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

(19) **World Intellectual Property Organization**
International Bureau

(43) **International Publication Date**
**5 February 2009 (05.02.2009)**

**PCT**

(10) **International Publication Number**
**WO 2009/017403 A1**

(51) **International Patent Classification:**
*G02C 7/02* (2006.01) *A61F 2/16* (2006.01)
*G02C 7/04* (2006.01)

(21) **International Application Number:** PCT/NL2008/050508

(22) **International Filing Date:** 24 July 2008 (24.07.2008)

(25) **Filing Language:** English

(26) **Publication Language:** English

(30) **Priority Data:**
07113561.0 31 July 2007 (31.07.2007) EP

(71) **Applicant** *(for all designated States except US)*: **AKKOLENS INTERNATIONAL B.V.** [NL/NL]; Overaseweg 9, NL-4836 BA Breda (NL).

(72) **Inventors; and**
(75) **Inventors/Applicants** *(for US only)*: **SIMONOV, Aleksey, Nikolaevich** [RU/NL]; Arthur van Schendelplein 137, NL-2624 CV Delft (NL). **ROMBACH, Michiel, Christiaan** [NL/NL]; Overaseweg 9, NL-4836 BA Breda (NL).

(74) **Agent: EVELEENS MAARSE, Pieter**; Patentwerk B.V., P.O. Box 1514, NL-5200 BN 's-hertogenbosch (NL).

(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, 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, HR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL, NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

**Declaration under Rule 4.17:**
— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

**Published:**
— *with international search report*

(54) **Title:** AZIMUTHAL AND RADIAL PROGRESSIVE OPHTHALMIC OPTICS

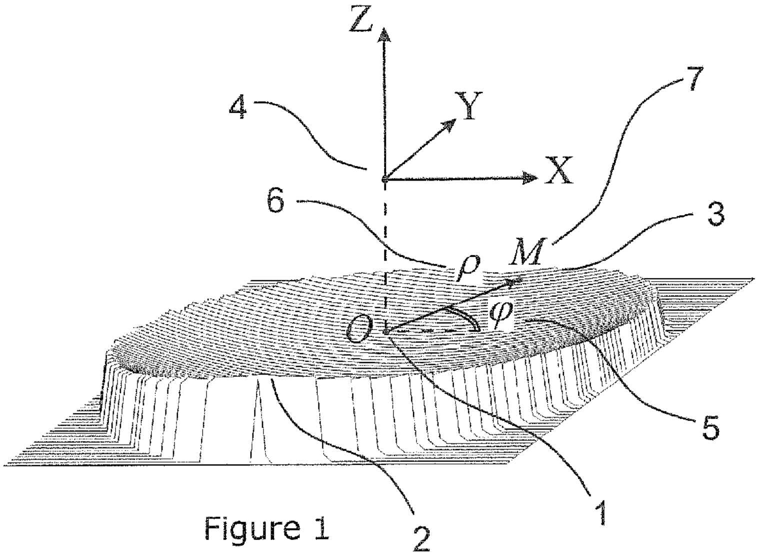

Figure 1

(57) **Abstract:** The invention relates to a multifocal ophthalmic lens comprising at least one azimuthal progressive optical surface, wherein the optical power of the lens varies in the radial direction and that said surface is smooth both in the azimuthal direction and in the radial direction. Consequently the ophthalmic lens has a progressive optical surface which extends along the azimuth of the ophthalmic lens, with or without additional distinct optical focal planes, and which, secondly, as a consequence of such azimuthal design, can offer single or multiple polarity,i.e. a sector of high optical power is positioned opposite a sector of low optical power. Such optical polarity offers advantages for use of such optics in the human eye. It is advantageous when such surface is combined with a basic refractive surface to correct for the fixed optical dioptric power.

WO 2009/017403 A1

# Azimuthal and radial progressive ophthalmic optics

This invention concerns novel optics for a progressive ophthalmic lens.
Such lenses can be included in (1) - spectacles (henceforth: “spectacles”), in which the lens is in front of the eye, in (2) - contact lenses, (henceforth: “CLs”), in which the lens is positioned on the outside of the cornea of the human eye and in (3) - intraocular lenses (henceforth: “IOLs”), which lenses are implanted inside the eye by an eye surgeon. Intraocular lenses can be either implanted to replace the natural lens after removal of the natural lens, e.g. during cataract surgery (defined as aphakic intraocular lenses, henceforth: “APIOLs”) or implanted to function in combination with the natural lens of the eye or in combination with an APIOL, (defined as phakic intraocular lenses, henceforth: “PIOLs”). The azimuthal progressive surfaces and additional optical surfaces described in this document can be applied to all the ophthalmic lenses and henceforth the term “ophthalmic lens” will be used as a general definition which covers all ophthalmic lenses mentioned above and, as an example of such lens, the application of the novel optical surfaces will be described in detail below for an APIOL. However, a men skilled in the art will conclude that the optical principles and surfaces can be applied to all ophthalmic lenses, to PIOLs, APIOLs and CLs in particular.

Applications in spectacles and contact lenses of the present inventions are included in this document in addition to applications in phakic and aphakic IOLs. However, the details of the inventions as well as explanations thereof will be described and illustrated with APIOLs as main examples. A men skilled in the art will conclude that the principles can also be applied to other ophthalmic lenses, certainly to CLs with minor modifications of such optics as described in this document and to spectacles for which the optics will need to be adapted mainly because of shifts of field of view of the eye over the surface of the lens which shift is largely absent in IOLs and which shift plays only a minor role in CLs. The present invention can be applied to the optical surfaces of all ophthalmic lenses, but major applications are foreseen for IOLs and Cls.

Two main types of IOLs are being implanted in the human eye:
Firstly, APIOLs are implanted in the eye after removal of the natural lens mostly due to a cataract which clouds vision of the eye. Recently IOLs are also implanted in a so-called Clear Lens Extraction (“CLE”) procedure, in which a non-cataracterous and

mostly presbyopic (“reading far-sighted”) clear lens of the eye is replaced with an IOL for spectacle-independency of presbyopic people. Cataract APIOLs are by the most important IOL type at present.
Secondly, PIOLs are implanted in the eye in addition to a clear natural lens, or, rarely, in combination with an APIOL which has replaced the natural lens of the eye. Such PIOL is generally positioned in the anterior chamber of the eye, i.e. between the cornea and iris, or in other parts of the eye. PIOLs generally used to correct significant refractive errors of the eye, mainly significant myopia.

In addition to the novel azimuthal surfaces corrections for various aberrations of the eye can be added. Most common is the addition of an additional toric surface to correct astigmatism of the eye or a spherical correction surface to correct for spherical aberrations.

Details of the inventions as well as explanations thereof will henceforth be described and illustrated with aphakic IOLs (“APIOL”) as main example.
Standard APIOLs are historically of a single focus type. An APIOL with one focal spot is implanted with the dioptric value of the APIOL chosen such that the eye has a fixed focus at a large distance or infinity, with the goal of the eye surgeon being creation of an emmetropic eye. After surgery the patient wears spectacles, generally progressive spectacles, to allow the patient to focus the eye at close distances, including reading distance.

Efforts have been made over approximately the last ten years to design APIOLs which allow the patient a spectacle-free life, i.e. provide a reasonably sharp vision over a wide range of distances. Multi-focal APIOLs (henceforth: “MFIOLs”) are the first generation of IOLs designed for this purpose, but also truly accommodating IOLs are being tested and in development.

MFIOLs offer to the retina of the human eye an image of the object composed of sharp images at several focal planes (e.g. WO2006060480, an example of a diffractive apodozing MFIOL), or, alternatively, a gradual mix of infinite focal planes over a certain focal range (e.g. WO2007047427, an example of a smooth aspheric IOL). The human brain apparently selects the sharpest image from this mix of images from different foci or, alternatively, composes a sharp image out of the gradual mix of infinite focal planes over the certain focal range. With MFIOLs a single optic, without moving parts can offer a, reasonably, sharp vision for several distances or over a range of distance. Note that none of the MFIOLs offers truly sharp imaging which results from a single focus IOL or truly accommodating IOLs – with MFIOLs a certain blur, scatter and other optical defects come with the package of the combination of a single, basically static and fixed, optics with multiple foci. The challenge of optical design of MFIOLs is to maximize optical dioptric range while minimizing the effects of undesirable aberrations. Multifocal CLs are less common, although bifocal CLs have been developed (e.g. PCT/NL9600428). The azimuthal optical surfaces and additional surfaces described herein are suitable to be applied for a multifocal CL.

Three types of MFIOLs can be defined: multizone diffractive (with or without additional apodizing functions, e.g. WO2006060480), multizone refractive (e.g. US2002135733, with annular rings of different dioptric optical power) and aspheric lenses (e.g. WO2007047427, with a gradual change of dioptric power).
Firstly, diffractive MFIOLs apply a diffractive surface on top of a refractive base. Generally these lenses divide the light between two distinct images through the use of diffractive orders with equal amonts of light directed to a near and a distant focus. Such design was introduced by the 3M company in 1988. The ReSTOR® MFOL currently produced by Alcon Surgical adds an apodizing function to such lens for further sharpening of the required image.

Secondly, multizone MFIOLs have multiple optical zones which are present across the pupil simultaneously with each of these zones having a different effective aperture (e.g. the Array Zoom lens from American Medical Optics, US202135733, US20022149743, US2003063254 and US2004156014). So, a pseudo-accommodation results because the pupil changes in diameter according to the ambient light levels and central areas of the IOL receive a relative emphasis at small pupil diameters, which generally occur at e.g. reading activities. Clearly, the degree of accommodation is not the effect of object distance but, in the case of these multifocal MFIOLs, a function of level of light.
Thirdly, aspheric optics provide an increase in depth of field of an IOL. The aphericity does not provide several distinct focal planes but extends the range focus. Such extension of focus inevitably results in a loss of contrast. Combinations of such aspheric

IOLs with added distinct regions of focus have been proposed as well. Refer, for detailed reviews of MFIOLs designs, for example to: Davison, J.A. and Simpson, M.J., 2006, J.Cataract Refract. Surg. 32, 849-858; Avitable, T, and Marano, F., 2001, Curr. Opin.Ophthalmol. 12, 12-16.

The prior art regarding MFIOLs covers, firstly, radial symmetrical annular optical constructions, i.e. the change of focus, being gradual or distinct progress from the optical centre outwards. Secondly, designs lack, in their basic designs, optical polarity, i.e. the focal power is distributed equally over one given azimuth, i.e. the same optical power applies at each point of a chosen concentric ring.

In this document a novel optical design for any ophthalmic lens is proposed which: firstly, has a progressive optical surface which extends along the azimuth of the ophthalmic lens, with or without additional distinct optical focal planes, and which, secondly, as a consequence of such azimuthal design, can offer single or multiple polarity, i.e. a sector of high optical power is positioned opposite a sector of low optical power. Such optical polarity offers advantages for use of such optics in the human eye, which advantages will be further explained below.

Hence the invention provides a multifocal ophthalmic lens comprising at least one azimuthal progressive optical surface, characterized in that the optical power of the lens varies in the radial and azimuthal directions and that said surface is smooth in both the azimuthal and radial direction. Note that it is advantageous but not required that such surface generally is combined with a basic refractive surface to correct for the fixed optical dioptric power to reach the goal of an emmetropic eye.

In a first embodiment the optical power of the optical surface varies according to a periodic function in the azimuthal direction. This puts the maximum optical value opposite the minimum optical value, defined in this document as “optical polarity”. The azimuthal surface can follow a linear function, i.e. the optical power changes linearly with the azimuthal direction. However, such surface can change optical power according to any sequence, e.g. linear, quadratic, logarithmic, exponential or according to any other smooth mathematical function, or staggered.

Even more preferably the periodic function has a single period .In this case there is question of optical polarity, i.e. the two sectors of highest and lowest optical power are opposite to each other, which is advantageous in ophthalmic applications.

Yet another embodiment provides the feature that the periodic function has an integer plurality of periods. Extension of the number of periods to the azimuthal direction creates multiple polarities, in a symmetrical position with even numbers of periods, asymmetrically with uneven numbers of periods. However, with ever larger integer number of periods polarity can be increasingly lost and the lens becomes, for all practical considerations, a rotational symmetrical design, or polarity can be included by increasing the diopter value of certain sectors, selected flat areas, which can be in groups or dispersed. For example, four optical zones resulting from two periods of which the zones can be positioned to cover the top and bottom viewing field as well as the nasal and temporal viewing fields. Again, preferably, the point of the lowest optical dioptric value of the first period should connect to point of the lowest optical dioptric value of the last period to maximize smoothness of the optical surface. Note that in this embodiment the central point in the optical axis is the point of origin, i.e. a central single point at which the refraction is undefined and such point is preferably smoothed out by a smoothing mask or smoothing function. The said single polarity can be used to advantage in the human eye because the human eye because objects at which humans look are generally slanted upward, i.e. with the closest object to be in focus at the bottom of the viewing field and the farthest object at the top of the image. For example: reading a book – the book is seldom held upside down, driving a car, with the dashboard at the underside and the horizon higher, upward slanted computer-screens, etc. So, in the case of IOLs, such a polar ophthalmic lens should be implanted in the human eye with the sector of maximum optical power at the bottom of the eye and the sector with the minimum optical power at the top. Equally, such lens can be applied as CL, of which some types can be weighted so that the CL stays in a rotational fixed position on the eye. Using the polarity of such lens also allows for an overall less steep progressive azimuthal surface, in turn, enhances overall sharpness, lens quality and contrast.

According to a preferred embodiment, the optical power of the lens progresses towards the centre of the lens. This feature connects to the application as a ophthalmic lens according to the general definition of the invention, wherein the centre of the lens, which is used in situations where the light levels are high and consequently the pupil is small, requires the highest optical power (myopic) for activities like reading.

According to yet another embodiment, the optical power of the lens varies according to a periodic function, leading to optimal freedom of design.

Calculation and production of the lens is simplified to a large extend when the optical surface is symmetrical.

Also, to any of these azimuthal paths at least one sector of constant dioptric power can be added to the surface. This will have the effect that a certain focal optical plane, or in the case of several such sectors, certain focal planes, are emphasized at the image plane. The rate of increase (the “step” to reach such plateau of constant dioptric power) can be according to any function. The number of such sectors of distinct focal planes and the extension thereof is dependent on the overall ophthalmic lens design, issues of light scattering, patient preferences and lens manufacturing constraints and lens material constraints.

In alternative embodiments, a radially extending progressive surface can be added to a design and preferably blended to the surface as set forth above with a smoothed mask. Such a progressive surface is, preferably, non-linear, and with, preferably, its sectors of highest optical power near the optical axis, the center of origin, of the lens with the optical power decreasing according to a non-linear function towards the rim of the lens. A man skilled in the arts will conclude that such an added surface will emphasize, on average, higher dioptric values of the total lens at small diameters of the pupil and lower average dioptric values at large pupil diameters. Such effects will aid functioning of the lens in the human eye (in the case of IOLs) and on the eye (in the case of CLs) because the eye has, on average, smaller pupils at close vision, e.g. reading and lager pupils at far vision.

Clearly, the progressive surfaces increase the total focal range, but also decrease contrast and sharpness of the image. Increasing progressive steepness increases focal range but decreases sharpness and contrast. Therefore, the steepness of such progressive surfaces should be minimized. Important human tasks such as e.g. reading occur at approximately 30cm distance from the eye and the iris diameter is minimized at this distance.

Therefore, addition of a small fixed power lens at the center of the lens is desirable. Firstly, the steepness of progressive surfaces can be minimized because such lens would cover the requirements for accommodation of the eye at close distances. Secondly, such lens can be positioned such that it covers the central point of the azimuthal progressive surface in which it can be blended with a smoothed mask. Note that such lens can be relatively small, e.g. only 1-1.5mm diameter on a total IOL lens diameter of, say, 6.5mm. The contribution of such lens to images at a large distance and large pupil diameters is likely negligible because an only ~1/15-1/30 of the total surface in the example above. Such a small lens is no necessity for the azimuthal ophthalmic lens to function, but can be additional to all embodiments described so far. Such small additional lens can also be applied to CLs.

Ophthalmic lenses as described in this document can be applied as ophthalmic lenses. i.e. as APIOLs to correct the optics of the eye after the natural lens is removed, e.g. for the treatment of cataracts or presbyopia, or as PIOLs to correct the optics of the eye in combination with the natural lens, or CLs, also generally in combination with the natural lens.

Such lenses also correct for the basic fixed refraction of the eye, i.e. must have a basic dioptric fixed value which functions as a natural lens at rest, with the eye in an emmetropic state. Such refractive surface can be added to all alternatives described above. Preferebly, the progressive surfaces and the small focusing lens should be included on the surface of the refractive lens. However, surfaces can also be applied to the front and back-side of an optical element, in any combinations.

Note that defocus is addressed as main optical aberration so far which, which defocus can be corrected for by the basic azimuthal surfaces or such azimuthal surfaces in combination with additional optical surfaces. Additional optical surfaces to correct for other aberrations such a spherical aberration and astigmatism can be added to the surfaces all optical lenses described above.

Lenses as described above can be produced from standard IOL materials and standard IOL manufacturing procedures. We refer here to surfaces of such lenses which are comparable in manufacturing complexity, e.g. PCT/NL9600428, US2006/0215109 and all of which lenses are being manufactured routinely from materials suitable for implantation in the human eye, e.g. hydrophilic acrylics. Also, smooth undulating surfaces for a novel accommodating IOL have been successfully manufactured by high precision lathing (EP1720489 and WO2006118452), surfaces which are of an equal complexity in comparison with the undulating azimuthal progressive surfaces described in this document.

Firstly, application of ophthalmic lenses as described above can be as intraocular lenses, IOLs including APIOLs and PIOLs. For APIOLs standard haptic designs can be added to the optics and the lens implanted in the capsular bag of the eye, however other positions for implant are an option with likely adaptations to the haptics. For PIOLs various haptic types are known to anchor such lens in the eye, generally in the anterior chamber, between cornea and iris, and designs which grab the iris tissue with small claws to position the lens in the anterior chamber.

Ophthalmic lenses as described in this document can also be applied as ophthalmic CL. The optical polarity, i.e. a sector of high dioptric value opposing a sector of low dioptric value of such lenses is also an advantage for contact lenses because contact lenses can be designed with an anchor to remain on the eye in a rotational fixed position. Relative small upward and downward shifts of the CL on the eye will further aid the multifocal process if the lens rotational position remains intact.

Ophthalmic lenses as described in this document can also be applied as spectacle lenses. Spectacle lenses differ from IOLs and CLs in that the eye can select a defined region from the lens. The design of the azimuthal surface has to adapted accordingly.

Any lens according to the descriptions above can be adapted so that any aberration can be corrected for, preferably within a sector of half a period. Also, a lens with, for example, two periods and thus with four optical zones, can be designed such that it will correct for defocus for the top and the bottom viewing fields in combination with defocus according to certain functions for the nasal and temporal viewing fields of which all four functions can be designed independently and which functions depend on the requirements of the individual eye for which the lens is designed. Such variation is caused by mainly. For details on viewing fields and illustrations of variability between several human eyes with regard to retinal eccentricity refer to: Navarro, R., Artal, P. and Williams, D.R., J. Opt. Soc Am.A/Vol.10(2), 1993, 201-212. Lenses with more than two periods can also be designed as such.

Apodizing functions have been included in ophthalmic lenses by diffractive designs, i.e. MFIOLs for optimization of contrast and sharpness of the image (e.g. the ReSTOR® MFIOL of the company Alcon Surgical; WO2006060480, EP0888564). Ophthalmic lens described in this document can have the option of being fitted with at least one apodizing structure or set of structures. Such structure can be fitted on any place of the optical surface, including but not restricted to following at least one azimuthal path. So, transmittance of the lens can be an additional function of the azimuthal angle.

Clearly, the ophthalmic lens must be implanted in the eye (IOLs) or remain on the eye (CLs) in a defined position to maximize the effects of said lenses with opposing sectors of highst and lowest dioptric values or said lenses with e.g. four zones. Such lens can be positioned with the highest dioptric value is positioned at the top or at the bottom of the human eye. Positioning at the bottom of the highest dioptric value seems to be most beneficial, but changing the polarity of the lens is an alternative.

Also, the azimuthal lens can be fitted in an intraocular lens construction which makes it an option for the lens to shift perpendicular, transverse, to the optical axis of eye, e.g. driven by the ciliary muscle of the eye so a multifocal design can have an additional accommodating\function. Contraction of the ciliary muscle moves an area of relaive high dioptre power towards the optical axis.

For a contact lens the lens can be fitted with a construction allowing a fixed vertical position of the lens on the cornea of the eye, generally an anchor or weight at the bottom of the lens. The lens is designed such that an upward shift of the lens on the cornea due to eye movement at close vision results in an increase in dioptre power.

Subsequently the present invention will be elucidated with the help of the accompanying drawings. Note that in all figures the steepness of change and amplitude of the progressive surface is exaggerated for illustration purposes - realistic optical surfaces of this type for ophthalmic applications have a considerably smaller amplitude and will lead to unclear illustrations.

In the drawings, the figures show:

Figure 1: a smooth azimuthal linearly progressive optical surface with one period;

Figure 2: a graph showing the curvature versus azimuthal angle of a smooth azimuthal linearly progressive optical surface with one period as shown in Figure 1;

Figure 3: a smooth azimuthal non-linear progressive optical surface with one period;

Figure 4: a graph, showing the curvature versus azimuthal angle of a smooth azimuthal linearly progressive optical surface with one period as shown in Figure 3;

Figure 5: a smooth azimuthal non-linear progressive optical surface with one period and two extended optical areas of distinct dioptric value;

Figure 6: a graph showing the curvature versus azimuthal angle of a smooth azimuthal non-linearly progressive optical surface with one period and two extended optical areas of distinct dioptric value as shown in Figure 5;

Figure 7: a smooth azimuthal non-linear progressive optical surface with one period and four extended optical areas of distinct dioptric value;

Figure 8: a graph showing the curvature versus azimuthal angle of a smooth azimuthal non-linearly progressive optical surface with one period and four extended optical areas of distinct dioptric value as shown in Figure 7;

Figure 9: a smooth azimuthal non-linear progressive optical surface with two periods;

Figure 10: a graph showing the curvature versus azimuthal angle of a smooth azimuthal non-linearly progressive optical surface with two periods as shown in Figure 9.

Figure 11: a smooth azimuthal non-linear progressive optical surface with eight periods;

Figure 12: a graph showing the curvature versus azimuthal angle of a smooth azimuthal non-linearly progressive optical surface with eight periods as shown in Figure 11;

Figure 13: a smooth azimuthal linear progressive optical surface with one period with the addition of a central small lens of a fixed optical dioptric power.

Figure 14: a graph showing the curvature versus azimuthal angle of a smooth azimuthal linearly progressive optical surface with one period as shown in Figure 13;

Figure 15: the axonometric projections of an embodiment of an azimuthally-progressive lens including an azimuthal surface with a small lens of a fixed dioptric power on one side of the optical element and a spherical lens of a fixed optical power on the other side of the optical element; and

Figure 16: the axonometric projections of an embodiment of an azimuthally progressive lens including an azimuthally progressive surface on top of a lens of a fixed optical dioptric power. The opposing side of the embodiment is concave and made to fit the human cornea as a CL.

Figure 1 shows a smooth azimuthal progressive optical surface covering the optical area in one period with the central point of origin, 1, and the sector of highest optical power, 2, and the sector of lowest optical power, 3. A reference system, 4, for clarification of azimuthal angles and direction as well as the X, Y, Z-coordinate system is superimposed on this figure which reference system originates from the point of origin, 1, and with which each point on the optical surface can be defined by the azimuthal angle, 5, and the transverse radius, 6. A particular point on the surface, 7, is the example in this figure. Note that in this figure and other figures the height of the progressive surface is exaggerated to show the surface structure. The refractive surface with the curvature (i. e. reciprocal radius ), and hence the optical power, is linearly distributed along the azimuthal direction ( ). The azimuthal angle changes from 0 to 2 rad. The curvature as a function of , i. e. increases linearly when the azimuthal angle changes from /2 rad to 3 /2 rad and decreases linearly when the azimuthal angle changes from 3 /2 rad to 0 rad. The curvature distribution is assumed to be a periodic function with a period of 2 rad, so that , where is an integer number, and N=1 in this example. Figure 2 illustrates a lens curvature, 8, as a function of the azimuthal angle, which surface is illustrated in Figure 1. In this example the lens curvature follows a linear function and covers one period. Various progressions, including a linear progression can be applied to such surface.

Figure 3 shows a smooth azimuthal progressive optical surface covering the optical area in one period with the central point of origin, 1, and the sector of highest optical power, 2, and the sector of lowest optical power, 3. The refractive surface with the curvature, and hence the optical power, is non-linearly distributed along the azimuthal direction. The curvature increases smoothly according to a non-linear function when the azimuthal angle changes from /2 rad to 3 /2 rad and decreases smoothly according to the same non-linear function when the azimuthal angle changes from 3 /2 rad to 0 rad. The curvature distribution is assumed to be a periodic function with a period of 2 rad, so that , where is an integer number, with N=1 in this example.
Figure 4 illustrates a lens curvature, 8, as a function of the azimuthal angle, which surface is illustrated in Figure 3. In this example the lens curvature follows a sinusoidal function and covers one period.

Figure 5 shows a smooth azimuthal progressive optical surface covering the optical area in one period with the central point of origin, 1, and the sector of highest optical power, 9, and the sector of lowest optical power, 10, with both sectors having added a larger optical area of a distinct dioptric value. The curvature, and hence the optical power, of the refractive surface is non-linearly distributed along the azimuthal direction with two distinct values of the optical power. The curvature changes stepwise when the azimuthal angle changes from 0 rad to 2 rad. The curvature distribution is assumed to be a periodic function with a period of 2 rad, so that , where is an integer number, with N=1 in this example.
Figure 6 illustrates a lens curvature, 8, as a function of the azimuthal angle, which surface is illustrated in Figure 5. In this example the lens curvature includes two areas with a distinct focusing power, 9, 10, which are represented as the flat areas in the otherwise non-linear progression.

Figure 7 shows an azimuthal progressive optical surface with the central point of origin, 1, a sector with a distinct high dioptric power, 11, a sector with a distinct low dioptric power, 12, and two sectors of distinct intermediate dioptric power, 13, with the respective sectors connected by a smooth surface extending linearly in an azimuthal

direction. Note that the two sectors of distinct intermediate dioptric power do not have to be exactly of a similar surface. The curvature , and hence the optical power, is distributed stepwise along the azimuthal direction and decreases stepwise to generate a discrete set of optical powers when the azimuthal angle changes from /2 rad to 3 /2 rad and increase stepwise when the azimuthal angle changes from 3 /2 rad to /2 rad. The curvature distribution is a periodic function with a period of 2 rad, so that , where is an integer number, with N=1 in this example.
Figure 8 illustrates a lens curvature, 8, as a function of the azimuthal angle, and the surfaces as illustrated in Figure 7.

Figure 9 shows a smooth azimuthal progressive optical surface covering the optical area in two periods with the central point of origin, 1, and two sectors of highest optical power, 2, and two sectors of lowest optical power, 3. Note that each of these four sectors can have shapes independently from each other and can have additional optical surfaces to, independently from the other sectors, correct for specific aberrations, in this example, defined quadrants (e.g. top, bottom, nasal and temporal, or any other system of quadrants) of the human retina. Clearly, a defined positioning of the lens in front of, on the cornea, or inside the human eye, is a prerequisite for such additional optical corrections. The curvature, and hence the optical power, is non-linearly distributed along the azimuthal direction. The curvature is a periodical function with a period of rad, so that , where is an integer number, with N=2 in this example.
Figure 10 illustrates a lens curvature, 8, as a function of the azimuthal angle, which surface is illustrated in Figure 9. In this example the lens curvature covers two periods in a sinusoidal progression.

Figure 11 shows a smooth azimuthal progressive optical surface covering the optical area in eight number of periods with the central point of origin, 1, and sectors of highest optical power, 2, and sectors of lowest optical power, 3. Such ophthalmic lenses with large number of periods become, in effect, radial symmetrical and, thus, loose larger defined sectors of higher and lower dioptric values which values are distributed over the optical lens surface more evenly. Such lenses might be of importance for applications, e.g. as types of contact lenses which will not remain in a fixed position on the cornea, i.e. contact lenses that rotate. The curvature, and hence the optical power, is non-linearly distributed along the azimuthal direction. The curvature distribution is a periodic function with a period of /4 rad, so that , where is an integer number, with N=8 in this example.

Figure 12 illustrates a lens curvature, 8, as a function of the azimuthal angle, which surface is illustrated in Figure 11.

Figure 13 shows a smooth azimuthal progressive optical surface covering the optical area in one period with the central point of origin, 1, and the sector of highest optical power, 2, and the sector of lowest optical power, 3, to which a small lens of fixed optical dioptric power, 14, is added centrally. The refractive surface has a constant-optical-power central part and the peripheral part with the curvature being linearly distributed along the azimuthal direction. The central lens has a smaller aperture and extends smoothly to the azimuthally progressive periphery. The curvature of the peripheral part as a function of , i. e. increases linearly when the azimuthal angle changes from /2 rad to 3 /2 rad and decreases linearly when the azimuthal angle changes from 3 /2 rad to 0 rad. The curvature distribution is a periodic function with a period of 2 rad, so , where is an integer number, with N=1 in this example.

Figure 14 illustrates the progressive azimuthal curvature, 8, as a function of the azimuthal angle, which surface is illustrated in Figure 13.

Figure 15 shows the axonometric views of an embodiment of an azimuthally-progressive lens that includes an anterior spherical surface, 16, providing a basic optical power and a posterior refractive surface, 17, that incorporates a constant-optical-power central small lens, 14, and the peripheral part with the azimuthal progressive curvature, 17, and hence the optical power, being, in this example, linearly distributed along the azimuthal direction. Note that the optical surfaces are distributed over two sides of the optical element, 15, in this example, and that other distributions and number of optical surfaces are feasible.

Figure 16 shows the axonometric views of an embodiment of an azimuthally progressive lens, 18, including, an azimuthal surface on top of a lens of fixed optical dioptre power, both on one side of the optical element, 17. The opposing side of the embodiment, 19, is concave and made to fit the human cornea as a CL.

## Claims

1. Multifocal ophthalmic lens comprising at least one azimuthal progressive optical surface, **characterized in that** the optical power of the lens varies in the radial direction and that said surface is smooth both in the azimuthal direction and in the radial direction.

2. Lens according to claim 1, **characterized in that** the optical power of the optical surface varies according to a periodic function in the azimuthal direction.

3. Lens according to claim 2, **characterized in that** the periodic function has a single period.

4. Lens according to claim 2, **characterized in that** the periodic function has an integer plurality of periods.

5. Lens according to any of the preceding claims, **characterized in that** the optical power of the lens in the radial direction progresses towards the centre of the lens.

6. Lens according to any of the claims 1-4, **characterized in that** the optical power of the lens in the radial direction varies according to a periodic function.

7. Lens according to any of the foregoing claims **characterized in that** the optical surface is symmetrical.

8. Ophthalmic lens according to foregoing claims **characterized in that** at least one sector of constant dioptric power is included along the azimuthal direction.

9. Ophthalmic lens according to foregoing claims **characterized in that** it has an additional radially extending progressive surface.

10. Ophthalmic lens according to claim 9 **characterized in that** the optical power of the radially extending progressive surface is non-linear in the radial direction.

11. Ophthalmic lens according to claim 10 **characterized in that** the highest optical power of the radially extending progressive surface is at the optical axis of the lens which optical power decreases towards the lens periphery.

12. Ophthalmic lens according to foregoing claims **characterized in that** it has a fixed power lens at the centre of origin of the azimuthal optical surface.

13. Ophthalmic lens according to foregoing claims **characterized in that** a refractive lens of a fixed optical power is added over total surface of area.

14. Ophthalmic lens according to foregoing claims **characterized in that** progressive optical surfaces and focusing lens form part of the surface of the refractive lens.

15. Ophthalmic lens according to foregoing claims **characterized in that** the optical surfaces are distributed in any combination on both sides of an optical element.

16. Ophthalmic lens according to foregoing claims **characterized in that** additional optical functions are added to any of the surfaces for correction of certain aberrations.

17. Ophthalmic lens according to claim 16 **characterized in that** additional optical functions are added to any of the surfaces for correction of spherical aberrations.

18. Ophthalmic lens according to claim 16 **characterized in that** additional optical functions are added to any of the surfaces for correction of astigmatic aberrations.

19. Ophthalmic lens according to foregoing claims **characterized in that** the lens is produced from materials suitable for implantation in the human eye.

20. Ophthalmic lens according to foregoing claims **characterized in that** the lens is produced by manufacturing methods suitable for producing human ophthalmic lenses.

21. Application of ophthalmic lenses according to foregoing claims **characterized in that** the lens is an intraocular lens.

22. Application of ophthalmic lenses according to foregoing claims **characterized in that** the lens replaces the natural lens of the eye.

23. Application of ophthalmic lenses according to foregoing claims **characterized in that** the lens is implanted in the eye in addition to the natural lens.

24. Application of ophthalmic lenses according to foregoing claims **characterized in that** the lens is a contact lens.

25. Application of ophthalmic lenses according to foregoing claims **characterized in that** the lens is a spectacle lens.

26. Ophthalmic lens according to foregoing claims with at least one periods **characterized in that** the lens corrects for any aberration for the opposing sectors of high and low dioptric power independently.

27. Ophthalmic lens according to foregoing claims with at least two periods **characterized in that** the lens corrects for any aberration for the quadrants.

28. Ophthalmic lens according to foregoing claims **characterized in that** it also includes at least one apodizing function.

29. Ophthalmic lens according to foregoing claims **characterized in that** at least one apodizing function follows at least one azimuthal path.

30. Method of implanting a lens in the human according to foregoing claims **characterized in that** the sector of the progressive surface with a defined dioptric value is positioned at a defined sector of the human eye.

31. Method of implanting a lens in the human according to claim 27 **characterized in that** the sector of the progressive surface with the highest dioptric value is positioned at the top of the human eye.

32. Method of implanting a lens in the human according to claim 27 characterized in that the sector of the progressive surface with the highest dioptric value is positioned at the bottom of the human eye.

33. Ophthalmic lens according to any of the foregoing claims **characterized in** that the lens is an intraocular lens fitted in a construction allowing a shift of the lens transverse to the optical axis.

34. Ophthalmic lens according to claim 33 **characterized in** that the lens is a contact lens which is fitted with a construction allowing a fixed vertical position of the lens on the cornea of the eye.

35. Ophthalmic lens according to claim 34 **characterized in** that an upward shift of the lens on the cornea results in an increase in dioptre power.

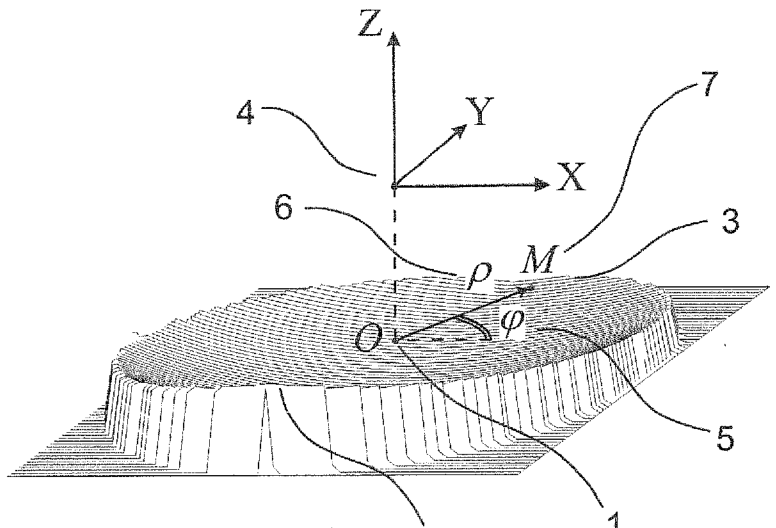

Figure 1

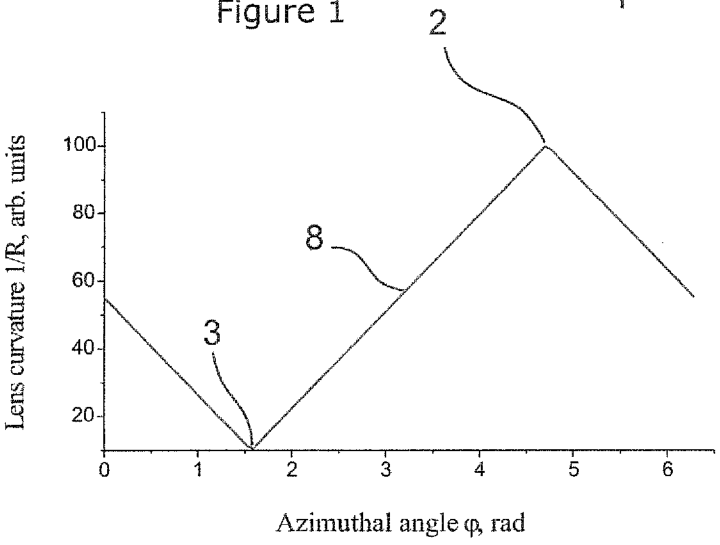

Figure 2

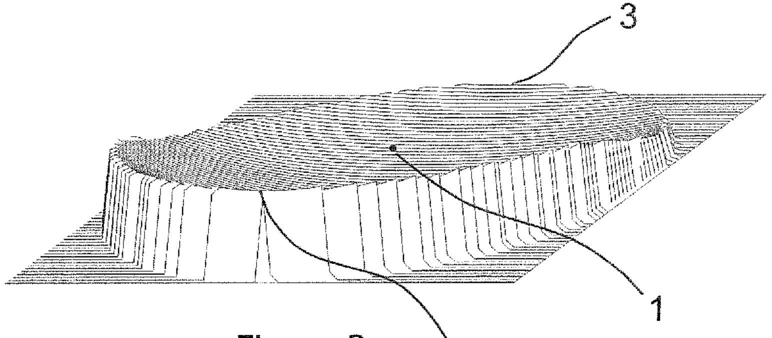

Figure 3

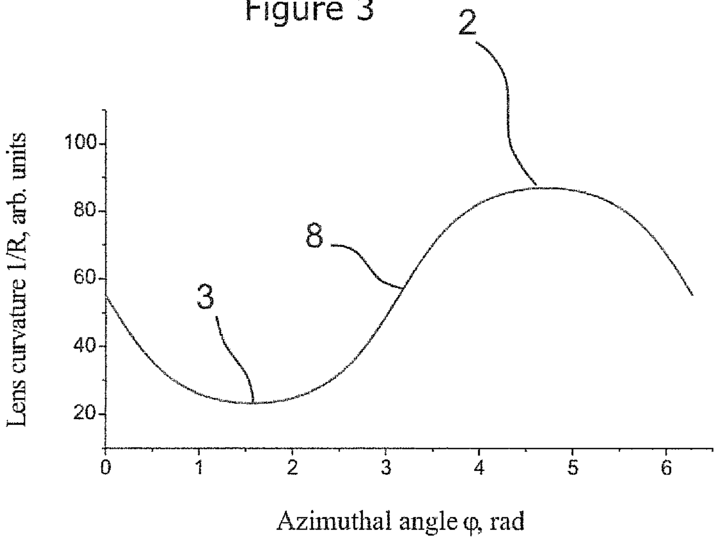

Figure 4

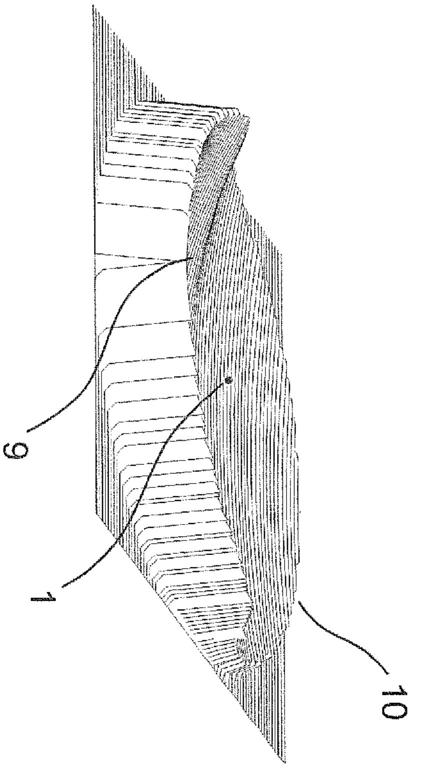

Figure 5

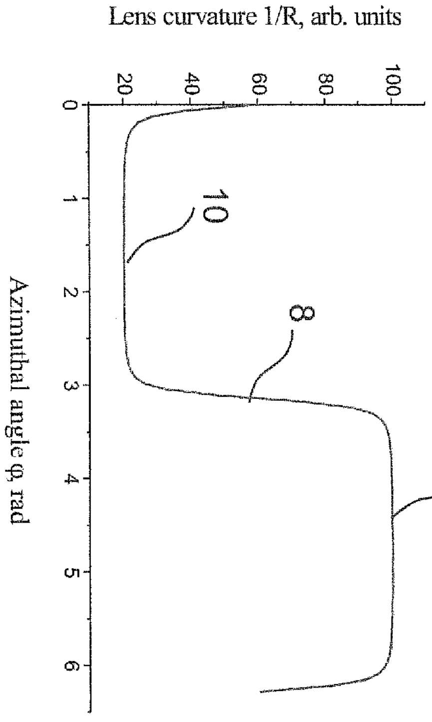

Figure 6

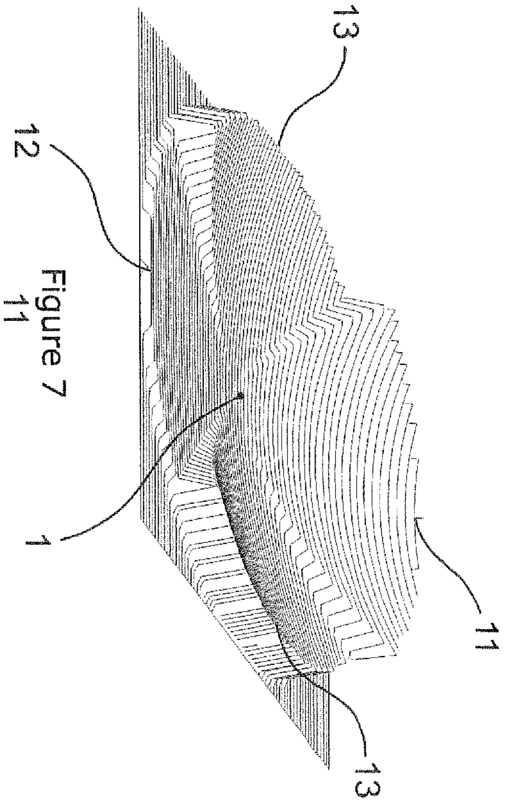

Figure 7

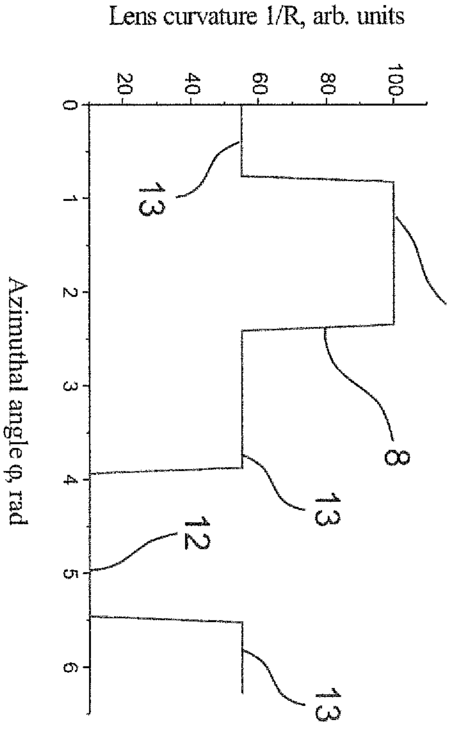

Figure 8

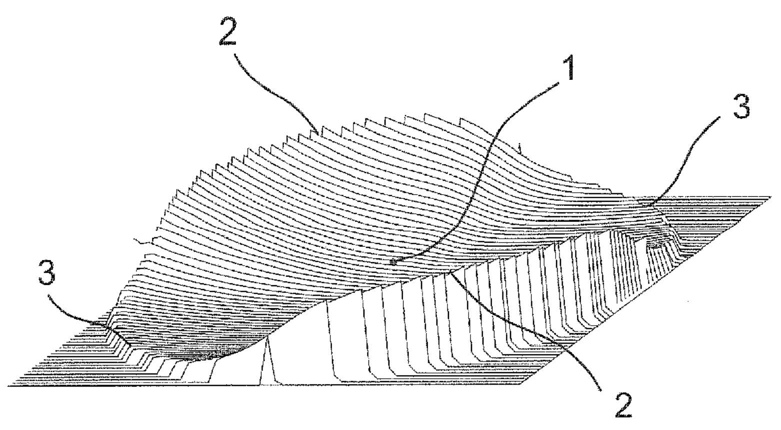

Figure 9

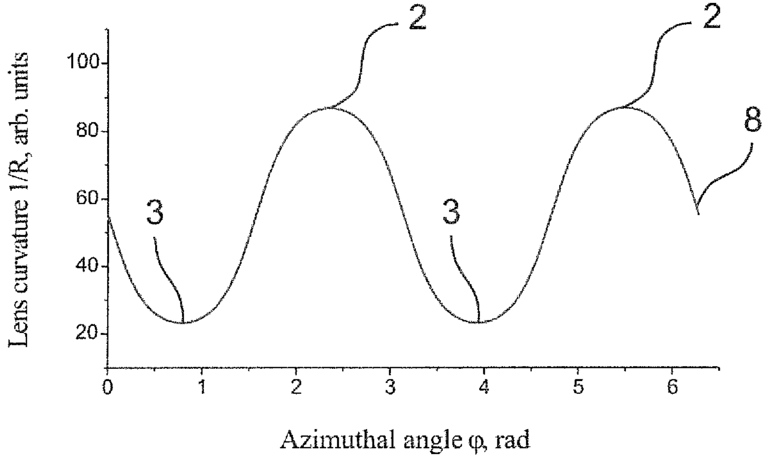

Figure 10

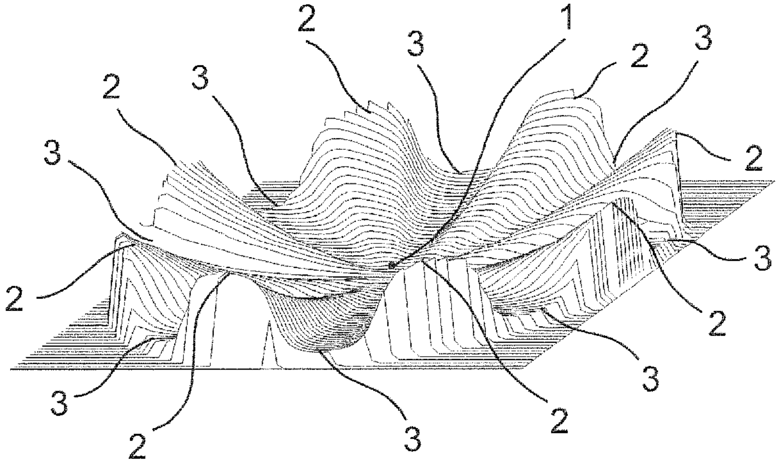

Figure 11

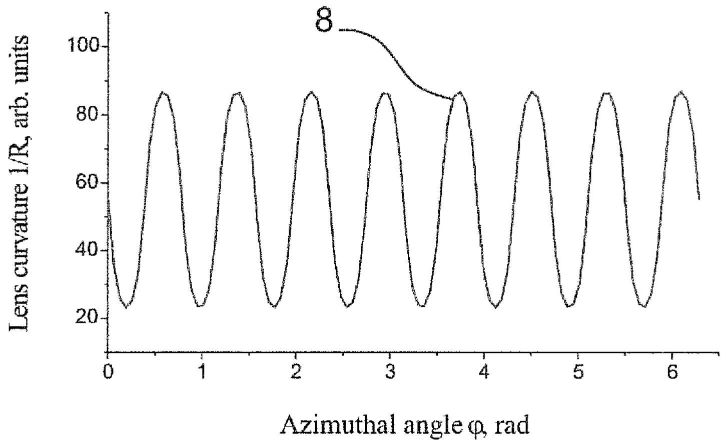

Figure 12

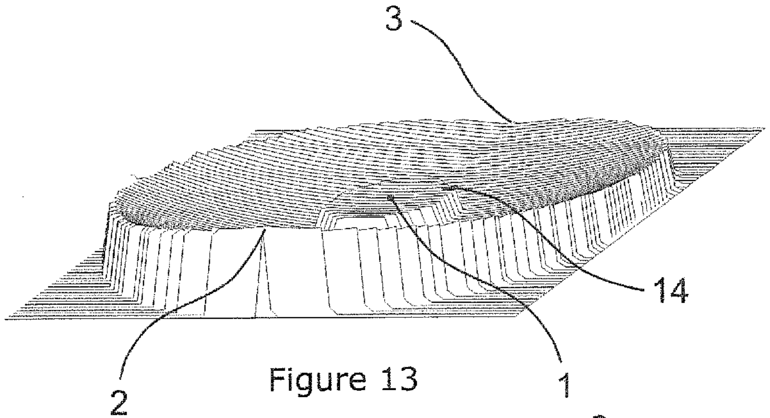

Figure 13

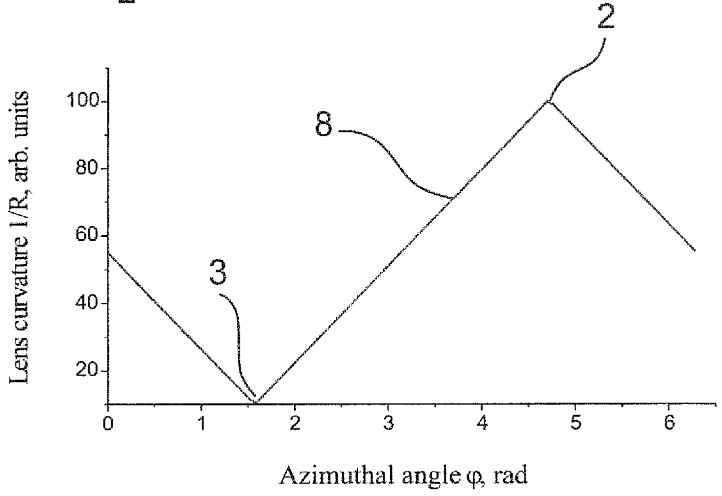

Figure 14

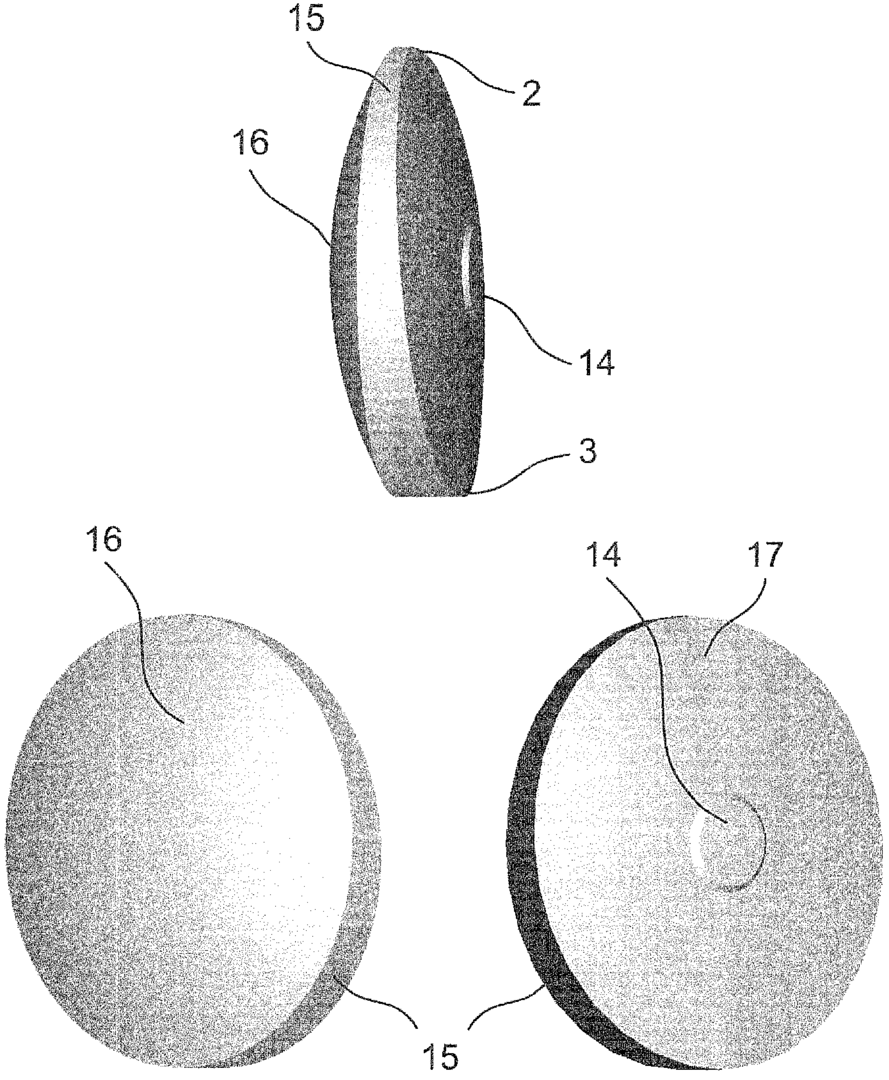

Figure 15

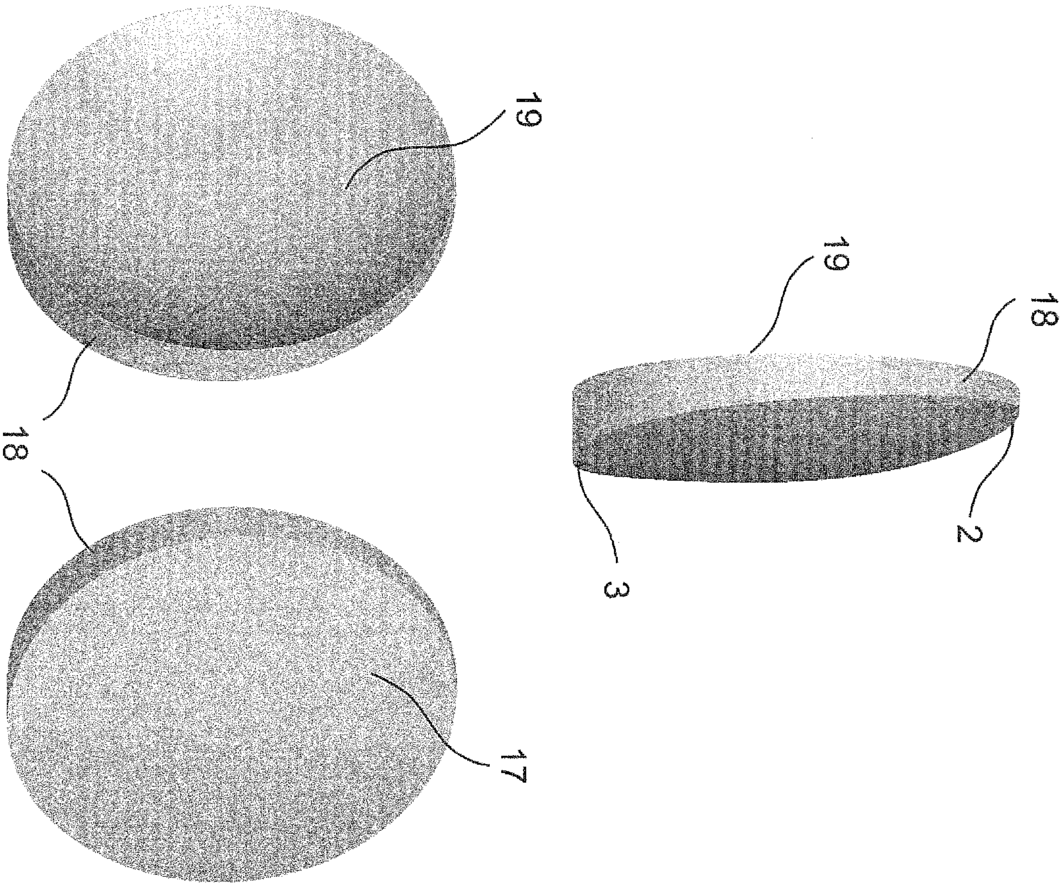

Figure 16

# INTERNATIONAL SEARCH REPORT

International application No

PCT/NL2008/050508

A. CLASSIFICATION OF SUBJECT MATTER

INV. G02C7/02 G02C7/04 A61F2/16

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G02C A61F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| X | WO 92/06400 A (VOLK DONALD A [US]) 16 April 1992 (1992-04-16) page 8, line 1 - page 27, line 3; figures 1-12 | 1-29, 33-35 |
| X | DE 102 41 208 A1 (TECHNOVISION GMBH GES FUER DIE [DE] HOHLA KRISTIAN [DE]) 25 March 2004 (2004-03-25) paragraph [0045] - paragraph [0075]; figures 1-7 | 1-29, 33-35 |
| X | WO 02/03126 A (CANTOR BRIAN DAVID [GB]) 10 January 2002 (2002-01-10) page 2, line 16 - page 4, line 11; figures 1-5 | 1-29, 33-35 |
| | -/-- | |

☒ *Further documents are listed in the continuation of Box C.*

☒ *See patent family annex.*

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

| | |
|---|---|
| Date of the actual completion of the international search<br>16 October 2008 | Date of mailing of the international search report<br>30/10/2008 |
| Name and mailing address of the ISA/<br>European Patent Office, P.B. 5818 Patentlaan 2<br>NL – 2280 HV Rijswijk<br>Tel. (+31-70) 340-2040,<br>Fax: (+31-70) 340-3016 | Authorized officer<br>Bratfisch, Knut |

## INTERNATIONAL SEARCH REPORT

International application No
PCT/NL2008/050508

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| A | US 3 751 138 A (HUMPHREY W)<br>7 August 1973 (1973-08-07)<br>column 1, line 57 - column 14, line 57;<br>figures 1a-11<br>----- | 1-29,<br>33-35 |

**FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210**

Continuation of Box II.1

Although claims are directed to a method of treatment of the human/animal body, the search has been carried out and based on the alleged effects of the compound/composition.

-----

Continuation of Box II.1

Claims Nos.: 30-32

Claims 30-32 are directed to a method of treatment of the human/animal body, which is excluded from patentability (Rule 67.1 (iv) PCT). Therefore, no search has been carried out for these claims.

The applicant's attention is drawn to the fact that claims relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure. If the application proceeds into the regional phase before the EPO, the applicant is reminded that a search may be carried out during examination before the EPO (see EPO Guideline C-VI, 8.2), should the problems which led to the Article 17(2)PCT declaration be overcome.

## INTERNATIONAL SEARCH REPORT

International application No.
PCT/NL2008/050508

**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☒ Claims Nos.: 30-32
because they relate to subject matter not required to be searched by this Authority, namely:
see FURTHER INFORMATION sheet PCT/ISA/210

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
see FURTHER INFORMATION sheet PCT/ISA/210

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

**Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)**

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers allsearchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search reportcovers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

**Remark on Protest**

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

# INTERNATIONAL SEARCH REPORT

International application No
PCT/NL2008/050508

| Patent document cited in search report | | Publication date | Patent family member(s) | | Publication date |
|---|---|---|---|---|---|
| WO 9206400 | A | 16-04-1992 | EP 0504393 | A1 | 23-09-1992 |
| | | | US 5173723 | A | 22-12-1992 |
| DE 10241208 | A1 | 25-03-2004 | AU 2003260387 | A1 | 29-03-2004 |
| | | | WO 2004023189 | A1 | 18-03-2004 |
| WO 0203126 | A | 10-01-2002 | AU 7428201 | A | 14-01-2002 |
| | | | EP 1295164 | A1 | 26-03-2003 |
| US 3751138 | A | 07-08-1973 | DE 2313223 | A1 | 04-10-1973 |
| | | | JP 890727 | C | 17-12-1977 |
| | | | JP 50047636 | A | 28-04-1975 |
| | | | JP 52015228 | B | 27-04-1977 |