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United States Patent [19]

L'Esperance, Jr.

[11] **Patent Number: 4,732,148**

[45] **Date of Patent: Mar. 22, 1988**

[54] **METHOD FOR PERFORMING OPHTHALMIC LASER SURGERY**

[75] Inventor: **Francis A. L'Esperance, Jr.**, Englewood, N.J.

[73] Assignee: **LRI L.P.**, New York, N.Y.

[21] Appl. No.: **891,285**

[22] Filed: **Jul. 31, 1986**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 778,801, Sep. 23, 1985, abandoned, said Ser. No. 778,801, is a continuation-in-part of Ser. No. 742,225, Jun. 6, 1985, abandoned, said Ser. No. 742,225, is a continuation-in-part of Ser. No. 552,983, Nov. 17, 1983.

[51] **Int. Cl.**[4] **A61N 5/06**

[52] **U.S. Cl.** ..... **128/303.1**; 128/395; 350/6.2; 350/6.5; 350/315; 219/121 LG; 219/121 LP; 219/121 LQ

[58] **Field of Search** ..... 128/303.1, 362, 395; 219/121 L, 121 CM, 121 LA, 121 LG, 121 LP, 121 LQ; 350/6.2, 6.5, 315

[56] **References Cited**

PUBLICATIONS

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"Excimer Laser Surgery of the Cornea", Stephen L. Trokel et al, Am. J. Ophthal., vol. 96, No. 6; 12/83; pp. 710–715.

Primary Examiner—Lee S. Cohen
Assistant Examiner—David Shay
Attorney, Agent, or Firm—Hopgood, Calimafde, Kalil, Blaustein & Judlowe

[57] **ABSTRACT**

The invention contemplates controlled ablation of the cornea, using ultraviolet laser radiation, wherein irradiated flux density and exposure time are so controlled as to achieve desired depth of the ablation. Sculpturing action results from controlled change of projected laser-spot size, in the course of a given treatment, wherein, in one illustrative case, projected laser-spot size ranges from a maximum which covers the entire area to be treated, down to a predetermined minimum tolerable size, wherein cornea-curvature change is myopia-corrective. Further illustrative techniques and situations are also disclosed, for achievement of hyperopia correction, for astigmatism correction, and in connection with corneal-transplant operations.

34 Claims, 33 Drawing Figures

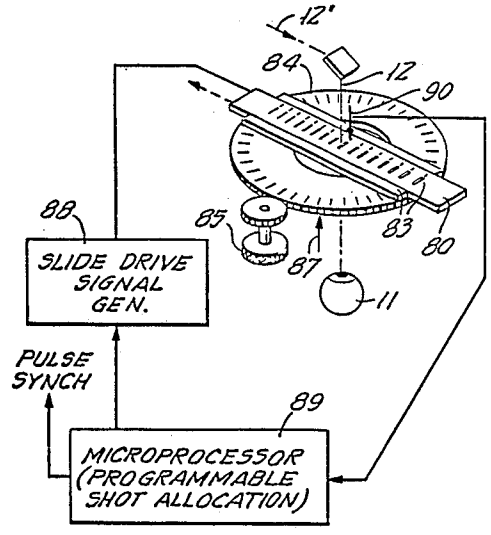


FIG. 1

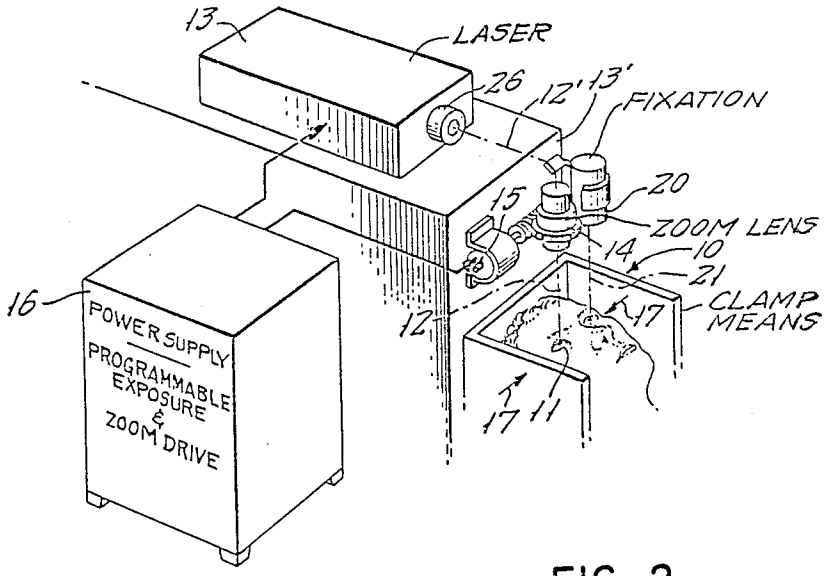


FIG. 2

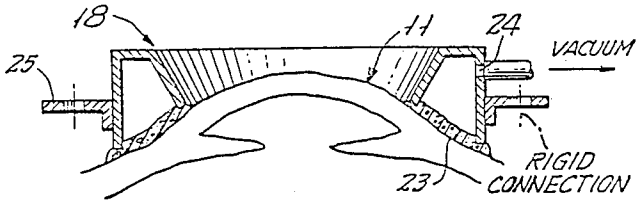


FIG. 3

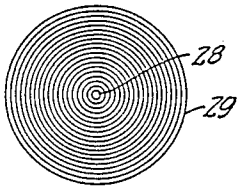


FIG. 4

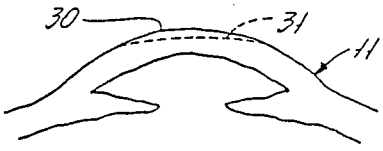


FIG. 5

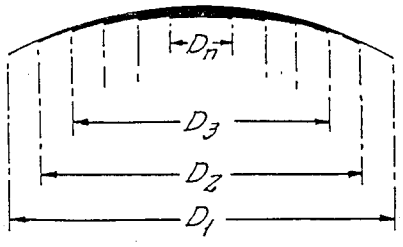


FIG. 6

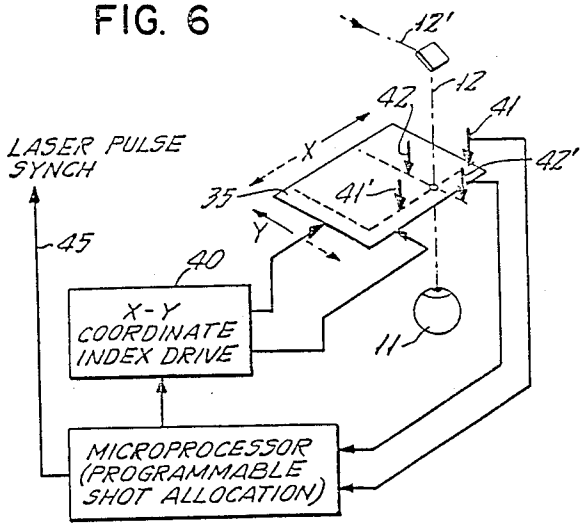


FIG. 7

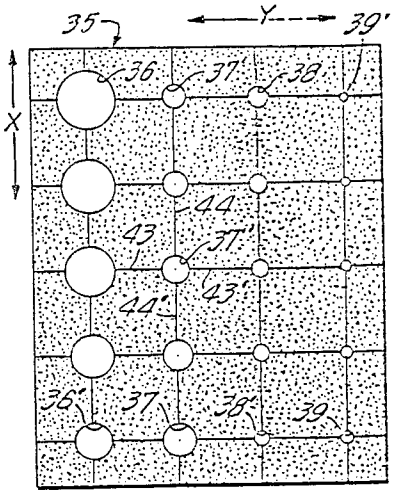


FIG. 8

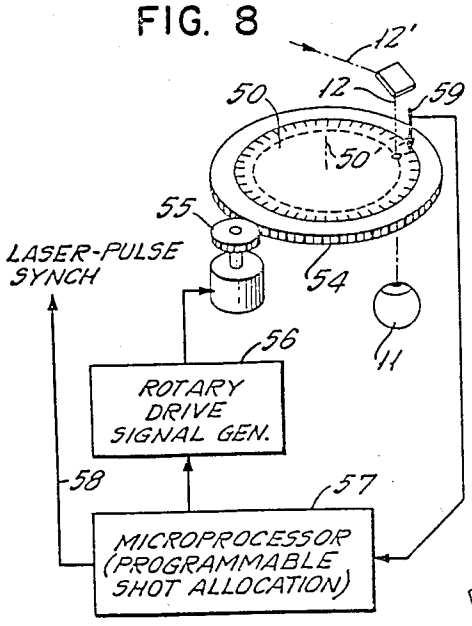


FIG. 9

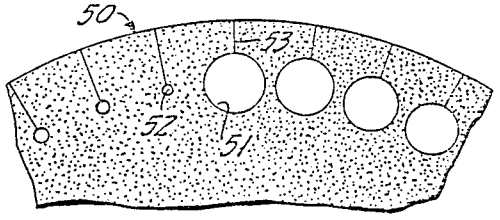


FIG. 10



FIG. 11

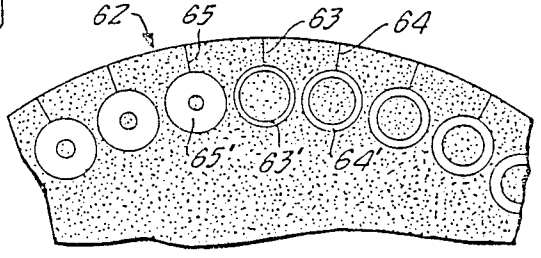


FIG. 14

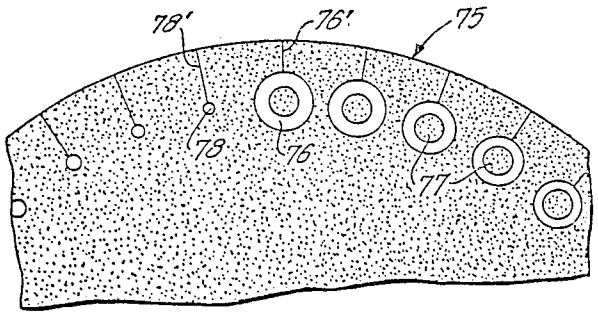


FIG. 12

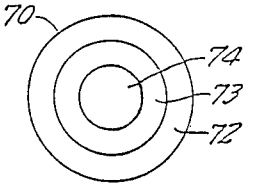


FIG. 13

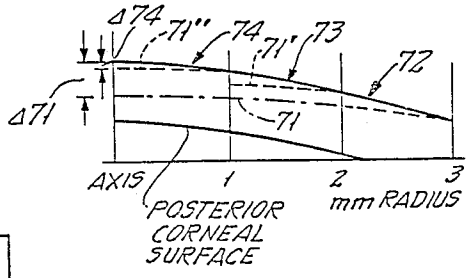


FIG. 15

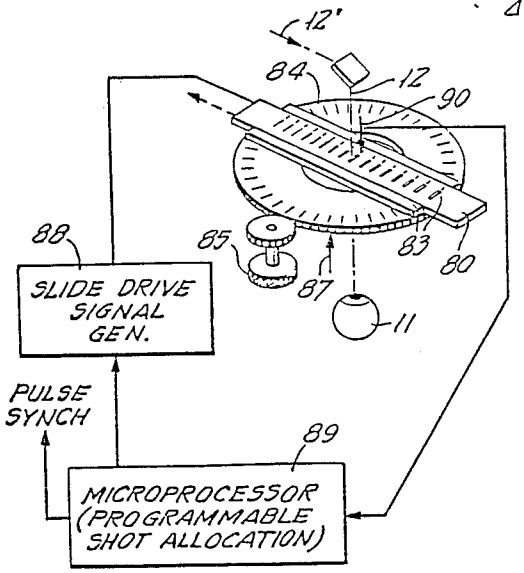


FIG. 17

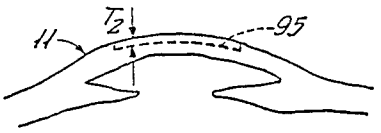


FIG. 18

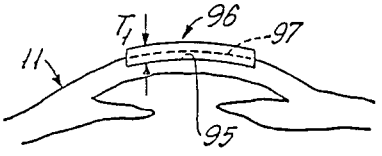


FIG. 16

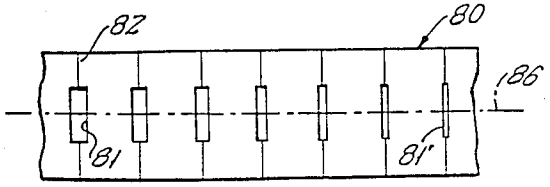


FIG. 19

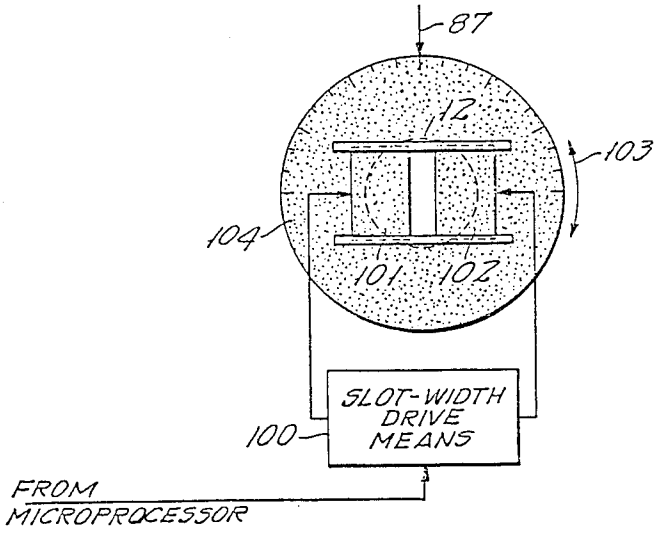

87
12
103
104
101
102
SLOT-WIDTH DRIVE MEANS
100
FROM MICROPROCESSOR

FIG. 20

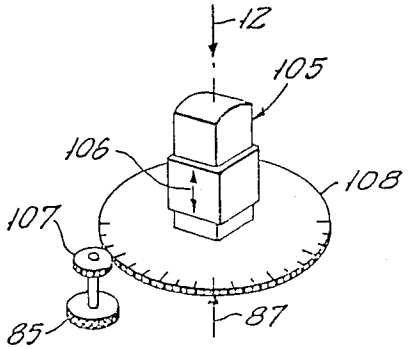

12
105
106
108
107
85
87

FIG. 21

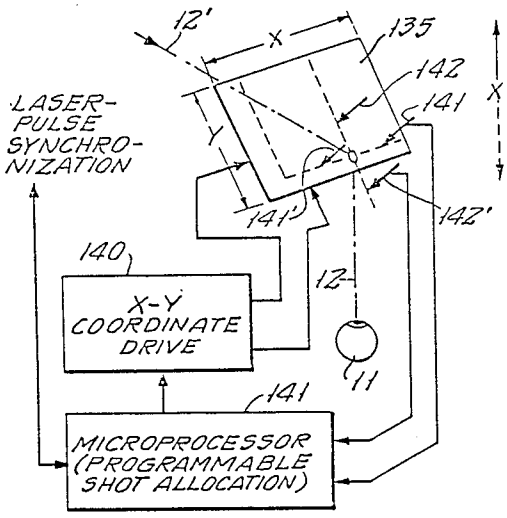


FIG. 22

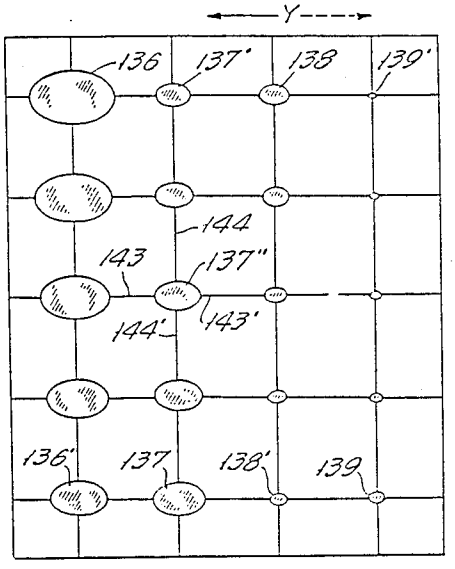


FIG. 24

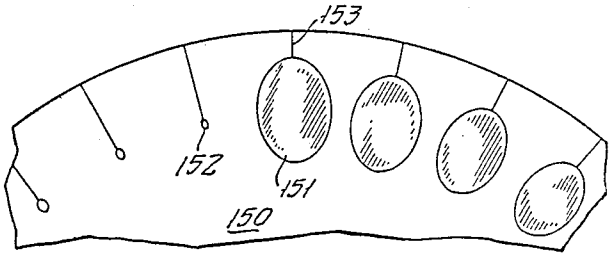


FIG. 25

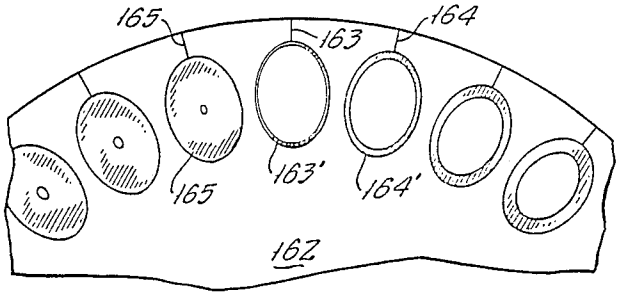


FIG. 23

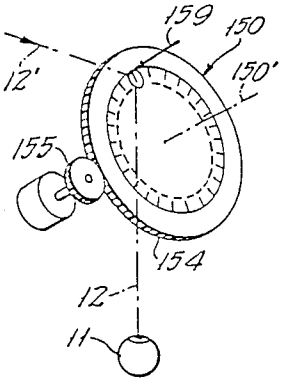


FIG. 26

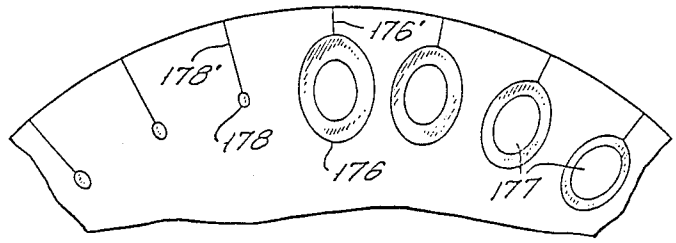


FIG. 27

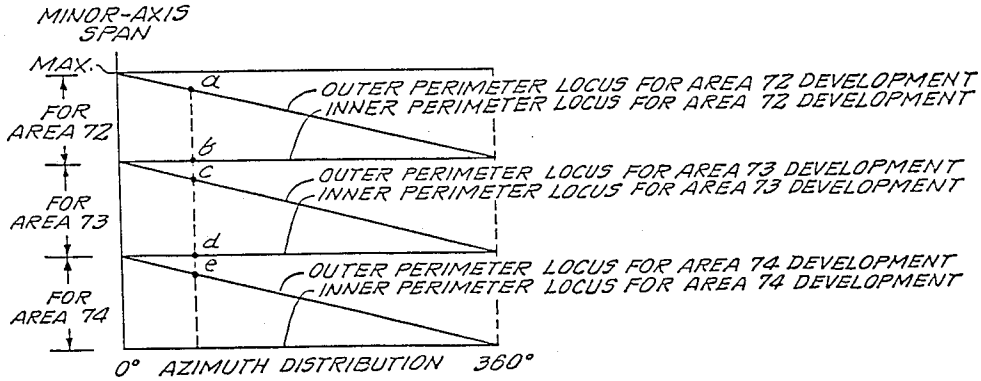


FIG. 28

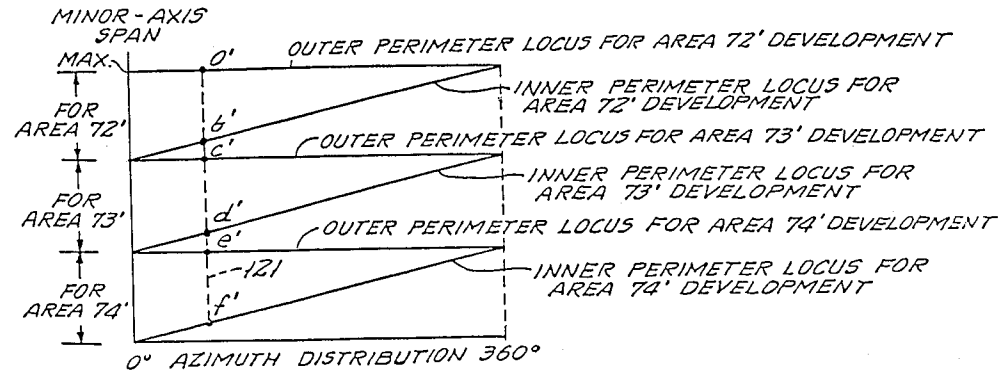


FIG. 29.

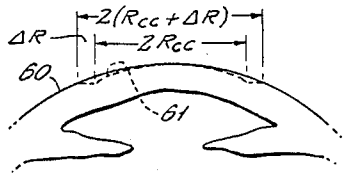


FIG. 30.

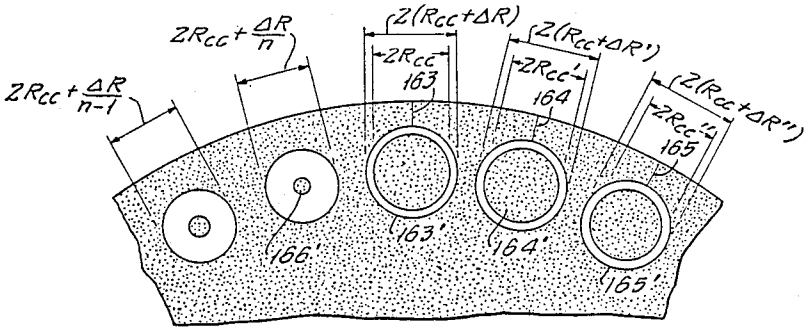


FIG. 31.

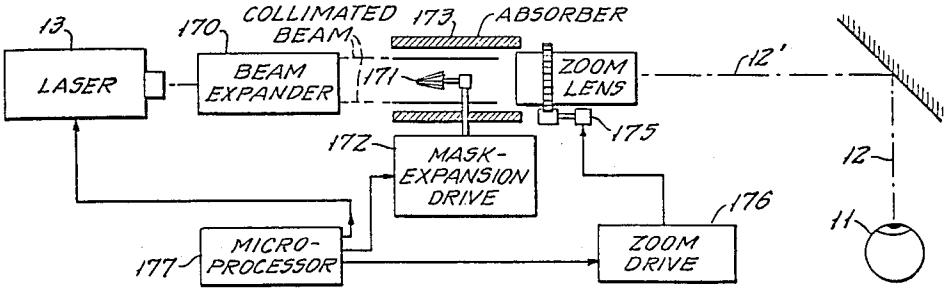


FIG. 32.

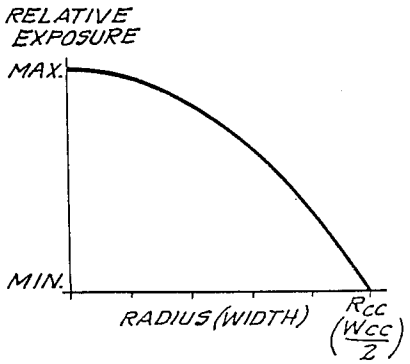
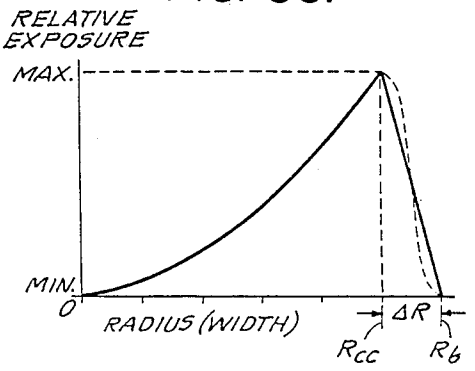


FIG. 33.



METHOD FOR PERFORMING OPHTHALMIC LASER SURGERY

RELATED CASE

This application is a continuation-in-part of copending application Ser. No. 778,801, filed Sept. 23, 1985, now abandoned, and said copending application is a continuation-in-part of application Ser. No. 742,225, filed June 6, 1985 (now abandoned); and said application Ser. No. 742,225 is a continuation-in-part of my original application Ser. No. 552,983, filed Nov. 17, 1983.

BACKGROUND OF THE INVENTION

The invention relates to that aspect of ophthalmological surgery which is concerned with operations upon the external surface of the cornea.

Operations of the character indicated include corneal transplants and keratotomies; such operations have traditionally required skilled manipulation of a cutting instrument. But, however keen the cutting edge, the mere entry of the edge into the surface of the cornea necessarily means a wedge-like lateral pressure against body cells displaced by the entry, on both sides of the entry. Such lateral pressue is damaging to several layers of cells on both sides of the entry, to the extent impairing the ability of the wound to heal, and resulting in the formation of scar tissue.

My original patent application Ser. No. 552,983, filed Nov. 17, 1983, includes a background discussion of the effects of various available wavelengths of laser radiation in ophthalmologic surgery and, in particular, surgery performed on the anterior surface of the cornea. It is explained that radiation at ultraviolet wavelengths is desirable by reason of its high photon energy. This energy is greatly effective on impact with tissue, in that molecules of tissue are decomposed on photon impact, resulting in tissue ablation by photodecomposition. Molecules at the irradiated surface are broken into smaller volatile fragments without heating the remaining substrate; the mechanism of the ablation is photochemical, i.e., the direct breaking of intra-molecular bonds. Photothermal and/or photocoagulation effects are neither characteristic nor observable in ablations at ultraviolet wavelengths, and cell damage adjacent the photodecomposed ablation is insignificant. The order of magnitude of this ablative process, in the case of radiation exposure at ultraviolet wavelengths (in the range of about 400 nm or less), is that an energy density of 1 joule/cm^2 incises to a depth of 1 micron (1μ). Said original patent application discloses a technique of scanning a laser beam over the anterior surface of a cornea in such a controlled pattern as to sculpture said surface, imparting a new curvature to said surface, whereby to achieve optical correction of an optically deficient eye. But the scanner and scanner control to perform the technique are relatively complex and expensive.

BRIEF STATEMENT OF THE INVENTION

It is an object of the invention to provide an improved apparatus and technique for surgically operating upon the outer surface of the cornea.

Another object of the invention is to simplify and reduce the cost of apparatus and technique for surgically modifying optical properties of the eye through surgical procedure on the outer surface of the cornea.

It is a specific object to achieve the above objects with surgical techniques and apparatus for reducing a myopic, for reducing a hyperopic, and/or for reducing an astigmatic condition of an eye.

Another specific object is to provide an improved surgical technique in performing corneal-transplant operations.

A still further specific object is to achieve the above objects with automatic means for safely applying ultraviolet irradiation in surgical procedures on the cornea.

It is also an object to achieve the above objects without use of scanning techniques or apparatus.

The invention achieves these objects with apparatus which effectively fixes the position of an eye with respect to a non-scanning laser characterized by ultraviolet radiation, at an energy level capable of achieving controlled ablative photodecomposition of the cornea, namely, of the epithelium, Bowman's membrane, and stroma levels of the cornea. Irradiated flux density and exposure time are so controlled as to achieve desired depth of the ablation. As distinguished from the scanning procedure described in said application Ser. No. 552,983, a sculpturing action results from controlled change of projected laser-spot size, in the course of a given treatment, wherein spot size ranges from a maximum which covers the entire area to be treated for curvature correction, down to a predetermined minimum tolerable size. In one embodiment, a zoom lens in the optical path of projection is the means of changing spot size, and in another embodiment an indexible mask or mirror is employed; in both cases, the weighted allocation of time as function of spot size is such as to achieve a desired ultimate optically corrected cornea, from prior ascertainment of an optically deficient corneal curvature. Spot-size control is not only disclosed for effecting spherical-curvature correction, but also for cylindrical correction in reduction of astigmatism; still further use is described in connection with a corneal-transplant procedure.

DETAILED DESCRIPTION

The invention will be illustratively described in detail, in conjunction with the accompanying drawings, in which:

FIG. **1** is a schematic diagram in perspective, to show the general arrangement of operative components of the invention;

FIG. **2** is a simplified view in longitudinal section, showing an eye-retaining fixture used with the apparatus of FIG. **1**;

FIGS. **3**, **4** and **5** are simplified diagrams to illustrate the nature of ablative corneal sculpture, performed with apparatus as in FIG. **1**, for the case of correcting a myopia condition;

FIG. **6** is a simplified diagram schematically showing operative components of another embodiment of the invention;

FIG. **7** is a plan view of an indexible mask usable in the embodiment of FIG. **6**;

FIG. **8** is a diagram similar to FIG. **6**, to show a modification;

FIG. **9** is a fragmentary plan view of an indexible mask usable in the modification of FIG. **8**;

FIGS. **10** and **11** are simplified diagrams to illustrate use of the invention, for the case of correcting a hyperopia condition;

FIGS. **12**, **13** and **14** are simplified diagrams to illustrate use of the invention to achieve a Fresnel-type

optically corrective contour at the anterior surface of the cornea;

FIGS. **15** and **16** respectively illustrate components and features of an embodiment of the invention to achieve correction of an astigmatic eye;

FIGS. **17** and **18** are simplified diagrams to illustrate use of the invention in connection with a corneal-transplant operation;

FIGS. **19** and **20** are simplified diagrams to illustrate two different alternatives for the embodiment of FIGS. **15** and **16**;

FIGS. **21** to **26** correspond to FIGS. **6**, **7**, **8**, **9**, **11** and **14**, respectively, in illustration of a further aspect of the invention;

FIGS. **27** and **28** are graphical diagrams to illustrate a principle of reflector design;

FIGS. **29** and **30** are diagrams similar to FIGS. **10** and **11**, respectively, to illustrate a special-purpose refinement of the invention;

FIG. **31** is a schematic diagram to illustrate an alternative for FIG. **30**; and

FIGS. **32** and **33** are similar diagrams illustrating different special-purpose refinements of the invention.

In FIG. **1**, clamp means **10** is shown for fixed retention of the head of a patient (reclined, face up) such that the eye **11** to be operated upon is fixedly aligned with a downwardly folded portion **12** of the central axis **12'** of beam output from a stationary laser device **13**, supported by a table or other base **13'**. The optical system of laser-beam projection to eye **11** includes zoom-lens means **14** having a reversible motor drive **15**, whereby laser-spot size at eye **11** can be caused to vary from a predetermined minimum, to a maximum of 3 or 3.5-mm radius, corresponding to the corneal frontal area to be subjected to laser action. A cabinet **16** is shown by legend to include a power supply for the laser, and cabinet **16** is also shown (by legend) to include programmable microprocessor means for controlling exposure and beam (spot) size on axis **12**, as will later become more clear.

Clamp means **10** preferably includes means, symbolized at **17**, to stabilize the patient's head via opposed engagements at the region of his temples, and an eye-retaining fixture (**18**, in FIG. **2**) peripherally engages eye **11** at the corneal-scleral area. Also Preferably, an optical-fixation device **20** is adjustably fixed, as to the table or base **13'**. Illustratively, device **20** includes a sighting reticle and lens, whereby the eye **11'** not being operated upon can view the reticle as if at infinity; the sighting alignment **21** for device **20** is parallel to the axis **12**, and it will be understood that adjustable means (not shown) may provide an adjustable offset, as needed for accommodation of the patient's inter-pupilary distance and to adapt to the particular mounted offset of device **20** from axis **12**. For an operation on the other eye **11'**, the eye **11** will be available for similar fixation, in conjunction with another fixation device (not shown) and associated adjustably offsetting means; alternatively, the fixation device **30** may be adjustably mounted at correct offset on the opposite side of scanner **14**. For purposes of operating on eye **11'**, clamp means **10** will have been indexed laterally with respect to laser **13** to the extent aligning axis **12** with the eye (**11'**) then to be operated upon, thereby positioning eye **11** for use of the fixation device.

The eye-retaining fixture **18** of FIG. **2** is seen to comprise a hollow annulus, having a convergent axial-end wall **23** of air-permeable material contoured to engage and retain the eye via a scleral-corneal region. A side-port connection **24** to a vacuum pump enables retention of eye engagement to wall **23**, and outward lug or flange means **25** enables rigid aligned and spaced connection of fixture **18** to laser **13** and its scanner **14** via means suggested by legend in FIG. **2**, such means being omitted from FIG. **1** for reasons of more simplified showing.

The laser selected for use at **13** preferably emits in the ultraviolet, namely, at wavelengths of less than substantially 400 nanometers. Such emissions for gas lasers are characteristically at 351-nm for xenon-fluoride lasers, 337-nm for nitrogen lasers, 308-nm for xenon-chloride lasers, 248-nm for krypton-fluoride lasers, 193-nm for argon-fluoride lasers, and 157-nm for fluorine lasers; and within this range, frequency-doubling techniques applied to other lasers, including crystal lasers, provide further alternative sources.

One of the existing commercial excimer-laser products of Lambda Physik GmbH, Göttingen, Germany, for example their Model EMG 103 operating with argon-fluoride, is satisfactory for use as laser **13**; for this product, maximum energy per pulse is 200 milli-joules, with a Pulse-repetition rate of 200 per second, 3×10^5 shots (pulses) being available from a single charge of the involved gas, before reducing to 50 percent of specified power at this repetition rate, it being noted that full rated power is not necessarily required in use of the present invention. Pulse width is about 15 nanoseconds, and typical beam dimensions are rectangular; as shown, however, the opening in a mask **26** reduces the laser beam to a circular section, and it will be understood that the optical elements of lens **14** are of quartz, calcium fluoride, magnesium fluoride, or otherwise as suitable for laser-beam accommodation.

FIG. **3** is an attempt to depict the action of laser output as modified by the setting of zoom lens **14**, it having already been indicated that, through the action of lens **14**, spot size at eye **11** can be caused to vary from a minimum diameter at **28** to a maximum diameter at **29**. The diagram shows a plurality of intermediate circular spot sizes, but it will be understood that since the zoom adjustment of lens **14** is continuously variable, there is no need to presuppose discrete circular spots of different diameter, except for the fact that in the course of a continuous variation in zoom adjustment the intermittent delivery of laser pulses will mean that each pulse is projected at a slightly different spot size.

FIGS. **4** and **5** are illustrative of use of the invention in an optically corrective ablation of the anterior surface **30** of eye **11**, wherein a myopia problem is to be solved, meaning that the curvature of surface **30** is of too-short radius to establish focus at the retina, for the case of distant objects. On the other hand, the dashed line **31** represents the ultimate curvature to which the anterior surface of the cornea should be modified to achieve a diopter-reducing corrective effect. To achieve the curve **31**, the minimum desired photodecomposition is at the outer boundary **29**, and the maximum is at the center. This is achievable by programming the microprocessor to progressively change the projected spot size (through driven adjustment of lens **14**) in the course of a predetermined succession of laser pulses. The result is the same whether spot size is caused to expand from minimum (**28**) to maximum (**29**) or to reduce from maximum (**29**) to minimum (**28**). Of course, for each laser pulse or "shot", ablative penetration into the cornea will be a function of delivered energy den-

sity, and therefore the number of pulses needed to achieve a given increment of ablative penetration will be greater, the larger the diameter of the projected spot.

FIG. 5 is a very much simplified diagram to represent the progressive ablative effect of a succession of laser-spot projections at successively reducing diameters D_1, D_2, $D_3 \ldots D_n$. The least resulting energy density is at the largest diameter D_1, which can be assumed to have made the least penetration, although such penetration will have been uniform over the entire spot area for diameter D_1. An incrementally greater energy density results at the next step D_2 of diameter reduction, in which event penetration has become cumulative with that of the first shot, over the area common to both shots. The cumulative penetration effect continues for shots of successively reduced diameter, so that a new, larger-radius curvature emerges from a pattern of stepped reduction in projected spot size. However, for a sufficiently great number of laser pulses (and hence, potentially discrete steps), individual steps cease to appear discrete, and a sufficiently smooth new spherical anterior surface characterizes the cornea. This is particularly so after a post-operative period of about two days, by which time a thin epithelial layer will have spread into smooth and protective coverage of the newly characterized surface.

The foregoing discussion in connection with FIGS. 1 to 5 presupposes a pulsed laser, exemplified by an excimer laser. But other lasers are known to emit at presently suitable energy levels and at ultraviolet wavelengths of present utility, and these other lasers will emit continuously for periods of controlled duration. For example, an organic-dye laser utilizing the proper organic dye can be made to produce laser emission in the region of 380-nm when pumped by ultraviolet laser sources such as a continuous-wave frequency-quadrupled neodymium-YAG laser operating at 266-nm; in this case, the organic-dye laser emission at 380-nm can be frequency-doubled by a proper non-linear crystal such as a potassium-deuterium-phosphate (KDP) crystal or a potassium-titanium-phosphate (KTP) crystal to an emission wavelength at 190-nm. The showing of FIGS. 1 to 5 will thus be understood to illustrate the further case wherein ultraviolet laser radiation on axis 12 is of continuous-wave nature, for a treatment duration predetermined by programming at 16, and wherein the programming at 16 further continuously drives the zoom-lens 14 to provide that time-variation of projected spot size as has been predetermined to achieve a myopia-correcting change in curvature, from curve 30 to curve 31, in the course of the treatment duration. And this result is achieved whether spot size (at the eye 11) is caused to expand continuously from minimum (28) to maximum (29) or to reduce continuously from maximum (29) to minimum (28).

In the embodiment of FIGS. 6 and 7, a masking technique is employed, in place of the zoom-lens technique of FIG. 1, to achieve a similar myopia-correcting curvature change in the anterior surface of the cornea. Such masking could proceed continuously with a suitably programmed variable iris diaphragm in place of lens 14, but in the form shown, a single precision masking plate 35 is employed. The masking plate 35 is rectangular and is mounted (by means not shown) for indexed unit displacement in each or both of two orthogonal axes X-Y. For each of the grid-like layouts of mask openings provided on plate 35, the size of the involved circular opening incrementally changes. Thus, for a first row of mask openings beginning and ending with openings 36 and 36', respectively, the openings are of progressively reducing diameter; in the next-adjacent row, beginning and ending with openings 37 and 37', respectively, the openings continue with progressively reducing diameter; in the third row, the progression continues to reduce from opening 38 to opening 38', and the final row reduces still further from 39 to the smallest opening 39'. An X-Y coordinate index drive 40 will be understood to provide correct X and/or Y successive displacements of masking plate 35 under control of microprocessor means 41 having programmable means for allocating numbers of excimer-laser "shots" (or, in the case of a CW laser, for allocating variously controlled pulse duration) at particular succeeding mask-opening sizes, whereby to effect a given desired ablative "sculpture" which will predictably and correctively change optical performance of the eye (11). As shown, optical-transducer elements in pairs 41—41' and 42—42' straddle each mask opening as it is indexed into the laser-projection axis 12; these transducer elements sense registry with grid lines, such as x-positioning grid lines 43–43' on opposite sides of a given mask opening 37" (FIG. 7) and orthogonally related y-positioning grid lines 44–44' on opposite sides of the same mask opening 37", whereby such registry may be certified to the microprocessor 41, for interlock purposes, to achieve correct mask-opening positioning on axis 12 before firing the next laser pulse, the latter being symbolized by a synchronizing connection 45.

In the arrangement of FIGS. 8 and 9, myopia-correcting sculpture relies on indexed shifting from one to another of successive different-area mask openings, via incremental angular indexing displacement of a masking disc 50 (about an indexing axis 50'); disc 50 has a peripherally distributed succession of mask openings, ranging from the largest opening 51 to the smallest opening 52. A radial mark, as at 53 for opening 51, identifies the angle at which the given opening is correctly indexed into position on the laser-projection axis 12. Disc 50 is shown mounted to an annular ring 54 which will be understood to be counterbored for central and keyed location of disc 50, and ring 54 is edge-driven by suitable means 55 under control of a rotary-drive signal generator 56. Again, a programmable microprocessor 57 is responsible for controlling the rotary-index drive 55–56 for predetermined allocation of laser pulses to given mask openings, to achieve the desired cornea-profile correction, with laser-pulse synchronization via lines 58, as an optical transducer 59 tracks registry with the particular radial-marker line for each given mask-opening area.

FIGS. 10 and 11 illustrate that the device of FIG. 8 is equally adaptable to making corrective sculpture of the cornea 60 of a far-sighted (hyperopic) eye, meaning that the anterior curvature is to be increased, as to achieve a new profile 61 (FIG. 10). This is illustratively done by substituting a different masking disc 62 for the disc 50 of FIG. 8. In the disc 62, for each of the angular mark locations (as at 63), a basic opening limit, e.g., of 3.5-mm radius, is the outer edge of each of an angularly distributed succession of annulus openings, produced by a central opaque masking spot of progressively changing diameter. Thus, for the smallest annular mask area 63' (which applies at radial mark 63), the central opaque spot is a circle of nearly the diameter of the basic limiting opening, to produce a first, or thinnest annulus 63'. At the next mark 64, the outer diameter of a slightly

thicker annulus 64' is determined by a central opaque spot of slightly lesser area. The progression continues, at increments of equal angle (about the index axis of disc 62), until reaching the largest annular opening 65' at angular location 65, where the central opaque masking circle is of least diameter. In use of the mask 62 in conjunction with the positioning and control apparatus of FIG. 8, the microprocessor 57 will be understood to so allocate laser pulses to particular sizes of annular mask openings that greatest cumulative ablative penetration of the cornea is at larger radii, while least penetration is at smaller radii, resulting in the corrected ultimate profile 61 of decreased radius.

The arrangement of FIGS. 12, 13 and 14 illustrates that above-discussed principles of the invention are further applicable to corrective sculpture of the cornea to achieve a Fresnel-type distribution of the desired ultimate curvature, which can be either hyperopia-correcting or, as shown, myopia-correcting. Such an operation (i.e., Fresnel-type) would be used when, in the surgeon's considered judgment, a single smoothly developed corrected curvature would entail excessive removal of tissue at the involved region of necessarily deepest cut. To avoid too deep a cut, FIGS. 12 and 13 illustrate that an ultimately reduced-curvature surface, as at 31 in FIG. 4 (dashed line 71 in FIG. 13), is achieved in annular increments within the field bounded at 70. In the outer one of these annuli (72), the curvature and depth of cut are precisely as would have applied to generate the continuous curve 71 (i.e., without Fresnel steps). But the intermediate annular area 73 effectively achieves a continuation of curve 71 with much less volume of corneal excision. Finally, the inner circular area 74 effectively completes curve 71, with minimal removal of corneal tissue.

The removal of tissue at the center is denoted Δ74 for the Fresnel cut 74 of FIGS. 12 and 13 and, comparatively, is but a small fraction of the maximum removal depth Δ71 which would have been needed to achieve the same optical correction with the smoothly developed corrected single-curvature surface 71. FIG. 14 illustrates an indexible rotary masking disc 75 of a type compatible with the system of FIG. 8, in substitution for the disc 50 of FIG. 8, to achieve Fresnel-type cuts of the nature described for different annuli 72, 73, 74. Beginning with the largest area of mask annulus 76 (at location 76') and proceeding for a first 120° sector of disc 75, the succession of annular mask openings will be understood to progress with decreasing radius, by reason of a constant-area central mask spot, in the context of a progressively shrinking outer-circle diameter. The programmable means 57 (of FIG. 8) will be understood to function as a control for allocation of laser-pulse shots, using a programmed distribution of the annular mask openings of this first sector, for achievement of the curvature 71 within outer annulus 72. A similar succession of annular mask openings will be understood to be similarly accessible via a second sector (not shown) of mask disc 75, in establishing the curvature 71' within the intermediate annulus 73. And finally, the curvature 71''is established within the inner circular area 74 by programmed projection of laser shots on axis 12, through an indexibly available succession of progressively shrinking circular openings, beginning with a mask-opening diameter of largest (circle-74) area, and reducing throughout the third sector to the smallest opening 78 at location 78', adjacent the location 76' (of the first sector).

The diagrams of FIGS. 15 and 16 are illustrative of the variable aperture or indexible-mask technique of the invention in the development of corrections for astigmatism, by ablative laser pulsing with a rectangular beam section wherein the width of the section is changed to create a cylindrical profile of cumulative ablative penetration. This can be done by masking the laser beam with a slit or diaphragm of variable width, and with the ability to selectively rotate the orientation at which the major dimension of the slit is positioned (i.e., based on prior measurement of the angle and of the cylindrical diopter strength of the particular eye's astigmatism; however, in the form shown in FIG. 15, the mask is an elongate strip 80 having a succession of rectangular slit openings of progressively different width. In the fragmentary showing of FIG. 16, these openings proceed from a largest area opening 81 to a smallest area opening 81', and the central axis of symmetry of each of these openings is identified with a mark, as at 82 for opening 81; preferably, all such marks are at equal spacing.

Strip 80 is a slide guided by means 83 forming part of a rotatable mask-supporting disc or ring 84; and guide means 83 locates the longitudinal axis 86 of slot symmetry on a diameter of ring 84. Manually operable means 85 has edge-drive coupling to ring 84 to enable selective angular orientation of strip 80 (about the laser-projection axis 12), as by observation via a fixed indicator mark 87 against azimuth edge markings on ring 84. A bidirectional slide-drive signal generator 88 is under control of a microprocessor 89 to coordinate slide (80) positioning with laser-pulse control, suitably synchronized by optical-transducer (90) tracking of the mark (82) applicable to the particular indexed mask opening, whereby each mask opening can be assuredly on the axis 12 of laser-beam projection.

In use of the invention for laser surgery upon an eye having need for both astigmatic and spherical correction, it is preferred that the astigmatic correction, described in connection with FIGS. 15 and 16, be the first of two procedures. This is considered advantageous because astigmatic errors are generally not as severe as spherical errors, so that fewer diopters of cylindrical curvature ablation will be involved than for the subsequent spherical-correction procedure. Furthermore, to have eliminated or substantially eliminated the astigmatism in a first procedure is to have constituted the anterior surface of the cornea to an essentially spherical surface, which (be it myopic or hyperopic in nature) is more assuredly correctively sculpted to the desired profile (also spherical) for emmetropia vision, particularly where, as in the case of this invention, all ablative-laser shots (whatever the currently operative mask opening) are effectively centered on the optical axis of the involved eye.

Quite aside from the variable-depth character of the removal of corneal tissue (FIGS. 4 and 10), the invention also lends itself to uniform-depth removals, over a single entire area of the cornea, in preparation for reception of a corneal transplant. In FIGS. 17 and 18, the cornea of an eye 11 is subjected to a succession of laser pulses which have been masked to the same area, of diameter D, e.g., 7-mm; the succession of pulsed laser shots will in such case be seen to produce a carved base or recessed-floor curvature 95 for reception and location of an implanted corneal transplant. Alternatively, in FIGS. 17 and 18, the cornea of eye 11 may be subjected to steady (CW) laser exposure of such intensity as

to ablate (a) via the same mask on constant diameter D and (b) at a rate of ablative penetration for which a given duration (exposure time) of laser-beam projection will achieve the desired depth of penetration.

Further with respect to a corneal-transplant procedure, the described apparatus will be seen to be further useful, as in preparation of the corneal insert to be implanted at and within the recess **95**. A donated eye may be reversibly held to a fixture as described at **18** in FIG. **2**; by "reversible" it is meant that, depending upon the manner of mounting flange **25**, either the epithelium or the endothelium of the donated eye may be mounted for upward exposure to the laser beam **12**, it being understood that for the latter situation with the donated eye, iris and other regions not needed for corneal-scleral mounting and for corneal operation will have been initially removed. A preferred procedure is first to so expose to laser action the concave inner side of the donated cornea; such action is to an extent (achieved by timed CW exposure, or by multiple pulsed-laser shots, of a full circular field exceeding the diameter of recess **95**) sufficient to remove tissue at least to a uniform depth within the donated stroma, whereupon the mounting of fixture **18** (and its partially machined corneal workpiece) is reversed, to expose to laser action the convex outer side of the donated cornea. Laser action on the outer side consists of two steps: first, timed CW exposure multiple laser pulses of the full circular field (exceeding the diameter of recess **95**) thereby excising at least the epithelium and to a depth which preferably achieves a transplant thickness T_1 exceeding the depth T_2 of recess **95**; second a scanner (not shown, but of the type disclosed in my said pending patent application, Ser. No. 552,983) is operated in a line-cutting mode wherein successive laser pulses sequentially advance along the circumference of a circle designed for precise acceptance in the circular recess **95**, until full severance of the circular cut-out, which then becomes the prepared transplant. Upon implanting, donated stroma is placed in full endothelium-free contact with the patient's prepared stroma, and the implant may be sutured. Later, upon removal of sutures, the outer surface of the eye **11** and its transplant **96** will have the appearance shown in FIG. **18**, wherein the transplant projects beyond adjacent areas of the patient's cornea, and this projecting surface of the transplant may be reduced by above-described laser sculpting to a finish contour **97** of preferably flush marginal conformance with non-sculptured adjacent tissue of the patient's eye. It will be further understood that, subject to the surgeon's decision, such a finishing cut may be to a curvature which does or does not effect a predetermined change in optical performance of the eye.

It will be seen that the described methods and apparatus achieve all stated objects and provide readily controlled procedure for correcting eye abnormalities attributable to cornea curvature. The ablative penetration of laser-beam action may be kept to a relatively harmless fraction of the thickness of the cornea, and whatever the depth of invasion, a natural body process provides protective epithelium coverage of the sculpted region, within a few days after an operation. The programmable coordination of laser-beam size and shape (circular, annular, or rectangular) in conjunction with numbers of pulses at given sizes and shapes will produce predictable and controlled changes in curvature, whereby cylindrical errors and/or spherical errors may be eliminated or substantially reduced, to the enhance comfort and convenience of the patient.

While the invention has been described in detail for various illustrative embodiments and modes, it will be understood that modifications may be made without departing from the spirit and scope of the invention. For example, what has been described above as manual means **85** to preset the angle at which astigmatic correction is to be achieved, may in fact be an automatically driven setting of the astigmatic-correction angle, wherein the angle-input data for making the automatic drive is produced by a diagnostic system or method as described in my copending patent application, Ser. No. 691,923, filed Jan. 16, 1985.

Also, by way of example, achievement of cylindrical sculpting in reduction of astigmatism does not necessarily require the indexible-slot technique of FIGS. **15** and **16**. As a first alternative (FIG. **19**), the variation in slot width may be achieved electromechanically, via microprocessor control of means **100** to differentially drive opposite side plates **101–102** of a variable-width opening which is always centered on the axis of the projected laser beam **12**, plates **101–102** being slidably mounted to an annular base **104** which is adjustable in rotation to the angle for which astigmatism is to be reduced (as suggested by a double arrow **103**). As a second alternative (FIG. **20**), a cylindrical-lens zoom system **105** is motor-driven by microprocessor output (as suggested by double arrow **106**) to establish a shaping of the projected laser beam **12** to a line of variable width, and said line is settable to the angle for which astigmatism is to be reduced, as by edge-drive means **107** to the rim **108** of an annular mount for zoom system **105**.

FIGS. **21** to **26** are illustrative of a different aspect of the invention wherein the variously described sequences of spot shaping to achieve laser-ablated corneal-curvature change are produced by reflection techniques. And because the identification of parts in these figures corresponds with parts in FIGS. **6**, **7**, **8**, **9**, **11** and **14**, the same numbers are used, as applicable, in a 100-series.

In the embodiment of FIGS. **21** and **22**, a transparent plate **135**, as of quartz, is characterized by a succession of elliptical reflection areas, oriented with their major axes parallel and respectively centered on each of the two-dimensionally (X-Y) indexible positions of plate **135**. For each of the grid-like layouts of elliptical reflecting areas on plate **135**, the size of the involved ellipse incrementally changes. Thus, for a first row of reflective ellipses beginning and ending with areas **136** and **136'**, respectively, the areas are progressively reducing; in the next-adjacent row, beginning and ending with areas **137** and **137'**, respectively, the reflecting ellipses continue their progressive reduction; in the third row, the progression continues to reduce from area **138** to area **138'**; and the final row reduces still further from **139** to the smallest, **139'**. Support for indexing displacement of plate **135** will be understood to position the reflective side thereof in inclined facing relation to the laser-output beam alignment **12'**, the inclination being preferably such that the major axis of each of the ellipses is at 45° to alignment **12'** when the center of the particular ellipse has been indexed for intersection with the alignment **12'**; at the same time, the minor axis of each ellipse is at 90° to alignment **12'** when the center of the particular ellipse has been indexed for intersection with alignment **12'**, and the major/minor axis-span relation is $\sqrt{2}$:1. This preferred relation deter-

mines that for each ellipse-index position, the reflection 12 of the laser beam will be at 90° to the alignment 12' and that this reflection will be a circle of diameter equal to the minor-axis span of the involved ellipse. The X-Y coordinate index drive 140 and the microprocessor 141 perform as described for FIGS. 6 and 7, and optically readable grid lines on plate 135 (between the reflective ellipses) enable optical-transducer pairs 141–141' and 142–142' to assure precise positioning of each reflecting ellipse, centered on axis 12', before firing the next laser pulse

The automated running of the FIG. 21 device, in the full two-coordinate program of indexing plate 135, will be seen to deliver the greatest density of ablating energy in the central part of the total circular corneal area which is operated upon, with such density decreasing as a function of increasing radius from the optical axis of the eye. The curvature change is therefore of myopia-correcting nature.

The embodiment of FIGS. 23 and 24 has its correspondence to FIGS. 8 and 9, and thus the circumferentially distributed pattern of reflecting ellipses is on an indexible circular plate or disc 150, plate 150 being suitably transparent and of quartz. Preferably, the centers of all ellipses are on one geometrical circle about the index axis 150', and the index axis 150' is oriented to bisect the right-angle relation between laser axis 12' and the (reflected) projection axis 12 to the eye, axis 12 being aligned with the optical axis of the eye 11; also preferably, the major axis of each of the ellipses is oriented radially of the indexing center of Plate 150, and, again, the major/minor axis relation of all ellipses is $\sqrt{2}$:1. The automated running of the rotary-indexed FIG. 23/24 arrangement will be seen to produce the same cornea-ablating result as the orthogonally indexed FIG. 21/22 arrangement, so that the result is again myopia-correcting.

The fragmentary showing of FIG. 25 illustrates that upon substitution of a different circular reflecting plate 162 (in place of plate 150 of FIG. 24), the microprocessor programming of rotary indexing and of laser pulsing will produce a hyperopia-correcting change in cornea curvature, of the nature shown in FIG. 10. The reflecting ellipses of FIG. 25 are in an angularly spaced succession of elliptical annuli of constant outer Periphery; the succession ranges from the radially thinnest ellipse 163' at index location 163, to the radially thickest ellipse 165' at index location 165. In other words, the succession of reflecting ellipses of FIG. 25 accounts for annular projection of a constant outer diameter and of a varying inner diameter, throughout a single indexed rotation of plate 162, accounting for maximum ablating penetration of the cornea at the outer diameter, and progressively reduced ablating penetration as a function of decreasing radius about the optical axis of eye 11. For all ellipses, the major/minor axis ratio is $\sqrt{2}$:1, in view of the 45° incidence of the laser beam on each indexed elliptical reflector.

The arrangement of FIG. 26, taken with FIGS. 12 and 13 is illustrative of the application of the reflection principles of FIGS. 24 and 25 to corrective sculpture of the cornea to achieve a Fresnel-type distribution of the desired ultimate curvature, which, as for FIG. 15, can be either hyperopia-correcting or, as shown, myopia-correcting. To avoid too deep a cut of ablative penetration, the ultimate reduced-curvature surface, as at 31 in FIG. 4 (dashed line 71 in FIG. 13), is achieved in annular increments within the circular area bounded at 70, and the curvature 71 is produced at steps 72-73-74.

As shown in FIG. 26, a transparent plate 175 serves as a replacement for plate 150 in FIG. 23 and is provided with an angularly stepped progression of reflecting elliptical annuli, beginning with the largest and thickest elliptical annulus 176 at location 176', and proceeding clockwise to the next elliptical annulus of incrementally smaller size and thickness, based on an inner limiting ellipse 177 of constant size. For the three-step profile 72-73-74 shown, the reflecting elliptical annuli based on the same inner limiting ellipse 177, are distributed over a first 120° sector of disc 175, with the outer elliptical periphery progressively shrinking to a final radially thin ellipse (not shown); and the programmable means 57 (of FIG. 8) will be understood to function as a control for allocation of laser-pulse shots, using a programmed distribution of the first-sector elliptical reflectors, for ablative achievement of the curvature 71 within outer annulus 72. A similar succession of reflecting elliptical annuli will be understood to be similarly indexible over a second 120° sector (not shown) of disc 175, in establishing the curvature 71' within the intermediate annulus 73. And finally, the curvature 71'' is established within the inner circular area 74 by programmed projection of laser shots on axis 12', through an indexibly available succession of progressively shrinking elliptical areas, beginning with an ellipse of largest minor-axis span (not shown, but equal to the diameter of the central circular area 74), and reducing throughout the third 120° sector to the smallest reflecting ellipse 178 at location 178', adjacent location 176' of the first sector.

A full rotation of disc 175, in the context of suitably programmed pulsed-laser delivery on alignment 12', thus creates the Fresnel steps 72-73-74 in succession. But it will be understood that by using the highly precise photo-reduction and metal-disposition techniques available from micro-circuit technology, each indexed step of a single disc (not shown) may be instrumental in the progressive formation of all annular components of a full Fresnel-type ablation pattern. To create reflecting elliptical patterns to achieve this result, FIG. 27 outlines the course of minor-axis size variation for all involved reflecting ellipses, for the case of myopia-correction, and FIG. 28 similarly outlines the course of minor-axis size variation for all involved reflecting ellipses, for the case of hyperopia correction.

In FIG. 27, it is seen that by dividing the full 360° angular extent of a given circular disc (utilizable in place of disc 150 in FIG. 23) into the desired number (n) of indexible steps at 360°/n spacing, and by drawing an ordinate line (e.g., at 120) for each such increment of azimuthal distribution, intercepts (e.g., a-b-c-d-e, for location 120) are obtained for each of five loci, establishing the requisite minor-axis span for each of the involved plural reflecting ellipses at each particular index location. The result for FIG. 27 relationships is myopia-reducing because all outer perimeters (for areas 72-73-74) vary, while inner perimeters remain constant. On the other hand, the result for FIG. 28 relationships is hyperopia-reducing because all inner perimeters (for areas 72'-73'-74', not otherwise shown) vary, while outer perimeters remain constant, noting intercepts a'-b'-c'-d'-e'-f' for location 121.

All discussion thus far, for laser projection via indexed reflective areas, has been concerned with essentially spherical curvature correction, treating the myopic or the hyperopic situation, as the case may be. It

should, however, also be apparent that similar principles are applicable to astigmatism correction, in which case the pattern of progressively indexed reflecting areas is rectangular, of progressively varying width, symmetrically developed on opposite sides of the central elongate axis of the most narrow rectangular pattern in the progression. The drawing of FIG. **16** may thus be considered illustrative of such a pattern development, wherein the indexible strip **80** is a transparent plate (as of quartz) and the series of rectangles **81** to **81'** is reflecting and at equal centerline-to-centerline spacing, with indexing from one centerline (**82**) to the next, and with the laser-beam axis **12'** directed at intersection with the central alignment **86** for each indexed position. It is realized that when strip **80** is supported on guide ring **84** and in an inclined plane as discussed for disc **150** in FIG. **23**, the angular orientation of ring **84** (by setting adjustment at **85**) will account for a range of width variation in rectangular spots incident at the eye, but the desired cumulative ablation can still be achieved at the eye for any and all selected angular orientations, by entering a suitable angularity correction into the microprocessor, the correction being a simple trigonometric function of orientation angle.

For the above-described reflective uses of the invention, it is to be understood that the individual patterns of reflection are operative upon a portion only of the laser-beam sectional area (on alignment **12'**), and that, whether the reflective patterns are mounted to or formed upon a transparent plate (as of quartz) or are otherwise mounted, the portion of any given shot of laser-beam output that is not reflected will be further transmitted on essentially the alignment **12'**. This further transmitted energy is not used for the surgery and may be trapped and dissipated by suitable means (not shown).

For the various embodiments thus far described in application to hyperopia-correction, FIG. **10** is illustrative of the fact that penetration into the cornea is deepest at the radially outer limit of the optically corrected area (surface **61**), thus leaving a relatively sharp circular edge, of depth proportional to the magnitude of diopter correction achieved. Such a sharp edge presents a problem for epithelial regrowth over the area (**61**) of surgery, in that epithelial regrowth is optimum for essentially continuous surfaces, i.e., when uninterrupted by sharp edges or by sharp discontinuities. To avoid such a sharp-edge development, the projected laser beam **12** should be of sectional area larger than that over which hyperopia-curvature correction is to be achieved, thus providing for an outer profile-smoothing annulus contiguous to and surrounding the circle of curvature-correction. In FIG. **29**, the optically corrected surface **61** is identified as having an outer radius of curvature correction R_{cc}, the diameter being shown as $2R_{cc}$; and the outer profile-smoothing annulus is shown to be of radial thickness ΔR, so that the full area of the laser-beam section is of diameter $2(R_{cc}+\Delta R)$. The smoothing action to be described accounts for the gently sloping transitional profile achieved in the annulus ΔR, as suggested in FIG. **29** by dashed lines connecting the curvature-correcting ablated area **61** to the outer corneal area not subjected to ablation.

More particularly, FIG. **30** shows an indexible rotary masking disc **162'** of the nature described in connection with FIG. **11** but incorporating the profile-smoothing feature of FIG. **29**. Dimensional legends in FIG. **30** show that, at a first index position **163**, the masking is such that the projected laser spot is a thin annulus wherein the inner diameter is determined by the outer diameter of the central masking circle **163'**; this outer masking diameter is labeled $2R_{cc}$, meaning twice the radius of the corrected-curvature surface **61** (FIG. **29**), and in successively indexed positions **164–165**, the central masking circle (**164'–165'**) exhibits progressively shrinking diameter, respectively identified $2R_{cc'}$ $2R_{cc''}$. Also, for these successively indexed positions (**164–165**), the outer diameter of the projected annular beam **12** exhibits progressive shrinkage, in a first decrement to the diameter $2(R_{cc}+\Delta R')$, and in the next decrement to the diameter $2(R_{cc}+\Delta R'')$. These progressive shrinkages continue in successive decrements, with each indexing displacement of disc **162**, culminating at a final index position **166**, with the smallest central masking circle **166'**, and with the most-reduced outer diameter ($2R_{cc}+(\Delta R,/n)$, where n is the number of index positions) equal or substantially equal to the outer diameter ($2R_{cc}$) of the area **61** of hyperopia-corrected curvature.

With a sufficient number n of index positions for disc **162**, the cumulative penetration of the cornea develops a smooth profile of the optically corrected surface **61**, as well as a smooth profile of the outer transitional annulus.

FIG. **31** provides a schematic description of another means whereby the described smoothing annulus ΔR may be achieved, without reliance on successively indexed masks. The beam projected from laser **13** is expanded by means **170** so as to project a collimated beam of enlarged section. Fixedly and centrally mounted within the enlarged beam section is a mask device **171** which can be controlled by drive means **172** to exhibit a range of varying outer diameters, illustratively corresponding to the range of diameters for the successive central masks **163'** to **166'** in FIG. **30**. The difference in FIG. **31** is that this outer-diameter progression is smoothly continuous, and mechanical structure at **171** to achieve this result may be adopted from an umbrella, the outer surface of which is preferably reflecting in nature, so that reflected laser-beam energy may be deflected to a surrounding annular absorber **173**. A zoom lens **174** focused on the expandable skirt of the umbrella/reflector device **171** is reversibly driven by motor means **175** and a drive circuit **176**, so as to progressively change the outer diameter of beam output **12'/12** over the range $2\Delta R$, while the reversible mask-expansion drive **176** is changing the skirt diameter of the umbrella/reflector device **171**. A microprocessor **177** is shown connected for coordinating control of laser **13**, of the mask drive **177**, and of the zoom drive **176**.

It will be understood that in discussion of changing diameters and exposures in the various embodiments of this invention, the nature of the change has for the most part been presented as linear, e.g., as in FIGS. **27** and **28**. However, for the case of uniform ablative depth penetration (of cornea tissue) per unit time and at a given flux density of laser-beam projection, the relation of diameter change to exposure time is more akin to a square-law function, hence, quasi-parabolic. FIG. **32** are presented to show that the relation is quasi-parabolic whether the curvature correction is to reduce or eliminate a myopia (FIG. **32**) condition, or to reduce or eliminate a hyperopia (FIG. **33**) condition.

In each of FIGS. **32** and **33**, relative exposure (cumulative flux density of laser-beam impact at the cornea) is displayed as a function of radius, out to R_{cc}, the outer

radius of curvature correction. In the myopia-correcting case (FIG. 32), maximum exposure is at the center (eye axis), and cumulative exposure decreases to a minimum (effectively zero) at the radius R_{cc}. In the hyperopia-correcting case, maximum exposure is at the radius R_{cc}, and cumulative exposure decreases to a minimum (effectively zero) at the center; also, it will be noted that in the hyperopia-correcting case, there is a smooth transition from maximum to minimum cumulative exposure in the outer annulus ΔR.

It will be further understood that the linear reduction in cumulative exposure shown in FIG. 33 for the annulus ΔR will account for minimum slope at all points within the annulus, meaning that for deepest surgical penetration of the cornea (e.g., 100 microns, for a 10-diopter correction over a 5-mm diameter circle of curvature correction), a linear characteristic is best; but for lesser penetrations such as for diopter corrections up to 5 diopters, a non-linear relationship (as suggested by the dashed line spanning ΔR in FIG. 33) enables provision (within the radial span ΔR) of continuously smooth curvature transition, from the radius R_{cc} of maximum penetration and radially outward to the untreated adjacent original profile of the cornea.

What is claimed is:

1. The method of using an ultraviolet laser beam to change optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to a maximum-area circular section producing a spot which is centered on and equal to the area of the cornea to be subjected to ablation, adjusting the intensity of laser-beam projection to a limited level at which resultant corneal-tissue ablation per unit time is to an ascertained elemental depth which is but a fraction of a predetermined maximum ablation depth into the stroma, directing the adjusted beam to the cornea in the context of reflection to define a central circular region within the confined beam, said directing step being by reflection to the anterior surface and for that period of time which will accomplish at least some ablative penetration to the predetermined maximum ablation depth, whereby laser-beam impingement upon the cornea is a circle having an outer diameter determined by the central circular region; and, in the course of said period of time, varying the diameter of said central circular region to thereby vary the outer diameter of the spot at corneal impact, said diameter variation proceeding in a range within said maximum-area circular spot; whereby the cornea is impacted with greatest cumulative ablating penetration per unit area at the central region of the ablated area and with ablative penetration decreasing with increasing radius to the outer portion of the ablated area, whereby a myopia-correcting change in the anterior surface may be effected by volumetric removal of corneal tissue.

2. The method of using an ultraviolet laser beam to effect a hyperopia-correcting change in optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to a circular spot which is centered on and at least equal to the area of the cornea to be subjected to hyperopia-correcting ablation, adjusting the intensity of laser-beam projection to a limited level at which resultant corneal-tissue ablation per unit time is to an ascertained elemental depth which is but a fraction of a predetermined maximum ablation depth into the stroma, and directing the adjusted beam to the cornea in the context of reflection to define the beam as a circular annulus having at least the outer diameter of said area of the cornea to be subjected to hyperopia-correcting ablation, said directing step being by reflection to the anterior surface and for that period of time which will accomplish at least some ablative penetration to the predetermined maximum ablation depth, while varying the inner diameter of the annulus and thus of the projected spot, said inner-diameter variation proceeding for a range of diameters less than the outer diameter of said area of the cornea to be subjected to hyperopia-correcting ablation; whereby the cornea is impacted with greatest cumulative ablating penetration per unit area at the perimeter of the area of the cornea to be subjected to hyperopia-correcting ablation, and with ablative penetration decreasing with decreasing radius to the central portion of the ablated area, whereby a hyperopia-correcting change in the anterior surface may be effected by volumetric removal of corneal tissue.

3. The method of claim 1 or claim 2, wherein the diameter variation is in the direction of diameter reduction.

4. The method of claim 1 or claim 2, wherein the diameter variation is in the direction of diameter expansion.

5. The method of using an ultraviolet laser beam to change optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to a maximum-diameter circular section producing a spot which is centered on and is predetermined to establish the outer perimeter of the area of the cornea to be subjected to ablation, adjusting the intensity of laser-beam projection to a limited level at which resultant corneal-tissue ablation per unit time is to an ascertained elemental depth which is but a fraction of a predetermined maximum ablation depth into the stroma, directing the adjusted beam to the anterior surface of the cornea in the context of reflection to define the beam as comprising (a) a first circular annulus having the outer diameter of said spot and a finite inner diameter and (b) a second circular annulus having an outer diameter contiguous to the finite inner diameter of said first annulus, said directing step being by reflection to the anterior surface and for that period of time which will accomplish at least some ablative penetration to the predetermined maximum ablation depth, while varying the outer diameter of both annuli to thereby vary the outer diameter of each of two concentric ablating spots at corneal impact, the variation in outer diameter of said first annulus proceeding in a range of diameters up to the diameter of said spot, and the variation in outer diameter of said second annulus proceeding in the range of diameters up to said finite diameter, whereby a myopia-correcting change in the anterior surface may be effected by volumetric removal of corneal tissue to achieve a Fresnel-type characterization of the anterior surface.

6. The method of using an ultraviolet laser beam to change optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to an intermediate-diameter circular section

producing a spot which is centered on and effectively expandable to the maximum diameter of the area of the cornea to be subjected to ablation, adjusting the intensity of laser-beam projection to a limited level at which resultant corneal-tissue ablation per unit time is to an ascertained elemental depth which is but a fraction of a predetermined maximum ablation depth into the stroma, directing the adjusted beam to the cornea in the context of reflection to define the beam as comprising (a) a first circular annulus having the outer diameter of said spot and a finite inner diameter and (b) a second circular annulus having an outer diameter contiguous to the finite inner diameter of said first annulus, said directing step being by reflection to the anterior surface and for that period of time which will accomplish at least some ablative penetration to the predetermined maximum ablation depth, while varying the inner diameter of both annuli to thereby vary the inner diameter of each of two concentric ablating spots at cornea impact, the variation in inner diameter of said first annulus proceeding in a range of diameters up to the diameter of said spot, and the variation in inner diameter of said second annulus proceeding in a range of diameters up to said finite diameter, whereby a hyperopia-correcting change in the anterior surface may be effected by volumetric removal of corneal tissue to achieve a Fresnel-type characterization of the anterior surface.

7. The method of using an ultraviolet laser beam to correct an astigmatic property of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to a maximum-area section producing a spot which is centered on and spans the area of the cornea to be subjected to ablation, adjusting the intensity of laser-beam projection to a limited level at which resultant corneal-tissue ablation per unit time is to an ascertained elemental depth which is but a fraction of a predetermined maximum ablation depth into the stroma, directing the adjusted beam to the cornea in the context of reflection to define the spot as a projected rectangle which is centered on and of elongate length which spans said area of the cornea, orienting the elongate length direction as a central longitudinal axis of the projected rectangular spot to accord with the orientation of the cylindrical axis of the astigmatism to be corrected, said directing step being by reflection to the anterior surface and for that period of time which will accomplish at least some ablative penetration to the predetermined maximum ablation depth, and varying the width of the projected rectangular spot, said width variation being symmetrical laterally of the central longitudinal axis and within the span of said maximum-area section, whereby the cornea is impacted with greatest cumulative ablative penetration per unit area along the central longitudinal axis of spot orientation and with ablative penetration decreasing with increasing width to the outer portion of the ablated area, whereby an astigmatism-correcting change in the anterior surface may be effected by volumetric removal of corneal tissue.

8. The method of using a pulsed ultraviolet laser beam to change optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the section of the laser beam to a maximum circular area which is centered on and equal to the area of the cornea to be subjected to ablation, adjusting the beam-exposure flux per pulse to a level at which resultant corneal-tissue ablation per pulse is to an ascertained elemental depth which is but a fraction of desired maximum ablation depth into the stroma, directing a succession of such pulses to the anterior surface of the cornea in the context of reflecting a central circular region of said beam, whereby laser-pulse impingement upon the cornea is a circle having a diameter determined by the reflection, and varying the diameter of said reflection to thereby vary the diameter of laser-pulse impingement upon the cornea, said diameter variation being in a range up to the diameter of said maximum circular-area, whereby the cornea is impacted with the greatest density of pulses per unit area at the central region of the ablated area and with pulse density decreasing with increasing radius to the perimeter of the ablated area, whereby a myopia-correcting change in the anterior surface is effected by volumetric removal of corneal tissue.

9. The method of using a pulsed ultraviolet laser beam to change optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the section of the laser beam to a maximum circular area which is centered on and equal to the area of the cornea to be subjected to ablation, adjusting the beam-exposure flux per pulse to a level at which resultant corneal-tissue ablation per pulse is to an ascertained elemental depth which is but a fraction of desired maximum ablation depth into the stroma, directing a succession of such pulses to the anterior surface of the cornea in the context of reflecting a radially narrow outer circularly annular region of said beam, whereby laser-pulse impingement upon the cornea is a circular annulus having an inner diameter determined by the reflection, and varying the inner diameter of said reflection to thereby vary the inner diameter of laser-pulse impingement upon the cornea, said diameter variation being in a range up to the outer diameter of said outer annular region, whereby the cornea is impacted with greatest density of pulses per unit area at the perimeter of the ablated area and with pulse density decreasing with decreasing radius to the center of the ablated area, whereby a hyperopia-correcting change in the anterior surface is effected by volumetric removal of corneal tissue.

10. The method of using an ultraviolet laser beam to change optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to a maximum-area circular spot which is centered on and equal to the area of the cornea to be subjected to ablation, adjusting the intensity of laser-beam projection to a limited level at which resultant corneal-tissue ablation per unit time is to an ascertained elemental depth which is but a fraction of a predetermined maximum ablation depth into the stroma, and directing the adjusted beam to the anterior surface of the cornea for that period of time which will accomplish at least some ablative penetration to the predetermined maximum ablation depth, while varying the diameter of the projected spot, said variation proceeding in a range within said maximum-area spot whereby the cornea is impacted with greatest density of laser-beam exposure per unit area at the central region of the ab-

lated area and with density of laser-beam exposure decreasing with increasing radius to the outer portion of the ablated area, whereby a myopia-correcting change in the anterior surface may be effected by volumetric removal of corneal tissue.

11. The method of using an ultraviolet laser beam to effect a hyperopia-correcting change in optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to a circular spot which is centered on and of at least the area of the cornea to be subjected to hyperopia-correcting ablation, adjusting the intensity of laser-beam projection to a limited level at which resultant corneal-tissue ablation per unit time is to an ascertained elemental depth which is but a fraction of a predetermined maximum ablation depth into the stroma, directing the adjusted beam to the anterior surface of the cornea in the context of masking a central circular region within said circular spot, said directing step being for that period of time which will accomplish at least some ablative penetration to the predetermined maximum ablation depth, whereby laser-beam impingement upon the cornea is a circular annulus having an inner diameter determined by the circular mask; and, in the course of said period of time, varying the diameter of said mask to thereby vary the inner diameter of the circular annulus, said mask-diameter variation proceeding to but short of the diameter of said maximum-area circular spot; whereby the cornea is impacted with greatest cumulative ablating penetration per unit area at the perimeter of the hyperopia-correcting area and with ablative penetration decreasing with decreasing radius to the center of the hyperopia-correcting area.

12. The method of using a pulsed ultraviolet laser beam to effect a hyperopia-correcting change in optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to a circular spot which is centered on and of at least the area of the cornea to be subjected to hyperopia-correcting ablation, adjusting the beam-exposure flux per pulse to a level at which resultant corneal-tissue ablation per pulse is to an ascertained elemental depth which is but a fraction of desired maximum ablation into the stroma, directing a succession of such pulses to the anterior surface of the cornea in the context of masking a central circular region within said circular spot, whereby laser-pulse impingement upon the cornea is a circular annulus having an inner diameter determined by the circular mask, and varying the diameter of the circular mask, said mask-diameter variation being up to the diameter of said hyperopia-correcting area, whereby the cornea is impacted with the greatest density of pulses per unit area at the perimeter of the hyperopia-correcting area and with pulse density decreasing with decreasing radius to the center of the hyperopia-correcting area.

13. The method of using a pulsed ultraviolet laser beam to change optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to a maximum-area circular spot which is centered on and equal to the area of the cornea to be subjected to ablation, adjusting the beam-exposure flux per pulse to a level at which resultant corneal-tissue ablation per pulse is to an ascertained elemental depth which is but a fraction of desired maximum ablation into the stroma, and directing a succession of such pulses to the anterior surface of the cornea in a succession of stepped increments of changing radius of circular spots which are concentric with respect to the optical center, said succession being continued over the range up to said maximum area, whereby the cornea is impacted with greatest density of pulses per unit area at the central region of the ablated area and with pulse density decreasing with increasing radius to the outer portion of the ablated area, whereby a myopia-correction change in the anterior surface may be effected by volumetric removal of corneal tissue.

14. The method of claim **10** or claim **11**, wherein the diameter variation is in the direction of diameter reduction.

15. The method of claim **10** or claim **11**, wherein the diameter variation is in the direction of diameter expansion.

16. The method of claim **11** or claim **12**, wherein the laser-beam spot is larger than the area of the cornea to be subjected to hyperopia-correcting ablation, thereby establishing an outer annulus of laser-beam exposure surrounding the hyperopia-correcting annulus, and varying the outer diameter of said outer annulus while effecting the hyperopia-correcting change, said outer-diameter variation commencing at substantially the outer diameter of the area of hyperopia-correcting change and proceeding with outward diameter expansion.

17. The method of claim **10** or claim **11** or claim **13** or claim **12**, in which the diameter variation is cumulatively such, in the course of said period of time, as to effect a radial distribution of laser-beam exposure which is quasiparabolic about the sectional center of laser-beam projection.

18. The method of claim **11** or claim **12**, in which the laser-beam spot is larger than the area of the cornea to be subjected to hyperopia-correcting ablation, thereby establshing an outer annulus of laser-beam exposure surrounding the hyperopia-correcting annulus while effecting the hyperopia-correcting change, said outer-diameter variation commencing at substantially the outer diameter of said area of hyperopia-correcting change and proceeding with outward diameter expansion, and in which the radial span between inner and outer diameters of said outer annulus is between 5 and 15 percent of the maximum diameter of the area of hyperopia-correcting change.

19. The method of claim **11** or claim **12**, in which the laser-beam spot is larger than the area of the cornea to be subjected to hyperopia-correcting ablation, thereby establishing an outer annulus of laser-beam exposure surrounding the hyperopia-correcting annulus while effecting the hyperpia-correcting change, said outer-diameter variation commencing at substantially the outer diameter of said area of hyperopia-correcting change and proceeding with outward diameter expansion, and in which the radial span between inner and outer diameters of said outer annulus is approximately 10 percent of the maximum diameter of the area of hyperopia-correcting change.

20. The method of claim **11** or claim **12**, in which the laser-beam spot is larger than the area of the corena to be subjected to hyperopia-correcting ablation, thereby establishing an outer annulus of laser-beam exposure surrounding the hyperopia-correcting annulus while

effecting the hyperopia-correcting change, said outer-diameter variation commencing at substantially the outer diameter of said area of hyperopia-correcting change and proceeding with outward diameter expansion, and in which said outer-diameter variation is cumulatively such, in the course of said period of time, as to effect a radial distribution of laser-beam exposure which is substantially linear in said outer annulus.

21. The method of using an ultraviolet laser beam to change optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to a maximum-diameter circular spot which is centered on and is predetermined to establish the outer perimeter of the area of the cornea to be subjected to ablation, adjusting the intensity of laser-beam projection to a limited level at which resultant corneal-tissue ablation per unit time is to an ascertained elemental depth which is but a fraction of a predetermined maximum ablation depth into the stroma, selecting an opaque circular mask of diameter less than maximum diameter to be subjected to ablation and centering the mask on an optical axis and between the cornea and the laser beam, and directing the adjusted beam to the anterior surface of the cornea for that period of time which will accomplish at least some ablative penetration to the predetermined maximum ablation depth, while reducing the spot diameter from said maximum to the diameter of said circular mask, removing the mask, and directing the adjusted beam to the anterior surface of the cornea while also continuing to reduce the spot diameter within the previously masked area, whereby a hyperopia-correcting change in the anterior surface may be effected by volumetric removal of corneal tissue to achieve a Fresnel-type characterization of the anterior surface.

22. The method of using an ultraviolet laser beam to change optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to an intermediate-diameter circular spot which is centered on and expandable to the maximum diameter of the area of the cornea to be subjected to ablation, adjusting the intensity of laser-beam projection to a limited level at which resultant corneal-tissue ablation per unit time is to an ascertained elemental depth which is but a fraction of a predetermined maximum ablation depth into the stroma, selecting an opaque circular mask of said intermediate diameter, centering the mask on an optical axis and between the cornea and the laser beam, and varying the expansion of the spot circle of the adjusted laser beam while directing the same to the anterior surface of the cornea for that period of time which will accomplish at least some ablative penetration to the predetermined maximum ablation depth, said expansion being continued to the point of expanded-spot size reaching the full periphery of the area to be subjected to ablation, removing the mask, and directing the adjusted beam to the anterior surface of the cornea in a program of spot-size variation in the range up to said intermediate diameter wherein the preponderance of ablation is near the center of said intermediate-diameter spot, whereby a myopia-correcting change in the anterior surface may be effected by volumetric removal of corneal tissue to achieve a Fresnel-type characterization of the anterior surface.

23. The method of using an ultraviolet laser beam to correct an astigmatic property of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to a projected rectangular spot which is centered on and of elongate length which diametrically spans the area of the cornea to be subjected to ablation, adjusting the intensity of laser-beam projection to a limited level at which resultant corneal-tissue ablation per unit time is to an ascertained elemental depth which is but a fraction of a predetermined maximum ablation depth into the stroma, orienting the elongate length direction of the projected rectangular spot to accord with the orientation of the cylindrical axis of the astigmatism to be corrected, and directing the adjusted beam to the anterior surface of the cornea for that period of time which will accomplish at least some ablative penetration to the predetermined maximum ablation depth, and varying the width of the projected rectangular spot, said width variation being in the range up to the diametrical span of said area, whereby the cornea is impacted with greatest cumulative ablative penetration per unit area along the diameter of spot orientation and with ablative penetration decreasing with increasing spot width to the outer portion of the ablated area, whereby an astigmatism-correcting change in the anterior surface may be effected by volumetric removal of corneal tissue.

24. The method of using an ultraviolet laser beam to change optical properties of an eye having both astigmatic and myopia errors, by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to a projected spot in the nature of an elongate line oriented on the corneal diameter which corresponds to the axis of astigmatic error, adjusting the intensity of laser-beam projection to a limited level at which resultant corneal-tissue ablation per unit time is to an ascertained elemental depth which is but a fraction of a maximum ablation depth, said maximum ablation depth having been predetermined in terms of the period of time necessary to reduce to substantially zero the cylindrical curvature responsible for the astigmatism, and for said period of time directing the adjusted beam to the anterior surface of the cornea while varying the width of the projected spot, whereby an astigmatism-correcting change may be effected in the anterior surface of the cornea by volumetric removal of corneal tissue, to thereby leave essentially only spherical error to be corrected; then confining the laser beam to a circular spot which is centered on and equal to the maximum area of the cornea to be subjected to myopia-correcting ablation, predetermining a second period of time for accomplishment of at least some further ablative penetration which corresponds to the maximum required for myopia-correction, and for said second period of time directing the circular spot to the anterior surface of the cornea while varying the diameter of the circular spot within the range up to the diameter of said maximum area, whereby a myopia-correcting change in the anterior surface may be effected by further volumetric removal of corneal tissue.

25. The method of using an ultraviolet laser beam to change optical properties of an eye having both astigmatic and hyperopia errors, by selectively ablating the anterior surface of the cornea with penetration into the

stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to a projected spot in the nature of an elongate line oriented on the corneal diameter which corresponds to the axis of astigmatic error, adjusting the intensity of laser-beam projection to a limited level at which resultant cornea-tissue ablation per unit time is to an ascertained elemental depth which is but a fraction of a maximum ablation depth, said maximum ablation depth having been predetermined in terms of the period of time necessary to reduce to substantially zero the cylindrical curvature responsible for the astigmatism, and for said period of time directing the adjusted beam to the anterior surface of the cornea while varying the width of the projected spot, whereby an astigmatism-correcting change may be effected in the anterior surface of the cornea by volumetric removal of corneal tissue, to thereby leave essentially only spherical error to be corrected; then confining the laser beam to a circular spot which is centered on and at least equal to the area of the cornea to be subjected to hyperopia-correcting ablation, predetermining a second period of time for accomplishment of at least some further ablative penetration which corresponds to the maximum required for hyperopia correction, selecting an opaque mask providing circular masking at diameters varying up to the diameter of said hyperopia-correcting area, and for said second period of time directing the circular spot to the cornea while varying the circular masking diameter up to substantially the diameter of said hyperopia-correcting area, whereby a hyperopia-correcting change in the anterior surface may be effected by further volumetric removal of corneal tissue.

26. The method of using a pulsed ultraviolet laser beam to change optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to a circular spot which is centered on and equal to a predetermined area of the cornea to be subjected to ablation, adjusting the beam-exposure flux per pulse to a level at which resultant corneal-tissue ablation per pulse is to an ascertained elemental depth which is but a fraction of desired maximum ablation into the stroma, selecting an opaque circular mask of area less than the predetermined area to be subjected to ablation, centering the mask on the optical axis and between the cornea and the laser beam, whereby an annular area is defined for ablation of an elemental Fresnel-characterized surface, and directing a succession of such pulses to the anterior surface of the cornea in a succession of varying outer radius of said annular area, such variation being between the area of the mask and said predetermined area, whereby a first myopia-correcting curvature change in the anterior surface may be effected by a first volumetric removal of corneal tissue within said annular area; removing the mask, and directing another succession of such pulses to the anterior surface of the cornea in a succession of stepped increments of varying circular-spot area which (a) are concentric to the optical center and (b) are within the previously-masked area, whereby a second myopia-correcting curvature change in the anterior surface may be effected by a second volumetric removal of corneal tissue within the previously-masked area.

27. The method of using a pulsed ultraviolet laser beam to change optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to a circular spot which is centered on and equal to a predetermined area of the cornea to be subjected to ablation, adjusting the beam-exposure flux per pulse to a level at which resultant corneal-tissue ablation per pulse is to an ascertained elemental depth which is but a fraction of desired maximum ablation into the stroma; directing a first succession of such pulses to the anterior surface of the cornea in a succession of varying outer radius within a central circle of diameter less than that of said predetermined area, whereby a first myopia-correcting curvature change in the anterior surface may be effected by a first volumetric removal of corneal tissue within said central circle; opaquely masking the central circle; and then directing a second succession of such pulses to the anterior surface of the cornea in a succession of varying outer radius within the annulus defined by presence of the mask within said predetermined area, whereby a second myopia-correcting curvature change in the anterior surface may be effected by a second volumetric removal of corneal tissue within said annulus.

28. The method of using a pulsed ultraviolet laser beam to change optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises confining the laser beam to a circular spot which is centered on and equal to a predetermined area of the cornea to be subjected to ablation, adjusting the beam-exposure flux per pulse to a level at which resultant corneal-tissue ablation per pulse is to an ascertained elemental depth which is but a fraction of desired maximum ablation into the stroma; opaquely masking the predetermined area with a succession of circles of varying outer diameter in a range between said predetermined area and the area of an intermediate circle of diameter less than that of said predetermined area, and directing a first succession of such pulses to the anterior surface of the cornea in the course of masking with said succession of circles of varying outer diameter, whereby a first hyperopia-correcting curvature change in the anterior surface may be effected by a first volumetric removal of corneal tissue within an annulus defined by the diameter of the predetermined area and by the diameter of said intermediate circle; masking said annulus to prevent further ablation within said annulus; then opaquely masking said intermediate circle with a succession of circles of varying outer diameter in a range within the inner diameter of said annulus, and directing a second succession of such pulses to the anterior surface of the cornea in the course of masking said intermediate circle with a succession of circles of varying outer diameter, whereby a second hyperopia-correcting curvature change in the anterior surface may be effected by a second volumetric removal of corneal tissue within said intermediate circle.

29. The method of using a pulsed ultraviolet laser beam to correct an astigmatic property of an eye by selectively ablating the anterior surface of a cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises focusing the laser beam to a rectangular spot which is centered on and of elongate length which diametrically spans the area of the cornea to be subjectd to ablation, adjusting the beam-exposure flux per pulse to a level at

which resultant corneal-tissue ablation per pulse is to an ascertained elemental depth which is but a fraction of desired maximum ablation into the stroma, orienting the elongate length direction of the rectangular spot to accord with the orientation of the cylindrical axis of the astigmatism to be corrected, and directing a succession of such pulses to the anterior surface of the cornea in a succession of stepped increments of varying width of rectangular spots which are symmetrically positioned with respect to the optical center, whereby the cornea is impacted with greatest density of pulses per unit area along the diameter of spot orientation and with pulse density decreasing with increasing spot width to the outer portion of the ablated area, whereby an astigmatism-correcting change in the anterior surface is effected by volumetric removal of corneal tissue.

30. The method of using an ultraviolet laser beam to effect a myopia-correcting change in optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of cornea tissue, which method comprises delivering the laser beam to impact the cornea as a circular spot having a variable radius that is centered on the central axis of the eye, and varying the radius of said spot in the course of at treatment program to achieve such ablative penetration depth and profile as to characterize the anterior surface with the myopia-correcting change.

31. The method of using an ultraviolet laser beam to effect a hyperopia-correcting change in optical properties of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises delivering the laser beam to impact the cornea as a circular annulus having a variable inner radius that is centered on the central axis of the eye, and varying the inner radius of said annulus in the course of a treatment program to achieve such ablative penetration depth and profile as to characterize the anterior surface with the hyperopia-corrected change.

32. The method of claim **30** or claim **31**, in which said correcting change in optical properties of the eye is effected upon the anterior surface of a donor-cornea inlay after transplanted assembly thereof to a host cornea, the correcting change being to such stroma-penetration depth in the donor inlay as to complete the correcting change with a profile that is continuous and smooth at adjacency of the anterior surfaces of the host and donor-inlay surfaces.

33. The method of claim **30** or claim **31**, in which said correcting change in optical properties of the eye is effected upon the anterior surface of a donor-cornea inlay after transplanted assembly thereof to a host cornea, the correcting change being to such stroma-penetration depth in the donor inlay as to complete the correcting change with a profile that is continuous and smooth at adjacency of the anterior surfaces of the host and donor-inlay surfaces, said host cornea having been first prepared for donor-cornea reception by laser-beam delivery using a circular spot of fixed radius to the point of accomplishing ablative penetration to predetermined maximum ablation depth, and said donor-cornea inlay having been first prepared from a donor cornea for such translated assembled by laser-beam delivery to the posterior surface of the donor cornea until achieving at least some ablative penetration into the stroma region of the donor cornea, the extent of the latter ablative penetration being such as to leave unpenetrated donor-cornea thickness which is at least as great as the extent of laser penetration into the host cornea, and assembling the donor inlay in stroma-to-stroma contact with the ablated region of the host cornea.

34. The method of using an ultraviolet laser beam to effect curvature-correcting change in optical propertries of an eye by selectively ablating the anterior surface of the cornea with penetration into the stroma to achieve a volumetric removal of corneal tissue, which method comprises delivering the laser beam to impact the cornea with a circular spot maximum area which is greater than the optically used central area of the cornea, causing the beam to impact the cornea within said central area in a treatment program of beam-size variation to produce an optically corrected curvature in said central area, and causing the mean to impact the cornea with beam-size variation in an outer area which is adjacent to said central area such that in the course of the treatment program the corneal profile in said outer area provides a relatively smooth transition from the area of optically corrected curvature to the corneal profile adjacent to but outside said maximum area, whereby to condition the eye for favorable epithelial regrowth over the area of surgery.

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