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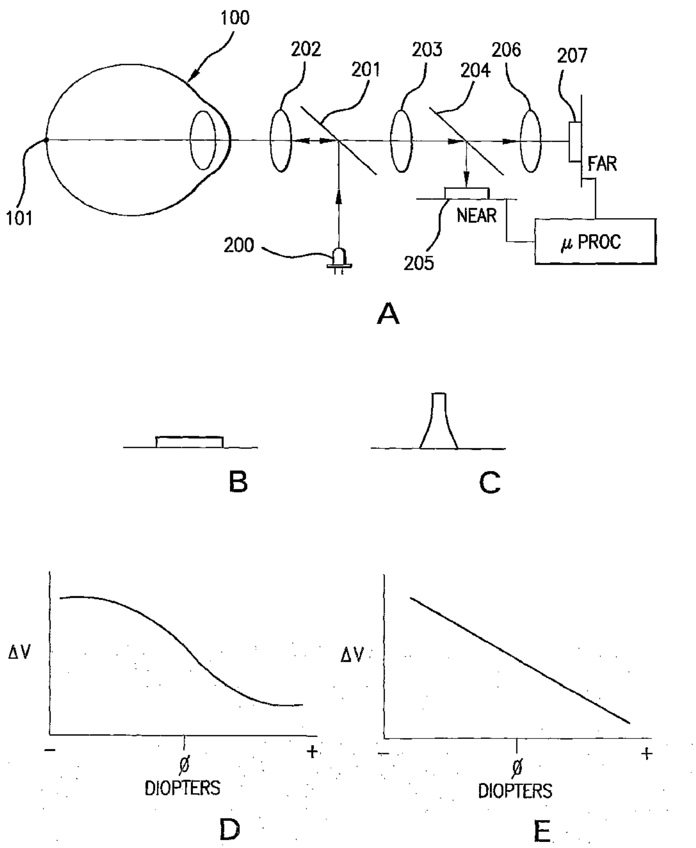
(54) Title: AUTOREFRACTOR FOR DETECTING LIGHT INTENSITIES TO EXTRACT HIGHER-ORDER REFRACTIONS AND METHOD FOR USE



(57) Abstract: An autorefractor is capable of determining higher order refraction characteristics of a patient's eye. An incident light beam projects into the patient's eye, producing a refracted light beam, which passes through a detector lens to produces a converged beam falling upon first and second sensors. Focal length of the detector and/or sensor position are variable. Focal length and/or position are changed so that one of the sensors lies in a position that corresponds to a retinal conjugate of the patient's eye, and first photosensor data is gathered. The first photosensor data is analyzed to determine retinal deep scatter. Then, the focal length and/or sensor position is changed so that the converged light that falls upon the sensor takes up a relatively larger area, producing second photosensor data. The determined retinal deep scatter from first photosensor data is subtracted from the second photosensor data.

WO 2007/082146 A2

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ABSTRACT

An autorefractor is capable of determining higher order refraction characteristics of a patient's eye. An incident light beam projects into the patient's eye, producing a refracted light beam, which passes through a detector lens to produces a converged beam falling upon first and second sensors. Focal length of the detector and/or sensor position are variable. Focal length and/or position are changed so that one of the sensors lies in a position that corresponds to a retinal conjugate of the patient's eye, and first photosensor data is gathered. The first photosensor data is analyzed to determine retinal deep scatter. Then, the focal length and/or sensor position is changed so that the converged light that falls upon the sensor takes up a relatively larger area, producing second photosensor data. The determined retinal deep scatter from first photosensor data is subtracted from the second photosensor data.

Autorefractor for Detecting Light Intensities to Extract Higher-Order Refractions and Method for Use

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to the field of autorefractors, which are devices used to take measurements of the eye of a patient.

Description of the Related Art

Machines to automatically and objectively measure the optics of the eye are essential for eye care. These machines, called "autorefractors," are of limited use and limited application.

Conventional autorefractors typically measure how light rays are bent or "refracted." Another method (Yancey, U.S. Pat. Nos. 5,329,322 and 5,684,561) uses measurement of intensity of light. These known refractors use various methods to obtain sphere (first order) and cylinder/axis (second order) refractions.

Correction of the eye's errors is conventionally achieved by lenses that correct for such first two orders of error. Third-order error is important for determining whether correction based on the first two orders of refraction is actually correcting vision as intended. Accordingly, third-order error can adversely affect vision. Significantly, third-order errors cannot be measured using conventional autorefractors.

Higher order refractions can be achieved by measuring displacement of a wavefront, using wavefront detecting techniques. What has not been known is an approach for measuring third-order error by considering intensity of light reflected back from the eye.

Until now, attempts to use charge-coupled devices (CCDs) and similar optical sensors to obtain refractions were largely unsuccessful. Underlying this lack of success is the inherent difficulty in achieving a useful signal-to-noise ratio (S/N) in measuring light reflected back from the eye. This is due to the fact that only a small amount of light falling on the eye is actually reflected back. The reflected light comes from a secondary emitter on the retina of the eye, which is a small spot of light projected onto the retina by an external light source, typically near-IR light. For the measured reflected light to have value, it must have a sufficiently high S/N so that the sensing apparatus can produce an output signal based thereon that allows for extracting refractions of the eye. It is these refractions that describe the optical characteristics related to the eye's optics.

SUMMARY OF THE INVENTION

The objective of this invention is to achieve optimal resolution and signal-to-noise (S/N) ratio for extracting higher order refractions from multi-segmented photodetectors such as charge-coupled devices (CCDs). The present autorefractor is intended to detect light intensities in an economical and unique manner to extract higher-order refractions.

Accordingly, this invention provides optical elements and photo sensors that provide better resolution and better S/N, allowing for new methods for extracting higher-order refractions, as well as new methods of signal processing to extract higher-order refractions based on intensity measurements of light reflected back from the eye. Moreover, these embodiments are simple, economical, and compact.

One object of the invention is to provide an autorefractor for determining refraction characteristics of an eye or other object. Such an autorefractor can include, among other elements, an incident light beam emitter arranged to project the incident light beam onto the eye or other object under test to produce a refracted light beam. A detector lens can be arranged so as to be in a path of the refracted light beam to produce a converged beam. First and second sensors can be provided so that each of the sensors is arranged to lie in a path of the converged beam, wherein a focal length of the detector lens is adjustable.

Another object of the invention is to provide a similar apparatus in which, instead of the focal length of the detector lens being adjustable, the location of one of the first and second sensors is adjustable along the converged beam. Yet another object is to provide an apparatus in which the detector lens focal length is adjustable and one or more of the sensors is adjustable as to location.

Another object of the invention is to provide a method for characterizing the optical characteristics of an object under test, such as an eye. The method can be used to detect light reflected from the eye or other optical object and subtract from such reflected light object deep scatter. In the case of an eye, this object deep scatter can be retinal deep scatter. Subtraction of such retinal deep scatter facilitates the determination of higher order refractions than would otherwise be possible.

Such a method can include, among other steps, projecting an incident light beam onto an eye or other object under test to produce a refracted light beam. The refracted light beam can then be passed through a detector lens to produce a converged light beam that is incident upon a photosensor. The photosensor can be moved with respect to the detector lens so that the photosensor lies in a position that corresponds to a retinal conjugate to produce first photosensor data. While the retina of an eye can result in such a retinal conjugate, this position can be more generally characterized as an object conjugate. The first photosensor data is analyzed to determine retinal deep scatter. Next, the photosensor can be moved away from the retinal conjugate position so that the converged light that falls upon the photosensor takes up a larger area of the photosensor compared to the retinal conjugate position, so as to produce second photosensor data. Finally, the determined retinal deep scatter can be subtracted from the second photosensor data.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be described by way of reference to the attached drawing figures, in which:

FIG. 1A illustrates an embodiment of the present invention utilizing two separate detectors/sensors/photosensors;

FIGS. 1B and 1C illustrate distributions of intensity of light under different conditions;

FIGS. 1D and 1E illustrate a relationship between voltage and diopters without and with the use of a field lens, respectively;

FIG. 2A illustrates another embodiment of the invention, utilizing an adjustable focal length lens;

FIGS. 2B-2E illustrate various methods of gathering data from strips of pixels on a detector;

FIG. 3 illustrates an embodiment of the invention utilizing a single detector movable into near and far positions;

FIG. 4 illustrates an embodiment for an apparatus for calibrating a device such as that of Figure 3;

FIG. 5A illustrates an alternative embodiment for a calibrator;

FIG. 5B illustrates a plot of a relationship between V and F_l or diopters;

FIG. 6A illustrates an embodiment of the present invention in consideration of retinal conjugate;

FIGS. 6B-6D illustrate a portion of the structure of Figure 6A, with the detector aligned with the retinal conjugate, together with the corresponding distribution of light or data on a detector and a profile of light intensity across the surface of the detector; and

FIGS. 6E-6G illustrate a portion of the structure of Figure 6A, with the detector moved away from the retinal conjugate, together with the corresponding distribution of light or data on a detector and a profile of light intensity across the surface of the detector.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 illustrated a first embodiment of the invention shown relative to an eye under measurement. Light source 200 produces a light that reflects off of beam splitter 201. The light reflected by the beam splitter 201 passes through relay lens 202 to eye 100.

The light than passes through the cornea and lens of the eye 100 and falls upon secondary emitter 101, located on the retina of the eye 100.

The light that falls upon the eye can be generically referred to as an incident light beam, or incident light. This light can be produced by an arrangement of elements other than those specifically described herein.

The secondary emitter 101 on the eye 100 reflects only a portion of the light that falls upon it. The light that is so reflected passes back through the lens and cornea of the eye 100 and then through the relay lens 202. The light that exits the eye after reflecting off of the retina and passing through the optics of the eye can be generically identified as a refracted light beam, or refracted light. Having passes through the relay lens 202, the reflected light falls upon and passes through the beam splitter 201. The light then passes through detector lens 203 and falls upon beam splitter 204. The light that passes through and is refracted by the detector lens 203 can be generically identified as converged light or a converged beam. A portion of the light falling upon the beam splitter 204 is reflected so as to fall upon near detector or sensor or photosensor 205. Light that was not reflected by the beam splitter 204 passes through field lens 206 and falls upon far detector or sensor or photosensor 207.

The near and far detectors 205 and 207 may be charge-coupled devices (CCDs). Alternatively, however, they may be any type of device that produces an output signal that is representative of the intensity of light that falls upon each of a plurality of points on the device.

Figures 1B and 1C illustrate intensity distribution of light falling upon the near and far detectors 205 and 207 under different conditions. The distribution of Figure 1B represents a large spot size with a low signal-to-noise ratio (S/N). The distribution of Figure 1C illustrates the opposite condition, namely small spot size with a relatively higher S/N.

When the eye 100 is characterized by extreme myopia, the near detector 205 will output a signal exhibiting the distribution of 1B (large spot and low S/N), whereas the far detector 207 will output a signal like that of Figure 1C (small spot and high S/N). In contrast, if the eye 100 is instead characterized by extreme hyperopia, the distributions will be reversed, with the near detector 205 outputting a signal with distribution like that of Figure 1C, and the far detector 207 outputting a signal with a distribution like that of Figure 1B.

In the absence of the field lens 206, the response curve would appear like that of Figure 1D. The presence of the field lens 206 provides a linear response curve like that of Figure 1E.

What is needed and desired is a spot size that provides a maximum S/N ratio with minimum required resolution for the order of refraction being measured. Figure 2A illustrates an embodiment to achieve this by providing a way to change both the spot size as well as the spot resolution, thereby providing a way to manipulate both S/N and spot resolution. In this way, the signals output by the near and far detectors 205 and 207 can be read and processed by the processor to generate the measurements of the characteristics of the patient's eye. The processor can be a conventional microprocessor running a program that performs the calculations needed to convert the data represented by the signals generated by the near and far detectors 205 and 207 into the required optical measurements. The processor can also be implemented by one or more application specific integrated circuits or programmable logic.

The apparatus of Figure 2A is in many ways similar to that of Figure 1A, with elements common between the two identified by the same reference numerals. In Figure 2A, however, the conventional detector lens 203 is replaced by adjustable lens 208. The adjustable lens 208 is a variable focal length lens.

One way to implement such a variable focal length lens is by way of a liquid lens. In a liquid lens the focal length changes in accordance with a voltage across the negative and positive terminals, as illustrated. While a voltage-controlled liquid lens is described in this embodiment, it is to be understood that any mechanism by which the focal length can be controlled can be used as a substitute for the particular technology described. This includes mechanically adjustable variable focal length lenses, which can be controlled by stepper motors.

As can be readily understood, changing the focal length of adjustable lens 208, electrically, mechanically, or otherwise, can controllably either increase or decrease the diopter range. A change in diopter range produces a change in resolution of the spot, and hence S/N and spot resolution can be controlled.

With this arrangement, it is important to know the precise focal length of the detector lens 203/208 as well as the precise positions of the near and far detectors 205 and 207. Stepper motors as control mechanisms for the near and far detectors 205 and 207 provide the necessary position information. To know the focal length of liquid lens 208 requires calibration of such lens using a known standard, and consistency of the system to ensure that calibration does not change between the time of calibration and the time of use.

Another difference between the embodiment of Figure 2A and that of Figure 1A is the adjustability of the position of near and far detectors 205 and 207. This adjustability is indicated by the two-headed arrows. The adjustment in position of the near and far detectors 205 and 207 also allows a change in the spot size as well as a change in resolution. Such a controllable change in position can be achieved in any number of known ways, including, but not limited to, the use of stepper motors.

It is possible to achieve the desired result by using only the adjustment in position of the near and far detectors 205 and 207. It is also possible to achieve the desired result by providing for only the adjustability of the focal length of the adjustable lens 208. As a third alternative, the adjustable focal length lens 208 can be combined with adjustable position detectors 205 and 207.

The signals output by the near and far detectors 205 and 207 are received by a processor. The processor performs the arithmetic manipulation of data represented by the signals to extract the measurements of the patient's eye. The same processor can be used to control the movements of the near and far detectors 205 and 207. Alternatively, a first processor can be used to control the movements of the detectors, and a second processor can be used to perform the arithmetic manipulation of the data from the detectors.

Figure 2B illustrates either of the near and far detectors 205 and 207. 209 represents a line or strip of selected pixels of the detector 205/207. In the strip illustrated, the strip runs from one edge of the detector to an opposite edge, and passes through a geometric center 210 of the detector, although this is not a requirement. The strip can be arranged on the detector in a different way.

The system can be constructed so that the pattern of light falling on either of the near and far detectors 205 and 207 is read from the detector 205/207 by reading the values of pixels that make up such a strip 209. By repeating the step of reading pixel data from a strip of 209 with a sequence of strips that represent a shift in strip position from one reading to the next, data from an entire surface of the detector 205/207 is possible. One embodiment has each of a sequence of strips 209 each passing through the geometric center 210 of the detector 205/207. The sequence of strips can be chosen as though the strip 209 were being rotated about the geometric center 210, as indicated by the arrow in Figure 2B.

This approach of sequential readings of data from strips 209 of pixels on the near or far detector 205/207 does not require finding edges of the spot on the detector 205/207. From these measurements of intensities of light along the strip 209, refraction of the eye can be obtained.

Figure 2C illustrates either of the near and far detectors 205 and 207, with a spot of light 211 falling upon such detector. As illustrated, the spot 211 need not be circular. It can be have the shape of an ellipse or another shape. The spot of light 211 need not be centered on the geometric center 210 of the detector 205/207. In the example illustrated in Figure 2C, the shape of the spot of light 211 approximates an ellipse centered on point 212.

As illustrated in Figure 2C, the center of the spot 211 can be determined and data from a sequence of strips 209 read from the detector 205/207. The location of the sequence of strips 209 can be defined as though the strip 209 were being rotated about the center 212 of the spot 211, as indicated by the arrow of Figure 2C.

Figure 2D illustrates a further variation on this embodiment. In this case, the strip 209 represents a set of pixels extending in only one direction from the center 212 of the spot 211. The sequence of readings of data from the detector 205/207 is taken as though the strip 209 were rotated about one end of the strip 209 located at the point 212.

As a further variation, the strip 209 can be defined as a set of pixels extending in a line outward from a center 212 of the spot 211 that does not reach an edge of the spot 211. The length of the strip 209 could be one-half of a radius of the spot 211, as an example. The length of the strip 209 in this instance can be determined based on the order of the refraction being extracted.

In the embodiments illustrated in Figures 2B-2E, measurements of the intensity of the light falling upon the near and far detectors 205 and 207 are taken by reading values produced from selected pixels of the detectors 205 and 207. The data of these values can then be used to extract refractions. These embodiments can be used to use the structure illustrated in Figures 1A and 2A to extract higher order refractions.

Figure 3 illustrates another embodiment in which individual near and far detectors are replaced with a single detector movable into near and far positions.

The arrangement and operation of the embodiment of Figure 3 is in many ways similar to those of the embodiment of Figure 2A. The arrangement and operation of the light source 200, beam splitter 201, relay lens 202, and adjustable lens 208 in relation to the eye 100 are essentially the same. However, instead of the second beam splitter 204 and separate near and far detectors 205 and 207, a single movable detector 213 is provided. The movable detector 213 is movable along the optical axis of adjustable lens 208. The adjustable lens 208 is constructed to be able to adjust its focal length to include at least the near and far focal lengths $F_l$near and $F_l$far. The focal lengths correspond to the positions of the near and far detectors 205 and 207 in the embodiment of Figure 2A.

In the embodiment of Figure 3, a field lens is not used to linearize the response curve, as illustrated in the relationship between the plots of Figures 1D and 1E. Instead, a lookup table implementation is used to define desired output values that correspond to respective input values. The values in the lookup table can be established as part of the process of calibrating the adjustable lens 208 when implemented as a liquid lens or another variety of adjustable focal length lens that requires calibration.

By replacing the dual-path and linearized implementation of Figure 2A with that of Figure 3, three elements are eliminated, namely one of the detectors 205/207, the beam splitter 204, and the field lens 206. In so doing, the embodiment of Figure 3 provides benefits in terms of size, simplicity, and economy.

An added cost of the embodiment of Figure 3 comcs in the requirement for calibration of the liquid lens when used as the adjustable lens 208. This calibration and the generation of data for the lookup table must be done with precision if one is to obtain accurate refractions. To offset some of the costs associated with the liquid lens of Figure 3, it is possible to replace the liquid lens with a lens whose focal length is adjustable mechanically.

The signals generated by the movable detector 213 while in the near position and the far position are sent to the processor. The processor manipulates the data represented by such signals to provide the needed measurements of the characteristics of the patient's eye. The same processor can be used to control the movement of detector 213.

Figure 4 illustrates one embodiment of a system that can be used to calibrate an adjustable lens such as a liquid lens. In this embodiment, a light source 214 produces one or more light beams that pass through one or more lenses 215. The lenses 215 are controllable to be movable along the optical axis. This can be achieved through use of a stepper motor or other means to provide for controlled movement. The light leaving the lenses 215 is reflected by reflector element 216 and through relay lens 217.

After passing through the relay lens the light passes through the adjustable lens 220 being calibrated, which can be a liquid lens. The light is then refracted by the liquid lens 220.

In this embodiment, 216 is a beam splitter comparable to beam splitter 201 illustrated in previous drawings. Beam splitter 216, however, is capable of rotating from a first position such as that of beam splitter 201 in Figure 3 to a second position illustrated in Figure 4. The first position is used during use of the device. The second position is used during calibration. In this way, the device can be placed into a calibration mode and calibrated by the user at any time.

The light beams from the light source 214 produce a series of "light spots" projected at optical distances corresponding to the diopter range of the instrument. These light spots are used to calibrate the liquid lens.

The schematically illustrated element ΔV is used to adjust the voltage applied to liquid lens 220 to control its focal length. ΔV is changed by the calibrator, which is in turn under the control of the microprocessor running a program which is within the knowledge of one of skill in the art. The calibrator creates increments in the voltage applied to liquid lens 220, thereby causing the focal length of liquid lens 220 to change from F_{l1} to F_{ln}. This controlled adjustment, in conjunction with lenses 215 and emitter 214 provides for establishing a correlation between focal lengths F_{l1} to F_{ln} and known diopter values of the combination of lenses 215 and emitter 214. The microprossor then records diopter values corresponding to F_{l1} to F_{ln} so that the autorefractor is properly calibrated.

The apparatus of Figure 4 includes the calibration optics in the form of lenses 215 between the emitter 214 and beam splitter 216. Alternatively, the calibration optics can be placed at any of 221, 222, or 223.

Element 219 is an IR emitter used to obtain actual refraction of the eye. That is, emitter 219 generates an IR beam that impinges on the retina, and the resulting "spot" of IR light produces a "secondary emitter" on the retina, which emitted IR light is propagated through the optics of the eye, and then out of the eye, which is captured by the moving sensor. This light is then analyzed for refractive measurements of the eye.

Figure 5A illustrates an alternative embodiment of a calibrator. The elements of the apparatus of Figure 5A correspond to many of those of Figure 3. The calibration apparatus of Figure 5A allows for precise determination of the focal lengths of an adjustable focal length lens, of which a liquid lens is one variety. The calibrator of Figure 5A advantageously has no moving parts.

In the apparatus of Figure 5A, an emitter 230 produces a beam that projects a small spot size at optical infinity as it passes through lens 231. The light is redirected by reflective element 232 through relay lens 233 and onto adjustable focal length lens 234, illustrated in this case as a liquid lens. The focal length of the liquid lens 234 is adjustable, and it is controlled by changes to the voltage across the positive and negative terminals. Such voltage is controlled by microprocessor 236. By adjusting the voltage, and hence the focal length, the focal length can be adjusted to any of a number of focal lengths over an available range, indicated in Figure 5A as F_{l1}, F_{l2} ... F_{ln}. Detector 235 is placed along the range of the available focal lengths.

As with element 216 of Figure 4, the reflective element can be a movable beam splitter rotatable between an operation mode and a calibration mode. In Figure 5A, this element is shown in calibration mode. The calibration can then be performed by the operator by putting the device into calibration mode. The calibration mode can even be performed while the device is in place for taking measurements of the patient's eye, just before such measurements are taken.

The apparatus of Figure 5A projects at optical infinity a small spot size into the apparatus under calibration, such as the autorefractor of Figure 3.

Calibration using the apparatus of Figure 5A produces a plot as in Figure 5B of the relationship between the voltage V across the positive and negative terminals of liquid lens 234 and corresponding focal length F_l/diopters. The focal length represents points F_{l1}, F_{l2} ... F_{ln} of Figure 5A. While the relationship between V and F_l is illustrated as linear in the plot of Figure 5B, this is not necessarily the case.

The points of the plot of Figure 5B by setting the voltage across the terminals of liquid lens 234 to a range of values, under the control of program running on the microprocessor 236. For each such voltage, the focal length F_l of the liquid lens 234 is determined. This can be achieved without any movement of the detector 235.

The focal length F_l can be determined by measuring the spot size of the light that falls on the detector 235. The data that is output by the detector 235 is received by the microprocessor 236. This allows the microprocessor 236 to receive as input the data from the detector 235 that corresponds to the voltage across the liquid lens 234 as determined by the microprocessor 236. This measurement of spot size can be performed, for example, by reading data from the detector 235 in the form of strips 209, as illustrated previously in connection with Figures 2B and 2C, but this is not a requirement of the present invention. By measuring spot size with detector 235 and knowing the distance between the detector lens 234 and detector 235, a current focal length of the liquid lens 234 can be calculated by the microprocessor 236.

The calibration apparatus of Figure 5A can be operated by first having the microprocessor 236 adjust the voltage across the terminals of liquid lens 234 until a smallest spot size is achieved. The smallest spot size can be determined by considering the data output by detector 235. This establishes a first relationship between the voltage V that produces such smallest spot size and the known positional relationship between liquid lens 234 and detector 235.

Under control of a calibration program running on microprocessor 236, the voltage across the terminals of liquid lens 234 is adjusted away from the voltage that produced the smallest spot size. By measuring the spot size determined from the data output by the detector 235 for the adjusted voltage, the focal length associated with the adjusted voltage can be calculated, in consideration of the known relationship between a direction of change of the applied voltage V and the resulting direction of change to focal length.

By establishing a data set of combinations of voltage and focal length, starting with a focal length that produces a smallest spot size and extending from there to voltages both greater and less then such starting voltage to identify both greater and lesser focal lengths, the plot of Figure 5B can be established as a representation of such data set. The plot then becomes a lookup table that can be used during operation of the apparatus for its intended use to provide a relationship between applied voltage and resulting focal length.

The principal underlying this calibration method and apparatus is equally applicable to a situation in which it is instead the detector 235 that is movable, as indicated by the double arrow in Figure 5A. A movable detector, in conjunction with a fixed focal length detector lens, can be used to establish the data set that underlies the plot of Figure 5B. In such a case, the microprocessor 236 would control the position of the detector 235 instead of the focal length of the detector lens. Such control, together with receiving as input the data output by the detector 235, allows the microprocessor 236 to collect the required data for calibration.

Figure 6A illustrates an embodiment of the apparatus underlying the present invention similar to that of Figure 3. While the detector lens 208 is illustrated as an adjustable focal length lens and the detector 213 is illustrated as movable, the invention underlying the present apparatus and method is applicable using an embodiment where only one of the detector lens and detector is controllable, as well as an embodiment in which both are controllable.

In the arrangement illustrated in Figure 6A, the apparatus is in use in connection with the eye of a patient. The characteristics of the patient's eye 100 and the secondary emitter 101 thereof produce reflected light that, after passing through the detector lens 208, is focused at the object conjugate. For purposes of optical analysis of the eye of a patient under examination, this will be referred to as retinal conjugate F_{RC}. The retinal conjugate location corresponds to the mean sphere error of the eye 100. In the illustration of Figure

6A, the F_{RC} is not located on a surface of the detector 213, but instead lies at a point between the detector lens 208 and detector 213.

The signals output by the detector 213 are received by the processor. The processor performs the arithmetic manipulation to extract the characteristics of the patient's eye represented by the pattern of light that falls on the detector 213. The same processor can be used to control the movement of detector 213.

Figure 6B illustrates only the detector lens 208 and detector 213 of Figure 6A, wherein the apparatus has been adjusted so that the detection surface of the detector 213 is now located at retinal conjugate F_{RC}. Depending upon the implementation of the apparatus, this may have been achieved by moving the detector 213, adjusting the focal length of detector lens 208, or both.

Figure 6C illustrates a plan view of detector 213 under the condition of Figure 6B. A small area and corresponding small number of pixels 240 are those which receive the majority of light focused by the detector lens 208. The surrounding area 241 represents an area or set of pixels lying outside the pixels/area 240 that receive a lower intensity of light than that seen by the pixels/area 240. This surrounding circle 241 exists because of the phenomenon of retinal deep scatter. While illustrated as being approximately circular, the area of retinal deep scatter is not necessarily geometrically symmetrical.

Under the phenomenon of retinal deep scatter, for wavelengths longer than that of yellow light penetration of the retina occurs. The longer wavelengths are scattered in the retinal layer. The degree to which such scattering occurs depends, at least in part, on the patient's pigmentation. Necessarily, the degree of retinal deep scatter varies from one patient to another. This phenomenon, described here in the context of the retina as a reflective object, may be more generally characterized as object deep scatter.

Figure 6D illustrates an exemplary distribution of light intensity illustrative of retinal deep scatter. The high value area in the center represents the high intensity light focused at the center by the detector lens 208 upon the surface of the detector 213. This corresponds to the pixels/area 240 of Figure 6C. The light that results from retinal deep scatter results in the areas of the curve on either side of the central high value section. These retinal deep scatter areas slope away from the central high value section toward a zero value. The retinal deep scatter areas of the curve correspond to the pixels/area 241 of Figure 6C.

By quantifying the retinal deep scatter by considering the distribution of data such as that illustrated in Figure 6D, the deep scatter can be analyzed mathematically. This can be performed by any of several known methods, including, but limited to, Fourier analysis and curve fitting. With the retinal deep scatter characterized by such analysis, it is then possible to subtract away the data representative of the retinal deep scatter from the totality of data received from the detector 213.

Figure 6E represents an adjustment to the arrangement illustrated in Figure 6B. In Figure 6E, the surface of the detector 213 is no longer located at the retinal conjugate F_{RC}. Instead, the detector 213 lies at a position in which the detector 213 is nearer the detector lens 208 than is the retinal conjugate F_{RC}. This can be achieved by moving the detector 213, adjusting the focal length of the detector lens 208, or both. In so doing, the light intensity is spread over a greater area, improving the resolution of data produced by the detector 213.

Figure 6F illustrates a comparative distribution of light intensity, comparable to that of Figure 6C. In Figure 6F, the light that had been focused at pixels/area 240 of Figure 6C has now been spread over a larger area 242, with the data representative of retinal deep scatter subtracted out.

Similarly, Figure 6G is comparable to Figure 6D. In Figure 6G, the data or light intensity of the center section of Figure 6D has been spread over a larger area, and the data or light intensity caused by retinal deep scatter has been subtracted out.

By spreading the useful light or data over a larger area of the detector, resolution of the resulting data is improved. The size of the enlarged area can be selected to achieve the desired result. The size can be set to one that provides, in effect, a constant S/N for required resolution, and one that provides sufficient resolution so that higher order refractions can be extracted from the light signal. The distribution of light or data with the retinal deep scatter effect removed as illustrated in Figures 6F and 6G can be used to extract such higher order refractions.

While the present invention has been described in terms of particular and exemplary embodiments, the scope of the present invention is defined by the attached claims, which may properly include in their scope embodiments and alternatives not specifically described herein but nonetheless representative of the invention disclosed. Accordingly, the application is not limited to the characterization of a human eye, or by extension, an eye at all. The method and apparatus are equally applicable to the characterization of an object that includes an optical system with an input/output aperture and a reflective plane.

CLAIMS:

1. An autorefractor for determining refraction characteristics of an object comprising:

an incident light beam emitter arranged to project the incident light beam onto an object under test to produce a refracted light beam;

a detector lens arranged to be in a path of the refracted light beam to produce a converged beam;

first and second sensors, each of the sensors being arranged to lie in a path of the converged beam, the first and second sensors constructed to generate output signals representative of the converged beam that is incident upon the first and second sensors; and

a processor connected to receive the output signals by the first and second sensors, the processor being constructed and arranged to calculate the refraction characteristics based on the signals output by the first and second sensors;

wherein a focal length of the detector lens is adjustable.

2. The autorefractor of claim 1, wherein the processor is constructed and arranged to control the focal length of the detector lens, the processor being further constructed and arranged to perform steps of:

changing the focal length of the detector lens so that one of the first and second sensors lie in a position that corresponds to a retinal conjugate of the object under test to produce first photosensor data;

analyzing the first photosensor data to determine retinal deep scatter;

changing the focal length of the detector lens so that the converged light that falls upon one of the first and second sensors takes up a larger area of one of the first and second sensors compared to the retinal conjugate position, so as to produce second photosensor data; and

subtracting the determined retinal deep scatter from the second photosensor data.

3. The autorefractor of claim 1, wherein the detector lens has a fixed position with respect to the object under test.

4. The autorefractor of claim 3, wherein the detector lens is a liquid lens, the focal length of the liquid lens being adjustable by changing a voltage applied to the liquid lens.

5. The autorefractor of claim 1, wherein the focal length of the detector lens is adjustable by changing a position of the detector lens along the path of the refracted light beam.

6. The autorefractor of claim 1, wherein the incident light beam emitter comprises:

a light source;

a beam splitter; and

a relay lens;

wherein the light source, the beam splitter, and the relay lens are arranged with respect to one another and the object under test so that light from the light source reflects off of the beam splitter, passes through the relay lens, reflects off of the object under test, passes back through the relay lens, and passes through the beam splitter.

7. The autorefractor of claim 1, further comprising a movable field lens, wherein the movable field can be arranged so that the converged beam passes through the field lens before falling on the second sensor.

8. An autorefractor comprising:

a incident light beam emitter arranged to project the incident light beam onto an object under test to produce a refracted light beam;

a detector lens arranged to be in a path of the refracted light beam to produce a converged beam;

first and second sensors, each of the sensors being arranged to lie in a path of the converged beam, the first and second sensors constructed to generate output signals representative of the converged beam that is incident upon the first and second sensors; and

a processor connected to receive the output signals by the first and second sensors, the processor being constructed and arranged to calculate the refraction characteristics based on the signals output by the first and second sensors;

wherein a location of one of the first and second sensors is adjustable along the converged beam.

9. The autorefractor of claim 8, wherein the processor is constructed and arranged to control the location of an adjustable one of the first and second sensors, the processor being further constructed and arranged to perform steps of:

moving the adjustable one of the first and second sensors with respect to the detector lens so that the adjustable one of the first and second sensors lies in a position that corresponds to a retinal conjugate of the object under test to produce first photosensor data;

analyzing the first photosensor data to determine retinal deep scatter;

moving the adjustable one of the first and second sensors away from the retinal conjugate position so that the converged light that falls upon the adjustable one of the first and second sensors takes up a larger area of the adjustable one of the first and second sensors compared to the retinal conjugate position, so as to produce second photosensor data; and

subtracting the determined retinal deep scatter from the second photosensor data.

10. The autorefractor of claim 8, wherein the incident light beam emitter comprises:

a light source;

a beam splitter; and

a relay lens;

wherein the light source, the beam splitter, and the relay lens are arranged with respect to one another and the object under test so that light from the light source reflects off of the beam splitter, passes through the relay lens, reflects off of the object under test, passes back through the relay lens, and passes through the beam splitter.

11. The autorefractor of claim 8, further comprising a movable field lens, wherein the movable field can be arranged so that the converged beam passes through the field lens before falling on the second sensor.

12. An autorefractor comprising:

a incident light beam emitter arranged to project the incident light beam onto an object under test to produce a refracted light beam;

a detector lens arranged to be in a path of the refracted light beam to produce a converged beam;

first and second sensors, each of the sensors being arranged to lie in a path of the converged beam, the first and second sensors constructed to generate output signals representative of the converged beam that is incident upon the first and second sensors; and

a processor connected to receive the output signals by the first and second sensors, the processor being constructed and arranged to calculate the refraction characteristics based on the signals output by the first and second sensors;

wherein a focal length of the detector lens is adjustable; and

wherein a location of one of the first and second sensors is adjustable along the converged beam.

13. The autorefractor of claim 12, wherein the processor is constructed and arranged to control the location of an adjustable one of the first and second sensors, the processor being further constructed and arranged to perform steps of:

moving the adjustable one of the first and second sensors with respect to the detector lens so that the adjustable one of the first and second sensors lies in a position that corresponds to a retinal conjugate of the object under test to produce first photosensor data;

analyzing the first photosensor data to determine retinal deep scatter;

moving the adjustable one of the first and second sensors away from the retinal conjugate position so that the converged light that falls upon the adjustable one of the first and second sensors takes up a larger area of the adjustable one of the first and second sensors compared to the retinal conjugate position, so as to produce second photosensor data; and

subtracting the determined retinal deep scatter from the second photosensor data.

14. The autorefractor of claim 12, wherein the detector lens has a fixed position with respect to the object under test.

15. The autorefractor of claim 14, wherein the detector lens is a liquid lens, the focal length of the liquid lens being adjustable by changing a voltage applied to the liquid lens.

16. The autorefractor of claim 12, wherein the focal length of the detector lens is adjustable by changing a position of the detector lens along the path of the refracted light beam.

17. The autorefractor of claim 12, wherein the incident light beam emitter comprises:

a light source;

a beam splitter; and

a relay lens;

wherein the light source, the beam splitter, and the relay lens are arranged with respect to one another and the object under test so that light from the light source reflects off of the beam splitter, passes through the relay lens, reflects off of the object under test, passes back through the relay lens, and passes through the beam splitter.

18. The autorefractor of claim 12, further comprising a movable field lens, wherein the movable field can be arranged so that the converged beam passes through the field lens before falling on the second sensor.

19. An autorefractor comprising:

a incident light beam emitter arranged to project the incident light beam onto an object under test to produce a refracted light beam;

a detector lens arranged to be in a path of the refracted light beam to produce a converged beam;

a combination near/far sensor arranged to lie in a path of the converged beam, the combination near/far sensor being constructed to generate output signals representative of the converged beam that is incident upon the combination near/far sensor; and

a processor connected to receive the output signals by the first and second sensors, the processor being constructed and arranged to calculate the refraction characteristics based on the signals output by the first and second sensors;

wherein a focal length of the detector lens is adjustable; and

wherein a location of the combination near/far sensor is adjustable along the converged beam.

20. The autorefractor of claim 19, wherein the processor is constructed and arranged to control the focal length of the detector lens and the location of the combination near/far detector, the processor being further constructed and arranged to perform steps of:

moving the combination near/far sensor with respect to the detector lens so that the combination near/far sensor lies in a position that corresponds to a retinal conjugate of the object under test to produce first photosensor data;

analyzing the first photosensor data to determine retinal deep scatter;

moving the combination near/far sensor away from the retinal conjugate position so that the converged light that falls upon the combination near/far sensor takes up a larger area of the combination near/far sensor compared to the retinal conjugate position, so as to produce second photosensor data; and

subtracting the determined retinal deep scatter from the second photosensor data.

21. A method for measuring optical refraction of an object under test, comprising the steps of:

projecting an incident light beam onto an object under test to produce a refracted light beam;

passing the refracted light beam through a detector lens to produce a converged light beam that is incident upon a photosensor;

moving the photosensor with respect to the detector lens so that the photosensor lies in a position that corresponds to a retinal conjugate of the object under test to produce first photosensor data;

analyzing the first photosensor data to determine retinal deep scatter;

moving the photosensor away from the retinal conjugate position so that the converged light that falls upon the photosensor takes up a larger area of the photosensor compared to the retinal conjugate position, so as to produce second photosensor data; and

subtracting the determined retinal deep scatter from the second photosensor data.

22. The method of claim 21, wherein the photosensor comprises a two-dimensional array of pixels, the step of analyzing at least one of the first and second photosensor data including analyzing data from selected subsets of the array of pixels, each of the selected subsets defining a strip of the pixels running across a surface of the photosensor.

23. The method of claim 22, wherein the selected subsets represent different strips of the pixels, all of the strips running through a single point on the surface of the photosensor.

24. The method of claim 23, wherein each of the strips of pixels runs from one edge of the two-dimensional array of pixels to another edge.

25. The method of claim 23, further comprising the step of analyzing at least one of the first and second photosensor data to identify a center of the converged light, a first end of each of the strips of pixels being the center of the converged light.

26. The method of claim 25, further comprising a step of identifying the edge of the converged light beam producing at least one of the first and second photosensor data, a second end of each of the strips of pixels lying on the edge of the converged light beam.

27. The method of claim 23, further comprising the step of analyzing at least one of the first and second photosensor data to identify a center of the converged light and an edge of the converged light, each end of each of the strips of pixels lying on the edge of the converged light, each strip of pixels passing through the center of the converged light.

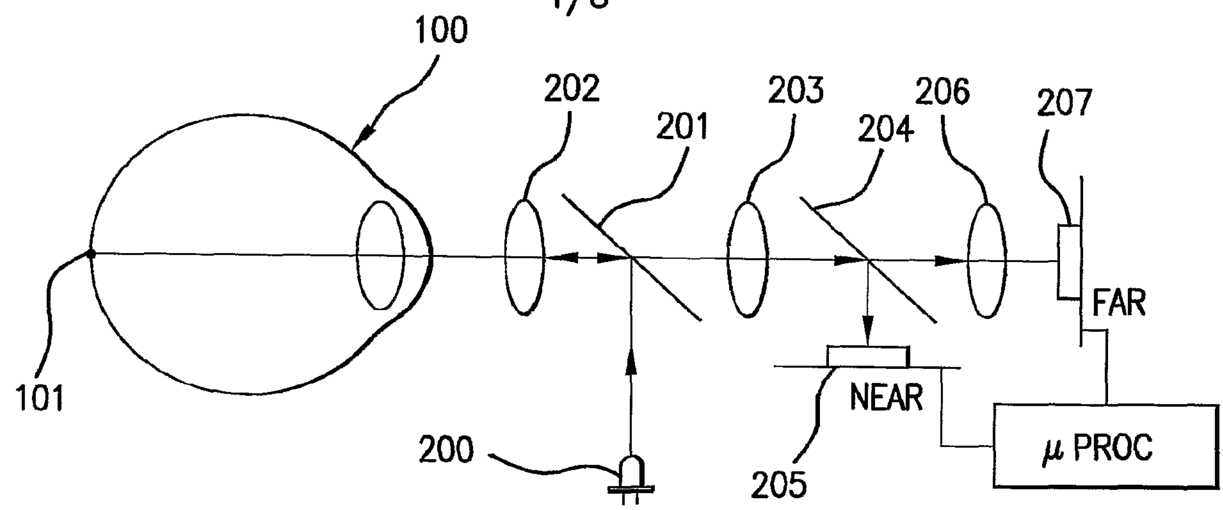


FIG.1A

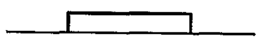


FIG.1B

FIG.1C

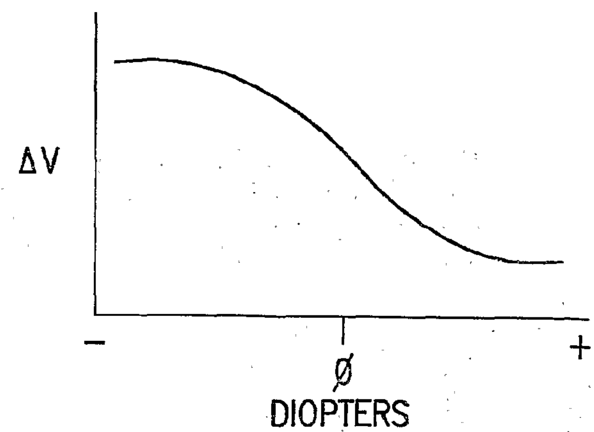


FIG.1D

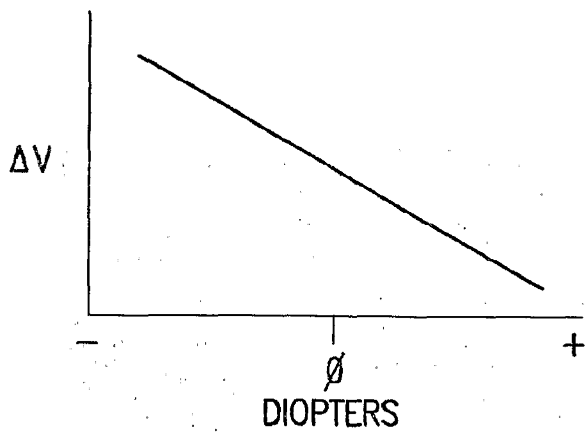


FIG.1E

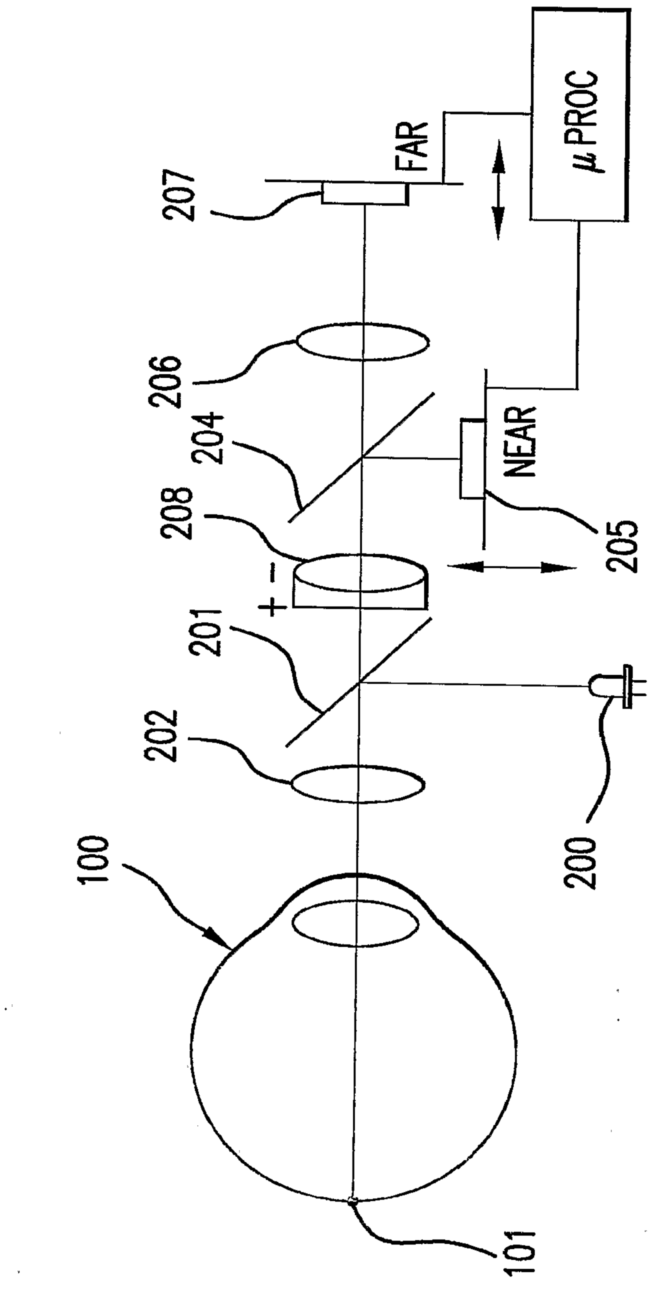


FIG.2A

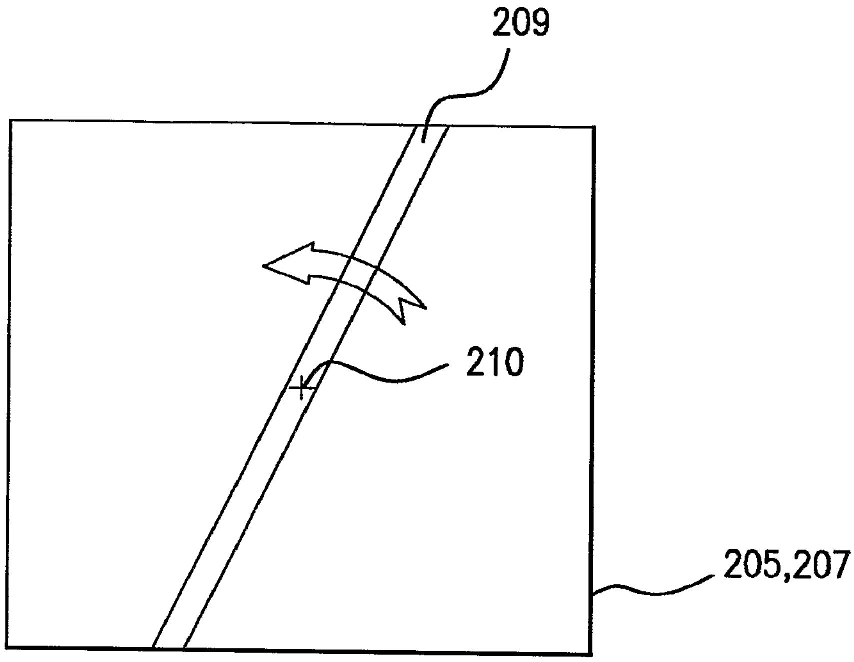


FIG.2B

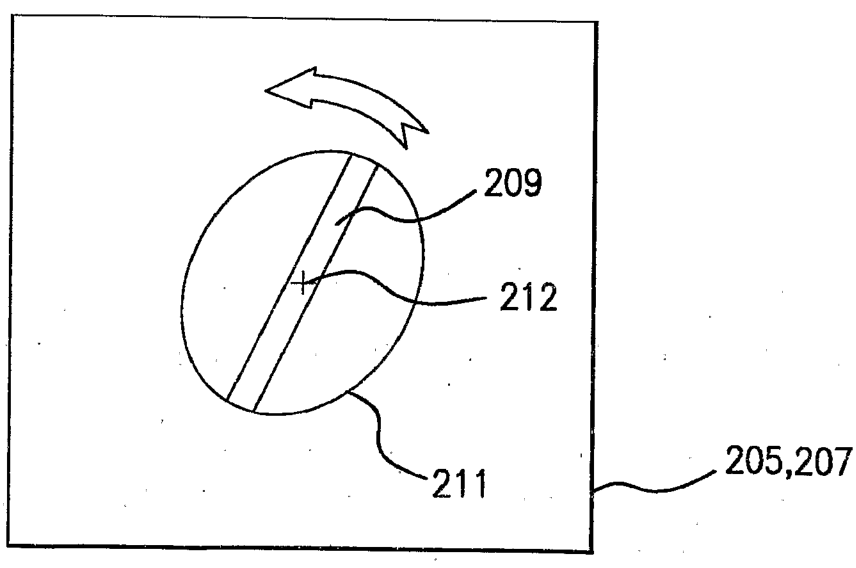


FIG.2C

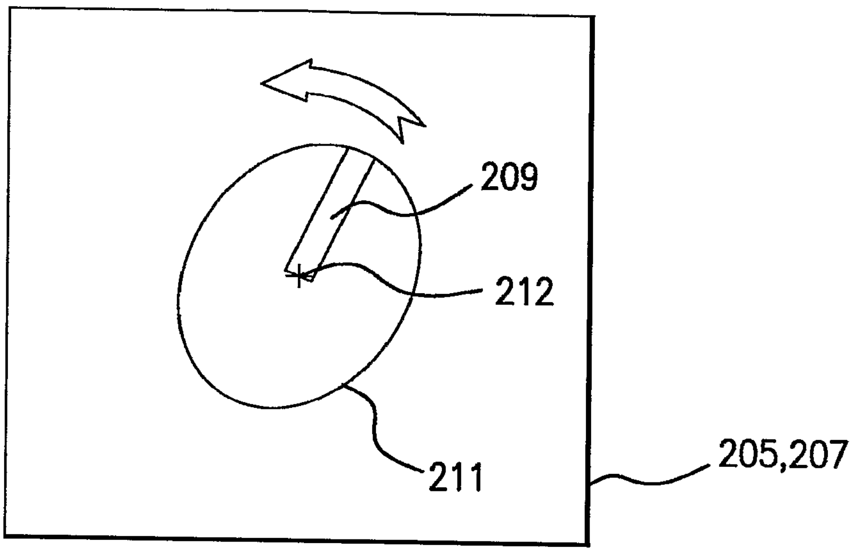


FIG.2D

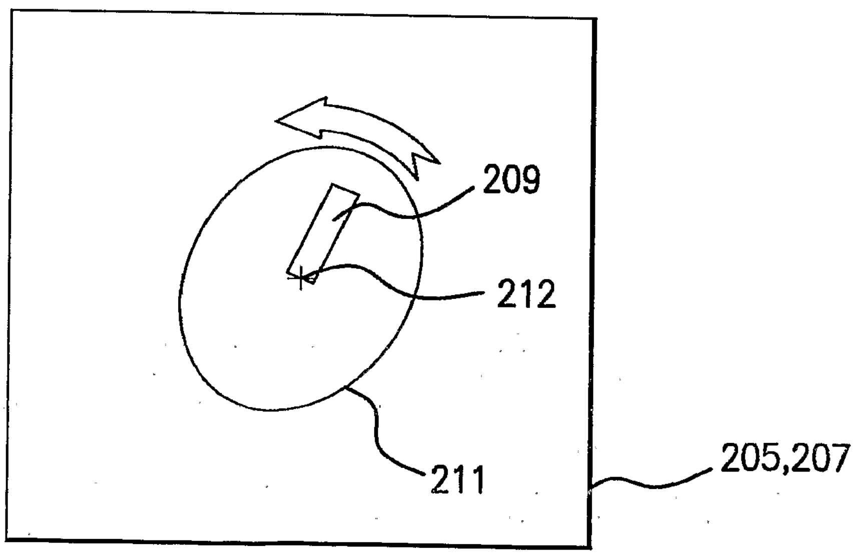


FIG.2E

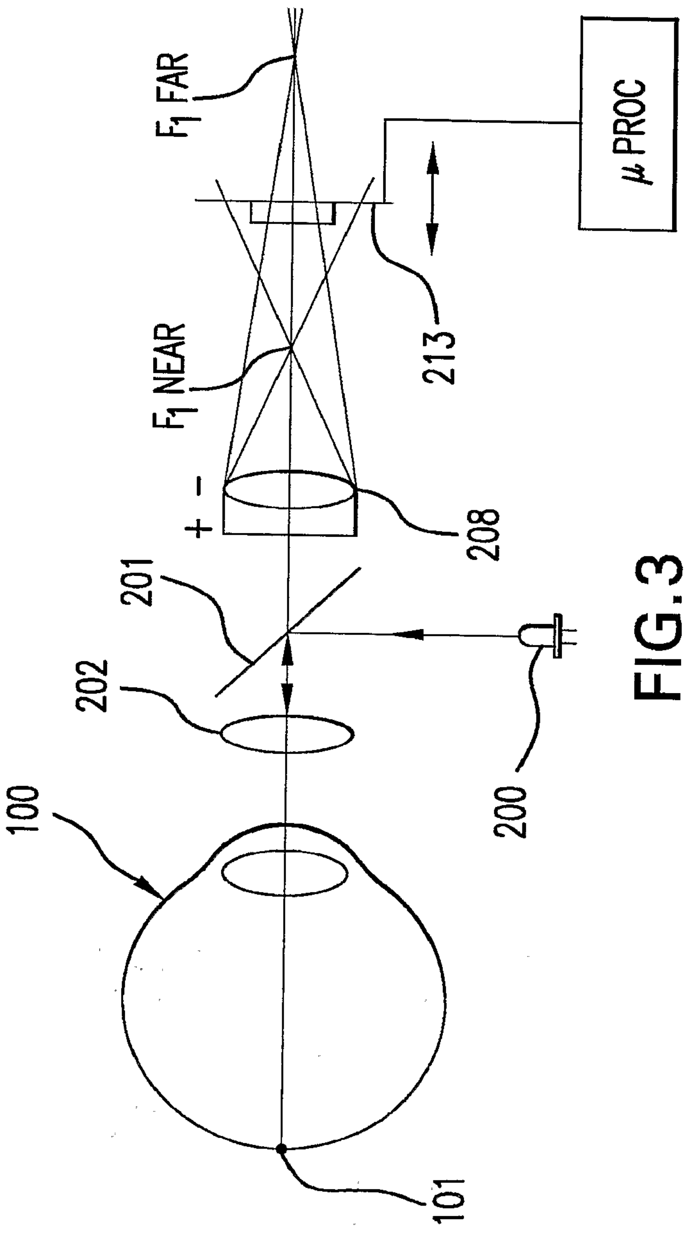
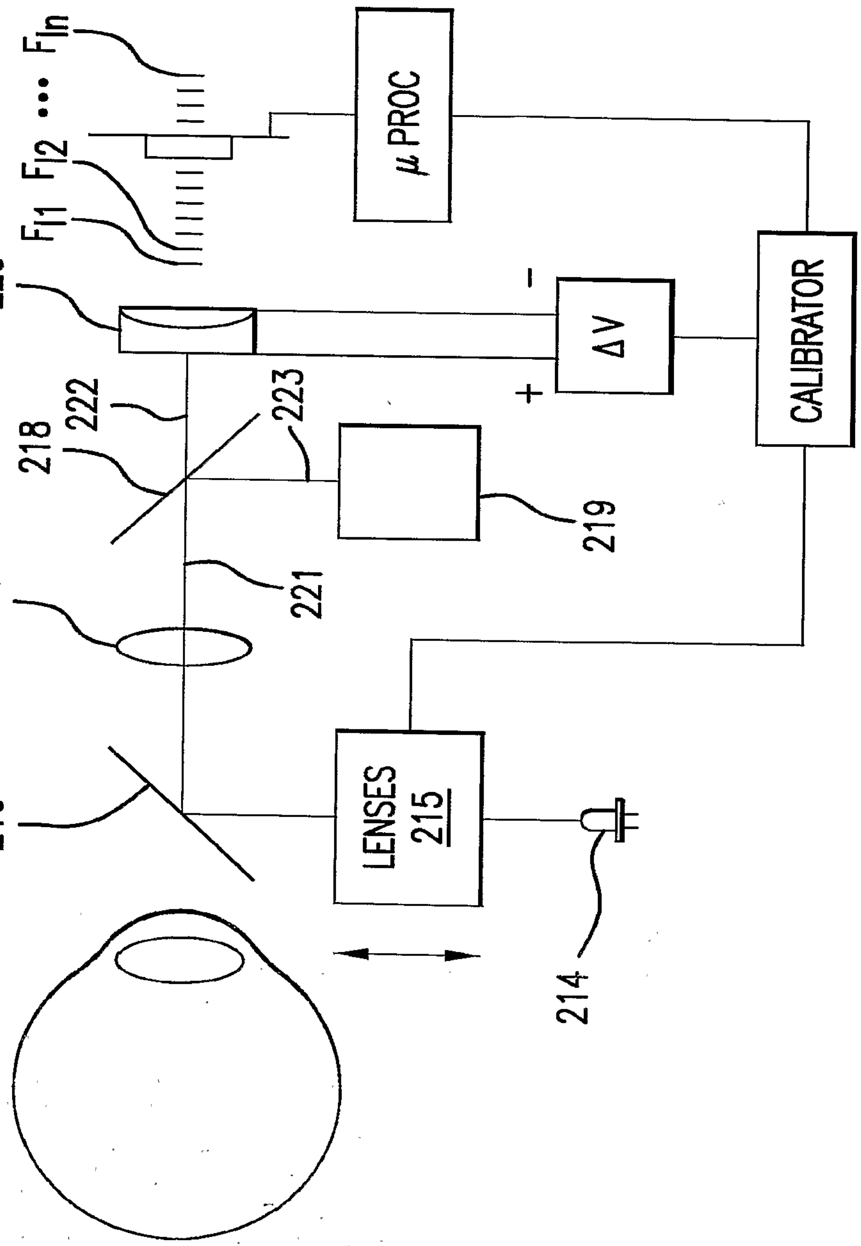


FIG.3



216
217
218
222
223
220
F_{I1}
F_{I2}
•••
F_{In}
μ PROC
−
ΔV
+
CALIBRATOR
219
221
LENSES
215
214

FIG.4

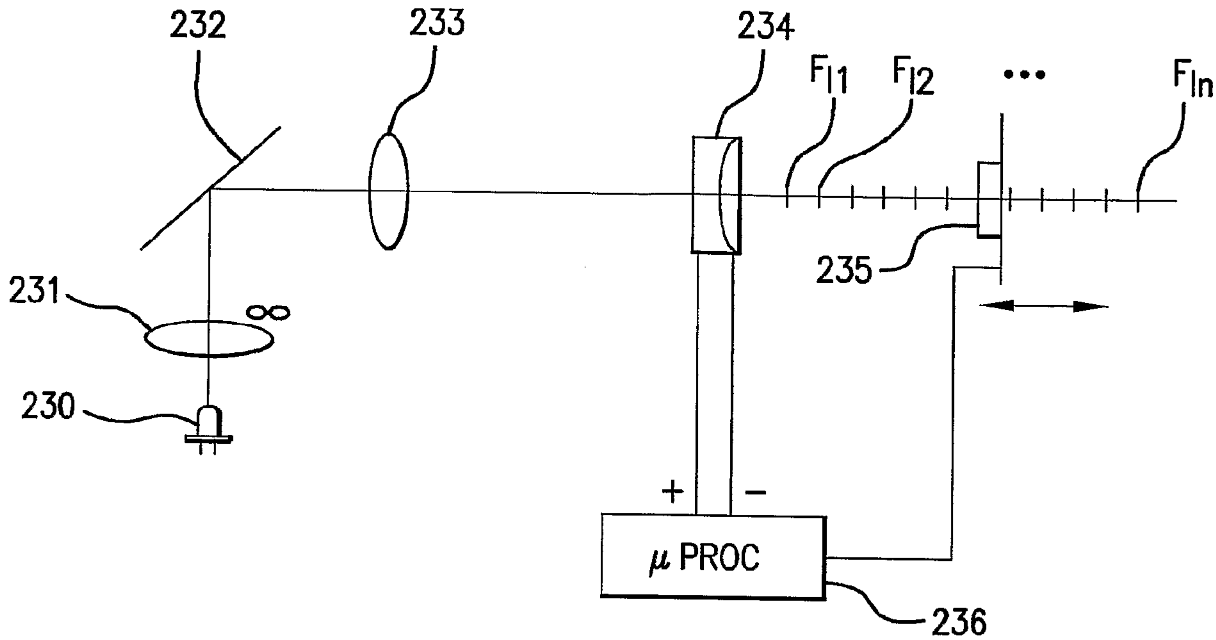


FIG.5A

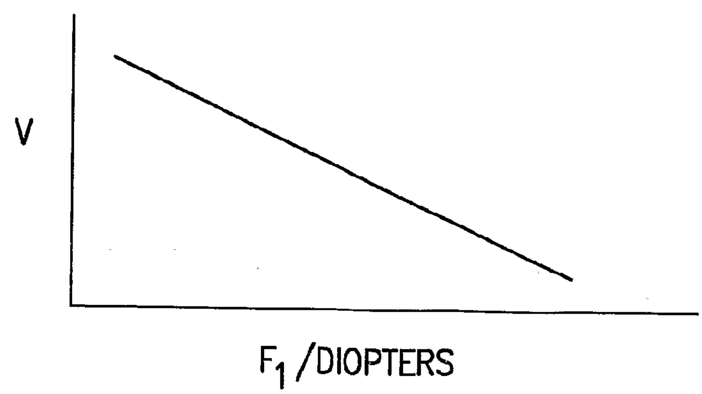


FIG.5B

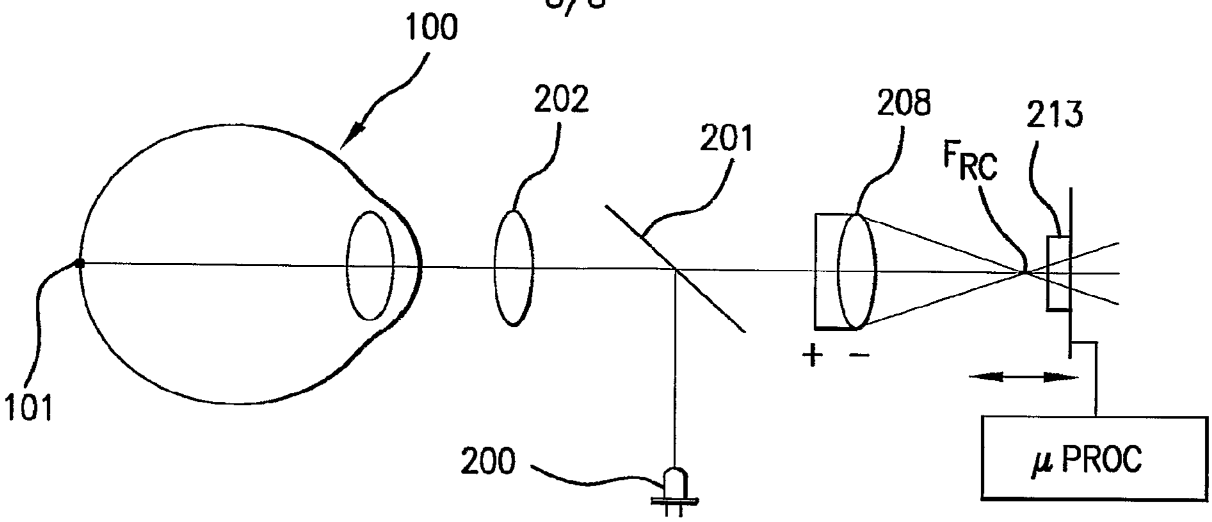


FIG.6A

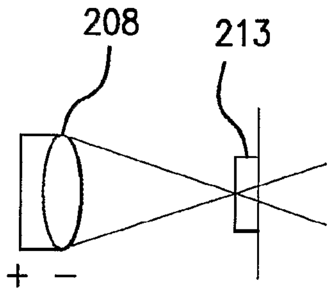


FIG.6B

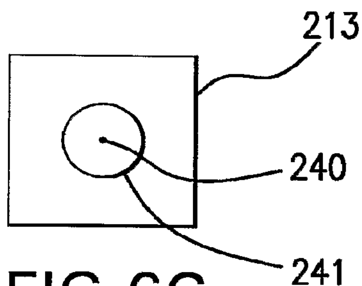


FIG.6C

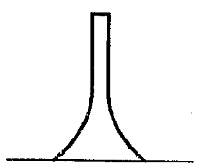


FIG.6D

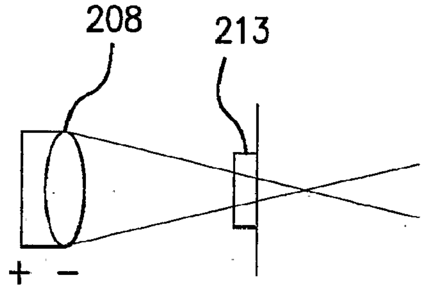


FIG.6E

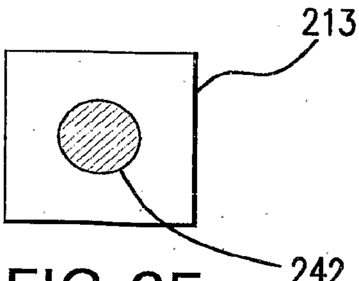


FIG.6F

FIG.6G