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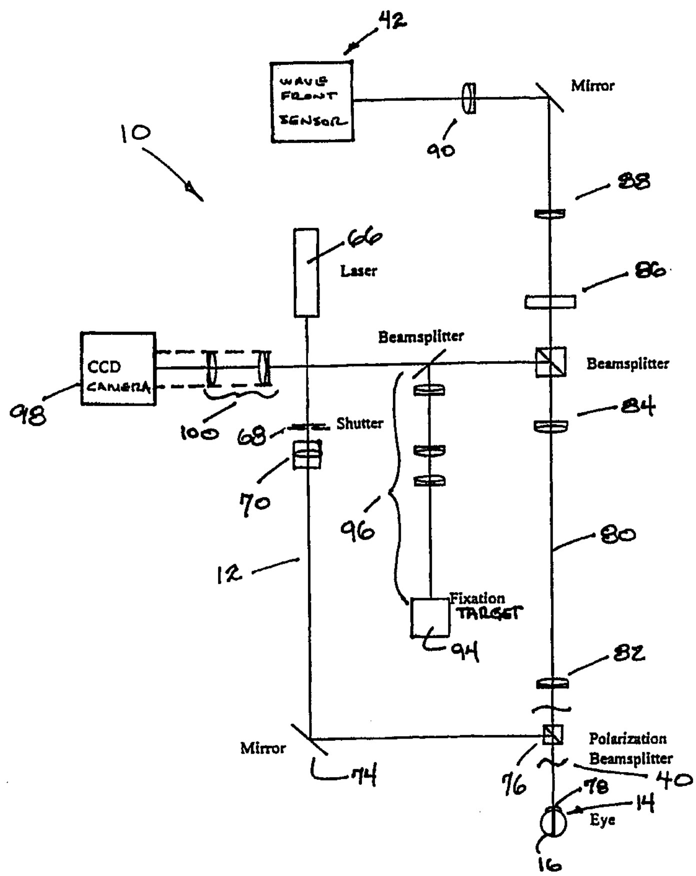
(57) Abstract

Optical characteristics of optical systems, such as the eye (14), are measured including vision defects of the eye using a collimated beam (12) from a diode laser (66) focused onto the anterior surface (22) of the cornea (24) of the eye for providing a finite source (16) of secondary radiation on the retina (18) of the eye, the image of which is close to a desired diffraction limited spot. The secondary radiation is reflected back from the retina (18) as a reflected wavefront of radiation that passes through the eye and is directed onto a wavefront analyzer (42) where distortions associated with the reflected wavefront are measured. By focusing on the cornea (24) through a long focal length lens (70) and thus converging the beam through a small angle (13), as opposed to typically focusing a collimated light onto the retina (18), the need for lenses or lens combinations, and the time required to adjust such to accommodate the differing vision of each patient is eliminated.



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APPARATUS AND METHOD FOR MEASURING VISION DEFECTS OF A HUMAN EYE

Related Application

This Application is related to Provisional Application having Serial No. 60/097,086, filed on August 19, 1998 for "Apparatus and Method for Measuring Vision Defects of a Human Eye" commonly owned with the instant application.

Background of Invention

Field of Invention

The invention relates generally to optical aberration measurements and correction, and in particular to projection techniques in the objective measurement and correction of the human eye using a wavefront sensor.

Description of Background Art

There has been and continues to be a need to provide a person with improved visual acuity. Remodeling of the cornea using refractive laser surgery or intra-corneal implants, adding synthetic lenses using intra-ocular lens implants or precision ground contact lenses or eye glasses provide known solutions. Further, it is known to correct vision astigmatically by surgical modification of myopic or hyperopic astigmatism through laser keratoplasty, keratomileusis or photorefractive keratectomy. Laser sources are used to erode or ablate surfaces of the eye, typically reshaping the cornea. Prior to and during such surgery, precise measurements must be made to determine required surgical corrections.

The imprecise measurement technique of placing lenses of known refractive power anterior to the cornea and asking a patient which lens or lens combination provides the clearest vision has been improved with the use of autorefractometers, as described in U.S. Patent No. 5,258,791 to Penny et al., or with the use of wavefront sensors as described by Liang et al. in "Objective Measurement of Wave Aberrations of the Human Eye with the Use of a Hartmann-Shack Wave-Front Sensor," Journal of the Optical Society of America, Vol. 1, No. 7, July 1994, p.p 1949-1957, by way of examples. Penny '791 discloses the use of autorefractometer measurements for determining the appropriate corneal surface reshaping to provide emmetropia, a condition of a normal eye when parallel rays are focused exactly on the retina and vision is optimum. Spatially resolved refraction data, in combination with measured existing surface contour of the anterior surface of the eye, enable a calculation of a detailed spatially resolved new contour which provides corrected vision. It would be an improvement in this art if such vision correction could be made without the need for this contour data, and further without the need for feedback from the patient regarding an appropriate lens. Liang et al. disclose the use of a Hartmann-Shack wavefront sensor to measure ocular aberrations by measuring the wavefront emerging from the eye by retinal reflection of a focused laser light spot on the retina's fovea. A parallel beam of laser light passes through beam splitters and a lens pair which brings the beam to a focus point on the retina by the optics of the eye. Possible myopia or hyperopia of the tested eye is corrected by movement of a lens within the lens pair. The focused light on the fovea is then assumed to be diffusely reflected and acts as a point source located on the retina. The reflected light passes through the eye and forms a distorted wavefront in front of the eye that results from the ocular aberrations. The aberrated wavefront is then directed to the wavefront sensor.

A point source of radiation on the retina would be ideal for such measurements. However, when the perfect eye receives a collimated beam of light, the best possible image on the retina is a diffraction limited spot. As illustrated by way of example, with Penny et al. and Liang et al., discussed above, and typical for those of skill in the art, parallel or collimated beams are used with the optics of the eye being measured to achieve this diffraction limited spot for such objective measurements. To do so requires that a setup for each patient include a corrective lens or lens combination and adjustments thereto for accommodating that patient's specific visual acuity. Providing a corrective or lens combination, as well as setting up for their use becomes cumbersome, time consuming, and requires additional expense. Eliminating the need for such corrective optics is desirable and eliminates a variable within optical measurement systems that typically include many variables. Further, there is a need for providing optical characteristics of an eye without requiring feedback from the patient. By way of example, the patient may be a wild or domestic animal, living or dead.

Summary of Invention

In view of the foregoing background, it is therefore an object of the present invention to provide a refraction measurement system that easily accommodates the measurement of vision characteristics of the eye, even in the presence of finite refractive errors. It is another object to improve upon the time required for a patient to be in a fixed position during examination, while at the same time providing a useful source of light on the retina of the eye to be measured regardless of the characteristics of the eye of that patient or other patients to be examined. It is further an object to measure such characteristics without requiring patient or operator feedback.

These and other objects, advantages and features of the present invention are provided by a method aspect of the invention for measuring optical characteristics of an optical system including the focusing of an optical beam proximate an anterior surface of the optical system for placing a finite source of secondary radiation on a focal surface of the optical system, which secondary radiation is emitted from the focal surface as a reflected wavefront of radiation that passes through the optical system, projecting the reflected wavefront onto a wavefront analyzer, and measuring characteristics of the optical system associated with the reflected wavefront. In a preferred embodiment, the method includes measuring defects of the eye which includes the steps of focusing an optical beam onto an anterior surface of the eye for providing a finite source of secondary radiation on the retina of the eye, which secondary radiation is emitted from the retina as a reflected wavefront of radiation that passes through the eye; directing the reflected wavefront onto a wavefront analyzer; and measuring distortions associated with the reflected wavefront. A preferred embodiment of the invention includes the step of focusing the projected optical beam on the anterior surface of the cornea.

An apparatus for effectively performing such measurements includes focusing means for focusing an optical beam onto an anterior surface of the optical system or eye for providing a finite secondary radiation source on the focal surface, or retina of the eye, which finite secondary radiation source is emitted from the retina as a reflected wavefront of radiation that passes through the eye, directing means for directing the reflected wavefront onto a wavefront analyzer, and a wavefront analyzer for measuring distortions associated with the reflected wavefront. In one preferred embodiment of the present invention, a laser beam is focused onto the surface of the cornea with a long focal length lens which converges the beam through a small angle for passing through the iris of the eye and providing a finite secondary radiation source on the retina of the eye, which finite secondary radiation source is emitted from the retina through the optics of the eye as the wavefront to be measured.

Brief Description of Drawings

A preferred embodiment of the invention as well as alternate embodiments are described by way of example with reference to the accompanying drawings in which:

FIG. 1 is a diagrammatic illustration of an apparatus for measuring visual defects of an eye, according to the present invention;

FIG. 2 is a diagrammatic illustration of a eye to be measured by the apparatus of the present invention;

FIGS. 3A and 3B are diagrammatic illustrations of an ideal eye with perfect vision and an aberrated ideal eye, respectively;

FIG. 4 is a diagrammatic illustration of an eye being measure with collimated light focused on the retina to a diffraction limited spot; and

FIG. 5 is a partial perspective view of a pinhole imaging plate and detector plane of a wavefront sensor used in a preferred embodiment of the present invention.

Detailed Description of Preferred Embodiments

The present invention will be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

A preferred embodiment of a measurement apparatus **10** of the present invention is herein initially described with reference to the schematic diagram of FIG.1. A projected beam **12** of optical radiation is directed into an eye **14** to be measured, so that a small area or measurable spot **16** is formed as a secondary radiation source in the foveal region of the retina **18** as illuminated with reference to FIG. 2. Specifically, the beam **12** is focused through a small angle **13** onto an anterior surface **20** of the eye **14**, and in a preferred embodiment of the present invention, focused on an anterior corneal surface **22** of the cornea **24** for further projection through the iris **26** and lens **28** and onto the retina **18**.

By way of further background, consider an "ideal" eye **14i** with ideal vision, as illustrated with reference to FIG. 3A. The ideal eye **14i**, having the ideal cornea **24i** and ideal lens **28i** will focus a collimated beam of light, illustrated with arrows **30** to a point **32**, as the secondary radiation source, on the ideal retina **18i**. This point **32** would then be a point source of light which would be diffusely reflected back through the optics of the ideal eye **14i** as a sequence of plane waves **34**. In actual fact, even an eye having perfect vision, as illustrated by way of example with reference to FIG. 4, will produce a diffraction limited illuminated area or spot **36**, as the secondary radiation source, on the retina of the eye, under the best possible circumstances. In a typical eye, as illustrated with reference to FIG. 4, such a spot **36** is even larger, where most of the blurring will be due to finite aberrations found in typical eyes. By way of further example, in an aberrated eye **14a**, if the point source **32** could be realized, distorted wavefronts **38** result as illustrated with reference to FIG. 3B. Having to deal with a series of distorted wavefronts **38** resulting from aberrations, and further dealing with a blurring of such distorted wavefronts **38** resulting from diffraction effects and the finite aberrations of the eye, results in a spot **36** source of light rather than a point **32** source. Such provides one of the challenges in measuring the visual defects or an eye.

It is typical in the art of eye measurements to form a collimated beam and attempt to focus the collimated beam onto the retina, using lenses and lens combinations with the optics of the eye to produce the smallest possible spot **36**, as earlier described with reference to FIG 4. Lenses and focusing techniques typically take valuable time and include multiple attempts to focus a spot on the retina using various lenses and lens combinations to accommodate each unique vision of each patient being measured. With the present invention, and the understanding that most of the blurring results from the curvature of the cornea, the present invention eliminates the need to find lenses or lens combinations to minimize the size of the spot on the retina that is used as the secondary source of radiation.

With reference again to the embodiment described in FIGS. 1 and 2, the optical wavefronts **40** scattered from the retina **18** are transferred by a series of optical elements, which will be described in further detail later in this section, to a wavefront sensor **42**, which wavefront sensor divides each incident wavefront into a group of "wavelets", referred to herein with numeral **50**, using an opaque plate **44** having a planar array of apertures **46** as illustrated with reference to FIG. 5. Further, the wavefront sensor **42** records the position **48** at which each wavelet **50** passing through the aperture **46** strikes a detector plane **54** such as a charged coupled device (CCD) herein provided as one preferred embodiment, which plane is held a fixed small distance **56** behind the plate **44**. The transverse displacement **58** of each wavelet **50** at the CCD detector plane **54** from a collimated light reference position **60** is then used to calculate a wavefront slope at each position of the apertures **46** within the planar aperture array. Alternate methods exist for using partial derivative data resulting from the measurements of the slope to calculate the wavefront **40**. One acceptable approach is that used by Liang et al. in the aforementioned paper where the wavefront is closely approximated using Zernike polynomials.

At each position **48**, a spot **62** typically extending beyond the light measurement area of one CCD element **64** is produced. As earlier discussed, blurring and a large diffraction limited spot make it difficult to make measurements. Thus, reducing blurring improves measurement at the detector plane **54**.

With reference again to FIG. 1, in one preferred embodiment of the present invention, the apparatus **10** includes the projected beam **12** of linearly polarized light (S-component) emitted from a diode laser **66** (670 nm, 3 mW by way of example), which beam of light passes through an electro-mechanical shutter **68**, which controls the duration of light exposure on the eye **14** of the patient, and in particular, the exposure of the retina **18** of the eye **14** illustrated with reference again to FIG. 2. It is expected that alternate sources of light, for example, non-coherent and non-polarized, as well as alternate light transmitting techniques will come to the mind of those skilled in the art without deviating from the teaching of the present invention. As herein described, the use of coherent light from a laser and polarization techniques are presently preferred. When the shutter **68** is open, the projected beam **12**, collimated light from the diode laser **66**, is directed by a long focal length lens **70** for focusing on the anterior surface **22** of the cornea **24** of the eye **14**, as illustrated with reference yet again to FIG. 2, passing through the pupil **72** and lens **28** of the eye **14**, and onto the retina **18** as the small measurable spot **16**. In an alternate embodiment, lens **70** comprises a zoom lens for varying the focus and moving the focus location as desired. By focusing on the cornea **24**, the measurement is minimally dependent on the curvature of the cornea. However, other locations proximate the corneal surface are acceptable.

While diffraction and various aberrations are present, the present invention avoids the aberration effects from the cornea which typically dominate. The lens **28** of the eye **14** contributes a relatively small aberration effect when compared to that of the cornea **24**. Further, and with regard to the selection of lens **70**, selecting a lens with a short focal length would provide a large angle **13**, a well focused point **78** on the surface of the cornea **24**, and less aberration effects from the cornea . However, a large angle **13** results in an undesirably larger retinal spot **16**. The small angle **13** herein described provides a larger focus point **78** on the cornea **24** but the more desirable smaller spot **16** on the retina **18**. The spot **16** will depend on the wavelength and starting point size and focal length of the lens **70** selected. In preferred embodiments of the present invention, lenses of approximate one half meter are selected for the lens **70**. A 100 mm lens **70** has been effectively used.

In one preferred embodiment herein described, a mirror **74** and polarization beam splitter **76** direct the projected beam **12** to a focus **78** on the anterior surface **20** of the cornea **24**. The projected beam **12**, focused on the anterior surface **22** of the cornea **24**, provides the measurable spot **16** as a light source (about 1.5 milliradians in visual space, by way of example) on the retina **18** of the eye **14** being measured, as illustrated with reference again to FIG. 2. Such a spot **16** provides an acceptable substitute for a diffraction limited spot typically sought.

By way of one preferred example of use, a method for measuring vision characteristics of the eye **14** includes directing the beam **12** through the long focal length lens **70** for providing the small angle **13**, as illustrated with reference again to FIG. 2, about an optical path for passing the beam **12** through the pupil **72** of the eye **14**. The beam **12** is first focused at a fixed location **78**, without the eye or patient in place. All measuring equipment, the apparatus **10**, is arranged without the patient in place and a convenient time prior to measuring. Then, the patient is positioned such that the anterior surface of the eye **14** of a patient is located at the fixed location **78** which in a preferred embodiment is the anterior surface of the cornea. This places a finite source of secondary radiation, the spot **16**, as herein described, on the retina **18** of the eye **14**, which provides light emitted from the retina **18** and through the pupil **72** as a reflected wavefront, the wavefront **38**, described with reference to FIG. 3B. This wavefront **38** is directed onto the wavefront analyzer **42** for measurement.

In a preferred embodiment, the laser power reaching the eye is physically limited to a maximum of 7μW. In measurements on human eyes using the apparatus **10**, a laser pulse duration of 700 ms was used so that the total energy entering the eye would not exceed 4.9 μJ. For comparison, according to the ANSI standard for direct "intrabeam" viewing, the maximum permissible exposure to a laser at the wavelength used is 530 μJ. Thus, the probing laser energies effectively used in the present invention are two orders of magnitude below an "eye-safe" limit.

With reference again to FIG. 2, the light diffusely reflected by the retina **18** produces the wavefront **40**, a distorted wavefront at the pupil plane due to the eye's aberrations. Diffuse reflection makes the returning light from the retina depolarized, containing not only an S-component but also a P-component of polarization light. The polarization beam splitter **76** in front of the eye **14** will only let the P-component pass through it and downstream to the wavefront sensor **42**. The S-component is essentially totally reflected towards the diode laser **66**. Because the light reflected by corneal surfaces preserves the polarization of the incoming beam (S-polarized), the corneal reflection is reflected by the beam splitter **76**, and is thus rejected from the path **80** heading toward the wavefront sensor **42**. The P-component of the aberrated wavefront **40** at the subject's pupil plane is then recreated by the combination of lens **82** and lens **84**, at a trial lens plane **86** indicated as "Trial Lens" in FIG. 2. In one preferred embodiment, the diameter and the aperture of the lens **82** and lens **84** are 40 mm and 120 mm, respectively. The combination of lens **82** and lens **84** form an afocal image system with the eye's pupil **72** (the object plane) at the focal plane of the lens **82**, and the image plane, trial lens **86**, at the focal plane of the lens **84**. Similarly, lens **88** and lens **90** also form an afocal image system with the possible trial lens **86** at the focal plane of the lens **88** and the lens combination at the image plane at the focal plane of the lens **90**. The focal plane of the lens **90** is located at the plate **44** of the wavefront sensor **42**, earlier described with reference to FIG. 5. In a preferred embodiment, Lens 4 has a diameter of 30 mm and a focal length of 80 mm. Lens 5 has a diameter of 40 mm and a focal length of 120 mm. With the apparatus **10**, measured wavefront slopes leaving the eye **14** are recreated at the aperture plane **44**, and magnified by a factor of 1.5. Magnification of the wavefront **40** at the detector plane **54** reduces the wavefront slopes by the same degree. This extends the dynamic range of eye aberrations over which the device can measure.

By way of further explanation about the trial lens location or plane **86**, because the wavefront **40** leaving the eye **14** is recreated at this location **86** with unity magnification, a trial lens of known refractive power inserted at this point should exactly compensate for a prescribed refractive error. For example, a perfect five diopter spherical lens placed at this location should remove five diopters of spherical curvature from an incident wavefront, without altering other aberrations that may exist in the wavefront. The capability of inserting trial lenses at this location **86** extends the dynamic measurement range of the apparatus **10**, without affecting wavefront analyzing capability.

In a preferred embodiment, and with reference again to FIG. 5, the aperture array **46** of the wavefront sensor **42** samples the incident wavefront **40** which forms focus spots **62** on the detector plane **54** This is repeated at the detector plane **54** for each aperture within the array **46**. As a result, a localized direction of the wavefront **40** is determined for each of a plurality of wavelets **50** within the array. By way of example, the use of lenslets **92** (as an alternate embodiment of apertures **46** alone), with a focal length of 87 mm and a dimension of 0.768 mm, forms an aerial image of the retinal light source (the spot **16** described earlier with reference to FIG. 2) on the detector plane **54**. If a plane wave, corresponding to an aberration-free eye, were measured, the lenslet **92** array would produce a regular array of focused spots on the image sensor. When the real eye **14** is measured, the wave aberration in the eye will displace the focus spot **62**, described earlier with reference to FIG. 5, of each lenslet **92** from the reference position **60** to the measured position **50** in proportion to the local slopes of the wavefront **40**. The wavefront sensor **42** measures the local wavefront slopes at an array of sampling locations across the pupil **72**, from which the wavefront **40** itself can be reconstructed.

As illustrated again with reference to FIG. 1, in an alternate embodiment of te present inventive methods, a fixation target **94** may be used to insure that the patient is looking along the optical axis of the apparatus **10**. The patient is asked to fixate on the target **94** located at the focal plane of a lens **96**. By linearly moving the optics combination **96** of the fixation target **94**, it is possible to provide the eye's spherical correction, and hence to make the fixation target **94** clearly visible to the subject. In one preferred use, the image of the fixation target **94** is intentionally under-corrected for each patient to ensure that the measured eye **14** is focused at infinity. By way of example, the fixation target consists of a dark cross-hair and a number of concentric circles on a white background that is back-illuminated by a tungsten lamp. The patient is asked to look at the center of the cross-hair. The position of the eye **14** in reference to the optical axis is recorded by CCD camera **98**. This CCD camera **98** is conjugate, in effect coupled, to the eye's pupil **72** through a second lens combination **100**, preferably mounted on the camera, and the lenses **82**, **84**. In one method of te present invention, the camera **98** is used to view the eye **14** for aligning the eye within the path of te beam **12** for assuring that the beam passes through the pupil **72**. The camera **98** is also useful in an alternate embodiment of the present invention, for viewing the size of the spot **16** formed on the retina **18** as the user changes the focus point **78** through various anterior surface locations in obtaining an optimum size of the spot **16**.

By way of further example of effective uses of the present invention, the earlier described Zernike coefficients of an eye, taken collectively, can be used as discriminating as fingerprints or DNA. The Zernike coefficients for a person might be used for identification of that person for permitting access to a confidential area, allowing funds to be distributed through an ATM, and the like. Further, the present invention allows eye measurements for a passive subject, such as in the examination of a corpse or sedated animal. The present invention is operable with human eyes, as herein described, as well as those of an animal, bird, or fish eyes, and in particular, non-biological focusing optical systems such as those found in cameras. The present invention is useful in developing optimized aspheric systems, where an aspheric element need to be designed last by observing and producing a single custom aspheric element that corrects the system. By way of example, the aspheric system may be designed on paper except for the correcting element, which would be developed experimentally using the present invention as herein described. The design of afocal systems such as a telescope, a searchlight, or a projector which require an added corrective focus element will benefit from the present invention.

Many modifications and other embodiments of the invention will come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed, and that modifications and alternate embodiments are intended to be included within the scope of the appended claims.

That Which Is Claimed Is:

1. A method for measuring vision defects of an eye, the method comprising the steps of:

focusing an optical beam proximate an anterior surface of the eye for placing a finite source of secondary radiation on the retina of the eye, which secondary radiation is emitted from the retina as a reflected wavefront of radiation that passes through the eye;

projecting the reflected wavefront onto a wavefront analyzer; and

measuring distortions associated with the reflected wavefront.

2. The method according to Claim 1, wherein the optical beam focusing step includes the step of focusing the optical beam on the anterior surface of the cornea.

3. The method according to Claim 1, wherein the optical beam comprises a collimated laser beam.

4. The method according to Claim 1, further comprising the steps of:

generating a linearly polarized, collimated beam of light; and

positioning a long focal length lens for directing the collimated beam of light through the long focal length lens, and wherein the focusing step includes the step of converging the collimated light through a small angle to a focal point on the anterior surface of the eye.

5. The method according to Claim 4, wherein the long focal length lens has a focal length between 0.5 and 5.0 meters in length.

6. The method according to Claim 4, further comprising the step controlling an amount of optical beam energy delivered to the eye.

7. The method according to Claim 1, wherein the distortion measuring step comprises the step of comparing the reflected wavefront received by the wavefront analyzer to a desirable wavefront received by the wavefront analyzer.

8. The method according to Claim 1, wherein the distortion measuring step comprises the step of determining an optical path difference between a plane wave and the wavefront emanating from the retina of the eye.

9. The method according to Claim 8, wherein the optical path difference results from a Zernike reconstruction of the wavefront.

10. The method according to Claim 1, wherein the distortion measuring step comprises the steps of:

positioning an opaque plate having an aperture therein for transmitting a portion of the emitted wavefront therethrough;

placing a light-sensitive material downstream of and in spaced relation to the opaque plate for receiving the portion of the reflected wavefront projected as a finite image onto a first position of the light-sensitive material;

projecting the reflected wavefront onto the plate for placing a first finite image onto the light-sensitive material;

projecting a desirable wavefront onto the plate for placing a second finite image at a second location on the light-sensitive material; and

measuring a difference between the first position and the second position.

11. The method according to Claim 10, wherein the aperture comprises an aperture array and wherein the light-sensitive material comprises a CCD array.

12. The method according to Claim 11, wherein the aperture array comprises a lens carried within each aperture for focusing light passing through the aperture onto the CCD array.

13. The method according to Claim 1, further comprising the step of converting the measured distortions to an optical correction based on a deviation of the reflected wavefront from a desirable wavefront.

14. The method according to Claim 13, wherein the desirable wavefront comprises a planar wavefront.

15. The method according to Claim 14, wherein the polarizing step comprises the steps of:

providing a beam splitter;

passing the reflected wavefront having an S-component and a P-component polarization light through the beam splitter; and

splitting the reflected wavefront by directing the P-component to the wavefront analyzer and the S-component therefrom.

16. The method according to Claim 1, further comprising the step of polarizing the optical beam.

17. The method according to Claim 1, further comprising the steps of:

positioning a fixation target for viewing;

focusing the eye on the fixation target for assuring that a patient whose eye is being measured is looking along a preferred direction.

18. The method according to Claim 17, further comprising the step of adjusting the fixation target for ensuring that the measured eye is focused at infinity.

19. The method according to Claim 1, further comprising the steps of:

viewing the pupil of the eye through a camera focused on the eye; and aligning the center of the eye along a beam path of the optical beam for confirming passage of the beam through the pupil of the eye.

20. A method for measuring vision characteristics of an eye, the method comprising the steps of:

projecting an optical beam through a sufficiently small angle about an optical path for passing the beam through the pupil of the eye and providing a finite spot on the retina of the eye;

focusing the optical beam proximate an anterior surface of the eye for placing a finite source of secondary radiation on the retina of the eye, which secondary radiation provides light emitted from the retina and through the pupil as a reflected wavefront of radiation; and

directing the reflected wavefront onto a wavefront analyzer for measuring distortions associated with the reflected wavefront.

21. The method according to Claim 20, wherein the optical beam focusing step includes the step of focusing the optical beam on the anterior surface of the cornea.

22. The method according to Claim 20, wherein the optical beam comprises a laser beam.

23. The method according to Claim 20, further comprising the steps of:

generating a linearly polarized optical beam; and

positioning a long focal length lens for directing the optical beam therethrough, and wherein the focusing step includes the step of directing the optical beam through the long focal length lens for providing the small angle in which to focus the optical beam.

24. The method according to Claim 23, wherein the long focal length lens has a focal length of at least one half meter in length.

25. The method according to Claim 20, further comprising the steps of:

providing a shutter within a beam path of the optical beam; and

controlling an amount of optical beam energy delivered to the eye by operating the shutter from a closed position to an open position.

26. The method according to Claim 20, further comprising the step of measuring an optical path difference between a desirable wavefront and the wavefront emanating from the retina of the eye.

27. The method according to Claim 26, wherein the measuring step comprises the steps of:

positioning an opaque plate having an aperture array therein for transmitting a plurality of emitted wavelets of the emitted wavefront therethrough; and

receiving finite images of the plurality of emitted wavelets on a light sensitive material downstream of and in spaced relation to the opaque plate.

28. The method according to Claim 27, further comprising the steps of:

determining positions for each of the plurality of emitted wavelet finite images;

projecting the desirable wavefront onto the plate for placing a plurality of reference wavelets onto the light sensitive material;

determining positions for each of the plurality of reference wavelet finite images; and

measuring a displacement between finite images, respectively, for the emitted wavelets and reference wavelets.

29. The method according to Claim 28, further comprising the step of converting the displacement to an optical correction based on a difference between the reflected wavefront and the desirable wavefront.

30. The method according to Claim 29, wherein the desirable wavefront comprises a planar wavefront.

31. The method according to Claim 30, further comprising the steps of:

polarizing the optical beam;

passing the reflected wavefront through a beam splitter, wherein an S-component and a P-component of the polarized optical beam pass through the beam splitter; and

splitting the reflected wavefront by directing the P-component to the wavefront analyzer and the S-component therefrom.

32. A method for measuring vision characteristics of an eye, the method comprising the steps of:

directing an optical beam through a long focal length lens for providing a sufficiently small angle about an optical path for passing the optical beam through the pupil of the eye;

focusing the optical beam at a fixed location;

positioning an anterior surface of the eye of a patient at the fixed location for placing a finite source of secondary radiation on the retina of the eye, which secondary radiation provides light emitted from the retina and through the pupil as a reflected wavefront of radiation; and

directing the reflected wavefront onto a wavefront analyzer for measuring the reflected wavefront.

33. The method according to Claim 32, wherein the anterior surface comprises the anterior surface of the cornea.

34. The method according to Claim 32, wherein the long focal length lens has a focal length of at least one half meter in length.

35. The method according to Claim 32, further comprising the steps of:

providing a shutter within a beam path of the optical beam; and

controlling an amount of optical beam energy delivered to the eye by operating the shutter from a closed position to an open position.

36. The method according to Claim 32, further comprising the step of measuring an optical path difference between a desirable wavefront and the wavefront emanating from the retina of the eye.

37. The method according to Claim 32, further comprising the steps of:

polarizing the optical beam;

passing the reflected wavefront through a beam splitter, wherein an S-component and a P-component of the polarized optical beam pass through the beam splitter; and

splitting the reflected wavefront by directing the P-component to the wavefront analyzer and the S-component therefrom.

38. The method according to Claim 32, wherein the positioning step comprises the steps of:

viewing the pupil of the eye through a camera focused on the eye; and

aligning the center of the eye along a beam path of the optical beam for confirming passage of the beam through the pupil of the eye.

39. A method for measuring vision characteristics of an eye comprising focusing an optical beam proximate an anterior surface of the eye for providing a finite source of secondary radiation on the retina of the eye, which secondary radiation is emitted from the retina as a reflected wavefront of radiation that passes through the eye.

40. The method according to Claim 39, wherein the optical beam focusing includes focusing the optical beam on the anterior surface of the cornea.

41. The method according to Claim 39, further comprising projecting the reflected wavefront onto a wavefront analyzer and measuring differences between the reflected wavefront and a desirable wavefront.

42. The method according to Claim 39, further comprising generating a linearly polarized, collimated beam of light and positioning a long focal length lens for directing the collimated beam of light through the long focal length lens, wherein the focusing includes converging the collimated light through a small angle to a focal point on the anterior surface of the eye.

43. The method according to Claim 42, wherein the linearly polarized collimated beam comprises a laser beam.

44. The method according to Claim 39, further comprising viewing the size of the finite secondary radiation source on the retina, and varying anterior surface focus locations for selecting a desired size of the source.

45. A method for measuring optical characteristics of an optical system, the method comprising the steps of:

focusing an optical beam proximate an anterior surface of the optical system for placing a finite source of secondary radiation on a focal surface of the optical system, which secondary radiation is emitted from the focal surface as a reflected wavefront of radiation that passes through the optical system;

projecting the reflected wavefront onto a wavefront analyzer; and

measuring characteristics of the optical system associated with the reflected wavefront.

46. The method according to Claim 45, wherein the optical system comprises a human eye, and wherein the focal surface comprises the retina of the eye.

47. The method according to Claim 45, wherein the distortion measuring step comprises the step of comparing the reflected wavefront received by the wavefront analyzer to a desirable wavefront received by the wavefront analyzer.

48. The method according to Claim 45, wherein the distortion measuring step comprises the step of determining an optical path difference between a plane wave and the wavefront emanating from the optical system.

49. The method according to Claim 48, wherein the optical path difference results from a Zernike reconstruction of the wavefront.

50. The method according to Claim 45, wherein the distortion measuring step comprises the steps of:

positioning an opaque plate having an aperture therein for transmitting a portion of the emitted wavefront therethrough;

placing a light sensitive material downstream of and in spaced relation to the opaque plate for receiving the portion of the reflected wavefront projected as a finite image onto a first position of the light sensitive material;

projecting the reflected wavefront onto the plate for placing a first finite image onto the light sensitive material;

projecting a desirable wavefront onto the plate for placing a second finite image at a second location on the light sensitive material; and

measuring a difference between the first position and the second position.

51. The method according to Claim 50, wherein the aperture comprises an aperture array and wherein the light sensitive material comprises a CCD array.

52. The method according to Claim 45, further comprising the step of converting the measured distortions to an optical correction based on a deviation of the reflected wavefront from a desirable wavefront.

53. The method according to Claim 45, further comprising the steps of:

viewing the focal surface through a camera; and

selecting a desired size of the finite source of secondary radiation.

54. An apparatus for measuring vision characteristics of an optical system, the apparatus comprising:

focusing means for focusing an optical beam proximate an anterior surface of the optical system for providing a finite source of secondary radiation on a focal surface, which secondary radiation is emitted from the focal surface as a reflected wavefront of radiation that passes through the optical system;

directing means for directing the reflected wavefront onto a wavefront analyzer; and

a wavefront analyzer for measuring distortions associated with the reflected wavefront.

55. The apparatus according to Claim 54, wherein the focusing means comprises a long focal length lens for converging the optical beam through a small angle and focusing the optical beam on the anterior surface.

56. The apparatus according to Claim 55, wherein the long focal length lens has a focal length of at least one half meter in length.

57. The apparatus according to Claim 54, wherein the focusing means comprises a zoom lens for converging the optical beam through a small angle and varying the focusing of the optical beam onto various anterior surfaces.

58. The apparatus according to Claim 54, further comprising a laser for providing the optical beam.

59. The apparatus according to Claim 54, further comprising the a shutter operable from a closed position to an open position for controlling an amount of optical beam energy delivered to the optical system.

60. The apparatus according to Claim 54, wherein the wavefront analyzer comprises:

an opaque plate having an aperture therein for transmitting a portion of the emitted wavefront therethrough; and

a light-sensitive material downstream of and in spaced relation to the opaque plate for receiving the portion of the reflected wavefront projected as a finite image thereon.

61. The apparatus according to Claim 60, wherein the aperture comprises an aperture array and wherein the light-sensitive material comprises a CCD array.

62. The apparatus according to Claim 61, further comprising a lens carried within each of the plurality of apertures of the aperture array.

63. The apparatus according to Claim 54, further comprising polarizing means for polarizing the optical beam.

64. The apparatus according to Claim 63, further comprising a polarization beam splitter for reflecting an S-component of the reflected wavefront and for transmitting a P-component of the reflected wavefront as a polarized wavefront therethrough.

65. The apparatus according to Claim 54, further comprising a camera positioned for viewing the focal surface.

66. An apparatus for measuring vision characteristics of an eye, the apparatus comprising:

a laser for providing an optical beam;

focusing means for focusing the optical beam on an anterior surface of the eye for providing a finite source of secondary radiation on the retina of the eye, which secondary radiation is emitted from the retina as a reflected wavefront of radiation that passes outward from the eye;

polarizing means placed within a path of the optical beam for transmitting a polarized wavefront therethrough; and

a wavefront analyzer receiving the polarized wavefront for measuring distortions associated therewith.

67. The apparatus according to Claim 66, wherein the focusing means comprises a long focal length lens for converging the optical beam through a small angle and focusing the optical beam on the anterior surface.

68. The apparatus according to Claim 67, wherein the long focal length lens has a focal length of approximately one half meter in length.

69. The apparatus according to Claim 66, further comprising the a shutter operable from a closed position to an open position for controlling an amount of optical beam energy delivered to the eye.

70. The apparatus according to Claim 66, wherein the wavefront analyzer comprises:

an opaque plate having an aperture therein for transmitting a portion of the emitted wavefront therethrough; and

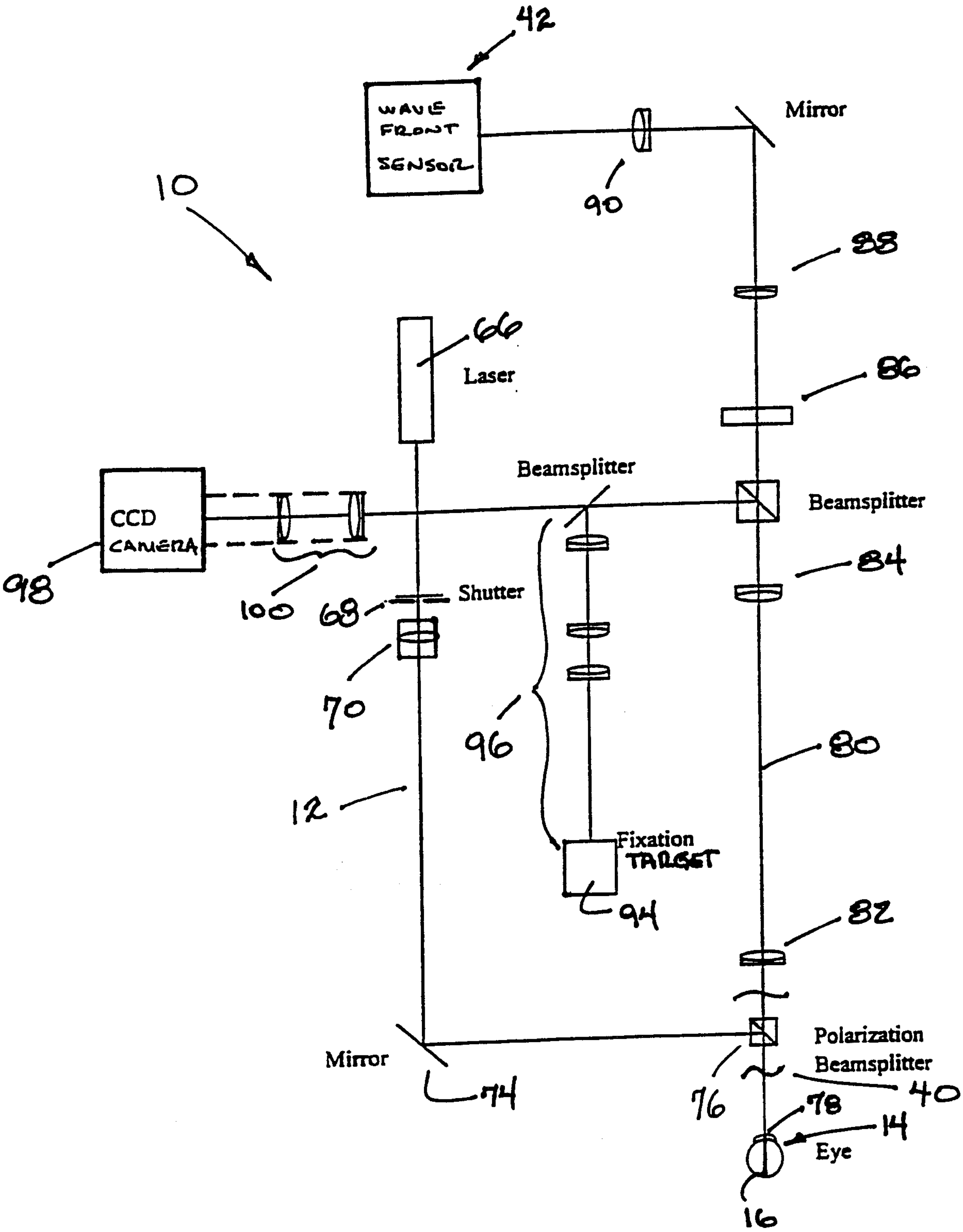
a light-sensitive material downstream of and in spaced relation to the opaque plate for receiving the portion of the reflected wavefront projected as a finite image thereon.

71. The apparatus according to Claim 70, wherein the aperture comprises an aperture array and wherein the light-sensitive material comprises a CCD array.

72. The apparatus according to Claim 71, further comprising a lens carried within each aperture of the aperture array.

73. The apparatus according to Claim 66, further comprising a fixation target for viewing by a patient whose eye is being measured, the fixation target assuring that a patient whose eye is being measured is looking along a preferred direction.

74. The apparatus according to Claim 66, further comprising a camera positioned for viewing the focal surface.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Shutter
70
96
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Polarization Beamsplitter
Mirror
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76
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78
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Eye
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FIG. 1

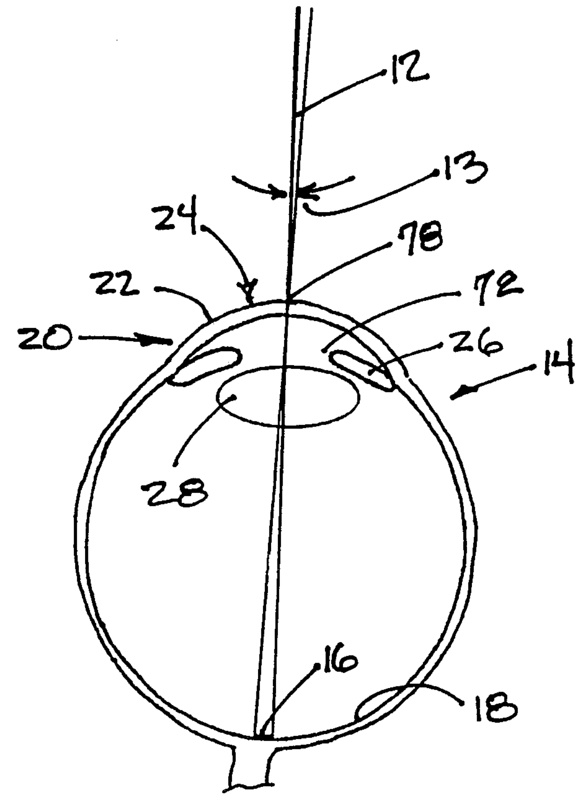

FIG. 2

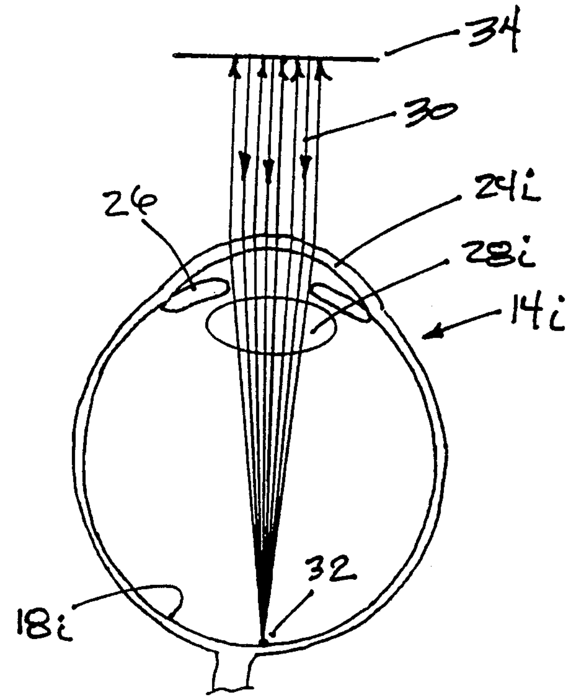

FIG. 3A

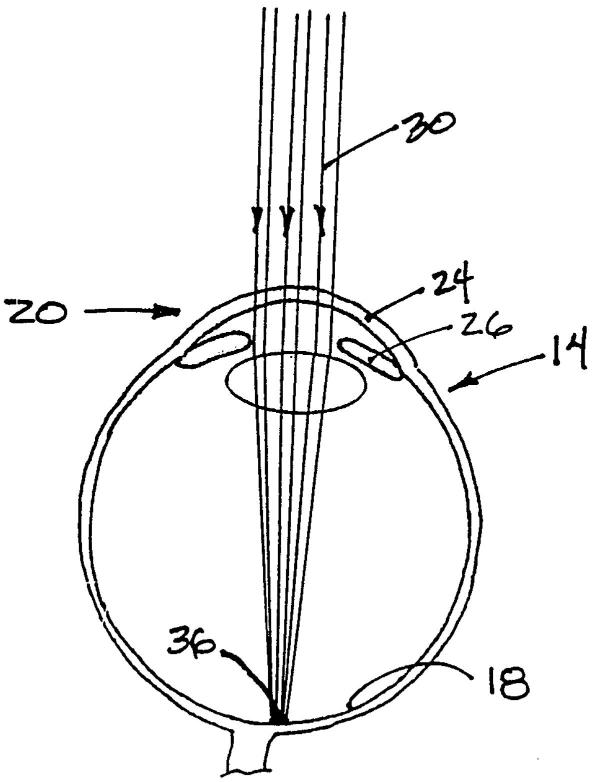

FIG. 4

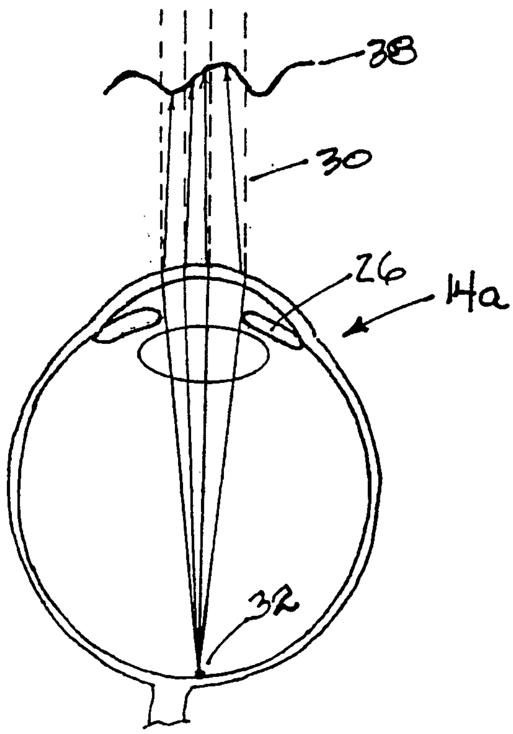

FIG. 3B

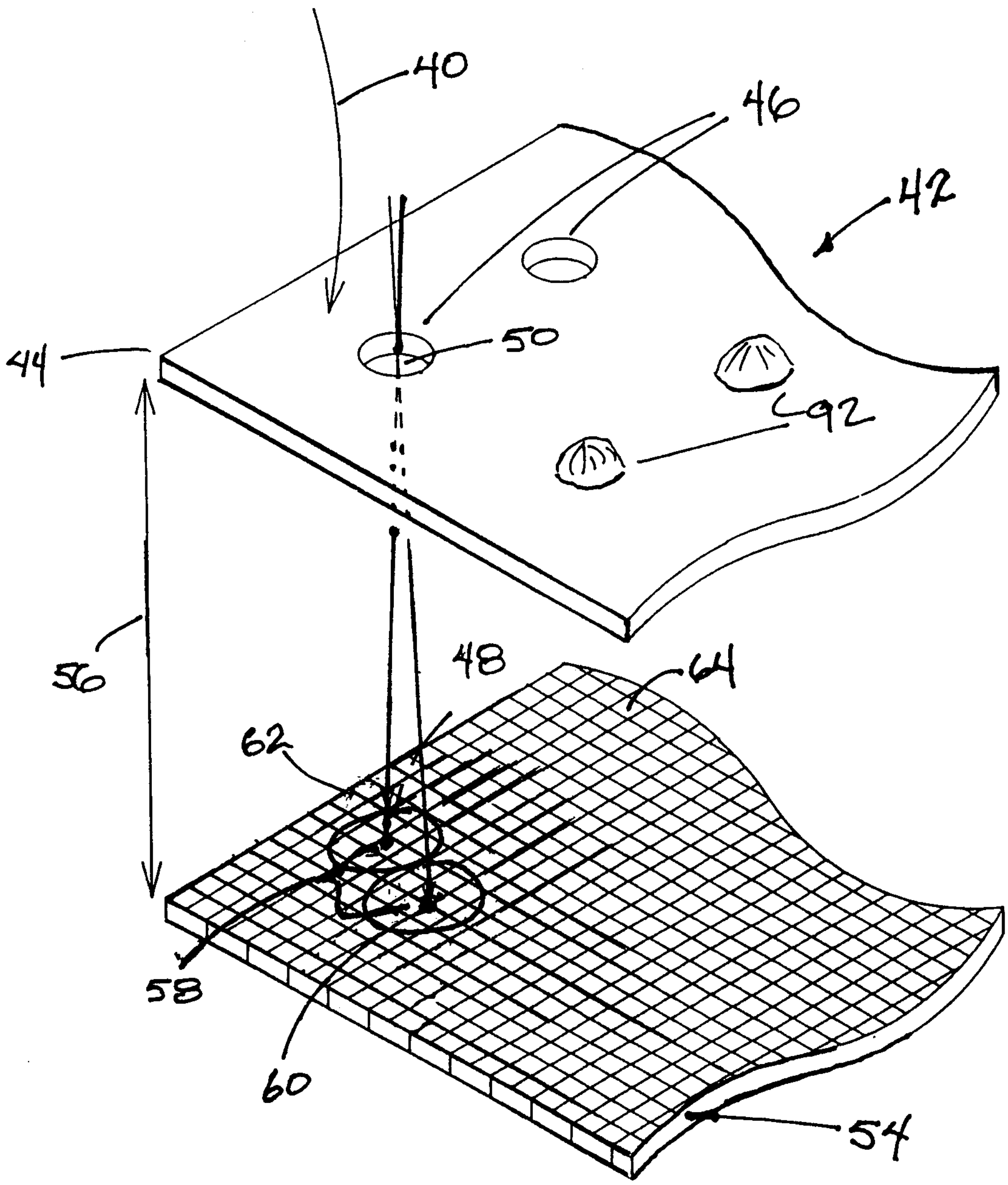

FIG. 5

INTERNATIONAL SEARCH REPORT

Int   ional Application No
PCT/US 99/08709

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 A61B3/103

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 A61B

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 98 27863 A (UNIVERSITY OF ROCHESTER) 2 July 1998 (1998-07-02) page 6, line 2 - page 9, line 9 figures 1,2	1,20,32, 39,45, 54,66
A		3,4, 6-17,22, 23, 25-31, 35-37, 42,43, 46-52, 58-64, 69-72

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
4 August 1999	11/08/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Chen, A

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 99/08709

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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A		2,4,21, 23,33, 55,67
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