersection of optical axis 20 with the anterior surface 16 (for purposes of illustration the curvature is greatly exaggerated). In this embodiment, the base profile 22a is aspherical with a selected degree of deviation from a putative spherical profile 24 having a radius of curvature R_1 that substantially coincides with the aspherical profile at small radial distances. Although in this exemplary embodiment the aspherical anterior surface 16 is flatter than the putative spherical profile, in other embodiments it can be steeper. The posterior surface 18 exhibits a spherical profile 22b with a radius of curvature R_2, as shown schematically in FIGURE 1C. The radii R_1 and R_2 are generally chosen to provide the lens with a desired optical power and a desired shape factor. In other embodiments, the posterior surface can also exhibit an aspheric profile, while in others the anterior surface can be spherical and the posterior surface aspherical. In other words, a desired degree of asphericity can be achieved by imparting an aspherical profile to only one of the refractive surfaces, or by dividing the total aspheric deviation between the two surfaces.

Referring again to FIGUREs 1A and 1B, in many embodiments, the aspheric profile of the anterior surface 16 is selected to control the aberrations of a patient's eye in which the IOL 10 is implanted so as to enhance the patient's image contrast relative to that provided by a substantially identical lens in which the anterior surface has the putative spherical profile 24, rather than the aspherical profile 22a, while providing the patient with a depth of field greater than about 0.75 D. More specifically, in many embodiments, the aspheric profile controls the aberrations of an eye in which the IOL 10 is implanted such that the combined lens and cornea, or the combined lens, the cornea and the natural lens, would exhibit a peak modulation transfer function (MTF) contrast of at least about 0.25 and a depth of field of at least about 0.75 Diopters for pupil diameters in a range of about 4.5 millimeters to about 5 millimeters when measured or calculated with monochromatic light at a wavelength of about 550 nanometers and at a spatial frequency of about 50 line pairs per millimeter. For example, the patient having the IOL can experience a peak MTF contrast at the retina in a range of about 0.25 to about 0.4 while having a depth of focus in a range of about 0.75 to about 1.5 D. In this manner, the image contrast is enhanced while maintaining a useful depth of field.

As known to those having ordinary skill in the art, a quantitative measure of image contrast provided by a lens can be obtained by calculating and/or measuring a modulation transfer function (MTF) associated with that lens. In general, a contrast or modulation associated with an optical signal, e.g., a two-dimensional pattern of light intensity distribution emanated from or reflected by an object to be imaged or associated with the image of such an object, can be defined in accordance with the following relation:

$$\frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

wherein $I_{\max}$ and $I_{\min}$ indicate, respectively, a maximum or a minimum intensity associated with the signal. Such a contrast can be calculated or measured for each spatial frequency present in the optical signal. An MTF of an imaging optical system, such as the combined IOL and the cornea, can then be defined as a ratio of a contrast associated with an image of an object formed by the optical system relative to a contrast associated with the object. As is known, the MTF associated with an optical system is not only dependent on the spatial frequencies of the intensity distribution of the light illuminating the system, but it can also be affected by other factors, such as the size of an illumination aperture as well as the wavelength of the illuminating light.

Although in many embodiments an IOL according to the invention is utilized to enhance a patient's image contrast, in some embodiments, it can be employed to primarily enhance a patient's depth of field with a potential moderate decrease in the image contrast. For example, a patient whose cornea exhibits a highly aspherical flattening can benefit from an aspherical IOL according to one embodiment of the invention that can partially compensate for the severe flattening to enhance the patient's depth of filed albeit with a potential small decrease in the image contrast.

In some embodiments, the aspherical profile of the anterior surface 16 of the IOL 10 as a function of radial distance (R) from the optical axis 20, or that of the posterior surface or both in other embodiments, can be characterized by the following relation:

$$z = \frac{CR^2}{1+\sqrt{1-(1+Q)C^2R^2}} + AR^4 + BR^6 + \text{ higher order terms},$$

wherein

z denotes a sag of the surface parallel to an axis (z), e.g., the optical axis, perpendicular to the surface,

C denotes a curvature at the vertex of the surface,

Q denotes a conic coefficient,

R denotes a radial position on the surface,

A denotes a fourth order deformation coefficient, and

B denotes a sixth order deformation coefficient.

In many embodiments, the conic constant Q alone can be adjusted to obtain a desired deviation from sphericity with the higher order aspherical constants A and B, and others set to zero. In other embodiments, one or both of the higher order constants A and B, in addition to, or instead of, the conic constant Q, can be adjusted to provide a selected aspherical profile for one or both refractive surfaces of an IOL. The higher order aspherical constants can be particularly useful for tailoring the profile of the peripheral portions of the lens surface, i.e., portions far from the optical axis.

The choice of the aspherical constants can depend, for example, on the aberrations of the eye in which the IOL is implanted, the material from which the IOL is fabricated, and the optical power provided by the IOL. In general, these constants are selected such that the IOL can provide a balance between a patient's image contrast and depth of field, e.g., enhancing the image contrast while substantially preserving the depth of field. For example, in some embodiments in which the IOL is fabricated from an acrylic polymeric material for implantation in an eye exhibiting a corneal asphericity characterized by a corneal conic constant in the range of zero (associated with severe spherical aberration) to about -0.5 (associated with a high level of aspherical flattening) the conic constant Q of the lens in the above relation can be in a range of about 0 to about -50, while the deformation coefficients A and B can be, respectively, in a range of about -1×10^{-3} to about 1×10^{-3} and in a range of about -1×10^{-4} to about 1×10^{-4}.

As noted above, the choice of the degree of sphericity of one or both surfaces of the IOL can depend, at least in part, on the lens's shape factor (X). For examples, in some embodiments in which the IOL exhibits a shape factor in a range of about 0 to about +1, the conic constant can be in range of about -50 to about 0.

An IOL according to the teachings of the invention can find a variety of different applications. By way of example, in phakic patients, the IOL 10 can be implanted in a patient's eye while retaining the eye's natural lens by inserting the optic 12 in the eye's anterior chamber 26 with the distal ends of the fixation members 14 in contact with an angle 28 of the iris 30, as shown in FIGURE 2. The IOL can provide an optical power for correcting a refractive defect of the eye. The aspherical profile of the anterior surface 16 of the IOL can control the overall aberrations of the natural eye, for example, the combined aberrations of the cornea 32 and the natural lens 34, so as to enhance the image contrast on the retina, especially for large pupil sizes, while maintaining a desired depth of field, as discussed above.

In another application, in pseudophakic patients, the IOL 10 can be implanted in a patient's eye after removal of the patient's natural lens during cataract surgery. The aspherical profile of the IOL 10 can control the aberrations exhibited by the cornea so as to enhance the image contrast while substantially preserving the depth of field. In some cases, the cornea is substantially spherical, characterized, for example, by a vanishing conic constant, while in other cases the cornea itself can show a certain degree of asphericity. The aspherical profile of the IOL 10 can be adjusted accordingly to provide the desired degree of image contrast, or depth of field, enhancement. For example, in some cases, the aspherical profile of IOL can be characterized by curve that is flatter than that of a putative spherical profile, while in other cases it is steeper.

A variety of techniques can be employed to determine the requisite degree of asphericity for the IOL 10. For example, in one approach, aberrations exhibited by a patient's eye, or by a group of patients, are measured preoperatively by employing known topographical methods and systems. For phakic eyes, the measured aberrations can correspond primarily to the combined aberrations of the natural lens and the cornea while for the pseudophakic patients, they can correspond to those of the cornea. In one such method, wavefront aberrations of the eye can be measured at a selected measurement plane, e.g., the entrance pupil of the patient's eye, and at a selected wavelength, e.g., at a wavelength of about 830 nm. Further details regarding measurements of aberrations of the eye can be found in U.S. Patent No. 6,786,603 and U.S. Patent Application No. 2002/0105617, both of which are herein incorporated by reference in their entirety.

Wavefront measurements can be employed to determine a requisite level of asphericity of the IOL needed for controlling the aberrations of the eye. For example, an aspherical profile of the IOL can be designed to reduce spherical aberrations of the cornea inferred from the wavefront measurements. One or more aspherical parameters of the IOL can be obtained theoretically or experimentally, or both. For example, a ray tracing program, such as OSLO, marketed by Lambda Research Corporation of Littleton, Massachusetts, U.S.A, can be employed to model the eye and its aberrations inferred from the wavefront measurements as well as an IOL having one or more aspherical surfaces. The asphericity of the IOL can then be adjusted, e.g., via adjusting the conic constant and possibly the higher order deformation constants, to obtain a desired MTF and depth of field. In some cases, average aberrations exhibited by the eyes of a selected group of patients are considered for designing an IOL suitable for controlling on average such aberrations.

The aspherical parameters of an IOL according to the teachings of the invention can also be determined experimentally. For example, an IOL can be inserted in a model eye exhibiting aberrations corresponding to those inferred from the wavefront measurements, e.g., a corneal aberration characterized by a conic constant. Subsequently, modulation transfer functions obtained by a combined system of the model eye and intraocular lenses having different aspherical profiles are measured to select a suitable aspherical profile.

As noted above, in some cases, the aberrations of a population of patients are measured to design a lens suitable for controlling average aberrations exhibited by patients. For example, in some cases, two or more types of intraocular lenses, each type designed to control average aberrations exhibited by the eyes of select group of patients, can be provided.

To demonstrate the efficacy of intraocular lenses according to the teachings of the invention to provide a more useful balance between the image contrast and the depth of field, theoretical ray tracing calculations were performed to determine modulation transfer functions exhibited by a combined system of an IOL according to the teachings of the invention having an aspherical profile and an eye modeled to have a selected corneal aberration in a range typically exhibited by patients in the general poplulation. More specifically, for each theoretically modeled lens, the modulation transfer function at 50 line pairs per millimeter (lp/mm) and at a wavelength of about 550 nm, as well as a depth of focus, were calculated for the combined lens and cornea, as discussed below. In addition, corresponding control calculations of MTF and depth of focus were performed for a substantially identical IOL having a spherical profile, i.e., an IOL exhibiting a vanishing conic constant. The depth of field was determined as the amount of defocus about a nominal focus corresponding to the peak MTF at which the MTF value drops to about 0.05.

As another example, FIGURE 3A presents a through-focus MTF plot 40 for a cornea having a conic constant of – 0.5 – a cornea exhibiting a high level of aspheric flattening – with an IOL having a vanishing conic constant (herein referred to as condition A), while FIGURE 3B presents a respective MTF plot 42 for the same cornea but with an IOL according to the teachings of the invention having an aspherical anterior surface with a conic constant of 2.8 (herein referred to as condition B). A comparison of the plots 40 and 42 shows that although the cornea with the aspherical lens exhibits a lower peak MTF contrast (an MTF of 0.41 for the aspherical case relative to 0.86 for the spherical case), it exhibits, however, a much improved depth of field (a depth of field of 0.8 for the aspherical case compared with 0.50 for the spherical case). Hence, in some cases the asphericity of the IOL is selected to reduce an asphericity exhibited by a cornea so as to enhance the depth of field at the expense of a slight decrease in the image contrast.

FIGURE 4A presents a calculated control through-focus modulation transfer function plot 36 for a spherical cornea – a cornea exhibiting severe spherical aberration – combined with an IOL having a spherical profile (i.e., a conic constant of zero), herein referred to as condition E, while FIGURE 4B presents a respective through-focus MTF plot 38 for the same cornea combined with an IOL according to the teachings of the invention having an anterior aspherical surface with a conic constant of – 6, herein referred to as condition D. A comparison of plots 36 and 38 shows that the use of the aspherical lens results in an increase of the peak MTF contrast from about 0.24 to about 0.4 (a 67 % increase), while substantially preserving the depth of focus (a depth of focus of 1.14 Diopters at 0.05 MTF for the spherical lens compared to a corresponding depth of focus of 1.02 Diopters for the aspherical lens).

An average patient may have a cornea with an asphericity characterized by a conic constant of –0.26. Although no calculation was performed for such a cornea with an aspherical IOL, FIGURE 5 shows a through-focus MTF plot 44 of such a cornea with a spherical IOL (herein referred to as condition C), indicating a peak MTF comparable with those obtained for the above conditions B and D, namely, for a spherical cornea with an aspherical lens having a negative conic constant of –6 and a cornea exhibiting severe aspherical flattening with an aspherical lens having a positive conic constant of 2.8.

To summarize the data discussed above for the exemplary conditions A-E, FIGURE 6 presents three graphs 46, 48 and 50 illustrating, respectively, peak MTF, and defocus in Diopter (D) at which the MTF has a value of 0.05 and 0.1 (herein also referred to as depth of focus at 0.05 or 0.1 MTF). For example, these graphs show that the peak MTF increases by employing an IOL according to the teachings of the invention having an aspheric profile for an eye with a spherical cornea while substantially preserving the depth of field.

In another embodiment, an intraocular lens (IOL) of the invention can have one or two toric refractive surfaces that exhibit two different optical powers along two orthogonal surface directions. Such toric IOLs can be employed, for example, to correct astigmatism. In some embodiments, one surface is toric and the other non-toric. A selected degree of asphericity can be imparted to the toric surface, to the non-toric surface or to both. Alternatively, both lens surfaces can be toric with at least one exhibiting asphericity. For example, at least one of the toric surfaces can exhibit an asphericity along one or both of the two surface orthogonal directions, each associated with an optical power different than the power along the other direction, such that a combination of the lens and the eye in which the lens is implanted provides not only a useful image contrast, but also a depth of field within an acceptable range, such as those discussed above in connection with the other embodiments. For example, with reference to FIGURE 7A, the toric surface exhibiting a selected asphericity in one of the two directions (herein identified with the x coordinate) can be characterized by an aspherical profile 52A having a central curvature R_1 at its vertex (i.e., intersection of an optical axis of the lens with the surface) and a selected deviation from a putative spherical profile 52B that substantially coincides with the aspherical profile at small radial distances. As shown in FIGURE 7B, along the other direction (herein identified with the y coordinate), a profile 54A of the toric surface can be characterized by a central curvature R_2, that is different than R_1, and a selected deviation from a putative spherical profile 54B that substantially coincides with the aspherical profile at small radial distances.

Those having ordinary skill in the art will appreciate that various modifications can be made to the above embodiments without departing from the scope of the invention.

CLAIMS

What is claimed is:

1. An intraocular lens (IOL), comprising:

an optic having an anterior refractive surface and a posterior refractive surface,

at least one of said anterior or posterior surfaces being characterized by an aspheric profile for controlling the aberrations of an eye in which the IOL is implanted such that a combined lens and cornea exhibit a peak calculated modulation transfer function (MTF) contrast of at least about 0.25 and a depth of field of at least about 0.75 diopters for pupil diameters in a range of about 4.5 mm to about 5 mm for monochromatic light at a wavelength of about 550 nm.

2. The IOL of claim 1, wherein said aberrations of the eye comprises a spherical aberration of the cornea.

3. The IOL of claim 1, wherein said combined lens and cornea exhibit a modulation transfer function (MTF) at the retina greater than about 0.3 for 50 line pairs per mm and a wavelength of about 550 nm.

4. The IOL of claim 1, wherein said combined lens and cornea exhibit a modulation transfer function (MTF) greater than about 0.35 for 50 line pairs per mm and a wavelength of about 550 nm.

5. The IOL of claim 1, wherein said combined lens and cornea exhibit a modulation transfer function (MTF) in a range of about 0.25 to about 0.4 at a spatial frequency of about 50 lp/mm, a wavelength of about 550 nm and a pupil size of about 4.5 mm.

6. The IOL of claim 1, wherein said optic is formed of a biocompatible soft material.

7. The IOL of claim 6, wherein said optic is formed of a soft acrylic material and exhibits an aspherical conic constant in a range of about 0 to about –50.

8. The IOL of claim 6, wherein said optic is formed of hydrogel and exhibits an aspherical conic constant in a range of about 0 to about –50.

9. The IOL of claim 6, wherein said optic is formed of silicone and exhibits an aspherical conic constant in a range of about 0 to about −50.

10. The IOL of claim 1, wherein said anterior surface is characterized by said aspheric profile exhibiting a selected deviation from a putative spherical profile having a radius of curvature R_1.

11. The IOL of claim 10, wherein said posterior surface is characterized by a spherical profile having a radius of curvature of R_2, wherein R_2 is larger than R_1.

12. The IOL of claim 11, wherein said lens exhibits a shape factor *K* defined as:

$$X = \frac{R_2 + \mathrm{R}_1}{R_2 - R_1},$$

wherein *K* is in a range of about 0 to about +1.

13. The IOL of claim 10, wherein said posterior surface is characterized by an aspheric base profile exhibiting a selected deviation from a putative spherical profile having a radius of curvature of R_2, wherein R_2 is larger than R_1.

14. An IOL, comprising:

a refractive optic providing a nominal diopter optical power,

said optic having a surface with an aspherical profile for controlling aberrations of an eye of a patient in which said lens is implanted so as to enhance the patient's image contrast relative to that by a substantially identical lens having a spherical optic, while providing the patient with a depth of field greater than about 0.75.

15. The IOL of claim 14, wherein said combined aspherical lens and the cornea exhibit a peak modulation transfer function (MTF) contrast of at least about 0.25 for 50 line pairs per millimeter and a substantially monochromatic wavelength of about 550 nm.

16. The IOL of claim 14, wherein said aspherical profile is adapted for controlling a spherical aberration of the cornea.

17. The IOL of claim 14, wherein said aspherical refractive surface comprises an anterior surface of said lens.

18. The IOL of claim 14, wherein said aspherical refractive surface comprises a posterior surface of said lens.

19. The IOL of claim 14, wherein said diopter optical power is in a range of about 0 to about 40.

20. An IOL, comprising
an optic having an anterior surface and a posterior surface,
at least one of said surfaces having an aspherical profile for controlling aberrations of an eye of a patient in which the lens is implanted so as to provide the patient with an image contrast characterized by a modulation transfer function (MTF) of at least about 0.25 and a depth of field of at least about 0.75 Diopters.

21. The IOL of claim 20, wherein said lens provides the patient with an MTF in a range of about 0.25 to about 0.4.

22. The IOL of claim 20, wherein said lens provides the patient with a depth of field of in a range of about 0.75 to about 1.5 diopters.

23. The IOL of claim 20, wherein said aspherical profile controls aberrations exhibited by the cornea.

24. The IOL of claim 20, wherein said aspherical profile controls aberrations exhibited by the combined cornea and the natural lens.

25. An intraocular lens, comprising:

an optic having at least one refractive surface,

said refractive surface having an aspheric portion for controlling average aberrations exhibited by the eyes of a selected patient group such that upon implantation of said lens in a patient's eye the combined lens and the cornea exhibit a peak modulation transfer function (MTF) contrast of at least about 0.25 for monochromatic light having a wavelength of 550 nm and a depth of field of at least about 0.75 Diopters.

26. The IOL of claim 25, wherein said refractive surface comprises any of an anterior surface or a posterior surface of the said lens.

27. An intraocular lens, comprising:

an optic comprising at least one refractive surface having a base characterized by a profile described by the following relation:

$$z = \frac{CR^2}{1+\sqrt{1-(1+Q)C^2R^2}} + AR^4 + BR^6,$$

wherein

z denotes a sag of the surface parallel to an axis (z) perpendicular to the surface,

C denotes a curvature at the vertex of the surface,

Q denotes a conic coefficient,

R denotes a radial position on the surface,

A denotes a fourth order deformation coefficient, and

B denotes a sixth order deformation coefficient,

wherein Q is in a range of about 0 to about 100, A is in a range of about -1×10^{-3} to about 1×10^{-3}, and B is in a range of about -1×10^{-4} to about 1x 10-^{4}.

28. A method of designing an intraocular lens having an anterior and a posterior refractive surface, comprising:

deriving a model average of aberrations of the eye based on wavefront measurements of aberrations exhibited by the eyes of a selected patient population, and

adjusting asphericity of at least one of said refractive surfaces for controlling said average aberrations such that a patient in which the lens is implanted would exhibit an image contrast characterized by a peak modulation transfer function (MTF) contrast of at least about 0.25 and a depth of field of at least about 0.75 D.

29. An intraocular lens (IOL), comprising:

an optic having an anterior refractive surface and a posterior refractive surface,

at least one of said surfaces having a generally toric shape exhibiting different optical power values along two orthogonal surface directions and having an asphericity along at least one of said orthogonal directions for controlling aberrations of an eye in which the IOL is implanted such that the combination of the lens and the eye exhibits a modulation transfer function of at least about 0.25 and a depth of field of at least about 0.75 D for a pupil size of about 4.5 mm and a monochromatic wavelength of about 550 nm as calculated in a model eye.

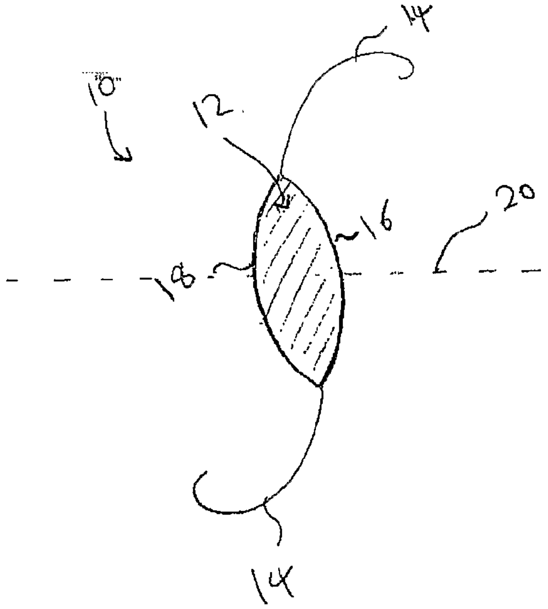

FIGURE 1A

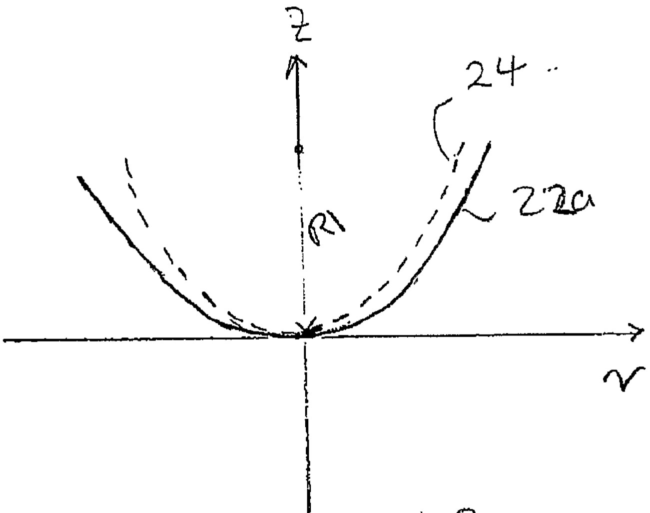

FIGURE 1B

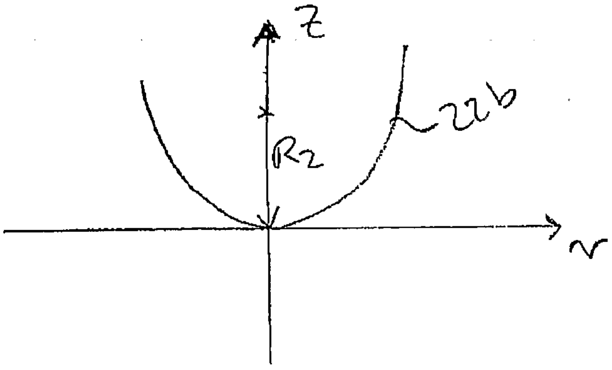

FIGURE 1C

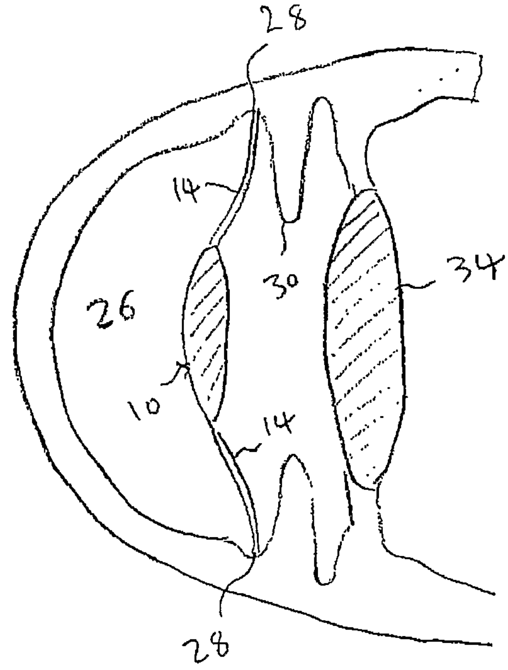

FIGURE 2

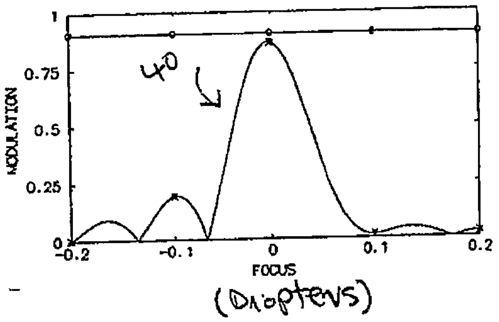

FIGURE 3A

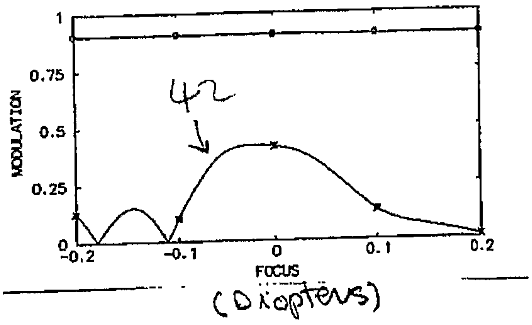

FIGURE 3B

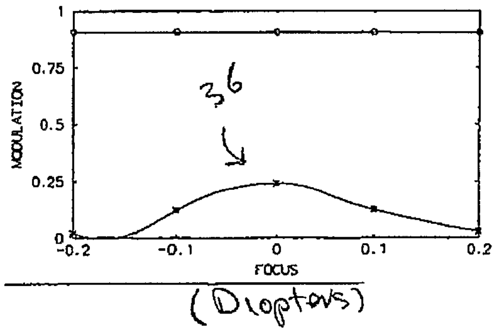

FIGURE 4A

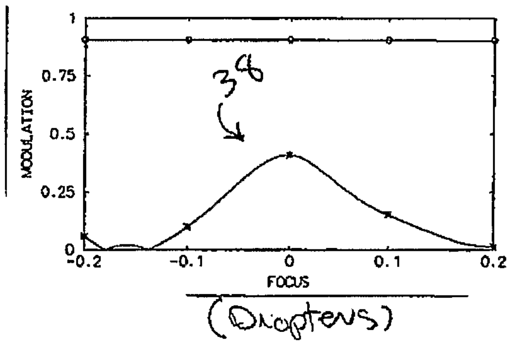

FIGURE 4B

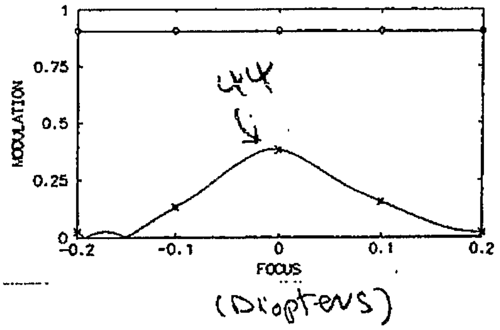

FIGURE 5

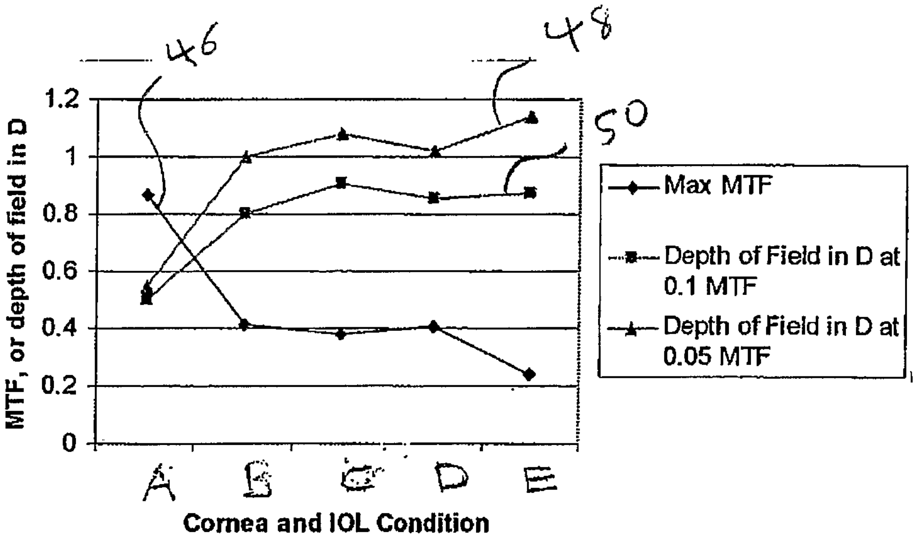
46
48
50
1.2
1
0.8
0.6
0.4
0.2
0
MTF, or depth of field in D
Max MTF
Depth of Field in D at 0.1 MTF
Depth of Field in D at 0.05 MTF
A
B
C
D
E
Cornea and IOL Condition

FIGURE 6

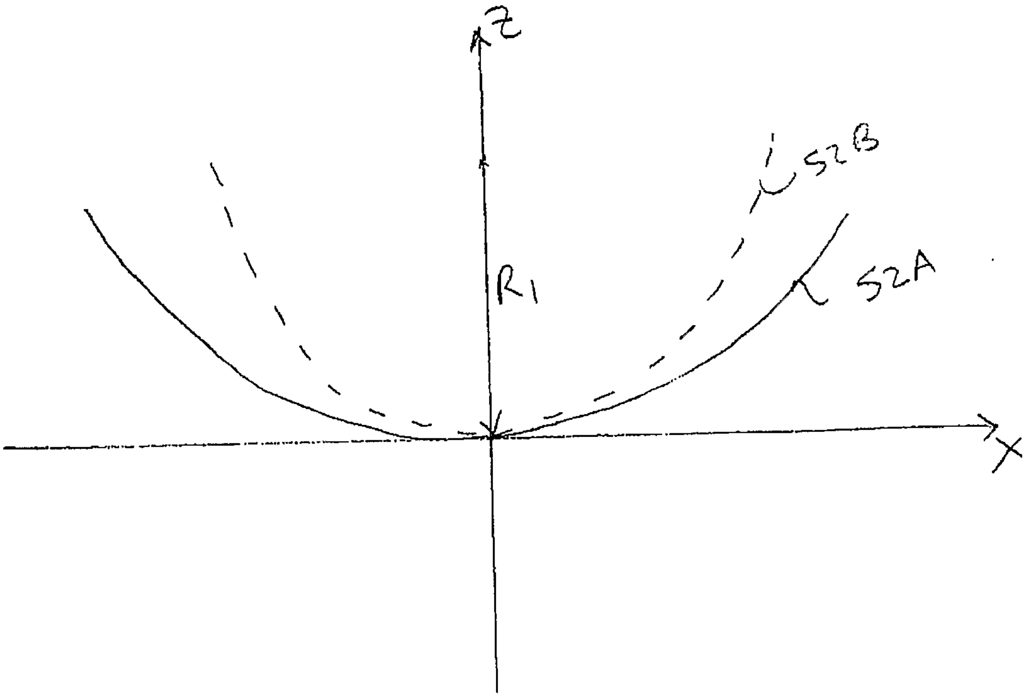

FIGURE 7A

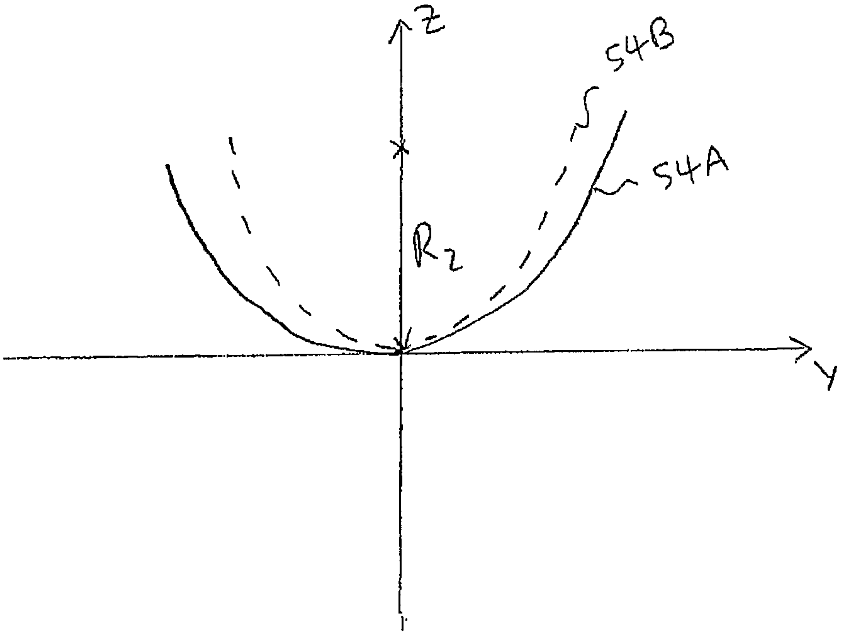

FIGURE 7B