(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
26 May 2006 (26.05.2006)

PCT

(10) International Publication Number
WO 2006/055707 A2

(51) International Patent Classification:
G02C 7/04 (2006.01) *G02B 1/04* (2006.01)
G02C 7/08 (2006.01)

(21) International Application Number:
PCT/US2005/041676

(22) International Filing Date:
18 November 2005 (18.11.2005)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/629,153 18 November 2004 (18.11.2004) US

(71) Applicant *(for all designated States except US)*: **OCULARIS PHARMA, INC.** [US/US]; 2436 South 6th Avenue, North Riverside, Illinois 60546 (US).

(72) Inventor; and
(75) Inventor/Applicant *(for US only)*: **HORN, Gerald** [US/US]; 1150 Heather Road, Deerfiled, Illinois 60015 (US).

(74) Agents: **TURANO, Thomas, A.** et al.; Kirkpatrick & Lockhart Nicholson Graham LLP, 75 State Street, Boston, Massachusetts 02109 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, LY, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SM, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *without international search report and to be republished upon receipt of that report*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

WO 2006/055707 A2

(54) Title: COMPOSITION AND METHOD FOR MODIFYING CONTACT LENS SHAPE

(57) Abstract: Disclosed herein are materials and methods suitable for modifying the shape of a contact lens. A contact lens contains an additive that is able to reversibly increase or decrease the dioptric power of the contact lens in response to the introduction, removal, or modification of a stimulus. The additive responds to the stimulus by swelling or shrinking to a degree sufficient to change a radius of curvature of the contact lens, such as increasing or decreasing the anterior or posterior radius of curvature of the lens. Additives including various polymer gels, including polymer gels embedded with magnetic particles, capable of modifying their size or location following introduction of a corresponding stimulus. Stimuli capable of inducing the desired modification include an electric field, a magnetic field, light, temperature, pH, an ionic solution or a combination thereof.

COMPOSITION AND METHOD FOR MODIFYING CONTACT LENS SHAPE

Technical Field of the Invention

[0001] This application relates to compositions and methods for modifying the shape of a contact lens, and more particularly to substrate polymer gels of a soft contact lens or intraocular lens implant that shrink or swell or otherwise change shape when exposed to selected environmental stimuli and reversibly change the shape of the lens to correct for presbyopia.

Background of the Invention

[0002] It is a well known property of contact lens design that several microns of additional tear film located centrally are associated with anterior vaulting of the central optic to minimize and or prevent contact of the lens with the corneal epithelium. The greater the vault of the central optic, the less diverging the optic and the greater the convergence relative to the starting power. If the vault is increased forward reversibly relative to the distance placement, the lens provides the desired presbyopic correction effect.

[0003] Various designs of bifocal soft contact and intraocular lenses have been proposed. However, all soft contact lens designs by definition require simultaneous exposure of both a distant and near image in focus to the brain, which is contrary to the natural physiogic condition in which the near image is blurred at distance and vice versa. As a result, bifocal intraocular lenses produce reduced contrast sensitivity, and may induce diplopia. Considerable amounts of chair-side time are required for satisfactory fitting of such lenses.

[0004] Other contact lens designs have been proposed in which the viewing area consists of a central circular zone, surrounded by concentric zones of alternating near (reading) and distant vision. This design has been proposed to try to ensure that at every pupil size, the amount of light transmitted through the reading and distant vision zones is substantially equal. It has been found that with such lenses, when correctly fitted, the wearer is able to concentrate on the clearest image focused on the retina.

[0005] While the lenses described above have made a useful contribution to the art, and can reduce the amount of fitting time required, there are still problems to be overcome. Lenses manufactured in accordance with the above technique are most effective when manufactured as hard lenses, or from lens material which have a low water content. If, on the other hand, lenses are made in accordance with the prior technique but in a polymer gel, high water content lens material, the zones formed on a posterior lenticular surface tend to be "ironed out" by the pressure of the upper eyelid.

[0006] Another, unrelated, problem of some prior art lenses is that in certain light conditions, reflections are seen from junctions between adjacent zones. This can have the effect of giving the appearance of rings around a light source.

[0007] Recently, intraocular lenses have been developed that vault, possibly on ciliary muscle contraction, creating a change in dioptric power that may facilitate accommodation. These designs have the inherent flaws of requiring strong ciliary muscle function, a physical requirement that is often absent in the aging population requiring intraocular lens insertion (post cataract extraction). These designs are also highly variable in their effectiveness due to variations in the geometry within the ciliary sulcus region. These designs also require proper anatomic placement and retention of the lens capsule, which is not always possible. And, because of the anterior vaulting, risk rubbing the lens against the posterior iris pigment epithelium and creating an inflammatory reaction or pigmentary glaucoma.

Summary of the Invention

[0008] According to one aspect, the invention relates to a contact lens comprising an additive that reversibly increases or decreases dioptric power in response to introduction of a stimulus. According to one embodiment, the additive responds to the stimulus by swelling or shrinking, to a degree sufficient sufficient to change a radius of curvature of the lens. According to various embodiment, the stimulus is selected from the group consisting of an electric field, a magnetic field, light, temperature, pH, a chemical, an enzyme, an eyelid blepharospasm, a solvent, a salt solution, or a radio wave.

[0009] According to various embodiments, the additive is magnetic particles, for example, magnetite, and the magnetic particles are distributed with a greater density of particles in a center portion of the lens and a lesser density of particles on a peripheral portion of the lens.

[0010] According to additional embodiments of the invention, the additive responds to the stimulus in one of the following responses: an increase in an anterior radius of curvature of the lens, a decrease in a posterior radius of curvature of the lens, both an increase in an anterior radius of curvature and a decrease in a posterior radius of curvature of the lens, a decrease in an anterior radius of curvature of the lens, an increase in a posterior radius of curvature of the lens, or both a decrease in an anterior radius of curvature and an increase in a posterior radius of curvature of the lens.

[0011] According to one embodiment, the additive is distributed on a surface of the lens. According to another embodiment, the additive is distributed within the lens. In one embodiment, the lens comprises a polymer gel and the stimulus is hydration. In another embodiment, the lens comprises an acidic or basic polymer gel and the stimulus is a change in pH. In another embodiment, the lens comprises an ionic polymer geland the stimulus is a saline solution capable of changing the ionic strength of the ionic polymer gel. In another embodiment, the lens comprises immobilized enzyme and the stimulus is topical application of enzyme. In another embodiment, the magnetic particles are dispersed in alginate microspheres within a

polymer gel matrix and the stimulus is an application of a local electric or magnetic field. In another embodiment, the lens comprises a thermoresponsive polymer gel, for example, a hydrogel matrix containing polyN-isopro-pylacrylamide, and the stimulus is a temperature change. In another embodiment, the lens comprises a polyelectrolyte and the stimulus is a local electric field. In another embodiment, the lens comprises ethyl vinyl alcohol and the stimulus is local ultrasonic energy.

[0012] In another aspect, the contact lens additive is polymer gel nanoparticle and the polymer gel nanoparticle undergoes chemical, mechanical, optical or electrical changes in response to a stimulus. According to one embodiment, the polymer gel nanoparticles are interspersed in a pattern to elicit accommodative radius of curvature change within the contact lens. According to another embodiment, the additive responds to the stimulus by swelling and wherein the additive is applied as a gradient with a greater density of additive on a central portion of the lens and a lesser density of additive on a peripheral portion of the lens. According to another embodiment, the additive responds to the stimulus by shrinking and wherein the additive is applied as a gradient with a greater density of additive on a peripheral portion of the lens and a lesser density of additive on a central portion of the lens.

[0013] In another aspect, the contact lens contains an additive that reversibly increases or decreases dioptric power in response to a change in a stimulus, wherein the response is specific to the selected additive, and wherein the additive responds to the stimulus by swelling, shrinking or central forward vaulting sufficient to change a radius of curvature of the lens. In one embodiment, the response reversibly reduces a negative dioptric power in a diverging central optic or increase the positive dioptric power in a converging central optic for correction of presbyopia. In another embodiment, the stimulus is selected from the group consisting of an electric field, a magnetic field, light, temperature, pH, a chemical, an enzyme, an eyelid blepharospasm, a solvent, a salt solution or a radio wave.

[0014] In another embodiment, the additive comprises magnetic particles and the magnetic particles are distributed in a pattern within the contact lens such that application of an electric field or a magnetic field results in introduction of an accommodative effect. According to another embodiment, the additive comprises

magnetic particles, the magnetic particles are distributed in a pattern within the contact lens, application of an electric field or a magnetic field results in introduction of a presbyopic correction, and the presbyopic correction comprises a reduced minus power or an increased plus power. In another embodiment, the magnetic particles are magnetite and the magnetic particles are distributed along a front surface, along a back surface, along both a front and back surface, or throughout the contact lens. In another embodiment, the magnetic particles are distributed with a greater density of particles in a central portion of the lens and a lesser density of particles in a peripheral portion of the lens and the stimulus results in a thickening of the central portion of the lens. In yet another embodiment, the magnetic particles are distributed along a front surface or a back surface of the lens and the stimulus results in a repulsive magnetic force sufficient to flatten the distribution of the particles. In another embodiment, the magnetic particles are distributed to increase an anterior radius of curvature, to decrease a posterior radius of curvature, or to both increase an anterior radius of curvature and decrease a posterior radius of curvature of the lens. According to another embodiment, the additive is distributed with a greater density of additive in a peripheral portion of the lens and a lesser density of additive in a central portion of the lens and the additive responds to the stimulus by shrinking.

[0015] According to an embodiment, the contact lens comprises a material selected from the group consisting of hydrogels, silicone hydrogels, silicone polymers, poly(urethanes), poly(siloxanes), silicones, poly(methyl methacrylate), poly(vinyl alcohol), poly(ethylenes), poly(vinyl pyrrolidone), poly(methyl methacrylate), poly(methacrylic acid), poly(acrylimide), poly(ethylene oxide), poly(propylene oxide), and poly(2-hydroxy ethyl methacrylate).

[0016] According to one embodiment, the contact lens comprises a hydrogel, the additive comprises poly(vinyl alcohol) and poly(acrylic acid), and the stimulus is an electric field. According to another embodiment, the contact lens comprises a polymer gel, the additive comprises chitosan and poly(hydroxyetheyl methacrylate), and the stimulus is an electric field applied in the presence of a saline solution. In yet another embodiment, the additive is distributed with a greater density of additive

in a peripheral portion and a lesser density of additive in a central portion, the stimulus is an electric field and the response results in a curvature away from the stimulus. In one embodiment, the electric field comprises a voltage of about 5 to 30 volts and the electric field is directed so that the positive field travels upward and around the body to the negative field.

[0017] In another aspect, the invention is a system comprising a contact lens and an electric field generator worn along a central portion of a body and wherein the cathode is directed superiorly. According to another embodiment, the electric field is applied toward the body and a positive charge is directed toward the anterior surface of an eye. In various embodiments, the saline solution comprises a salt concentration of about 0 to 5% or about 0.04 to 1.2%. In another embodiment, the electric field produces a voltage at a surface of an eye of about 3 to about 30 volts or about 15 to about 20 volts. In yet another embodiment, the electric field produces a peripheral curvature deflection of about 10 to 150 microns or about 30 to 75 microns.

[0018] According to another embodiment, the contact lens further comprises monomer voids and the stimulus comprises electrolytes wherein the electrolytes are preferentially absorbed within the monomer voids. According to one embodiment, the monomer voids are distributed with a greater density of voids in a peripheral portion of the lens and a lesser density of voids in a central portion of the lens. In one embodiment, the electrolyte is hypertonic saline. In another embodiment, the additive comprises ion exchange polymer metal composite poly sodium acrylate. In one embodiment, the additive is distributed in a gradient producing an aspherical curvature change.

[0019] In another aspect, the invention is a method of using the contact lens wherein a patient wears the contact lens in one eye to create monovision and to reduce the risk of inadvertent curvature transformation. In another embodiment, the stimulus produces about 10 to 100 microns of lens curvature or about 30 to 60 microns of lens curvature. In another embodiment, the stimulus produces anterior vaulting of the central optic and the anterior vaulting moves the optic forward 5 to 150 microns, 25 to 100 microns, 50 to 250 microns or 250 to 2000 microns. In

another embodiment, the electric field is oriented asymmetrically relative to the surface of the contact lens.

Brief Description of the Drawings

[0020] In the drawings, like reference characters generally refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the invention are described with reference to the following drawings, in which:

[0021] FIG. 1A is a transverse view of a positive meniscus contact lens according to an illustrative embodiment of the invention.

[0022] FIG. 1B is a transverse view of a negative meniscus contact lens according to an illustrative embodiment of the invention.

[0023] FIG. 2A is a transverse view of a positive meniscus contact lens with increased central vaulting according to an illustrative embodiment of the invention.

[0024] FIG. 2B is a transverse view of a negative meniscus contact lens with increased central vaulting according to an illustrative embodiment of the invention.

[0025] FIB. 2C is a transverse view of a positive meniscus contact lens with peripheral shrinkage on the anterior surface according to an illustrative embodiment of the invention.

[0026] FIG. 2D is a transverse view of a negative meniscus contact lens with peripheral shrinkage of the anterior surface according to an illustrative embodiment of the invention.

[0027] FIG. 2E is a transverse view of a positive meniscus contact lens curving away from an environmental stimulus according to an illustrative embodiment of the invention.

[0028] FIG. 2F is a transverse view of a negative meniscus contact lens curving away from an environmental stimulus according to an illustrative embodiment of the invention.

Detailed Description of the Invention

[0029] The present invention relates to a composition for application on or within a contact lens, for example, a soft contact lens, an intraocular lens or an intracorneal insert, allowing for curvature transformation from distance to near reversibly and repeatedly as desired in response to specifically selected exposure to an environmental stimulus such as, for example, a change in hydration, a change in heat, a change in pH, or the presence of an electric, magnetic, or ionic field. In particular, the central optic of the present invention retains the desired distance curvatures in the absence of such stimulus. When the stimulus is present, the modified soft contact lens or intraocular lens material of the present invention is caused to thicken or swell to alter the anterior and or posterior radius of curvature of the central optic and induce an accommodative dioptric power change.

[0030] Exemplary dioptic power changes include reduced minus power for minus lenses and increased plus power in plus lenses. Similarly, the same refractive effect can be achieved by shrinkage of the peripheral curvature relative to the center, curvature away from the directed source peripherally, or vault towards the external source centrally. The latter is a particularly effective option for inducing presbyopic corrective optical effect in an intraocular lens, and particularly for an intraocular lens placed within the capsular bag where space allows for more than 1 mm of anterior vaulting to occur.

[0031] The present invention is directed to achieve the physiologic optics of true accommodation through material modification of the central optic or intraocular lens using a user controlled environmental trigger. In the absence of such trigger, the lens creates an in focus distance image with a blurred near image. When the environmental stimulus is triggered, the shape of the lens is modified to effect a virtually immediate change to a near point in focus, with blurring of the distance focus at a desired distance. The present invention allows for potential adjustment of

the range of near point triggered by the user via length of time and or strength of the environmental stimulus. Effecting presbyopic correction via real time transformation of lens curvature has the advantage of replacing the ciliary muscle natural lens complex for this purpose, which in presbyopic patients no longer functions adequately. The present invention relies on materials development to effect such transformation via environmental trigger. Such advance has come largely from the fields of nanotechnology, drug delivery development, biomimetic sensor development, and novel actuators, particularly those developed in the field of robotics for artificial muscle systems development.

[0032] Polymer gels have been developed for effecting transformation in shape within each of these disciplines. For example, nanotechnology has been used to create magnetic particles within a siloxane polymer fluid capable of responding to a magnetic field and moving within the fluid to cover retinal tears or holes in retinal detachment surgery. Exemplary magnetic materials include magnetic particles, including magnetite particles, nanogels or ferrogels. A ferrogel is a chemically cross-linked polymer network swollen by a ferrofluid. A ferrofluid, or a magnetic fluid, is a colloidal dispersion of monodomain magnetic particles. The typical size of a particle is about 10 nm and they have superparamagnetic behavior. In the ferrogel, the finely distributed magnetic particles, for example, magnetite particles, are located in the swelling liquid and attached to the flexible network chains by adhesive forces.

[0033] Similarly, polymer gels such as hydrogels have been modified to induce shrinking or swelling in response to environmental stimuli for the production of robots, synthetic muscle, and drug delivery platforms.

[0034] Controlled drug delivery systems rely on increasingly sophisticated development of polymer gels, which can shrink or thicken in response to environmental stimuli. A range of materials have been employed to control the release of drugs and other active agents. The earliest of these polymers were selected because of their desirable physical properties: poly(urethanes) for their elasticity; poly(siloxanes) or silicones for their insulating ability; poly(methyl methacrylate) for its physical strength and transparency; poly(vinyl alcohol) for its

hydrophilicity and strength; poly(ethylene) for its toughness and lack of swelling; and poly(vinyl pyrrolidone) for its suspension capabilities.

[0035] To be successfully used in controlled drug delivery formulations as well as most biomedical applications, a material must be chemically inert and free of leachable impurities, at least where such impurities have any toxicity. The material must also have an appropriate physical structure, with minimal undesired aging, and be readily processable. Some materials that are currently used or studied for controlled drug delivery include poly(2-hydroxy ethyl methacrylate); poly(N-vinyl pyrrolidone); poly(methyl methacrylate); poly(vinyl alcohol); poly(acrylic acid); polyacrylamide; poly(ethylene-co-vinyl acetate); poly(ethylene glycol); and poly(methacrylic acid).

[0036] The physical properties and responses of some of these polymer gels are shown below—a list not intended to represent all possibilities but to provide relevant examples and an indication of the range of structural, chemical, and processing properties that can affect thickening or shrinkage of polymer gel materials.

PH	Acidic or basic hydrogel	Change in pH—swelling—release of drug
Ionic strength	Ionic hydrogel	Change in ionic strength—change in concentration of ions inside gel—change in swelling—release of drug
Chemical species	Hydrogel containing electron-accepting groups	Electron-donating compounds—formation of charge/transfer complex—change in swelling—release of drug
Enzyme-substrate	Hydrogel containing immobilized enzymes	Substrate present—enzymatic conversion—product changes swelling of gel—release of drug
Magnetic	Magnetic particles dispersed in alginate microspheres	Applied magnetic field—change in pores in gel—change in swelling—release of drug
Thermal	Thermoresponsive hydrogel poly(N-isopro-pylacrylamide)	Change in temperature—change in polymer-polymer and water-polymer interactions—change in swelling—release of drug
Electrical	Polyelectrolyte hydrogel	Applied electric field—membrane charging—electrophoresis of charged drug—change in swelling—release of drug
Ultrasound irradiation	Ethylene-vinyl alcohol hydrogel	Ultrasound irradiation—temperature increase—release of drug

[0037] Most of the materials used in swelling-controlled release drug delivery systems are based on hydrogels, which are polymers that will swell without dissolving when placed in water or other biological fluids. These hydrogels can absorb a great deal of fluid and, at equilibrium, typically comprise 60–90% fluid and only 10–30% polymer. One of the most remarkable, and useful, features of a polymer's swelling ability manifests itself when that swelling can be triggered by a change in the environment surrounding the delivery system. Depending upon the polymer, the environmental changes include, without limitation, hydration, pH, temperature, magnetic, electric or ionic strength. It is contemplated that the system can either shrink or swell upon a change in any of these environmental factors. A number of these environmentally sensitive or "intelligent" hydrogel materials are listed above. For most of these polymers, the structural changes are reversible and repeatable upon additional changes in the external environment.

[0038] Artificial muscle development relies frequently on ion-exchange polymer-metal composites (IPMC) that are active actuators, show large deformation in the presence of low applied voltage, and exhibit low impedance. They have been modeled as both capacitive and resistive element actuators that behave like biological muscles and provide an attractive means of actuation as artificial muscles for biomechanical and biomimetic applications. Polyelectrolytes possess ionizable groups on their molecular backbone. These ionizable groups have the property of dissociating and attaining a net charge in a variety of solvent media. These net charge groups, which are attached to networks of macromolecules, are called polyions and give rise to intense electric fields of the order of 10^{10} Volts per meter. Thus, the essence of electromechanical deformation of such polyelectrolyte systems is their susceptibility to interactions with externally applied fields as well as their own internal field structure. In particular, if the interstitial space of a polyelectrolyte network is filled with liquid containing ions, then the electrophoretic migration of such ions inside the structure due to an imposed electric field can also cause the macromolecular network to deform accordingly.

[0039] Biomimetic sensors mimic the ability of biologic systems to sense changes in their environment, and then to react to them. For example, researchers have discovered how proteins bind with other molecules to create a molecular switch that enables them to turn an enzyme on and off. These innovations utilize polymer gels modified to respond to environmental stimuli, frequently called "smart polymers." To build the switch, the researchers attach tiny smart polymer chains next to the active sites, or the spots where the enzyme binds with target molecules to do their work. Depending on conditions, the polymer threads either extend or contract: one state blocks the site, while the other leaves it open. The function of the change in state depends on the size of the target molecule. For example, in the case of endoglucanase, a contracted polymer thread blocks the active site and an expanded thread exposes the active site. As another example, two synthetic polymers, DMAA and DMAAm, change in response to visible light. When exposed to visible light, DMAA becomes hydrophilic, attracts water molecules, and expands. When the visible light is replaced by ultraviolet light, DMMA becomes hydrophobic, expels the water molecules and contracts into a coil. DMMAm works in reverse. When exposed to UV light it expands, and when exposed to visible light it contracts. The switch works by enabling endoglucanase to bind or unbind with cellulose, depending on the type of light applied.

[0040] Over the last 10 years, there has been a great deal of effort directed toward developing more dexterous robots and master controllers capable of permitting human control of these complex devices. In the development of these systems, a great deal of effort was spent in developing the mechanism of getting power to the individual finger joints and in making the system as light as possible so that the limited power available was not wasted on supporting the structure. The robot hand most similar to the human geometry, the UTAH/MIT hand, has a "remotizer" which consists of numerous pulleys (nearly 400) and tendons filling approximately a 12" by 4" by 3" area. Original efforts to develop such robots were working around a fundamental limitation in today's actuator technology. Actuators small and strong enough to be placed proximal to the joint, as muscles are in the human system, were not available. Recent research in polymer gels has resulted in a potential revolution in actuator design and the material possibilities of the present invention.

[0041] First, much research on gel-based actuation has focused on the material itself, resulting in a good understanding of the physics of gel contraction. Second, a number of innovations have made gel based actuation much more practical. For example, thin films and fine fibers have been fabricated, allowing faster contraction rates and higher strength. Finally, technological innovations such as robotics and implantable artificial biological organs have created a demand for such devices.

[0042] A polymer gel soft contact or intraocular lens typically has a minus power (diverging) with a negative meniscus lens design, or a plus power (converging light) and a positive meniscus lens design. FIG. 1A is a transverse view of a positive meniscus contact lens 10 according to an illustrative embodiment of the invention. FIG. 1B is a transverse view of a negative meniscus contact lens 20 according to an illustrative embodiment of the invention.

[0043] According to the present invention, a desired environmental stimulus trigger is selected and the corresponding polymer gel modifying material is applied to the lens in a desired pattern. When the modified gel is exposed to the selected environmental stimulus, it is triggered to undergo its change in hydration (swelling), peripheral gradient (shrinkage), or anterior movement (vaulting).

[0044] A preferred aspect of this invention provides for a curvature transformation to change a single focal length, particularly as desired via external stimuli. This method of curvature transformation is an improvement over the previous known method requiring providing simultaneous presentation of two or more focal powers to the eye. In addition to the advantage of achieving physiologic optics most resembling true accommodation, the present invention allows for the possibility of altering the change in focal length to a desired point. This primary focal point modification allows for the largest field of view in addition to less confusion and light scatter than bifocal intraocular lens designs with two or more focal lengths, and a more complete, stable, predictable, and repeatable presbyopic corrective effect than surgically implanted intraocular lens vaulting designs relying on the ciliary muscle contraction.

[0045] In a preferred embodiment of the invention, the polymers capable of being modified by environmental stimuli are placed on the central optic of the contact lens with an appropriate distribution to correct for an individual patient's presbyopia. Depending on the needs of the patient, the placement of a particular polymer in the contact lens may be used to increase the convergence curvature of the lens. The polymer and its placement may also be used to change the anterior curve of the lens, the posterior curve, or both curvatures. The polymer may modify the shape of the lens by modifying the substance of the lens centrally, peripherally, or both, depending on the modifications required by the individual patient. According to a preferred embodiment, the environmental stimulus induces a deflection in the contact lens of about 5-150 microns, more preferably about 30 to 75 microns, depending upon the degree of correction required by the patient.

[0046] For example, FIG. 2 illustrates six possible patient conditions requiring a change in curvature to correct for presbyopia. A polymer gel-modifying additive, according to one embodiment of the invention, may respond to a specified environmental stimulus by thickening at the site of application. According to another embodiment of the invention, the polymer gel responds to the environmental stimulus by thinning at the site of application. Accordingly, the placement of the polymer gel-modifying additive is important to correct for the presbyopia if an individual patient. The polymer gel may be applied to a central region of the lens or a peripheral region of the lens. The polymer gel also may be applied as a gradient across either the entire lens or a region of the lens.

[0047] According to one embodiment of the invention, the polymer gel selected responds to the environmental stimulus by swelling or thickening. To create a larger central forward vault on the lens, the gradient of the swelling or thickening polymer will be greater centrally than peripherally, again resulting in a relative increase in the central forward vault of the lens. Where magnetic nanoparticles are used, this gradient may be altered by the stiffening or flattening of the particles when placed on that surface. For example, FIG. 2A is a transverse view of a positive meniscus contact lens 10 with increased central forward vaulting 40 according to an illustrative embodiment of the invention. FIG. 2B is a transverse view of a negative

meniscus contact lens 20 with increased central forward vaulting 40 according to an illustrative embodiment of the invention. In both examples, the modifiable polymer is applied centrally and responds to the selected environmental stimulus by thickening and thereby increasing the central forward vault 40.

[0048] For example, in another embodiment of the invention, the polymer gel selected responds to the selected environmental stimulus by shrinking. To create a larger central vault on the lens, the gradient of the shrinking polymer will be greater peripherally than centrally, resulting in a relative increase in the central vault of the lens compared to the peripheral shrinkage. FIB. 2C is a transverse view of a positive meniscus contact lens 10 with peripheral shrinkage 50 on the anterior surface according to an illustrative embodiment of the invention. FIG. 2D is a transverse view of a negative meniscus contact lens 20 with peripheral shrinkage 50 of the anterior surface according to an illustrative embodiment of the invention. In both examples, the modifiable polymer is applied peripherally and responds to the selected environmental stimulus by shrinking and thereby proportionately increasing the central vault.

[0049] According to another embodiment of the invention, the posterior surface of the lens may be designed with increased deformablility, such as with increased voids and nonbound water, to increase the ease of inducing curvature changes. For example, FIG. 2E is a transverse view of an increased deformability positive meniscus contact lens 10 curving away from an environmental stimulus 60 according to an illustrative embodiment of the invention. FIG. 2F is a transverse view of an increased deformability negative meniscus contact lens 20 curving away from an environmental stimulus 60 according to an illustrative embodiment of the invention.

[0050] According to one embodiment of the invention, the polymer gels are hydrogel polymers. Increased or decreased hydration of a hydrogel polymer results in the swelling, shrinkage, or forward vaulting of the gel. Additives, appropriately placed within the lens, may be selected for their ability to release or imbibe water molecules when exposed to an environmental stimulus to which they are sensitive. Upon exposure to the environmental stimulus, the additive responds by swelling,

shrinking, or causing a change in the curvature of the hygrogel, changing the forward vault of the optic. Forward vaulting of an intraocular lens assembly not only increases the anterior curvature of the lens, but also treats presbyopia via forward movement of the entire optic, particularly in the case of exposure to electric or magnetic fields.

[0051] According to another embodiment of the invention, the polymer gel is an acidic or basic polymer gel. A change in the pH of the lens results in the desired swelling, shrinking or forward vaulting of the lens. According to yet another embodiment, the polymer gel is an ionic polymer gel that responds to a change in its ionic properties following the introduction of a saline or other ionic solution sufficient to result in the desired swelling, shrinking or forward vaulting of the lens. Alternatively, the polymer gel contains an enzyme or substrate that responds to the introduction of a conjugate enzyme or substrate by swelling, shrinking or forward vaulting the lens.

[0052] According to a preferred embodiment of the invention, the contact lens contains magnetic particles contained within or attached to alginate microspheres, distributed throughout the lens. Application of a local electric or magnetic field results in the desired swelling, shrinking or forward vault of the lens. In another embodiment, the lens comprises a thermoresponsive polymer gel, for example, a hydrogel matrix containing polyN-isopro-pylacrylamide, that responds to a change in temperature by swelling, shrinking or forward vaulting of the lens.

[0053] According to another embodiment of the invention, the contact lens contains a polyelectrolyte and responds to the application of an electric field by swelling, shrinking or forward vaulting of the lens. In another embodiment, the contact lens contains ethyl vinyl alcohol and responds to local ultrasonic energy by swelling, shrinking or forward vaulting of the lens.

[0054] The modified polymer gel transforms the curvature of the lens in response to the selected environmental stimulus either for a pre-selected period of time, varying based on the properties of the selected polymer gel additives, or until the stimulus is removed.

[0055] The polymer gel additives include but are not limited to chitosan, magnetite, other ferrogels, poly(vinyl alcohol), polyN-isopro-pylacrylamide poly(hydroxyetheyl methacrylate), styrene-ethylene/butylene-styrene triblock polymer gels, ethylene vinyl alcohol, and other polyelectrolytes or additives to polymer gels to allow modification of their hydration or otherwise cause a change in shape when exposed to specific environmental stimuli.

[0056] Environmental stimuli capable of inducing a modification in the shape of a lens according to this invention include, but are not limited to, an electric field, a magnetic field, light, mechanical stress, including lid blink with momentary blepharospasm, thermal change, hydration change, or pH change.

[0057] Intraocular lens design generally utilizes both soft and hard materials. Soft lens materials include polymer gels such as hydrogels. While multifocal lens designs mimic the physiology of accommodation by providing both a near and far point, they do so with the great disadvantage of providing constant dual focal points in focus, requiring the brain to selectively suppress the appropriate focal length images as needed. This causes some confusion and the multiple zones reduce contrast sensitivity with greater undesirable scatter and diffracting of light across the retina and particularly across the macula. Designs intended to further mimic accommodation vault the optic forward as the ciliary muscle contracts, but have the disadvantages of being highly variable in effect, difficult to insert, dependent on ciliary muscle strength in a group of elderly patients with variations in such strength which can be minimal in many cases, and offering limited accommodative effect. It is generally recognized that about three diopters of accommodative amplitude are required to change the vault of the optic from distance to near. About five diopters of amplitude are required to minimize fatigue with reading. Vaulting intraocular lenses can rarely offer this degree of amplitude and therefore induce significant anesthenopia (eye strain) compared to the intraocular lens of the present invention.

[0058] While true accommodation results in movement of the focal point from a distant to near point via ciliary muscle contraction, the current invention allows virtually the same optical change in focus at the discretion of the user using an environmental stimulus.

[0059] According to a preferred embodiment of the invention, a central optic is comprised of a ferrogel and the curvature of the lens is modified by the application of a magnetic field. A ferrogel is a chemically cross-linked polymer network swollen by a ferrofluid. A ferrofluid, or a magnetic fluid, is a colloidal dispersion of monodomain magnetic particles, such as iron oxide or magnetite. The typical size of the magnetic particles is about 10 nm and they have superparamagnetic behavior. In the ferrogel, the finely distributed magnetic particles are located in the swelling liquid and attached to the flexible network chains by adhesive forces. Alginate microspheres are frequently used to contain the magnetic particles. The particles are placed in a pattern to allow for optimal central vaulting, swelling, or peripheral curvature. When an asymmetrical magnetic stimulus is directed towards the gel, the magnetic particles move away from the field and induce desired curvature change. The curvature change corrects for presbyopia. According to one embodiment of the invention, a magnet of appropriate strength is placed about fifteen inches away from the eye, an optimal distance for reading materials.

[0060] Both central optics and intraocular lenses can be induced to vault the entire central optic forward. In the case of an intraocular lens assembly where the peripheral haptics are relatively fixed in position, represent flexible attachments, and the central optic contains, preferentially, the ferrogel particles, there is room for up to approximately 2.5 mm of movement. If the haptics are in the ciliary sulcus, the iris will bow forward slightly. If the haptics are placed further posteriorly in the capsular bag, considerable forward vaulting can occur without such contact, reducing divergence of the optic and therefore improving presbyopic correction.

[0061] A second preferred embodiment utilizes an electric field as the environmental stimulus trigger. It is well known that voltages far in excess of 20 volts can be directed at the human body safely. The exterior surface of the body often amplifies the electric field, particularly in curved surfaces, and particularly where an electrolyte is present, as at the surface of a central optic where 0.9% saline solution is the main constituent of tear film. Voltages below 20V can be considered safe to touch (the current does not exceed 10 mA in normal conditions). If the skin is dry, voltages up to around 80V do not cause over 30 mA current.

[0062] Chitosan, obtained from the deacetylation of chitin, has known properties of dehydrating aqueous saline solutions, is biocompatible, nonantigenic, antibacterial and nontoxic. Poly(hydroxyethyl methacralate) (PHEMA) is a hydrogel that swells when placed in contact with water. It is insoluble and is a commonly used polymer gel for contact lens wear. Cross-linked PHEMA hydrogels can be prepared by polymerization of an aqueous saline reaction mixture containing a monomer, a cross linking agent, and an initiator. An example of such a mixture contains HEMA, azobisisobutyronitrile (AIBN), and EGDMA as an initiator (Aldrich Chemical Co., USA). A polymer gel with a semi-interpenetrating polymer network composed of chitosan and poly(hydroxyethyl methacrylate) results in a polymer gel that exhibits electrically sensitive behavior. There is an inverse relationship between the ability of this monomer to swell and the ratio of saline present in the solution. A solution of 0.9% saline (tears) demonstrates a swelling ratio of about 170% compared to 215% swelling with a 0% saline solution. When voltages of about 5 to 25 volts are applied, the polymer gel bends away from the cathode and toward the anode. The bending is inversely related to the swelling ratio. For example, when a 0.9% saline solution is used, the degree of bending approaches the peak of 35%. As the voltage increases, the time of onset decreases. The magnetic field exposure must be asymmetrically placed in relation of the poles to the eye.

[0063] The additive response time, the time necessary for the additive to respond to the stimulus by modifying the shape of the contact lens, ranges from about 0-15 seconds, preferably 0-5 seconds. Similarly, additive relaxation time, the time necessary for the additive to resume its original distribution following removal of the stimulus, ranges from about 0-15 seconds, preferably 0-5 seconds. A skilled practitioner will appreciate the variations in response and relaxation time of a variety of additives within various contact lens materials and can select combinations of contact lens material, additive material, additive distribution and stimulus to achieve the desired response and relaxation times.

[0064] By creating an electric field enveloping the body, perpendicular field exposure around the body is induced along the body surfaces. According to one embodiment, a user generated positive voltage is directed at the front surface of the eye perpendicular to the corneal surface. According to this illustrative embodiment of the invention, a horizontal electric field is directed at the central opticanterior saline tear surface of the central optic and an asymmetrical electric field with cathode polarity above the anode is directed from the front to the back of the head central optic. The shape of the electric field created according to this embodiment creates the necessary cathode to anode front to back surface field directed effect from front to back surface of the central optic. Optionally, additional voids may be created along the posterior peripheral surface or portion of the lens or intraocular implant. Voids are empty spaces that increase the nonbound water within the lens and increase the ability of the peripheral curvature to be directed away from the electric field. Using simple disposable batteries, such as a 1.5 Volt AA battery, a circuit with fixed or variable resistance generates voltages of 5 to 50 Volts to generate about 10 to 20 Volts at the surface of the eye. Electric fields direct the electric force, and thus the electric field, perpendicular to the surface of an object. Therefore, a field at the surface of the modified lens is positive in front of the lens and negative behind the lens. Electric field exposure of up to 20 kV / meter has been shown to be innocuous. Direct contact to the skin over 120 volts is considered dangerous, but at 20 to 40 volts, the voltage source (inductor circuit) of the preferred embodiment is harmless.

[0065] Although there has been hereinabove described a particular invention, it should be appreciated that the invention is not limited thereto. Accordingly, any and all modifications, variations or equivalent arrangements, which may occur to those skilled in the art, should be considered to be within the scope of the present invention as defined in the appended claims.

Claims

I claim:

1. A contact lens comprising an additive that reversibly increases or decreases dioptric power in response to introduction of a stimulus.

2. The contact lens of claim 1 wherein the additive responds to the stimulus by swelling or shrinking, to a degree sufficient to change a radius of curvature of the lens.

3. The contact lens of claim 1 wherein the stimulus is selected from the group consisting of an electric field, a magnetic field, light, temperature, pH, a chemical, an enzyme, an eyelid blepharospasm, a solvent, a salt solution, or a radio wave.

4. The contact lens of claim 1 wherein the additive comprises magnetic material.

5. The contact lens of claim 4 wherein the magnetic material is magnetic particles, magnetite particlesm, a ferrogel or a nanogel.

6. The contact lens of claim 4 wherein the magnetic material is distributed with a greater density of magnetic material in a center portion of the lens and a lesser density of magnetic material on a peripheral portion of the lens.

7. The contact lens of claim 1 wherein the additive response results in an increase in an anterior radius of curvature of the lens.

8. The contact lens of claim 1 wherein the additive response results in a decrease in a posterior radius of curvature of the lens.

9. The contact lens of claim 1 wherein the additive response results in both an increase in an anterior radius of curvature and a decrease in a posterior radius of curvature of the lens.

10. The contact lens of claim 1 wherein the additive response results in a decrease in an anterior radius of curvature of the lens.

11. The contact lens of claim 1 wherein the additive response results in an increase in a posterior radius of curvature of the lens.

12. The contact lens of claim 1 wherein the additive response results in both a decrease in an anterior radius of curvature and an increase in a posterior radius of curvature of the lens.

13. The contact lens of claim 1 wherein the additive is distributed on a surface of the lens.

14. The contact lens of claim 1 wherein the additive is distributed within the lens.

15. The contact lens of claim 1 wherein the lens comprises a polymer gel.

16. The contact lens of claim 15 wherein the polymer gel is a hydrogel

17. The contact lens of claim 16 wherein the stimulus is hydration.

18. The contact lens of claim 1 wherein the lens comprises an acidic or basic polymer gel.

19. The contact lens of claim 18 wherein the stimulus is a change in pH.

20. The contact lens of claim 1 wherein the lens comprises an ionic polymer gel.

21. The contact lens of claim 20 wherein the stimulus is a saline solution capable of changing the ionic strength of the ionic polymer gel.

22. The contact lens of claim 1 wherein the lens comprises immobilized enzyme.

23. The contact lens of claim 22 wherein the stimulus is topical application of enzyme.

24. The contact lens of claim 4 wherein the magnetic particles are dispersed in alginate microspheres within a polymer gel matrix.

25. The contact lens of claim 24 wherein the stimulus is an application of a local electric or magnetic field.

26. The contact lens of claim 1 wherein the lens comprises a thermoresponsive polymer gel.

27. The contact lens of claim 26 wherein the thermoresponsive polymer gel is a hydrogel matrix containing polyN-isopro-pylacrylamide.

28. The contact lens of claim 26 wherein the stimulus is a temperature change.

29. The contact lens of claim 1 wherein the lens comprises a polyelectrolyte.

30. The contact lens of claim 29 wherein the stimulus is a local electric field.

31. The contact lens of claim 1 wherein the lens comprises ethyl vinyl alcohol.

32. The contact lens of claim 31 wherein the stimulus is local ultrasonic energy.

33. The contact lens of claim 1 wherein the additive comprises polymer gel nanoparticles and wherein the polymer gel nanoparticles undergo chemical, mechanical, optical or electrical changes in response to a stimulus.

34. The contact lens of claim 33 wherein the polymer gel nanoparticles are interspersed in a pattern to elicit accommodative radius of curvature change within the contact lens.

35. The contact lens of claim 1 wherein the additive responds to the stimulus by swelling and wherein the additive is applied as a gradient with a greater density of additive on a central portion of the lens and a lesser density of additive on a peripheral portion of the lens.

36. The contact lens of claim 1 wherein the additive responds to the stimulus by shrinking and wherein the additive is applied as a gradient with a greater density of additive on a peripheral portion of the lens and a lesser density of additive on a central portion of the lens.

37. A contact lens comprising an additive that reversibly increases or decreases dioptric power in response to a change in a stimulus, wherein the response is specific to the selected additive, wherein the additive responds to the stimulus by swelling, shrinking or central forward vaulting sufficient to change a radius of curvature of the lens.

38. The contact lens of claim 37 wherein the response reversibly reduces a negative dioptric power in a diverging central optic or increase the positive dioptric power in a converging central optic for correction of presbyopia.

39. The contact lens of claim 37 wherein the stimulus is selected from the group consisting of an electric field, a magnetic field, light, temperature, pH, a chemical, an enzyme, an eyelid blepharospasm, a solvent, a salt solution or a radio wave.

40. The contact lens of claim 37 wherein the additive comprises magnetic particles and wherein the magnetic particles are distributed in a pattern within the contact lens such that application of an electric field or a magnetic field results in introduction of an accommodative effect.

41. The contact lens of claim 37 wherein the additive comprises magnetic particles, wherein the magnetic particles are distributed in a pattern within the contact lens, wherein application of an electric field or a magnetic field results in introduction of a presbyopic correction, and wherein the presbyopic correction comprises a reduced minus power or an increased plus power.

42. The contact lens of claim 41 wherein the magnetic particles are magnetite and wherein the magnetic particles are distributed along a front surface, along a back surface, along both a front and back surface, or throughout the contact lens.

43. The contact lens of claim 41 wherein the magnetic particles are distributed with a greater density of particles in a central portion of the lens and a lesser density of particles in a peripheral portion of the lens and wherein the stimulus results in a thickening of the central portion of the lens.

44. The contact lens of claim 41 wherein the magnetic particles are distributed along a front surface or a back surface of the lens and wherein the stimulus results in a repulsive magnetic force sufficient to flatten the distribution of the particles.

45. The contact lens of claim 41 wherein the magnetic particles are distributed to increase an anterior radius of curvature, to decrease a posterior radius of curvature, or to both increase an anterior radius of curvature and decrease a posterior radius of curvature of the lens.

46. The contact lens of claim 37 wherein the additive is distributed with a greater density of additive in a peripheral portion of the lens and a lesser density of additive in a central portion of the lens and wherein the additive responds to the stimulus by shrinking.

47. The contact lens of claim 1 or claim 37 wherein the contact lens comprises a material selected from the group consisting of hydrogels, silicone hydrogels, silicone polymers, poly(urethanes), poly(siloxanes), silicones, poly(methyl methacrylate), poly(vinyl alcohol), poly(ethylenes), poly(vinyl pyrrolidone), poly(methyl methacrylate), poly(methacrylic acid), poly(acrylimide), poly(ethylene oxide), poly(propylene oxide), and poly(2-hydroxy ethyl methacrylate).

48. The contact lens of claim 37 wherein the contact lens comprises a hydrogel, wherein the additive comprises poly(vinyl alcohol) and poly(acrylic acid), and wherein the stimulus is an electric field.

49. The contact lens of claim 37 wherein the contact lens comprises a polymer gel, wherein the additive comprises chitosan and poly(hydroxyetheyl methacrylate), and wherein the stimulus is an electric field applied in the presence of a saline solution.

50. The contact lens of claim 49 wherein the additive is distributed with a greater density of additive in a peripheral portion and a lesser density of additive in a central portion, wherein the stimulus is an electric field and wherein the response results in a curvature away from the stimulus.

51. The contact lens of claim 50 wherein the electric field comprises a voltage of about 5 to 30 volts and wherein the electric field is directed so that the positive field travels upward and around the body to the negative field.

52. A system comprising the contact lens of claim 49 and further comprising an electric field generator worn along a central portion of a body and wherein the cathode is directed superiorly.

53. The system of claim 52 wherein the electric field is applied toward the body and a positive charge is directed toward the anterior surface of an eye.

54. The contact lens of claim 49 wherein the saline solution comprises a salt concentration of about 0 to 5%.

55. The contact lens of claim 49 wherein the saline solution comprises a salt concentration of about 0.04 to 1.2%.

56. The system of claim 52 wherein the electric field produces a voltage at a surface of an eye of about 3 to about 30 volts.

57. The system of claim 52 wherein the electric field produces a voltage at a surface of an eye of about 15 to about 20 volts.

58. The system of claim 52 wherein the electric field produces a peripheral curvature deflection of about 10 to 150 microns.

59. The system of claim 52 wherein the electric field produces a peripheral curvature deflection of about 30 to 75 microns.

60. The contact lens of claim 37 further comprising monomer voids and wherein the stimulus comprises electrolytes wherein the electrolytes are preferentially absorbed within the monomer voids.

61. The contact lens of claim 60 wherein the monomer voids are distributed with a greater density of voids in a peripheral portion of the lens and a lesser density of voids in a central portion of the lens.

62. The contact lens of claim 60 wherein the electrolyte is hypertonic saline.

63. The contact lens of claim 37 wherein the additive comprises ion exchange polymer metal composite poly sodium acrylate.

64. The contact lens of claim 37 wherein the additive is distributed in a gradient producing an aspherical curvature change.

65. The method of using the contact lens of claim 37 wherein a patient wears the contact lens in one eye to create monovision and to reduce the risk of inadvertent curvature transformation.

66. The contact lens of claim 37 wherein the stimulus produces about 10 to 100 microns of lens curvature.

67. The contact lens of claim 37 wherein the stimulus produces about 30 to 60 microns of lens curvature.

68. The contact lens of claim 37 wherein the stimulus produces anterior vaulting of the central optic and wherein the anterior vaulting moves the optic forward 5 to 150 microns.

69. The contact lens of claim 37 wherein the stimulus produces anterior vaulting of the central optic and wherein the anterior vaulting moves the optic forward 25 to 100 microns.

70. The contact lens of claim 37 wherein the stimulus produces anterior vaulting of the central optic and wherein the anterior vaulting moves the optic forward 50 to 250 microns.

71. The contact lens of claim 37 wherein the stimulus produces anterior vaulting of the central optic and wherein the anterior vaulting moves the optic forward 250 to 2000 microns.

72. The contact lens of claim 49 wherein the electric field is oriented asymmetrically relative to the surface of the contact lens.

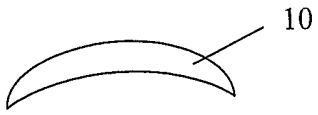

FIG. 1A

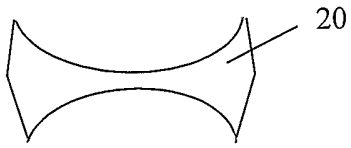

FIG. 1B

FIG. 2A

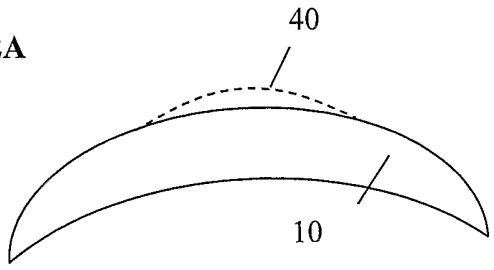

FIG. 2B

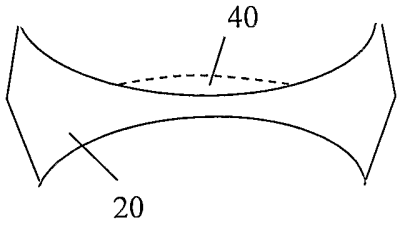

FIG. 2C

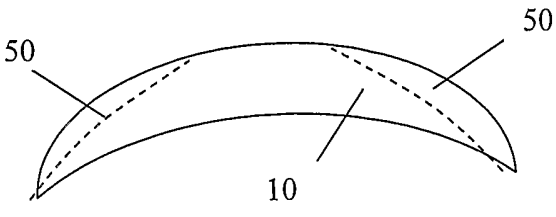

FIG. 2D

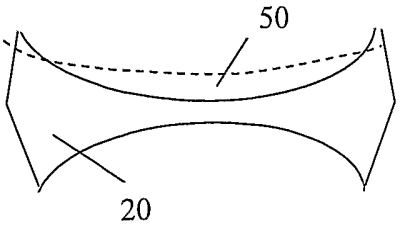

FIG. 2E

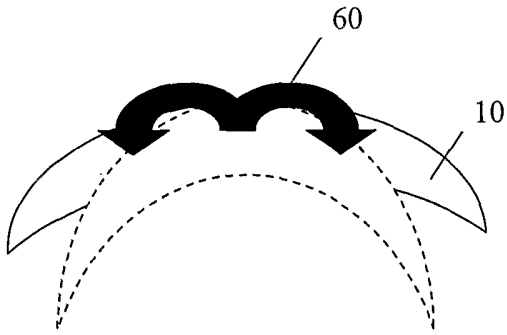

FIG. 2F