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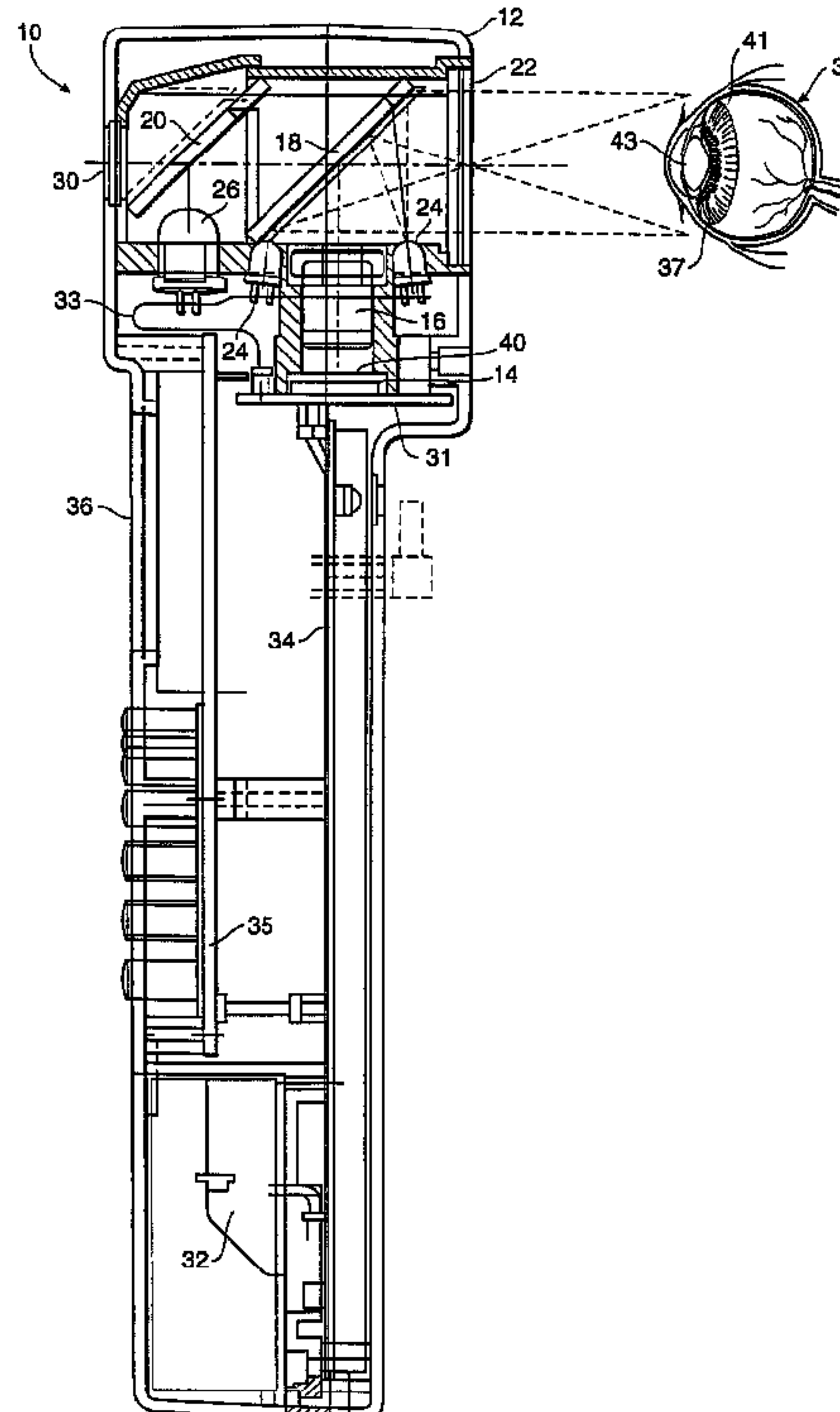
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(54) Titre : PUPILLOMETRE DE DETECTION D'IRREGULARITE DE PUPILLES, DE SUIVI VISUEL, ET A CAPACITE DE DETECTION DE LA REACTION PUPILLAIRE, A CAPACITE DE DEPISTAGE DE GLAUCOME, A CAPACITE DE MESURE DE LA TOPOGRAPHIE CORNEENNE, A CAPACITE DE DETECTION DE LA PRESSION INTRACRANIEENNE, ET A CAPACITE DE MESURE DE L'ABERRATION OCULAIRE

(54) Title: PUPILOMETER WITH PUPIL IRREGULARITY DETECTION, PUPIL TRACKING, AND PUPIL RESPONSE DETECTION CAPABILITY, GLAUCOMA SCREENING CAPABILITY, CORNEAL TOPOGRAPHY MEASUREMENT CAPABILITY, INTRACRANIAL PRESSURE DETECTION CAPABILITY, AND OCULAR ABERRATION MEASUREMENT CAPABILITY



(57) Abrégé/Abstract:

This invention is a pupilometer (10) having a pupil irregularity or non-uniformity detection capability. The pupilometer may comprise an imaging sensor (14) for generating signals representative of a pupil of an eye (43), a data processor, a program

(57) Abrégé(suite)/Abstract(continued):

executable by the data processor for enabling the data processor to process signals received from the imaging sensor, and to thereby identify one or more regions of non-uniformity within an image of a perimeter of the pupil. The pupilometer may incorporate several innovative calibration, threshold routines, which may provide the basis for an innovative medical diagnostics system, when coupled to a network containing a suitable medical database, and data processing hardware.

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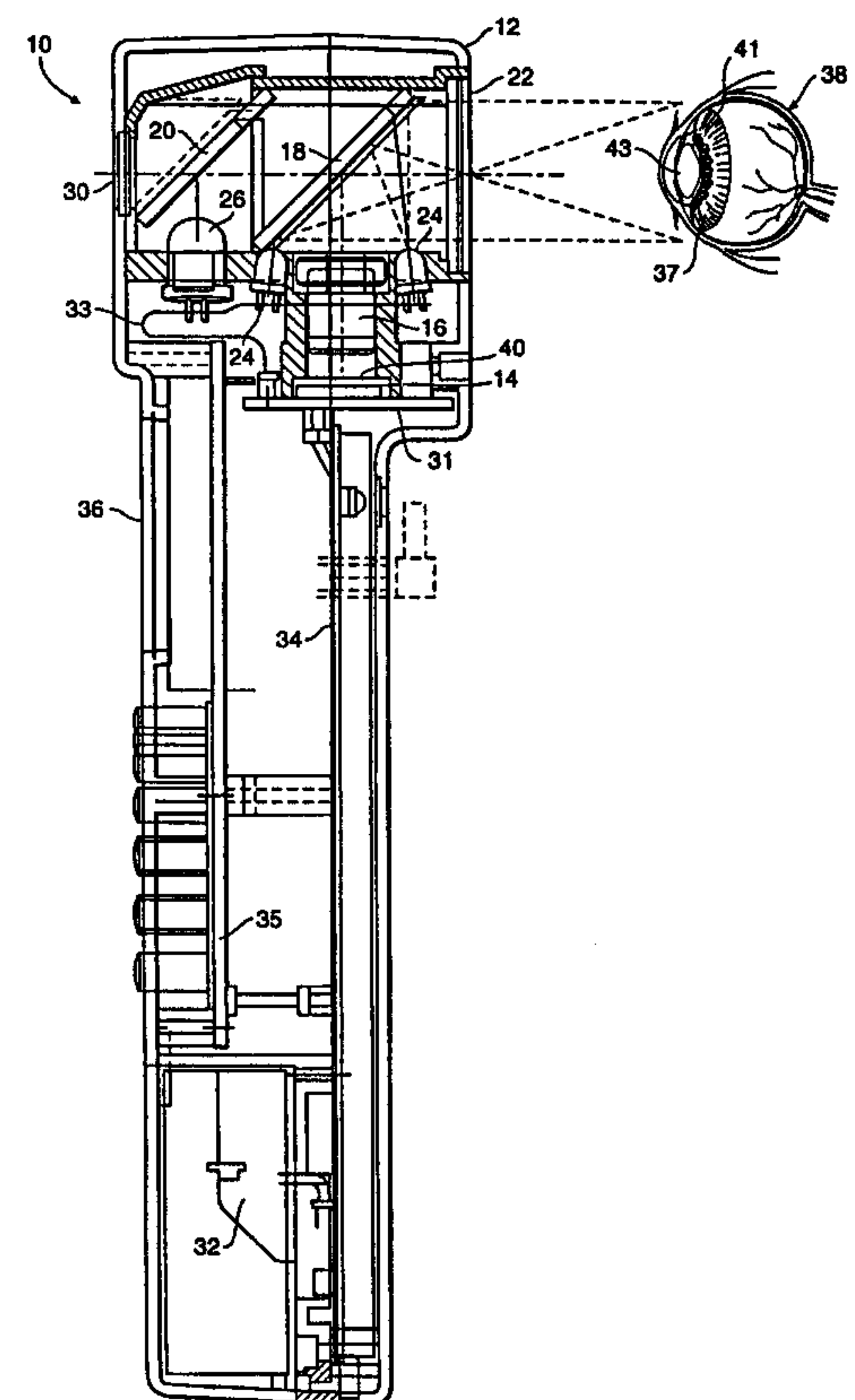
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(54) Title: PUPILOMETER WITH PUPIL IRREGULARITY DETECTION, PUPIL TRACKING, AND PUPIL RESPONSE DETECTION CAPABILITY, GLAUCOMA SCREENING CAPABILITY, CORNEAL TOPOGRAPHY MEASUREMENT CAPABILITY, INTRACRANIAL PRESSURE DETECTION CAPABILITY, AND OCULAR ABERRATION MEASUREMENT CAPABILITY

(57) Abstract

This invention is a pupilometer (10) having a pupil irregularity or non-uniformity detection capability. The pupilometer may comprise an imaging sensor (14) for generating signals representative of a pupil of an eye (43), a data processor, a program executable by the data processor for enabling the data processor to process signals received from the imaging sensor, and to thereby identify one or more regions of non-uniformity within an image of a perimeter of the pupil. The pupilometer may incorporate several innovative calibration, threshold routines, which may provide the basis for an innovative medical diagnostics system, when coupled to a network containing a suitable medical database, and data processing hardware.



DESCRIPTION

Pupilometer With Pupil Irregularity Detection, Pupil Tracking, And Pupil Response
Detection Capability, Glaucoma Screening Capability, Corneal Topography Measurement
Capability, Intracranial Pressure Detection Capability, And Ocular Aberration
Measurement Capability

Field of the Invention

The present invention relates generally to pupilometry systems and, more particularly, to pupilometry systems having a pupil irregularity detection, pupil tracking, and pupil response detection capability, as well as glaucoma screening capability, corneal topography measurement capability, intracranial pressure detection capability, and ocular aberration measurement capability. In one particularly innovative aspect, the present invention relates to hand-held pupilometry systems having a pupil irregularity detection capability, to methods and processing sequences used within such systems, and to methods of using such systems.

In another innovative aspect, the present invention relates to a medical diagnostics system incorporating a pupilometer and medical database for correlating actual or derived pupillary image analysis data with stored medical data to formulate medical diagnoses, and to methods of implementing and utilizing such a diagnostics system.

In another innovative aspect, the present invention relates to a medical diagnostics system incorporating a pupilometer which can be used to screen for Glaucoma, and for methods of implementing and utilizing such a diagnostics system.

In another innovative aspect, the present invention relates to a medical diagnostics system incorporating a pupilometer for detecting elevated intracranial pressure, and for methods of implementing and utilizing such a diagnostics system.

In another innovative aspect, the present invention relates to a medical diagnostics system incorporating a pupilometer for assessing the level of brain function, and for methods of implementing and utilizing such a diagnostics system.

In another innovative aspect, the present invention relates to a medical diagnostics system incorporating a pupilometer for testing the functional integrity of afferent peripheral and cranial pathways as well as testing efferent cranial nerve involvement in patients with afferent pupillary defects, and for methods of implementing and utilizing such a diagnostics system.

In another innovative aspect, the present invention relates to a medical diagnostics system incorporating a pupilometer for testing the functional integrity of auditory pathways, and for methods of implementing and utilizing such a diagnostics system.

Background of the Invention

5 Systems for monitoring pupil size and pupil responsiveness characteristics are well known in the art and are generally referred to as pupilometry systems or, simply, pupilometers. One early pupilometer is described in U.S. Patent No. 3,533,683, which issued to Stark et al. on October 13, 1970 and is entitled "Dynamic Pupilometers Using Television Camera System" (incorporated herein by reference). The Stark et al. system
10 employed a television camera system, a digital computer system, an infrared light source, and a visual light stimulator for determining the instantaneous size of a pupil as an eye (or neurologic pupillary control system) of a patient was exposed to various stimuli. Like the early Stark et al. system, conventional pupilometers measure, for example, the diameter of a pupil before and after the pupil is exposed to a light stimulus pulse and also measure the
15 rates at which the pupil may constrict and dilate in response to the initiation and termination of the light stimulus pulse. Pupilometers may comprise hand-held units or, alternatively, may comprise desk or table-mounted, stand-alone units. Pupilometers also generally include some mechanism for ensuring that an imager within the pupilometer is properly positioned in relation to a pupil to be imaged. For example, U.S. Patent No.
20 5,646,709 (incorporated herein by reference), issued to Elbert P. Carter, describes an electronic centering system for ensuring that a pupilometer is properly positioned in relation to a pupil to be imaged. Similarly, U.S. Patent No. 5,187,506 (incorporated herein by reference), issued to Elbert P. Carter, describes an eye orbit housing for ensuring proper positioning between a pupilometer and an eye of a subject prior to the initiation of a
25 pupillary scanning procedure.

Those skilled in the art will appreciate, however, that for a pupilometer to have maximum utility maximum flexibility should be provided for positioning the imager. For example, in the case of a hand-held system few, if any, restrictions should be placed upon the orientation of the imager prior to enabling an imaging function. The reason for this is
30 that medical personnel at, for example, an accident site may have difficulty in positioning an imager in a prescribed position for acquiring pupillary response data. Thus, it is believed that, for hand-held units in particular, a need exists within the pupilometer field for improved data acquisition and processing systems and methods, as such systems and methods may substantially reduce system dependence on imager orientation and may
35 allow pupilometers to become more user friendly.

Similarly, those skilled in the art will appreciate that a need exists for pupilometers that are capable of evaluating more than a mere pupillary response to light stimulus pulses. For example, it is believed that a substantial need exists for a pupilometer that is capable not only of measuring changes in pupillary diameter in response to one or more light stimulus pulses, but also of evaluating pupil shape and/or segmental responses to a visual stimulus. Stated somewhat differently, it is believed that a substantial need exists for a pupilometer having a pupillary shape irregularity or non-uniformity detection capability.

Finally, it is believed that a substantial need exists for pupilometer-based diagnostics systems, as such systems may provide medical practitioners with a cost effective, non-invasive means for gathering and assessing numerous physiologic parameters.

For example, the present invention can be used to screen for Glaucoma, which is the second leading cause of blindness in the world. Visual field perimetry is presently used for diagnosing Glaucoma. In visual field perimetry, a white background and multiple green flicker sources are used. The green sources are randomly turned on for approximately one second durations and the subject patient is asked to press a button if he/she sees a green light. The procedure is repeated until the entire visual field is mapped for each eye. Loss of visual field sensitivity is indicative of Glaucoma.

The current standard of care for Glaucoma detection, however, suffers from inaccuracy and human/patient error. The current standard of care relies on the patient to respond to his or her visual detection of green light by pressing a button. The patient has a limited window of time in which to respond to the green light. Thus, if the patient is not concentrating or responds too quickly or too slowly, the perimetry device will not register the patient's response, and the accuracy of the diagnosis is comprised. Furthermore, current perimetry devices are large machines that are immobile. They are for use in doctors' offices only. Thus, a need exists for improved systems and methods for Glaucoma detection, and the present invention meets these needs and solves the problems associated with standard techniques.

Another area of diagnostic need relates to assessing the level of brain function to diagnose disorders such as autism, age-related disorders, and drug impairment or intoxication. Neurological exams today do not typically include pupilometry beyond the use of a pin-light. Currently, expensive and/or time-consuming tests are required to diagnose impairment of brain function. And, the pin-light test is subjective, non-quantifiable, and inaccurate. The present invention solves these by providing a method and system to closely track the pupil while presenting the eye with a moving visual stimuli to determine the level of coordination. The present invention is capable of quantifying

tracking errors, which might occur in the course of a neurological exam, and reduces the subjectivity and increases the repeatability of exams to assess brain function.

Another area of diagnostic need is diagnosis of neurological disease or trauma. Dermatome mapping of patients is commonly done with a pin-prick to determine the level of dorsal root or spinal cord injury. This test, however, is subjective and usually requires cognitive response from a patient. There exists a need for noninvasive diagnosis of neural damage or trauma. The present invention fills that need by providing a means of quantitatively measuring pupillary response to noxious stimulation. Furthermore, this invention is useful in diagnosing dorsal root and spinal cord injuries in unconscious patients with no cognitive response capabilities. It is further useful in diagnosing and monitoring the progression of demyelinating diseases such as multiple sclerosis, which affects conduction velocity through nerve fibers. In addition, testing the level of epidural anesthetic block may be accomplished using pupilometry with this automated stimulus control.

Finally, an area of diagnostic need relates to testing the functional integrity of auditory pathways, i.e., hearing screening. Particularly with infants, hearing has been subjectively screened using stimuli such as in a clap test while observing the startle response. Other tests, such as EEG-type brain stem audible evoked potential (AEP) monitoring systems have been used, but require attachment of electrodes to the scalp and are cumbersome to use. Middle ear tone-feedback monitoring is also used, but is not capable of measuring latency information. The present invention solves these and other problems associated with the prior art by providing hearing screening using objective pupilometer-based testing systems and methods. The pupilometer-based systems are not cumbersome, are easy to use and provide latency information for diagnosing and monitoring the progression of demyelinating diseases.

Summary of the Invention

In one particularly innovative aspect, the present invention is directed toward a pupilometer having a pupil shape irregularity detection capability. For example, a pupilometer in accordance with the present invention may comprise an imaging sensor for generating signals representative of a pupil of an eye, a data processor coupled to the imaging sensor, and a program executable by the data processor for enabling the data processor to process signals received from the imaging sensor and to thereby identify one or more regions of non-uniformity or irregularity within an image of a perimeter of the imaged pupil.

In one presently preferred embodiment, the one or more regions of pupillary non-uniformity or irregularity are identified by identifying a center point of a pupil and determining a plurality of radii representing distances from the center point to the perimeter of the pupil along a respective plurality of angles in a R, θ coordinate system.

5 In another innovative aspect, the present invention is directed to a medical diagnostics system incorporating a pupilometer and medical database for correlating actual or derived pupillary image analysis data with stored medical data to formulate medical diagnoses, and to methods of implementing and utilizing such a diagnostics system.

10 In still other innovative aspects, the present invention is directed to improved thresholding and image data processing algorithms for use within a pupilometer. For example, a pupilometer in accordance with the present invention may utilize a plurality of row and column histogram data sets in an iterative fashion to identify a preferred threshold value for locating the pupil of an eye within an image data frame.

15 A pupilometer in accordance with the present invention may also process image frame data to determine a shape and/or diameter of the sclera/iris border of an eye and, thereafter, use the determined shape or diameter to evaluate an orientation of the eye of the patient and/or to correlate measured units with defined units of measurement.

20 When provided with an additional armature supporting, for example, a visible light emitting diode (LED), a pupilometer in accordance with the present invention may be used to measure afferent or consensual pupillary responses to visual stimulus pulses. In such embodiments, a visual stimulus is applied to an eye under examination, and the response of the monitored pupil is recorded and evaluated. Then, as the monitored pupil is allowed to dilate, a stimulus pulse is applied to the other eye of the patient, to see whether or not the monitored pupil again constricts. Following the second stimulus pulse, the monitored
25 pupil is allowed again to dilate, and a final visual stimulus is applied to the eye under examination. During the final stimulus pulse, the constrictive response of the monitored pupil (or lack thereof) is again measured. By measuring the response of the monitored pupil to each stimulus pulse, it is possible to detect retinal impairment in each eye of the patient.

30 In another innovative aspect, the present invention is directed to a medical diagnostics system incorporating a pupilometer, which can be used to screen for Glaucoma, and for methods of implementing and utilizing such a diagnostics system. This system comprises a pupilometer comprising an imaging sensor for generating signals representative of a pupil of an eye, a data processor, and a program executable by said data
35 processor for enabling said data processor to process signals received from said imaging sensor and to thereby identify the pupil's dynamic response to a light stimulus. The

program is further capable of storing the pupil's response data and comparing it to a database of normal measurements to determine if the test responses fall out of range. Alternatively, the program can transmit the data to a microprocessor or peripheral computer, which has stored therein a database of normal measurements, and wherein the
5 microprocessor or peripheral computer is capable of comparing the pupil's response data to the database of normal measurements and providing conclusions as to whether the pupil's response data falls outside of the norm and indicates Glaucoma.

In another innovative aspect, the present invention is directed to a medical diagnostics system incorporating a pupilometer for detecting elevated intracranial
10 pressure, and for methods of implementing and utilizing such a diagnostics system. This system comprises a pupilometer for generating a light source and projecting it to the eye and obtaining data descriptive of one or more pupillary characteristics. The system can further comprise a database for storing data descriptive of one or more pupillary characteristics, and a central processing unit, which may be coupled to the pupilometer,
15 for comparing the data obtained by the pupilometer to the data stored within the database such that the comparison will reveal whether the oculomotor nerve (CNIII) is compromised, thus indicating elevated intracranial pressure.

An exemplary embodiment of the invention is illustrated by a method of detecting elevated intracranial pressure. The method comprises the steps of: providing a
20 pupilometer, wherein the pupilometer comprises a light source that is amplitude modulated; continuously projecting light generated by the light source for a given length of time onto the eye of a patient in a predetermined pattern of amplitude modulation; obtaining, using the pupilometer, a first set of data representative of the pupil's response to the modulated light; storing within a database a second set of data representing pupillary
25 response to light stimulus received in said predetermined pattern of amplitude modulation; and comparing within a data analysis system said first set of data with said second set of data in order to determine whether the oculomotor nerves are compromised, thus indicating intracranial pressure.

In another innovative aspect, the present invention is directed to a medical
30 diagnostics system incorporating a pupilometer for assessing the level of brain function, and for methods of implementing and utilizing such a diagnostics system. This aspect of the invention provides a system comprising a pupilometer for obtaining data descriptive of one or more pupillary characteristics from a subject. The pupilometer may comprise means for providing a visual field to the subject such as a light generated from a visual
35 light source. The system further comprises a database for storing data descriptive of a plurality of pupillary characteristics associated with a set pattern of visual field movement,

and a central processing unit coupled to the pupilometer and the database for comparing the data obtained by the pupilometer to the data stored within the database to assess the subject's level of brain function.

In another innovative aspect, the present invention is directed to a medical
5 diagnostics system incorporating a pupilometer for testing the functional integrity of
afferent peripheral and cranial pathways as well as testing efferent cranial nerve
involvement in patients with afferent pupillary defects, and for methods of implementing
and utilizing such a diagnostics system. This system and associated method comprise a
pupilometer as previously described, for obtaining data descriptive of a plurality of
10 pupillary characteristics from an eye of a patient. The system further comprises a database
for storing data descriptive of a plurality of pupillary characteristics, and a central
processing unit coupled to the pupilometer for comparing the data obtained by the
pupilometer to the data stored within the database such that neurological disease or trauma
may be diagnosed based upon that comparison. The pupillary characteristics being
15 compared may be the amplitude of the pupillary response to a noxious stimulus or the
velocity of pupillary response to a noxious stimulus. The method associated with this
aspect of the invention comprises the steps of providing a pupilometer, and obtaining,
using the pupilometer, pupillary response data from the eye of a patient. The pupillary
response data can represent one or more pupillary response characteristics of the eye being
20 tested. The method can further comprise the steps of storing within a database data
representative of a plurality of pupillary response characteristics, and comparing with a
data analysis system the pupillary response data obtained from the patient with the stored
data to determine whether neurological disease or trauma is indicated.

In another innovative aspect, the present invention is directed to a medical
25 diagnostics system incorporating a pupilometer for testing the functional integrity of
auditory pathways, and for methods of implementing and utilizing such a system. The
system comprises a pupilometer for obtaining data descriptive of one or more pupillary
characteristics of an eye of a patient, as described herein. The system further comprises a
sound generating transducer in connection with an ear-piece, wherein the transducer is
30 synchronized to the pupilometer such that images of the eye are captured by the
pupilometer in sequence with the generation of sound. Thus, hearing can be tested in a
quantifiable and objective manner by analyzing pupillary response rather than relying on
the patient to consciously respond to the stimulus.

A method for testing the functional integrity of auditory pathways comprises the
35 steps of providing a pupilometer as described herein, providing a sound generating
transducer in connection with an ear-piece, and obtaining, using the pupilometer, a first set

of data descriptive of one or more pupillary characteristics from an eye of a patient or subject. The method may further comprise the steps of storing within a database a second set of data descriptive of a plurality of one or more pupillary characteristics associated with pupillary response to sound, and comparing within a data analysis system the first and the
5 second sets of data to determine whether the subject's hearing is impaired.

Other objects and features of the present invention will become apparent from consideration of the following description taken in conjunction with the accompanying drawings.

Brief Description of the Drawings

10 Fig. 1 is a cross-sectional view of a hand-held pupilometer in accordance with a preferred form of the present invention.

Fig. 2 is an illustration of a liquid crystal display and keypad that may be provided on a hand-held pupilometer in accordance with the present invention.

15 Fig. 3 is an enlarged cross-sectional view of an imaging section of a hand-held pupilometer in accordance with the present invention.

Fig. 4 is a three-dimensional plan view showing a preferred arrangement of a plurality of IR, blue and yellow LEDs that may be used for ocular illumination and stimulation within a pupilometer in accordance with the present invention.

20 Fig. 5 is a block diagram illustrating a group of programming objects that preferably comprise an operating program of a pupilometer in accordance with the present invention.

Fig. 6 is a timing diagram illustrating a typical stimulus/illumination sequence for the IR, blue and yellow LEDs that may be used within a pupilometer in accordance with the present invention.

25 Figs. 7(a) and 7(b) are illustrations of histogram data sets that may be developed in accordance with a preferred thresholding algorithm utilized by a pupilometer in accordance with the present invention.

Fig. 8 is a flow chart illustrating a basic operating protocol for a pupilometer in accordance with the present invention.

30 Fig. 9 is an illustration of a pupilometer incorporating a consensual measurement attachment in accordance with the present invention.

Description of Preferred Embodiments

A. Hardware Components of a Pupilometer in Accordance with the Present Invention

Turning now to the drawings, Fig. 1 provides a cross-sectional view of a hand-held pupilometer 10 in accordance with the present invention. Fig. 2 provides an illustration of a liquid crystal display and key pad that may be provided on the hand-held pupilometer 10, and Fig. 3 is an enlarged cross-sectional view of an imaging section of the hand-held pupilometer 10.

As shown in Figs. 1-3, the pupilometer 10 preferably includes a housing 12 wherein an imaging sensor 14, an objective lens 16, first and second beam splitters 18 and 20, a shield 22, four infrared (IR) LEDs 24, two yellow LEDs 26, a blue LED 28 (shown in Fig. 4), a reticle 30, a battery 32, an image signal processing board 34 and a liquid crystal display 36 are mounted. Stated somewhat differently, the pupilometer may comprise a viewing port (reticle 30 and shield 22), an imaging system (objective lens 16, imaging sensor 14 and related image processing electronics), an illumination system (IR LEDs 24, blue LED 28 and related control circuitry) and a stimulus system (yellow LEDs 26 and related control circuitry).

1. The Viewing Port

The viewing port (reticle 30 and shield 22) is provided to aid a user in properly positioning the pupilometer 10 for initial data acquisition. By looking through the reticle 30 and shield 22, the user of the pupilometer 10 is able to properly position the pupilometer 10 in front of an eye 38 of a patient, such that an image of the pupil of the patient's eye may be projected onto the imaging sensor 14. The reticle 30 preferably has circular targets (not shown) silk screened or etched on one surface. The targets are positioned along the user's line of sight so as to appear concentric with the iris and pupil of an eye 38 under observation.

Those skilled in the art will appreciate that the reticle 30 and shield 22 also serve as environmental barriers and function to minimize exposure of the imaging system to caustic cleaning agents, biological material and airborne dust, all of which can have a negative impact upon the performance of the imaging system.

2. The Imaging System

The imaging sensor 14 preferably comprises a NxM bit CMOS imaging sensor of a type that is commercially available. One such imaging sensor is the 384x288 bit, Model OV5017, CMOS imaging sensor manufactured and distributed by Omnivision Technologies, Inc. of Sunnyvale, California. The imaging sensor 14 is mounted to an imager board 31 of the pupilometer 10 and is coupled to a microprocessor (not shown) provided on a main processing or mother board 34 of the pupilometer 10. This allows for

direct capture of digital images. Images in the form of 8 bit (or greater) gray scale bit maps are stored in system memory for image analysis and display on the liquid crystal display 36 (shown in Fig. 2). The microprocessor (not shown) preferably comprises an Elan SC 400 manufactured and distributed by Advanced Micro Devices, Inc., of Austin, TX.

The imaging system of the present invention is designed such that, when the hand-held pupilometer 10 is positioned in front of the eye 38 of a subject, a properly illuminated and in-focus image of the pupil 43 of the subject's eye 38 is obtained at the sensor plane 40 of the pupilometer 10. The objective lens 16 and a first beam splitter (i.e., wavelength selective filter) 18 preferably are used to focus an image of the pupil 43 of the subject's eye 38 on the sensor plane 40. In a preferred form, the objective lens 16 comprises a five element lens having a focal length of 7.0 mm. The first beam splitter 18 preferably comprises a glass substrate having a thickness of 1.6 mm that is coated with a multi-layer dielectric coating (not shown) to form a wavelength selective filter. The subject side 42 of the beam splitter 18 is coated to enhance reflection at the blue and infrared (IR) wavelength bands with a 45° angle of incidence. The user side 44 of the beam splitter 18 is AR coated to minimize effects resulting from multiple reflections in the image path.

Thus, as shown in Figs. 1 and 3, the beam splitter 18 functions to direct blue and/or IR light generated by the blue and IR LEDs 24 and 28, respectively, toward the eye 38 of a patient and to provide a return path to the imaging sensor 14 for blue and/or IR light that is reflected from the eye 38 of the patient.

The microprocessor (not shown) provided on the main signal processing board 34 controls the operation and function of the various components comprising the imaging system as described more fully below.

3. The Illumination System

The illumination system preferably comprises a blue light emitting diode (LED) 28 and four infrared (IR) LEDs 24. The IR LEDs 24 preferably are arranged symmetrically about the objective lens 16 of the imaging system. The IR LEDs 24 and blue LED 28 are coupled to a flex circuit 33 that is coupled to the main signal processing board 34. When activated by the microprocessor (not shown), the IR LED's 24 emit IR light preferably having a wavelength of substantially 850 nm. Thus, those skilled in the art will appreciate that the emission bandwidth of the IR LEDs 24 lies beyond the physiological response of the human eye but within the photoelectric response of the imaging sensor 14. Stated somewhat differently, while the human eye is unable to detect the IR light emitted by the IR LEDs 24, IR light generated by the IR LEDs 24 and reflected by the eye 38 of a subject may be detected by the imaging sensor 14. The four IR LEDs 24 preferably are arranged

in diametrically opposed groups of two, as shown in Fig. 4. By arranging the IR LEDs 24 in the manner shown in Fig. 4, it is possible to more precisely control the IR illumination of a patient's eye 38 and, moreover, to achieve levels of 0, 50 and 100% illumination, if desired.

5 The blue LED 28 is used for ocular illumination in situations where the sclera/iris border of a patient's eye 38 may be difficult to detect with IR illumination alone. As shown in Fig. 4, the blue LED 28 preferably is placed on the same radial arc that is defined by the IR LEDs 24, which surround the objective lens 16. The blue LED 28, when activated by the microprocessor (not shown), preferably emits light having a
10 wavelength of substantially 470 nm. It has been discovered by the inventors hereof that light in the blue color band may be used to substantially improve sclera/iris border image contrast because the iris 37 and sclera 41 of a subject's eye 38 generally have substantially different light absorption and reflection characteristics in the blue color band. Thus, the use of a blue LED 28 for sclera/iris border imaging is believed to be a particularly
15 innovative aspect of the present invention.

Because the human eye is responsive to blue radiation, the blue LED 28 preferably is only activated for brief periods of time in relation to the temporal response of a subject's eye 38 or, alternatively, is used in conjunction with the stimulus LEDs 26 described below. Moreover, in a preferred form, IR and blue light illumination of the eye 38 of a
20 subject may be performed in a multiplexed fashion, such that the eye of the subject is illuminated with IR light for a first period of time and, thereafter, illuminated with blue light for a second period of time. This is discussed more fully below with reference to Fig. 6.

The microprocessor (not shown) provided on the main signal processing board 34
25 controls the operation and function of the various components comprising the illumination system as described more fully below.

4. The Stimulus System

The stimulus system of the pupilometer 10 comprises two yellow LEDs 26 and a second beam splitter 20. The yellow LEDs 26 preferably are coupled to the flex circuit 33
30 and, when activated by the microprocessor (not shown), emit light having a wavelength of substantially 570 nm. Like the first beam splitter 18, the second beam splitter 20 preferably comprises a glass substrate having a thickness of 1.6 mm and is coated with a multi-layer dielectric coating (not shown) to form a wavelength selective filter. The subject side 50 of the beam splitter 20 is coated to enhance reflection at the yellow
35 wavelength band with a 45° angle of incidence, and the user side 52 of the beam splitter 20 is AR coated to minimize effects resulting from multiple reflections in the user's

observation path. The stimulus system of the pupilometer 10 preferably provides on-axis illumination of the pupil 43 of the eye 38 of a patient, as shown in Fig. 1.

B. Software Components of a Pupilometer in Accordance with the Present Invention

Turning now to Figs. 5-7, a pupilometer 10 in accordance with the present invention is a microprocessor based system and, therefore, preferably includes several software components or modules for controlling its operation. As is well known in the art, an operating system provides fundamental machine level interfaces between the hardware elements comprising the pupilometer 10. More specifically, various device drivers are used to provide an interface between the microprocessor (not shown) and the imaging sensor 14, IR LEDs 24, yellow LEDs 26, blue LED 28, keypad 39 and liquid crystal display 36.

The highest level of programming or code used within the pupilometer 10 is referred to herein as the P-Program, and the P-Program preferably is divided into five principal objects corresponding to different hardware and mathematical components. The five principal objects are illustrated in block diagram form in Fig. 5 and preferably include a graphic user interface (GUI) object 100, a stimulus/illumination object 102, a CMOS camera object 104, a feature extraction object 106 and an analysis object 108. All of the above-listed objects preferably are developed in Microsoft Visual C++ and Windows CE, and the graphic user interface (GUI) object 100 preferably is based on Win32 Api functions that are available in Windows CE. Visual C++ and Windows CE are software products distributed by Microsoft Corp. of Redmond, Washington.

1. Graphic User Interface (GUI) Object

The graphic user interface object 100 allows for data/information exchange between a user and the pupilometer 10. Information relating to the current status of the pupilometer 10 including mode of operation (i.e., direct or consensual response, left or right eye measurement etc.) and the battery level is displayed via the graphic user interface object 100. All inputs and outputs of the pupilometer 10 preferably are coordinated via the graphic user interface object 100. Verification of subject ID numbers and/or patient identification data may be accomplished under control of the graphic user interface object 100. Measurement parameters are determined and set with the assistance of the graphic user interface object 100. Instructions during measurement sequences and images of the iris 37 of the eye 38 of a subject are provided on the liquid crystal display 36 under control of the graphic user interface object 100. Similarly, results of measurement sequences are displayed on the liquid crystal display 36 under control of the graphic user interface object

100, and the option to transfer measurement results to a printer or network computer (not shown) is available through the graphic user interface object 100.

2. Stimulus/Illumination Object

5 The stimulus/illumination object 102 defines and controls the function of the yellow LEDs 26, IR LEDs 24 and blue LED 28 and, therefore, controls the stimulation and illumination of the eye 38 of a subject. The stimulus/illumination object 102 defines the various light profiles (i.e., yellow, IR and blue) as a function of time and controls activation of the yellow, IR and blue LEDs 26, 24 and 28, accordingly. In a typical stimulus/illumination sequence, the LEDs 26, 24 and 28 preferably are activated in the
10 manner described below. However, those skilled in the art will appreciate that the stimulus/illumination sequence may be varied depending upon the circumstances of any given situation, and that variations in the stimulus/illumination sequence may be effected through the user interface object 100.

During a typical stimulus/illumination sequence, the LEDs 24, 26 and 28 may be
15 operated as shown in Fig. 6. For example, during a typical measurement sequence, the yellow LEDs 26 may be activated and deactivated for successive 1 second intervals (i.e., "on" for 1 second and "off" for 1 second) for a period of 10 seconds total. Simultaneously, the IR LEDs 24 may be activated for all periods when the yellow LEDs 26 are "off," and may be deactivated, activated and deactivated (i.e., turned "off," "on"
20 and "off") for respective 0.04, 0.92 and 0.04 second intervals, while the yellow LEDs 26 are turned "on." Similarly, the blue LED 28 may be activated, deactivated and activated for respective 0.04, 0.92 and 0.04 second intervals, while the yellow LEDs 26 are turned "on," and may be deactivated during all periods when the yellow LEDs are turned "off." This allows for the operation of the IR LEDs 24 and blue LED 28 to be multiplexed. In
25 such an embodiment, the image frame transfer rate preferably would be set, for example, to 50 frames per second.

3. The CMOS Camera Object

The CMOS camera object 104 controls the transfer of image data frames between the CMOS imaging sensor 14 and memory associated with the microprocessor (not
30 shown) provided on the main signal processing board 34 (i.e., between the imaging sensor 14 and the P-Program). Preferably, the rate of image frame transfer between the imaging sensor 14 and the memory associated with the microprocessor (not shown) may be programmably set within a range from 1 frame per second to 50 frames per second, depending upon the needs and/or desires of the user. However, those skilled in the art will
35 appreciate that in some instances it may be desirable to provide for faster frame transfer rates, and that such rates might be as high or higher than 100 frames per second. The

image frame acquisition or transfer rate is defined by the user under control of the graphic user interface object 100.

4. The Feature Extraction Object

The feature extraction object 106 defines several image processing procedures that are used to isolate a pupil within an image and to extract several pupil features such as size, shape and position from each pupil image data frame. All processing procedures defined by the feature extraction object preferably are performed on each image data frame, with the exception of the automatic thresholding procedure described below. The automatic thresholding procedure is applied during an initial calibration phase and, therefore, does not need to be applied to each image data frame. Rather, the results of the automatic thresholding procedure are used during feature extraction processing for each image data frame. The results of the automatic thresholding procedure also may be used to set and/or adjust image exposure gain settings within the system.

The feature extraction object 106 employs a flying spot processing algorithm to identify the center of the pupil, a fitted circumference and/or radius of the pupil and, preferably, 48 radii representing the distance between the center and perimeter of the pupil at 48 separate angles in an R, θ coordinate system, where θ defines an angular orientation about the center of the pupil, and R represents the radius of the pupil at that orientation. The fitted radius of the pupil is determined by selecting a circumference that best fits a contour of the pupil and by solving the equation $2\pi r$ to obtain the radius value (r).

Those skilled in the art will appreciate that, by defining and evaluating 48 distinct radii about the center of the pupil, it is possible in accordance with the present invention to detect one or more non-uniformities or irregularities that may exist around the perimeter of the pupil. It also is possible to characterize the shape of the pupil as circular, elliptical etc. based upon the determined radii. It also is possible to evaluate selected sections of a pupil perimeter to determine whether or not those sections exhibit normal contour characteristics and/or normal responses to visual stimulus. It is believed that these capabilities represent significant improvements over conventional pupilometry systems, as these features allow not only for the performance of conventional pupil aperture and response evaluations, but also for the performance of pupil shape and sectional contour evaluations. Thus, where a particular affliction may produce a defined irregularity in pupil shape or defined sectional response to visual stimulus, the affliction may be identified through the use of a pupilometer in accordance with the present invention.

The inputs to, and outputs obtained from, the flying spot algorithm may be defined as follows:

Input Parameters:

Frame = eye image frame generated by the CMOS imaging sensor 14

Threshold = gray level threshold value; any pixel having a gray scale value greater than the threshold value is considered to be part of the pupil.

Output Parameters:

5 Output = fitted radius and center of pupil, 48 radii.

It is assumed herein that within the gray scale used by the pupilometer 10 the color black will be associated with a high gray scale value, such as 255, and the color white will be associated with a low gray scale value, such as 0. However, those skilled in the art will appreciate that the relative maximum and minimum values could be reversed.

10 It is believed that the use of flying spot algorithms are well known in the art and, therefore, that the flying spot algorithm need not be described in detail herein. Nonetheless, the basic flying spot procedure may be described as follows. The flying spot procedure starts with a large circumference centered on the image of an eye and iteratively reduces the size of the circumference. In reducing the size of the circumference and
15 adjusting the center location of the circumference, for each iteration the following momentums will be computed:

$$\mu_x = 1 / N * \sum_{x,y} \text{gray_level_sign}(x,y)(x-x_0)$$

20
$$\mu_y = 1 / N * \sum_{x,y} \text{gray_level_sign}(x,y)(y-y_0)$$

$$\mu_r = 1 / N * \sum_{x,y} \text{gray_level_sign}(x,y)$$

25

where N represents the number of pixels having coordinates x,y in the circumference contour; $\text{gray_level_sign}(x,y)$ is +1, if the gray level value of the pixel (x,y) is greater than the threshold value; $\text{gray_level_sign}(x,y)$ is -1, if the gray level value of the pixel (x,y) is less than the threshold value; and x_0, y_0 are the center coordinates of the
30 circumference.

The x and y coordinates of the circumference center and the radius are updated as follows:

$$x_0 = x_0 + \mu_x * \text{Gain}_x$$

$$y_0 = y_0 + \mu_y * \text{Gain}_y$$

35
$$\text{radius} = \text{radius} + \mu_r * \text{Gain}_r.$$

As indicated above, the updating procedure is applied iteratively, each time calculating the momentum and then changing the center and radius of the flying spot, such that the circumference finally converges to a circumference that best fits the contour of the pupil.

5 Once the fitted radius and center of the pupil are determined, 48 radii representing the distance between the center and perimeter of the pupil at 48 separate angles in an R, θ coordinate system preferably are determined, where θ defines an angular orientation about the center of a pupil, and R represents the radius of the pupil at that orientation. By evaluating the 48 determined radii, it is possible to characterize the overall shape of the
10 pupil and to determine whether or not any sectional non-uniformities or irregularities are present about the perimeter of the pupil. Such processing may be performed either by the feature extraction object 106 or the analysis object 108.

Another principal function performed by the feature extraction object is thresholding. The thresholding function automatically identifies a gray level value that
15 separates the pupil from the background in an image data frame. Moreover, when an appropriate threshold value is determined, all pixels having a gray level value greater than the threshold value are considered to comprise part of the image of the pupil, and all pixels having a gray level value less than the threshold are considered to correspond to background.

20 Preferably, the defined threshold value represents the average of a maximum hypothetical threshold value and a minimum hypothetical threshold value. The maximum and minimum hypothetical threshold values are derived through respective histogram analysis routines. Moreover, as shown in Figs. 7(a) and 7(b), for each hypothetical threshold value two histograms are evaluated, one for the rows of pixels within an image
25 frame, and one for the columns of pixels within the image frame. The histogram value for a given row or column is determined by counting the pixel locations in that row or column that have a gray level value that exceeds the hypothetical threshold level. Thus, the number of values within a histogram preferably corresponds to the number of rows or columns in the image data frame, and each value represents the number of pixels in the
30 specific row or column that have a gray level exceeding the hypothetical threshold value.

Turning now in particular to Figs. 7(a) and 7(b) the hypothetical maximum and hypothetical minimum threshold values are determined by iteratively altering a hypothetical threshold value until a prescribed histogram profile is achieved. An acceptable profile is illustrated in Fig. 7(a) and is one in which a null-high-null pattern is
35 achieved for both a row histogram (y Hist) and column histogram (x Hist). More

specifically, an acceptable profile preferably comprises a single “high” bordered by a pair of “nulls.” Unacceptable profiles are illustrated, for example, in Fig. 7(b).

The hypothetical maximum threshold value is determined by selecting an absolute maximum value and iteratively decreasing that value and deriving corresponding
5 histogram data sets until acceptable row and column histogram profiles are achieved. Similarly, the hypothetical minimum threshold value is determined by selecting an absolute minimum value and iteratively increasing that value and deriving corresponding histogram data sets until acceptable row and column histogram profiles are achieved. Once the hypothetical maximum and minimum threshold values are determined, those
10 values are averaged to determine the defined threshold value that will be used by the feature extraction object 106. Those skilled in the art will appreciate that the defined threshold value may correspond to the maximum hypothetical threshold value, the minimum hypothetical threshold value, or any value that is between those values. Thus, in alternative embodiments, the defined threshold value could be determined, for example,
15 based on a weighted average of the maximum and minimum hypothetical threshold values. In such an embodiment, the defined threshold value may comprise a value corresponding to the sum of the minimum hypothetical threshold value and $2/3$ of the difference between the maximum and minimum hypothetical threshold values.

5. The Analysis Object

20 The analysis object 108 analyzes the configuration characteristics of a pupil as a function of time. Preferably, the analysis object 108 receives, as inputs, from the feature extraction object 106 a plurality of data sets for each captured image data frame. The data sets preferably include the time of image capture in msec, x and y coordinates of the pupil center, radius of the flying spot circumference, 48 radii representing the distance between
25 the center and border of the pupil for 48 selected angles within an R, θ coordinate system, and an applied stimulus record for the relevant entry. Upon receiving the input data sets, the analysis object 108 preferably derives at least the following information from the data sets: minimum pupil aperture, maximum pupil aperture, difference between maximum and minimum pupil apertures, latency of pupil response to yellow light stimulus, pupil
30 constriction velocity, first and second pupil dilation velocities and, if desired, pupil irregularity magnitude and location information. Where pupil irregularities are detected, the location of the irregularity preferably is identified by its θ coordinate. However, graphical indications also may be provided on the display 36 of the pupilometer 10.

Further, in alternative embodiments, the analysis object 108 may include
35 programming for effecting a multi-varied analysis wherein a plurality of selected variables including, for example, latency indicia, constriction velocity indicia, first and second

dilation velocity indicia, segmental static and/or dynamic analysis indicia, constriction/dilation velocity ratio indicia, and maximum and minimum diameter indicia are evaluated for one or both eyes of a patient to arrive at one or more scalar values that are indicative of an overall physiologic or pathologic condition of the patient or, alternatively, to arrive at one or more scalar values that are indicative of an overall opto-neurologic condition of the patient.

With regard to the information derived by the analysis object 108, the maximum pupil aperture, minimum pupil aperture and difference determinations require the identification of the maximum pupil aperture and minimum pupil aperture within a set of image data frames and, thereafter, computation of the difference between those values. The latency determination provides an indication in milliseconds of the time that it takes for a pupil to begin to respond to a visible (i.e., yellow) light stimulus pulse. Further, those skilled in the art will appreciate that, when a pupil is exposed to a visual light stimulus pulse, the pupil generally will, after some latency period, constrict and, once the stimulus is discontinued, dilate and return to its original size and configuration. Thus, the analysis object 108 evaluates the response of a pupil to a visual stimulus to determine a pupil constriction velocity and evaluates the response of the pupil to termination of the stimulus to determine first and second dilation velocities. First and second dilation velocities are evaluated because a pupil generally will dilate quickly for a first period of time and, thereafter, will dilate more slowly until its original size and configuration are achieved. Finally, as explained above, an analysis object 108 in accordance with the present invention also preferably identifies any irregularities in the shape of the pupil. Such irregularities may be either static or dynamic in nature. For example, a static irregularity may take the form of an irregular pupil shape in ambient light, whereas a dynamic irregularity may take the form of increased latency for a particular section of the pupil during a response to a the initiation or termination of a visual stimulus. With regard to static irregularities, such irregularities may be identified by identifying the angular orientations of radii that do not fall within prescribed limits, differ from other calculated radii by a predetermined deviation or differ from the fitted radius by a predetermined amount, deviation or percentage.

Finally, an analysis object 108 in accordance with the present invention preferably includes programming for identifying statistical anomalies within derived results. This allows an analysis object 108 in accordance with the present invention to discard either actual pupillary response data sets (i.e., fitted radius, center and radii calculations) or derived data sets (i.e., max aperture, min aperture, latency, constriction rate or dilation rates) when a selected value differs from other values by a statistically significant degree.

When such anomalies are identified, the relevant data sets are not included in averaging functions, and where many anomalies are identified, an imaging sequence will be invalidated and must be repeated.

C. Operation of a Pupilometer in Accordance with the Present Invention

5 Turning now to Fig. 8, operation of a pupilometer 10 in accordance with the present invention proceeds as follows. Generally the pupilometer 10 will be configured according to a default mode of operation. The default mode defines a set of values for basic operation of the device. The defined values may include, for example, values for scan duration, illumination duration and/or profile, stimulus duration and/or profile and
10 stimulus intensity level. However, it will be appreciated that all of the above-listed values may be programmably set under control of the graphic user interface object 100. Thus, it will be appreciated that default programming values generally will be utilized by the pupilometer 10 absent entry of an override by the user in a scan sequence program mode.

 A typical image acquisition and analysis procedure may proceed as follows. If the
15 pupilometer 10 has been idle for a predetermined period of time (e.g., 120 seconds), the pupilometer 10 is automatically placed in a battery-conserving sleep mode (step 202). By depressing the "scan" button 45 (shown in Fig. 2), the user causes the pupilometer 10 to enter a "ready" mode (step 200). At this time, the user is prompted to enter an alphanumeric subject or patient identification number via the keypad 39 or to download
20 any necessary patient information from a network computer via an infrared data interface, such as an IrDA interface that is provided on numerous conventional personal computer products (step 204). Once any requisite patient identification data has been entered into the system, the user is prompted via the liquid crystal display 36 or an audio prompt to hold down the "scan" button 45 and to position the pupilometer 10 in front of the eye 38
25 of a subject (step 210).

 When the user depresses the "scan" button 45, the microprocessor (not shown) initiates an imaging test sequence. The yellow LEDs 26 preferably are not activated during the test sequence. During the test sequence the images that are acquired by the imaging sensor 14 may be displayed on the liquid crystal display (LCD) 36. Preferably,
30 the P-program analyzes the image data frames that are acquired during the test sequence, determines whether or not the pupilometer 10 is properly positioned for obtaining measurements, and determines if all necessary parameters are met to ensure high-quality data recovery. If the test criteria are not met, the user is prompted to reposition the pupilometer 10. After any requisite test criteria are met, the P-program will continue to
35 run the test sequence until the "scan" button 45 is released.

Once the scan button 45 is released, the P-program preferably will initiate a prescribed measurement sequence and will activate the illumination system of the pupilometer 10 as needed during the measurement sequence. Upon completion of the measurement sequence, the user is informed via the LCD 36 or an audio prompt that the measurement sequence has been completed (steps 226-228).

Following completion of the measurement sequence, the P-program preferably will analyze the image data frames that have been obtained and will display the results of the analysis on the LCD 36. If the results are satisfactory (i.e., are statistically sound), the user may then be prompted to download the results to a printer or related network via the IrDA interface (not shown) (step 246). If the results are not satisfactory, the user is prompted to repeat the measurement sequence (step 222).

Finally, after an initial set of measurement are obtained, the user may be prompted for a decision to measure the pupillary characteristics of the other eye of the subject/patient, or the user may be prompted for a decision to make a consensual response measurement (steps 238, 242). The consensual response measurement may take the form of a "swinging flashlight" measurement discussed more fully below. If a consensual measurement is to be performed, the user may be prompted to couple a consensual measurement attachment (shown in Fig. 9) to the pupilometer and to position a yellow LED 52 mounted on the attachment in front of the appropriate eye of the subject/patient. If the consensual measurement attachment is permanently affixed to the pupilometer 10, the user may only need to deploy and/or properly position the attachment.

D. Incorporation of Consensual Measurement Apparatus in a Pupilometer in Accordance with the Present Invention

Turning now to Fig. 9, a pupilometer 10 in accordance with the present invention may incorporate a consensual measurement apparatus or armature 50 to enable consensual pupillary responses to be analyzed. In a preferred embodiment, the armature 50 may detachably engage a main body 11 of the pupilometer 10. However, as explained above, the armature 50 also may be permanently affixed to the main body 11 of the pupilometer 10.

One test for analyzing consensual pupillary responses is commonly referred to within the medical community as a "swinging flashlight test." During a typical swinging flashlight test one eye of a subject is monitored, and a visible light stimulus is applied first to the eye of the patient that is being monitored, then to the eye of the patient that is not monitored and, finally, again to the eye that is monitored. If the eyes of the patient are normal, the pupil of the monitored eye should constrict in response to all of the light

stimulus pulses (regardless of which eye the stimulus pulse is applied to). Following application of the first light stimulus, the pupil of the monitored eye should begin to dilate, and upon application of the second light stimulus (i.e., upon application of stimulus to the non-monitored eye), the pupil of the monitored eye should again constrict. If the monitored pupil does not respond adequately to the second stimulus pulse, it may be inferred that the retina of the non-monitored eye somehow may be impaired. If the monitored pupil does not respond adequately to the third stimulus pulse, it may be inferred that the retina of the monitored eye somehow may be impaired.

By using a consensual measurement attachment 50 in accordance with the present invention, it is possible to perform a "swinging flashlight" test using the pupilometer 10. For example, when performing a "swinging flashlight" test, the P-program may first cause the yellow LEDs 26 within the pupilometer 10 to be activated for a period of, for example, 1 second. The P-program then may deactivate the yellow LEDs 26, and 0.5 second following deactivation of the yellow LEDs 26 may activate for 0.5 second the yellow LED 52 located at the distal end 54 of the consensual attachment. Finally, after deactivating the yellow LED 52 and waiting for a period of, for example, 0.5 second, the P-program may again activate the yellow LEDs 26 for a period of 1 second. Image frames may be obtained by the imaging sensor 14 at a rate of, for example, 10 frames per second and for a total period of 5.0 or more seconds to evaluate the consensual response of the imaged eye. If desired, the process may be repeated a predetermined number of times.

E. Miscellaneous System Calibration and Pupil Identification Processing Techniques

In alternative embodiments, the P-program of a pupilometer 10 in accordance with the present invention may incorporate a calibration algorithm that uses acquired data descriptive of the perimeter of the iris 37 of the eye 38 of a patient to define a relationship between pixel spacing data and real world measurement parameters and/or to evaluate an orientation of a patient's eye 38 in relation to the pupilometer 10.

For example, in one innovative aspect, the P-program of a pupilometer 10 may cause the iris of the eye of a patient to be illuminated by blue light (i.e., may activate the blue LED 28) and, while the patient's eye is so illuminated, may obtain an image of the sclera/iris border of the patient's eye. A flying spot or similar processing algorithm may then be used to identify a best fitting elliptical circumference for the sclera/iris border of the patient's eye, and the radii or horizontal and vertical diameters of the circumference may be compared to or correlated with assumed sclera/iris border radii or diameters to provide a correlation between a pixel count and a real world measurement. For example, if the horizontal diameter of a sclera/iris border is assumed to be 11.7 mm, and the

sclera/iris border measures 117 pixels in diameter, the P-program of the pupilometer 10 may derive a pixel measurement to real world correlation factor of 10 pixels/mm, and that correlation factor may be used to provide the user with pupil measurement information. In accordance with one preferred form of the present invention, the horizontal diameter of the sclera/iris border is assumed to be 11.75 mm for in all subjects. However, those skilled in the art will appreciate that a different diameter, such as 11.0 mm or 12.0 mm, may also be assumed.

Similarly, by evaluating the shape of the sclera/iris border of an eye it is possible to estimate the angular orientation of the eye with respect to the pupilometer 10 and, moreover, to evaluate the orientation of an eye with relation to a vertical axis of the eye. Preferably, this may be done by evaluating a degree of ellipticity of the imaged sclera/iris border and assuming that the shape of the sclera/iris border has a predetermined elliptical shape. Such, measurements may be further refined by comparing the shape of a pupil to the shape of a surrounding sclera/iris border to determine whether variations in the shape of a pupil arise from angular orientation of the eye in relation to the pupilometer 10, or from non-uniformities or irregularities in the perimeter of the pupil.

In another innovative aspect, a pupilometer 10 in accordance with the present invention may include software for utilizing physical landmarks to assist in locating a pupil within an image data frame. In such an embodiment, the feature extraction object 106 of the P-program executed by the microprocessor (not shown) may include code for identifying characteristic structures of ocular tissue such as eyelids and/or eyelashes within an image data frame, and for using the location of those structures to predict the location of a pupil within the image data frame. Additional landmarks that may be located in accordance with the present invention include the lachrymal punctum, lachrymal caruncula, and lateral and medial papebral commissures of a patient's eye. These landmarks also may be used to identify which eye of a patient is being monitored.

F. Diagnostics Systems and Methods in Accordance with the Present Invention

In still another innovative aspect, the present invention is directed to improved diagnostics systems and methods incorporating a pupilometer 10 and medical database (not shown). For example, it is contemplated in accordance with the present invention that data representative of a plurality of pupillary response or configuration characteristics associated with one or more physical or pathological conditions may be stored within a medical diagnostics data base, that a pupilometer 10 may be used to obtain data descriptive of one or more pupillary response or configuration characteristics from a patient, and that the obtained data may be compared to the stored data within a data

analysis system to identify one or more physiologic or pathologic characteristics or conditions of the patient. Further, in a preferred form, the obtained and/or stored pupil configuration data may be descriptive of one or more static or dynamic regional non-uniformities that may exist within the perimeter of a patient's pupil.

5 One example is a medical diagnostics system wherein the pupilometer 10 can be used to screen for Glaucoma. This can be done by providing pupilometer 10 with a diffuse yellow illumination (retinal)(not shown) in conjunction with series N concentrated (optically) blue LEDS (not shown) which are imaged onto the retina of an eye in such a way as to illuminate N specific regions. Sensitivity and accuracy of Glaucoma detection
10 are improved by this system and method, which employs the diffuse yellow light in order to bias the background as yellow and the N concentrated blue LEDS as flicker sources for stimulating the retina of the eye. Alternatively, the background light can be white while the source of flicker light can generate green light. Again, the IR LEDS are activated to illuminate the eye and enable the imaging sensor to detect pupillary response to the
15 stimulatory light, i.e., the blue or green light. The microprocessor 34 controls the operation and function of this illumination system as previously described. The subject patient's point-of-gaze is verified for each measurement utilizing the tracking features of pupilometer 10. The pupillary response for each of N blue (or green) illumination regions is documented and compared to a database of normal measurements to determine if the
20 response falls out of range. Alternatively, the pupillary response for each of N blue (or green) illumination regions can be compared to a database of measurements that indicate Glaucoma to determine whether they fall within those measurements and therefore indicate Glaucoma. Both amplitude and velocity of pupillary response is detected by the imaging sensor 14 and recorded by the image signal processing board 34. It is expected
25 that in the presence of Glaucoma peripheral retinal response to blue (or green) light stimulus will be compromised.

 The pupilometer 10 can also be used to diagnose elevated intracranial pressure. Under conditions of elevated ICP, the profusion of the oculomotor nerve (CNIII) is compromised, therefore affecting the propagation properties of action potentials through
30 nerve fibers. Therefore, under amplitude modulated conditions, which elicit maximal pupillary response, the dynamic properties of the light-reflex as a function of time will deteriorate to a greater extent in those individuals with elevated levels of intracranial pressure. The pupilometer 10 may comprise an amplitude modulated stimulus source (not shown) to repeatedly cycle the pupil reflex. The pupilometer 10 is used to capture a
35 sequence of images of the eye while a continuous and amplitude modulated light stimulus is applied to the eye. The P-program software detects the pupil margin and calculates the

average rate of change of the pupil as a response to an extended duration amplitude modulated light stimulus source. The average rate of change data is then compared to normative or previously recorded data for the patient or a normal subject as an indicator of abnormality and CNIII involvement due to elevated intracranial pressure.

5 When the amplitude of the light projected to the eye is increased, the constriction velocity of the pupil should increase. But, the constriction velocity for each successive increase in light stimulus amplitude is generally lower in those individuals who are diagnosed with elevated intracranial pressure. On the other hand, as the amplitude is decreased, dilation velocity in individuals with intracranial pressure increases at a more
10 rapid pace. Thus, constriction and dilation velocity, as well as pupillary amplitude, can be used to determine whether an individual has elevated levels of intracranial pressure.

The pupilometer 10 can also be used to diagnose impairment to brain function. The task of fixating on a target and maintaining this fixation as the target is moved about the visual field requires constant cortical feedback and cerebellar eye movement
15 correction. The ability to visually track a moving target can be assessed by tracking actual point-of-gaze and comparing this information to a stored expected value for a set pattern of target movement. Substantial deviation from the expected value is an indication of brain disorder. Alternatively, the stored expected value can represent brain function impairment rather than representing a normal brain with no brain function impairment. In
20 this case, values that fall within the range of the stored expected value represent brain function impairment. In addition, simultaneous presentation of multiple target points in the visual field has a predictable effect on point of gaze for normally functioning brains even at a young age. Deviation from the predicted behavior to multiple point targets may give rise to the early diagnosis of Autism.

25 The system for diagnosing impairment to brain function comprises a pupilometer, a moveable target, a database for storing data descriptive of one or more pupillary characteristics associated with a set pattern of target movement, and a central processing unit coupled to the pupilometer. The target may be on the pupilometer itself (not shown), and may be comprised of a light generated by a visible light source, or any other visible
30 object. The point-of-gaze is determined by detecting features of the eye in addition to the pupil and using fiducial alignment references generated by the system. The P-program will generate a frame by frame history of the point-of-gaze and compare the test results to a figure-of-merit for a normal brain given the same set of visual stimuli. Ultimately the system will indicate the type of tracking error that occurred (i.e., degree of overshoot,
35 magnitude of lag, static dwell time) each of which indicate specific brain disorders.

The pupilometer 10 of the present invention can also be used to test the functional integrity of afferent peripheral and cranial pathways as well as testing efferent cranial nerve involvement in patients with afferent pupillary defects. The pupil is mediated by a complex control system for which the output (pupil size) is determined by the sum of various autonomic inputs. The autonomic inputs that affect the pupil include both sympathetic and parasympathetic constituents. Noxious stimulation such as a pin-prick, sudden exposure to hot or cold, electrical current or pinching should result in a pupillary response. The response may include pupillary amplitude response to pain, reflexive point-of-gaze eye-movement or reflexive blinking.

In the pupilometer testing system described herein, the pupil is observed under a constant background light condition, such as IR light from IR LEDS 24, or yellow light from yellow LEDS 26 of the pupilometer 10. Meanwhile, noxious stimulation is presented to the subject patient, and this stimulation is controlled with precise timing by the pupilometer's 10 microprocessor 34. The magnitude, direction of gaze and temporal characteristics of the eye response including blinking are determined by image processing means in the P-program software. Sources of noxious stimuli, which are controlled by the pupilometer without exposing the patient to tissue damaging effects, include brief pulses of air, release of small bursts of cryogenic spray, and small electrical currents. These stimuli are applied to various dermatopic areas in addition to afferent-sensory areas such as the tympanic membrane and the cornea, which are innervated by cranial nerves.

The noxious stimuli are generated by dangled attachments to the pupilometer 10 (not shown). For dorsal root and spinal cord involvement a small canister of compressed CO2 gas with an electronically controlled regulation valve is electrically coupled to an output port on the pupilometer 10. The valve releases a metered volume of CO2 gas providing a source of extreme cold which can be directed to any dermatome area. The pupil is evaluated for the pain/cold response at progressively lower dermatopic areas until a differential in pupillary response is detected. The P-program software calculates/detects the pupil margin and calculates the gross rate of change of the pupil as a response to the noxious stimulus.

The corneal-blink reflex, which is mediated by afferents of the ophthalmic branch of the trigeminal nerve (CNV) can be tested by the system using compressed air or a fan which produces a small puff of air on the cornea while the P-program monitors pupil as well as eyelid response.

The eye moves away from an ice water stimulus on the tympanic membrane in the ear. A cryogenic spray can produce the same behavior via noxious stimulus to the ear. A CO2 canister and regulated valve as described earlier and electrically coupled to the

pupilometer 10, is used to measure the eye movement in response to this tympanic membrane stimulation.

Finally, the pupilometer 10 as described herein can also be used in connection with a system for testing the functional integrity of auditory pathways (vestibulocochlear nerve and the auditory cortex) by detecting pupillary response to sound stimulus. In this implementation of a pupilometer-based hearing testing system, the pupil is observed under a constant background light condition while an audible stimulus is presented to the subject or patient. This stimulus is controlled with precise timing, amplitude and frequency by the pupilometer's 10 microprocessor 34. The amplitude and temporal (i.e., velocity) characteristics of the pupillary response are detected by the imaging sensor 14 and recorded by the microprocessor 34 (i.e., signal processing board).

This aspect of the invention can also be implemented by a system comprising a pupilometer as described herein, a sound generating transducer capable of generating sound in various amplitudes and frequencies and in electrical communication with one or more ear-pieces, a database for storing data descriptive of one or more pupillary characteristics associated with a set pattern of sound stimuli, and a central processing unit. The data stored in the database can represent pupillary responses that are normal and indicative of healthy auditory pathways, or can represent pupillary responses that represent abnormal or dysfunctional auditory pathways. In either case, a comparison of the data representing the patient's or subject's pupillary response to the data stored in the database, using the central processing unit, can determine the functional integrity of the patient's auditory pathways.

While the invention is susceptible to various modifications and alternative forms, specific examples thereof have been shown by way of example in the drawings and are herein described in detail. It should be understood, however, that the invention is not to be limited to the particular forms or methods disclosed, but to the contrary, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the appended claims.

Claims

1. A pupilometer comprising:
an imaging sensor for generating signals representative of a pupil of an eye;
5 a data processor; and
a program executable by said data processor for enabling said data processor to
process signals received from said imaging sensor and to thereby identify one or more
regions of non-uniformity within an image of a perimeter of said pupil.

10 2. A pupilometer comprising:

imaging means for generating image data representative of a pupil of a patient; and

deformation detection means coupled to said imaging means for identifying one or
more selected regions within an image of a perimeter of said pupil that exhibit a
predetermined amount of regional distortion.

15 3. The pupilometer of claim 2, wherein said imaging means comprises a
CMOS sensor.

20 4. The pupilometer of claim 2, wherein said imaging means comprises a CCD
camera.

25 5. The pupilometer of claim 2, wherein said deformation detection means
comprises a microprocessor and image data analysis software for identifying one or more
selected regions within said image of said perimeter of said pupil that exhibit said
predetermined amount of regional distortion.

30 6. A pupilometer comprising:
a microprocessor,
a memory coupled to said microprocessor;
an imaging device coupled to said microprocessor;
a visible light source coupled to said microprocessor; and

an IR light source coupled to said microprocessor;

said memory having stored therein a program for enabling said microprocessor to cause a plurality of visible light stimulus pulses to be generated by said visible light source, to cause said IR light source to generate IR light for illuminating a pupil, to enable
5 said imaging device to acquire a plurality of images of said illuminated pupil, to process data sets representative of said images of said illuminated pupil to obtain information descriptive of a response of said pupil to said visible light stimulus pulses, and to cause said information to be depicted on said display;

said information descriptive of a response of said pupil to said visible light
10 stimulus pulses comprising information indicative of a degree of non-uniform deformation of a selected segment of a perimeter of said pupil.

7. A pupilometer comprising:

an imaging apparatus for obtaining image data representative of a pupil of a
15 patient;

a microprocessor coupled to said imaging apparatus; and

a memory coupled to said microprocessor, said memory having stored therein a program for enabling said microprocessor to control said imaging apparatus, for enabling said microprocessor to process image data generated by said imaging apparatus, and for
20 enabling said microprocessor to locate and measure one or more local non-uniformities that may appear around a perimeter of said pupil of said patient.

8. The pupilometer of claim 7 further comprising a display coupled to said microprocessor, said display being capable of displaying an image of said pupil of said
25 patient and being capable of displaying information descriptive of said local non-uniformities in the event that such local non-uniformities are located within an image of said pupil of said patient.

9. A pupilometer comprising:

30 means for acquiring image data representative of ocular tissue, means for processing said image data, and means for displaying information derived from said image data,

said means for processing said image data comprising a microprocessor and programming for determining a pixel brightness threshold value, for locating a pupil

within a plurality of image data sets using said pixel brightness threshold value, and for locating and identifying perimeter regions of said pupil which exhibit a predetermined degree of micro-deformity when said pupil is exposed to at least one visible light stimulus pulse.

5

10. A handheld pupilometer comprising:

a housing having a display, microprocessor, memory, imaging device, visible light source and IR light source mounted therein;

10 said microprocessor being electronically coupled to said display, said memory, said imaging device, said visible light source and said IR light source; and

15 said memory having stored therein a program for enabling said microprocessor to cause at least one visible light stimulus pulse to be generated by said visible light source, to cause said IR light source to generate IR light for illuminating a pupil, to enable said imaging device to acquire a plurality of images of said illuminated pupil, and to process a plurality of data sets representative of said plurality of images of said illuminated pupil to obtain information descriptive of a response of said pupil to said at least one visible light stimulus pulse, and to cause said information to be depicted on said display;

20 said information descriptive of a response of said pupil to said at least one visible light stimulus pulse comprising information indicative of a degree of deformation of a selected segment of a perimeter of said pupil.

11. The handheld pupilometer of claim 10, wherein said information descriptive of a response of said pupil to said at least one visible light stimulus pulse comprises information descriptive of a dynamic response of said selected segment of said perimeter of said pupil.

25

12. The pupilometer of claim 10, wherein said imaging device comprises a CMOS NxM sensor.

13. The pupilometer of claim 10, wherein said imaging device comprises a CCD camera.

14. The pupilometer of claim 10 further comprising means coupled to said
5 microprocessor for downloading to a remote storage device said information descriptive of a response of said pupil to said at least one visible light stimulus pulse.

15. The pupilometer of claim 14 wherein said means for downloading comprises at least one of either an IR transmitter circuit or a RF transmitter circuit.

10

16. The pupilometer of claim 14 wherein said means for downloading comprises at least one of either a data port or a modem for coupling said pupilometer to a computer.

15

17. A handheld pupilometer comprising:

a housing having mounted therein means for acquiring image data representative of ocular tissue, means for processing said image data, and means for displaying information derived from said image data,

said means for processing said image data comprising a microprocessor and
20 programming for determining a pixel brightness threshold value, programming for locating a pupil within a plurality of image data sets using said pixel brightness threshold value, and programming for identifying one or more regions around a perimeter of said pupil that exhibit a non-uniform change in shape when said pupil is exposed to illumination of a predetermined type.

25

18. The pupilometer of claim 17, wherein said illumination comprises at least one visible light stimulus pulse.

19. The pupilometer of claim 17, wherein said illumination comprises exposure to ambient light.

20. The pupilometer of claim 16, wherein said means for acquiring image data comprises a source of infrared light, a source of visible light and an imaging device under microprocessor control.

21. The pupilometer of claim 20, wherein said imaging device is selected from a group consisting of a CCD camera and a NxM CMOS imaging sensor.

22. A method for correlating pupillary responses with pathological indications, said method comprising the steps of:

storing within a database data representative of a plurality of pupillary response characteristics associated with one or more pathological indications;

using a pupilometer obtaining pupillary response data from a patient, said pupillary response data being representative of one or more pupillary response characteristics of said patient; and

comparing within a data analysis system said pupillary response data obtained from said patient with said data representative of a plurality of pupillary response characteristics to identify one or more pathological conditions of said patient.

23. A method for correlating pupillary measurements with pathological indications, said method comprising the steps of:

storing within a database data representative of a plurality of pupillary configurations and associated pathological conditions;

using a pupilometer obtaining pupillary configuration data from a patient; and

comparing within a data analysis system said pupillary configuration data obtained from said patient with said data representative of said plurality of pupillary configurations to identify one or more pathological conditions of said patient.

24. The method of claim 23, wherein said pupillary configuration data comprises data descriptive of a pupillary response to at least one visible light stimulus pulse.

5

25. The method of claim 23, wherein said pupillary configuration data comprises data descriptive of a pupillary change in shape responsive to at least one light stimulus pulse.

10

26. The method of claim 23, wherein said pupillary configuration data comprises data descriptive of a pupillary response to ambient light exposure.

27. A method for correlating pupillary responses with pathological indications, said method comprising the steps of:

15

storing within a database data representative of a plurality of pupillary sectional configurations and associated pathological conditions;

using a pupilometer obtaining pupillary configuration data from a patient, said pupillary configuration data including data indicative of selected regional non-uniformities of a pupil of said patient if said patient's pupil exhibits such regional non-uniformities;

20

and

comparing within a data analysis system said pupillary configuration data obtained from said patient with said data representative of said plurality of pupillary sectional configurations to identify one or more pathological conditions of said patient.

25

28. A method for correlating pupillary responses with a scalar value indicative of a state of health of an individual or physiological system of said individual, said method comprising the steps of:

storing within a database data representative of a plurality of pupillary response characteristics associated with one or more pathological indications;

using a pupilometer obtaining pupillary response data from a patient, said pupillary response data being representative of one or more pupillary response characteristics of said patient; and

5 comparing within a data analysis system said pupillary response data obtained from said patient with said data representative of said plurality of pupillary response characteristics to derive said scalar value.

29. A system for use in diagnosing pathological conditions, said system comprising:

10 a pupilometer for obtaining data descriptive of one or more pupillary characteristics from a patient;

a database for storing data descriptive of a plurality of pupillary characteristics and associated physical conditions; and

15 a central processing unit coupled to said digital pupilometer and said database for comparing said data obtained by said pupilometer to said data stored within said database such that a pathological condition of said patient may be diagnosed based upon said comparison.

20 30. The system of claim 29 further comprising a processing subroutine for generating a scalar indicator based upon a result of said step of comparing said data stored within said pupilometer to said data stored within said database.

25 31. The system of claim 29 further comprising a display coupled to said central processing unit for displaying images of said patient's pupil and for providing an indication of whether or not said pupillary characteristics of said patient correspond to any of said pupillary characteristics represented by said data stored within said database.

32. A method for locating a pupil within an image of ocular tissue, said method comprising the steps of:

establishing a pixel brightness threshold value for discriminating between light and dark gray scale data comprising said image, and

comparing gray scale image data at a plurality of pixel locations within said image of ocular tissue to said pixel brightness threshold value to identify a region within said
5 image of ocular tissue that represents said pupil,

wherein said step of establishing a pixel brightness threshold value comprises the steps of selecting a pixel brightness threshold value, constructing vertical and horizontal histogram data sets from said image of ocular tissue, wherein each histogram data set comprises a plot of sums of pixel locations having a value exceeding said threshold value
10 along respective rows or columns of pixels comprising said image, determining whether curves mapped from said vertical and horizontal histogram data sets comprise at least one maximum value bordered by a pair of null values, and repeating said selecting, constructing and determining steps until a pixel brightness threshold value is identified that satisfies said determining step.

15

33. The method of claim 32, wherein said step of selecting a pixel brightness threshold value comprises the steps of selecting a maximum pixel brightness threshold value and decreasing said pixel brightness threshold value in increments from said maximum pixel brightness threshold value upon each repetition of said selecting step.

20

34. The method of claim 32, wherein said step of selecting a pixel brightness threshold value comprises the steps of selecting a minimum pixel brightness threshold value and increasing said pixel brightness threshold value in increments from said minimum pixel brightness threshold value upon each repetition of said selecting step.

25

35. The method of claim 32, wherein said step of selecting a pixel brightness threshold value comprises the steps of

selecting a maximum pixel brightness threshold value and decreasing said pixel brightness threshold value in increments from said maximum pixel brightness threshold value until a first predetermined histogram plot is achieved and a relative
30 maximum pixel brightness threshold value is identified,

selecting a minimum pixel brightness threshold value and increasing said pixel brightness threshold value in increments from said minimum pixel brightness threshold value until a second predetermined histogram plot is achieved and a relative minimum pixel brightness threshold value is identified, and

5 assigning said pixel brightness threshold value a level between said relative maximum pixel brightness threshold value and said relative minimum pixel brightness threshold value.

10 36. The method of claim 34, wherein said assigning step comprises the step of deriving a pixel brightness threshold value comprising the sum of the relative minimum pixel brightness threshold value and $2/3$ times the difference between the relative maximum and relative minimum pixel brightness threshold values.

15 37. A method of processing data representative of an image of ocular tissue, said method comprising the steps of:

generating digital image data representative of said image of said ocular tissue;

processing said digital image data representative of said image of said ocular tissue to locate one or more landmarks within said image of said ocular tissue;

20 using said one or more landmarks to locate a pupil within said image of said ocular tissue; and

processing one or more data sets representative of said pupil to identify at least one predetermined characteristic of said pupil.

25 38. The method of claim 37, wherein said landmarks correspond to eyelash images located within said image of ocular tissue.

39. The method of claim 37, wherein said landmarks correspond to eyelid images located within said image of ocular tissue.

40. The method of claim 37, wherein said landmarks correspond to eyebrow images located within said image of ocular tissue.

41. The method of claim 37, wherein said landmarks correspond to one of a lachrymal punctum, a lachrymal caruncula, a lateral papebral commissure or a medial papebral commissure of a patient's eye.

42. A method of processing data representative of an image of ocular tissue, said method comprising the steps of:

10 generating digital image data representative of said image of said ocular tissue;

processing said digital image data representative of said image of said ocular tissue to locate one or more landmarks within said image of said ocular tissue;

using said one or more landmarks determine whether a right eye or left eye of a patient is being monitored.

15

43. A method of calibrating a pupilometer comprising the steps of:

acquiring at least one data set representative of an image of an eye including a pupil and an iris,

20 deriving from said data set information descriptive of a degree of ellipticity of an outer perimeter region of said iris, and

using said information descriptive of said degree of ellipticity of said outer perimeter region of said iris to derive calibration information descriptive of an orientation of said eye.

25

44. A method of calibrating a pupilometer comprising the steps of:

acquiring at least one data set representative of an image of an eye including a pupil and an iris,

deriving from said at least one data set information descriptive of a shape of an outer perimeter region of said iris,

deriving from said at least one data set information descriptive of a shape of a perimeter region of said pupil, and

- 5 comparing said information descriptive of said shape of said outer perimeter region of said iris to said information descriptive of said perimeter region of said pupil to normalize and establish a frame of reference for said information descriptive of said shape of said pupil.

45. A method for calibrating a pupilometer comprising the steps of:

- 10 acquiring at least one data set representative of an image of an eye including a pupil and an iris,

deriving from said at least one data set an indication of a diameter of an outer perimeter of said iris,

- 15 comparing said indication of said diameter of said outer perimeter of said iris to an assumed diameter of said iris, and

utilizing a difference between said indication of said diameter of said outer perimeter of said iris and said assumed diameter to calibrate said pupilometer.

- 20 46. The method of claim 45, wherein said assumed diameter of said iris is a horizontal diameter and is approximately 11.75 mm.

47. A method for calibrating a pupilometer comprising the steps of:

illuminating a portion of an eye including an iris and a pupil with low intensity blue light,

- 25 using an imaging sensor, obtaining data descriptive of an image of said portion of said eye illuminated by said low intensity blue light,

analyzing said data to identify an outer perimeter of said iris of said eye within said image, and

using said identified outer perimeter of said iris of said eye to calibrate said pupilometer.

48. A method for acquiring pupilometry data, said method comprising the steps
5 of:

exposing an eye of a patient to blue light pulses and IR pulses in a predetermined sequence,

obtaining data descriptive of a shape of an iris of said eye when said eye is exposed to said blue light pulses, and

10 obtaining data descriptive of a shape of a pupil of said eye when said eye is exposed to said IR pulses.

49. The method of claim 48, wherein said light pulses and IR pulses, and said respective data obtaining steps, are multiplexed.

15 50. A method of calibrating a pupilometer, said method comprising the steps of:

exposing an eye to a plurality of light stimulus pulses,

20 using said pupilometer obtaining a plurality of image data sets representative of respective pupillary responses of said eye to said light stimulus pulses,

using said plurality of obtained image data sets deriving response curves representative of said respective pupillary responses, and

using said response curves to evaluate a degree of adaptation of said eye to said stimulus pulses.

25 51. The method of claim 50 further comprising the step of using an estimate of said degree of accommodation of said eye to said stimulus pulses to normalize one or more image data sets representing a pupillary response to a selected stimulus pulse.

52. A pupilometry system comprising:

a display, microprocessor, memory, imaging device, first and second visible light sources and an IR light source;

5 said microprocessor being electronically coupled to said display, said memory, said imaging device, said visible light sources and said IR light source; and

10 said memory having stored therein a program including stimulus control code for enabling said microprocessor to cause said first visible light source to generate a first visible light stimulus pulse for illuminating a first eye, to cause said second visible light source to generate a second visible light stimulus pulse for illuminating a second eye at a predetermined time following termination of said first visible light stimulus pulse, and to cause said first visible light source to generate a third visible light stimulus pulse for illuminating said first eye at a predetermined time following termination of said second visual light stimulus pulse; including illumination control code for enabling said microprocessor to cause said IR light source to generate IR light for illuminating a pupil of
15 said first eye during a duration of said first, second and third visible light stimulus pulses; including image acquisition code for enabling said microprocessor to cause said imaging device to acquire a plurality of images of said IR illuminated pupil; including image analysis code for enabling said microprocessor to process data sets representative of said images of said IR illuminated pupil to obtain information descriptive of a response of said pupil to said visible light illumination of said first eye and said second eye; and display
20 code for enabling said microprocessor to cause said information to be depicted on said display.

53. The pupilometer of claim 52 further comprising an armature that extends
25 from a main body of said pupilometer for supporting said second visible light source.

54. The pupilometer of claim 53, wherein said armature detachably engages said main body of said pupilometer.

30 55. A pupilometer comprising:
a first visible light source for generating background light;
a second visible light source for generating light to stimulate a retina of an eye;

an IR light source for generating IR light for illuminating a pupil of the eye;
an imaging sensor for generating signals representative of the pupil of the
eye;

a microprocessor; and

5 a program executable by said microprocessor for enabling said
microprocessor to process signals received from said imaging sensor and to thereby
identify the pupil's dynamic response to the visible light generated by the second visible
light source.

10 56. The pupilometer of claim 55, wherein the first visible light source generates
white light.

57. The pupilometer of claim 55, wherein the first visible light source generates
a yellow diffuse light.

15

58. The pupilometer of claim 55, wherein the second visible light source
generates green light.

59. The pupilometer of claim 55, wherein the second visible light source
20 generates blue light.

60. The pupilometer of claim 55, wherein the signal received from the imaging
sensor represents the amplitude of the pupil's response to the light generated from the
second visible light source.

25

61. The pupilometer of claim 55, wherein the signal received from the imaging
sensor represents the velocity of the pupil's response to the light generated from the
second visible light source.

30 62. The pupilometer of claim 55, wherein the light generated from the second
visible light source is projected onto at least one region on the retina of the eye.

63. The pupilometer of claim 62, wherein the light generated from the second
visible light source is projected onto multiple regions on the retina of the eye in
35 succession.

64. The pupilometer of claim 55, wherein the data processor is electrically coupled to the second visible light source, and wherein the program enables said data processor to cause a plurality of light stimulus pulses to be generated by said second visible light source, and enables said imaging device to acquire a plurality of images of said pupil.

65. A method of detecting Glaucoma comprising the steps of:
providing a pupilometer;

obtaining, using the pupilometer, pupillary response data from an eye of a patient,
said pupillary response data being representative of one or more pupillary response characteristics of said eye;

storing within a database data representative of a plurality of pupillary response characteristics;

comparing within a data analysis system said pupillary response data obtained from said patient with said data representative of a plurality of pupillary response characteristics to determine whether the patient's pupillary response data indicates Glaucoma.

66. The method of claim 65, wherein the pupilometer comprises a first visible light source, a second visible light source, an IR light source, an imaging sensor, a microprocessor, and a program executable by said microprocessor.

67. The method of claim 66, wherein the step of obtaining the patient's pupillary response data comprises the steps of:

providing background light generated by the first visible light source;

illuminating the eye with IR light from the IR light source;

projecting a first image of the eye to the imaging sensor;

transmitting data representative of the first image of the eye to the microprocessor;

and

transmitting said data representative of the first image of the eye to the data analysis system.

68. The method of claim 67 further comprising the steps of:

projecting light from the second visible light source onto a retina of the eye;

projecting a second image of the eye to the imaging sensor;

transmitting data representative of the second image of the eye to the microprocessor; and

transmitting data representative of said second image of the eye to the data analysis system.

69. The method of claim 65, wherein the data representative of a plurality of pupillary response characteristics is associated with Glaucoma.

70. The method of claim 65, wherein the data representative of a plurality of pupillary response characteristics is associated with a healthy eye.

71. The method of claim 65, wherein the pupillary response characteristics of said eye comprise the velocity of pupillary response to retinal stimulation by light.

72. The method of claim 65, wherein the pupillary response characteristics of said eye comprise the amplitude of pupillary response to retinal stimulation by light.

73. The method of claim 65, wherein the database is in electrical communication with the pupilometer.

74. The method of claim 65, wherein the data analysis system is in electrical communication with the pupilometer.

75. A system for use in diagnosing Glaucoma, said system comprising:
a pupilometer for obtaining data descriptive of one or more pupillary characteristics from an eye of a patient;
a database for storing data descriptive of a plurality of pupillary characteristics; and
a central processing unit coupled to said pupilometer and said database for comparing said data obtained by said pupilometer to said data stored within said database such that Glaucoma may be diagnosed based upon said comparison.

76. The system of claim 75, wherein the pupilometer comprises a first visible light source, a second visible light source, an IR light source, and an imaging sensor.

77. The system of claim 76, wherein the first visible light source generates white light.

78. The system of claim 76, wherein the first visible light source generates a yellow diffuse light.

79. The system of claim 76, wherein the second visible light source generates
5 green light.

80. The system of claim 76, wherein the second visible light source generates blue light.

10 81. The system of claim 75 further comprising a display coupled to said central processing unit for displaying images of said patient's pupil and for providing an indication of whether or not said pupillary characteristics of said patient correspond to any of said pupillary characteristics represented by said data stored within said database.

15 82. A system for use in diagnosing impairment to brain function, said system comprising:

a pupilometer for obtaining data descriptive of one or more pupillary characteristics from a subject;

a movable target;

20 a database for storing data descriptive of one or more pupillary characteristics associated with a set pattern of target movement; and

a central processing unit coupled to the pupilometer and the database for comparing the data obtained by the pupilometer to the data stored within the database to assess the subject's level of brain function.

25

83. The system of claim 82, wherein the pupilometer comprises a visible light source, and the movable target comprises light generated by said visible light source.

84. The system of claim 83 further comprising a second movable target.

30

85. A method for diagnosing impairment to brain function comprising the steps of:

providing a pupilometer;

providing a movable target in the visual field of a subject;

35 moving the target within the visual field of the subject in a set pattern of target movement;

obtaining, using the pupilometer, a first set of data descriptive of one or more pupillary characteristics from an eye of the subject as the subject follows the target;

storing within a database a second set of data descriptive of a plurality of pupillary characteristics associated with the set pattern of target movement;

5 comparing within a data analysis system said first set of data with said second set of data to determine whether the subject's brain function is impaired.

86. The method of claim 85 further comprising the step of providing a second moveable target in the visual field of the subject.

10

87. The method of claim 85, wherein the second set of data is associated with impairment to brain function.

88. The method of claim 85, wherein the second set of data is associated with
15 normal levels of brain function.

89. The method of claim 85, wherein the database is in electrical communication with the pupilometer.

20 90. The method of claim 85, wherein the data analysis system is in electrical communication with the pupilometer.

91. A system for diagnosing neurological disease or trauma, said system comprising:

25 a pupilometer for obtaining a first set of data descriptive of one or more pupillary characteristics from an eye of a patient;

a source of a noxious stimulus in electrical communication with the pupilometer;

a database for storing a second set of data descriptive of a plurality of pupillary characteristics;

30 a central processing unit coupled to the pupilometer, source of noxious stimulus, and database, said central processing unit being capable of activating the source of noxious stimulus to deliver noxious stimulus to the patient and comparing the first set of data and second set of data such that neurological disease or trauma may be diagnosed based on such comparison.

35

92. The system of claim 91, wherein the pupilometer comprises a light source for generating light.

93. The system of claim 91, wherein the source of the noxious stimulus is a
5 canister of compressed CO₂ gas.

94. The system of claim 91, wherein the source of the noxious stimulus is a container of compressed air.

10 95. A method of diagnosing neurological disease or trauma, said method comprising the steps of:

providing a pupilometer;

providing a source of a noxious stimulus;

stimulating an anatomical structure of a patient with the noxious stimulus;

15 obtaining, using the pupilometer, a first set of data descriptive of one or more pupillary characteristics from an eye of the patient;

storing within a database a second set of data descriptive of a plurality of pupillary characteristics associated with pupillary response to a noxious stimulus;

20 comparing within a data analysis system said first set of data with said second set of data to determine whether neurological disease or trauma in the patient is indicated.

96. The method of claim 95, wherein the pupilometer comprises a light source.

25 97. The method of claim 95, wherein the pupilometer is in electrical communication with the source of the noxious stimulus, and wherein the pupilometer is capable of activating the source of noxious stimulus to deliver noxious stimulus to the patient.

30 98. The method of claim 95, wherein the pupillary response characteristics of the eye comprises the velocity of pupillary response to said noxious stimulation.

99. The method of claim 95, wherein the pupillary response characteristics of the eye comprises the amplitude of pupillary response to said noxious stimulation.

35 100. The method of claim 95, wherein the pupillary response characteristics of the eye comprises blinking.

101. The method of claim 95, wherein the anatomical structure that is stimulated with the noxious stimulus comprises the cornea.

5 102. The method of claim 95, wherein the anatomical structure that is stimulated with the noxious stimulus comprises the ear.

103. The method of claim 95, wherein the anatomical structure that is stimulated comprise dermatopic areas.

10

104. The method of claim 95, wherein the database is in electrical communication with the pupilometer.

15 105. The method of claim 95, wherein the data analysis system is in electrical communication with the pupilometer.

106. A system for testing the functional integrity of a patient's auditory pathways, said system comprising:

20 a pupilometer for obtaining data descriptive of one or more pupillary characteristics of the patient;

a sound generating transducer;

one or more ear-pieces in electrical communication with the sound generating transducer;

25 a database for storing data descriptive of one or more pupillary characteristics associated with a set pattern of sound stimuli; and

a central processing unit coupled to the pupilometer and the database for comparing the data obtained by the pupilometer to the data stored within the database to assess the functional integrity of the patient's auditory pathways based upon said comparison.

30

107. The system of claim 106, wherein the sound generating transducer is capable of generating sound in more than one amplitude and more than one frequency.

35 108. The system of claim 106, wherein the central processing unit is capable of activating and controlling the sound generating transducer.

109. The system of claim 106, wherein the sound generating transducer and the pupilometer are synchronized.

5 110. A method for testing the functional integrity of a patient's auditory pathways, said method comprising the steps of:
providing a pupilometer;
providing a sound generating transducer capable of transmitting an auditory stimulus;
providing one or more ear-pieces in electrical communication with the transducer;
10 inserting the one or more ear-pieces into one or both ears of the patient;
activating the transducer so that the transducer produces a sound;
obtaining, using the pupilometer, a first set of data descriptive of one or more pupillary characteristics from an eye of the patient;
storing within a database a second set of data descriptive of one or more pupillary
15 characteristics associated with a set pattern of sound stimuli; and
comparing within a data analysis system said first set of data with said second set of data to assess the functional integrity of the patient's auditory pathways based upon said comparison.

20 111. The method of claim 110, wherein the pupilometer comprises a light source.

112. The method of claim 110, wherein the pupilometer is in electrical communication with the sound generating transducer.

25 113. The method of claim 112, wherein the pupilometer is capable of activating and controlling the transducer.

114 The method of claim 110, wherein the transducer is capable of generating sound in more than one amplitude and more than one frequency.

30 115. The method of claim 110, wherein the transducer and pupilometer are synchronized.

116. The method of claim 110, wherein the response characteristics of the eye
35 comprises the velocity of pupillary response to auditory stimulus generated by the transducer.

117. The method of claim 110, wherein the response characteristics of the eye comprises the amplitude of pupillary response to auditory stimulus generated by the transducer.

5

118. The method of claim 110, wherein the database is in electrical communication with the pupilometer.

119. The method of claim 110, wherein the data analysis system is in electrical
10 communication with the pupilometer.

120. A system for detecting an elevated level of intracranial pressure, said system comprising:

15 a pupilometer for obtaining a first set of data descriptive of one or more pupillary characteristics;

an amplitude modulated light source in electrical communication with the pupilometer;

a database for storing a second set of data descriptive of one or more pupillary characteristics; and

20 a central processing unit for comparing the data obtained by the pupilometer to the data stored within the database to determine whether an elevated level of intracranial pressure is indicated.

121. The system of claim 120, wherein the first and second sets of data represent
25 pupillary constriction velocities.

122. The system of claim 120, wherein the first and second sets of data represent pupillary amplitude.

30 123. The system of claim 120, wherein the central processing unit is capable of activating and controlling the amplitude modulated light source.

124. The system of claim 120, wherein the amplitude modulated light source and the pupilometer are synchronized.

35

125. A method of detecting an elevated level of intracranial pressure, said method comprising the steps of:

providing a pupilometer;

providing an amplitude modulated light source for generating light;

5 continuously projecting the light for a given length of time onto the eye of a patient in a predetermined pattern of amplitude modulation;

obtaining, using the pupilometer, a first set of data representative of a pupil's response to the modulated light;

10 storing within a database a second set of data representing pupillary response to light stimulus received in said predetermined pattern of amplitude modulation; and

comparing within a data analysis system said first set of data with said second set of data in order to determine whether an elevated level of intraocular pressure is indicated.

126. The method of claim 125, wherein the pupilometer is in electrical
15 communication with the light source.

127. The method of claim 125, wherein the pupilometer is in electrical communication with the database.

20 128. The method of claim 125, wherein the pupilometer is in electrical communication with the data analysis system.

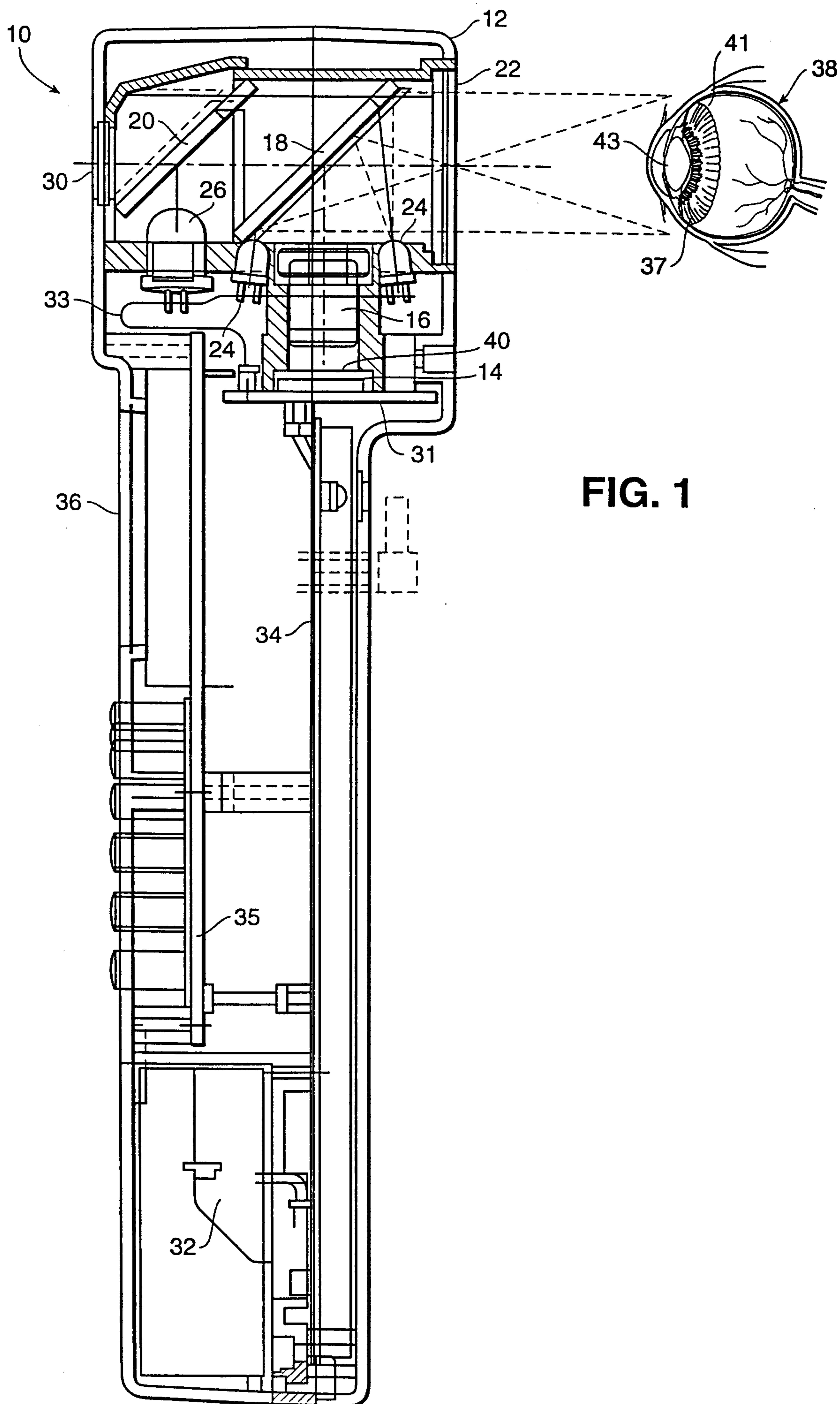
129. The method of claim 125, wherein the first and second sets of data represent pupillary constriction velocities.
25

130. The method of claim 125, wherein the first and second sets of data represent pupillary amplitude.

30 131. The method of claim 125, wherein the second set of data represents data taken from a healthy individual.

132. The method of claim 125, wherein the second set of data represents data taken from an individual with an elevated level of intraocular pressure.

1 / 10



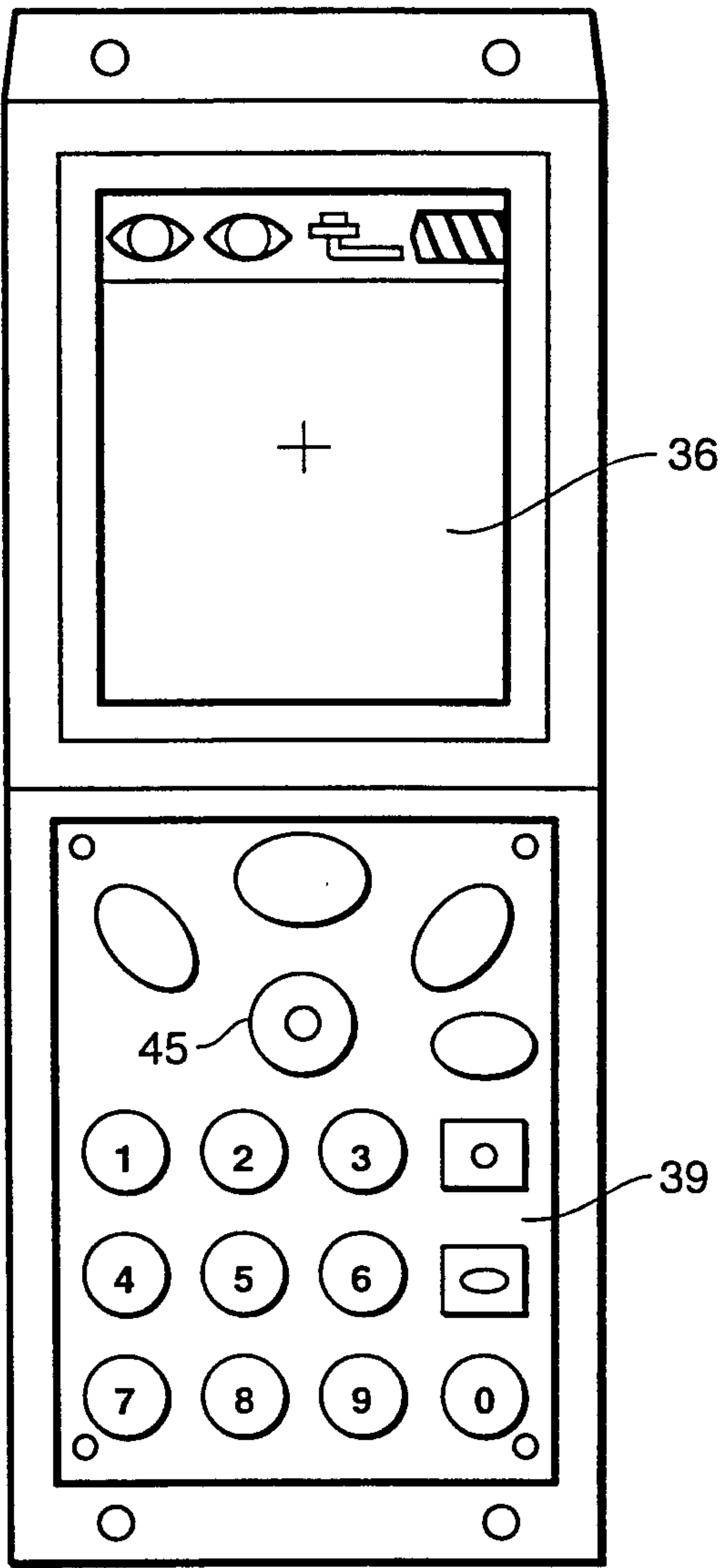


FIG. 2

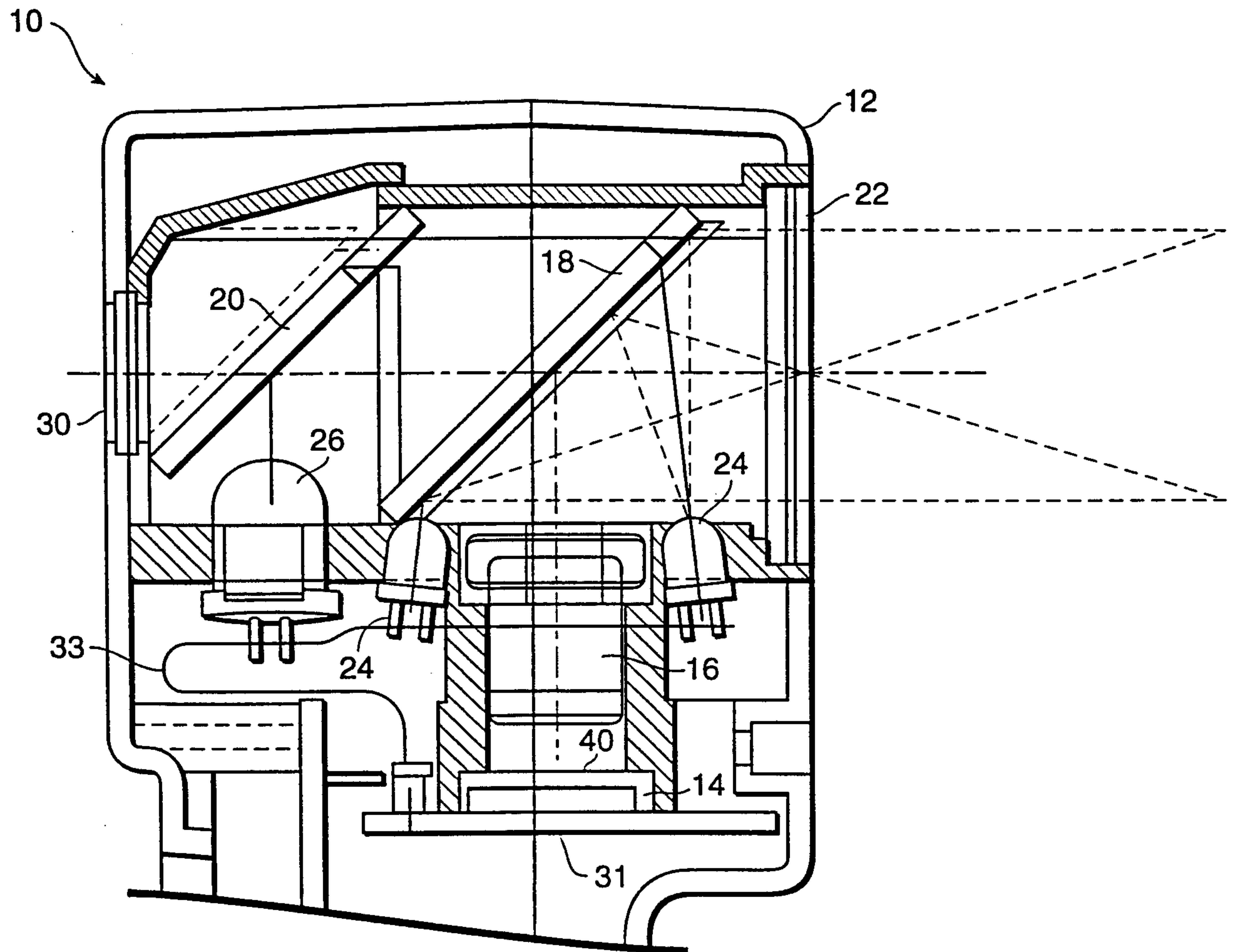
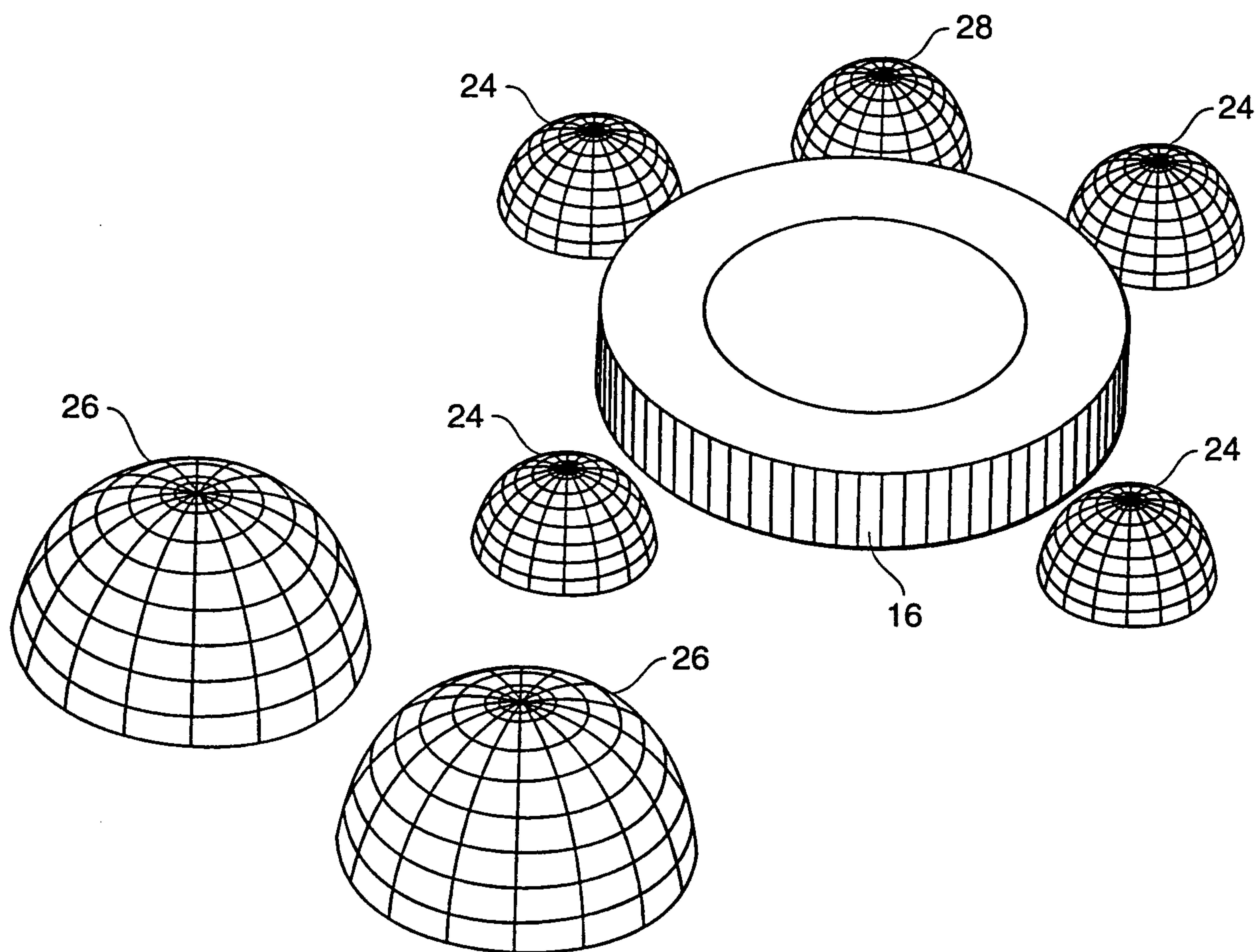
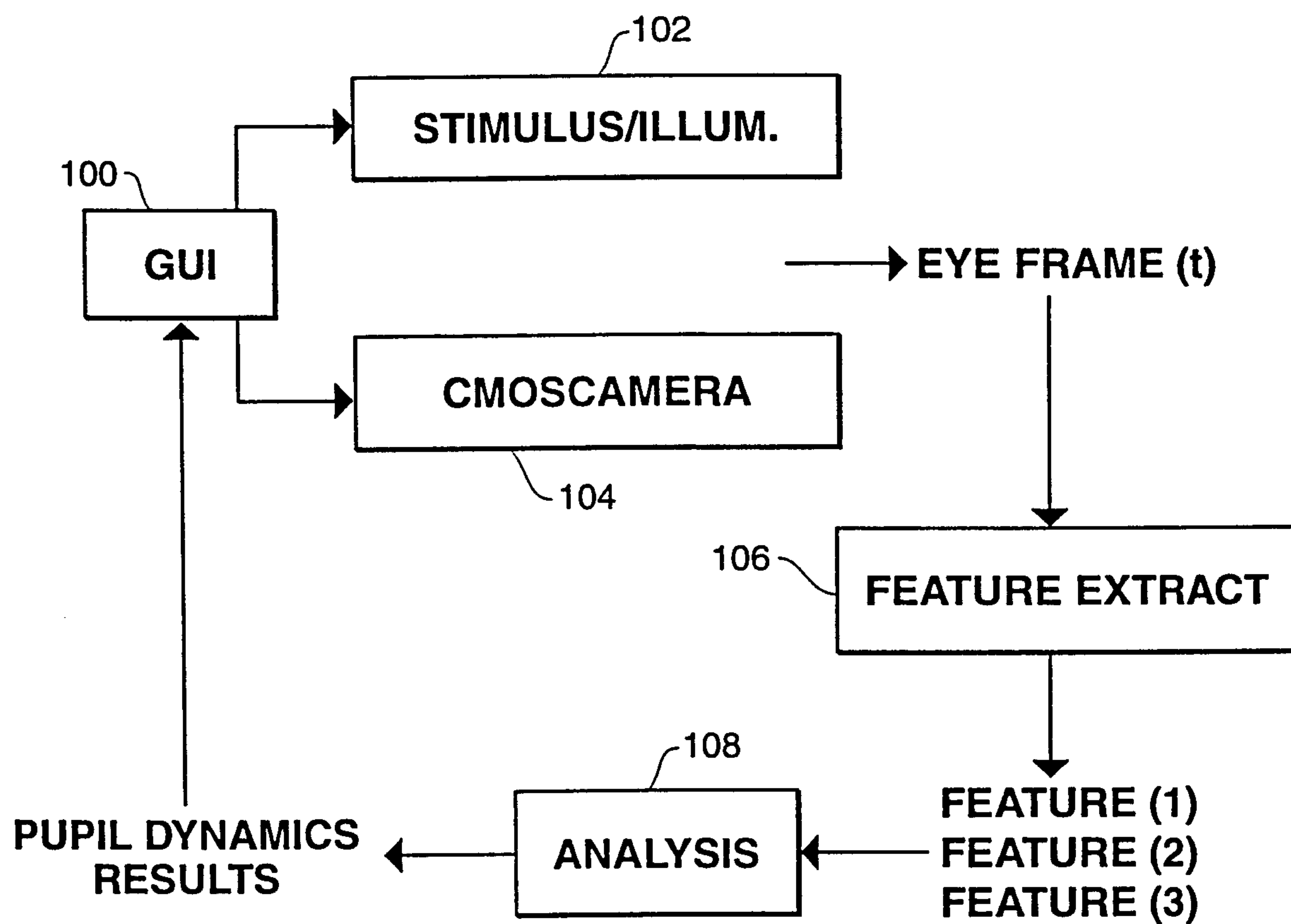


FIG. 3

**FIG. 4**

**FIG. 5**

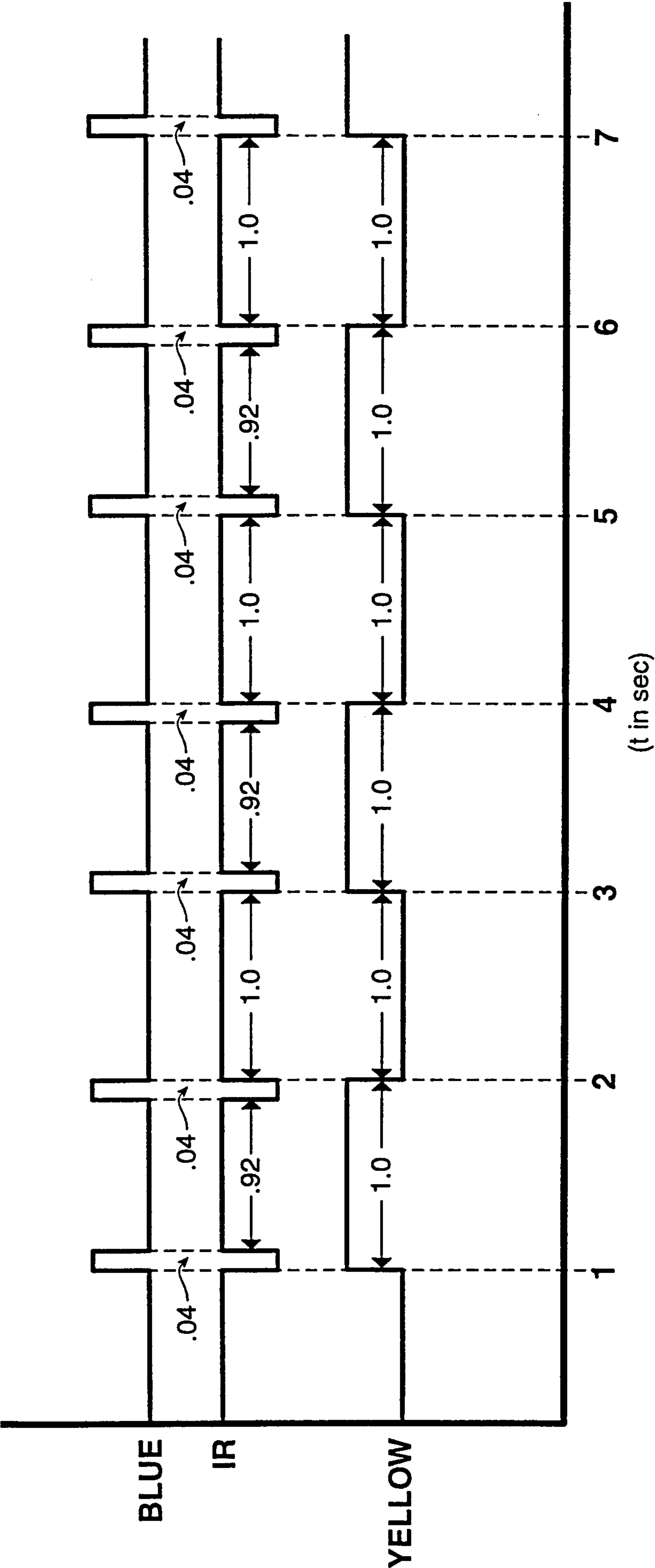
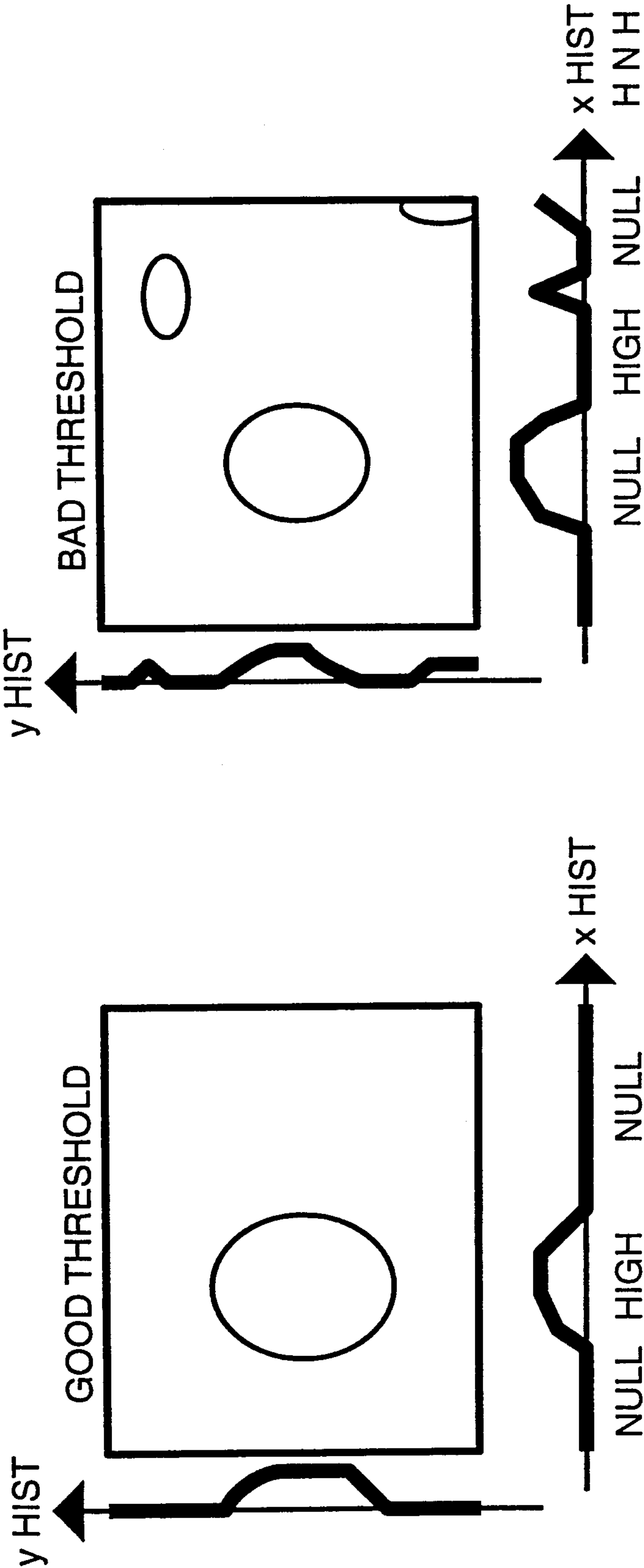


FIG. 6



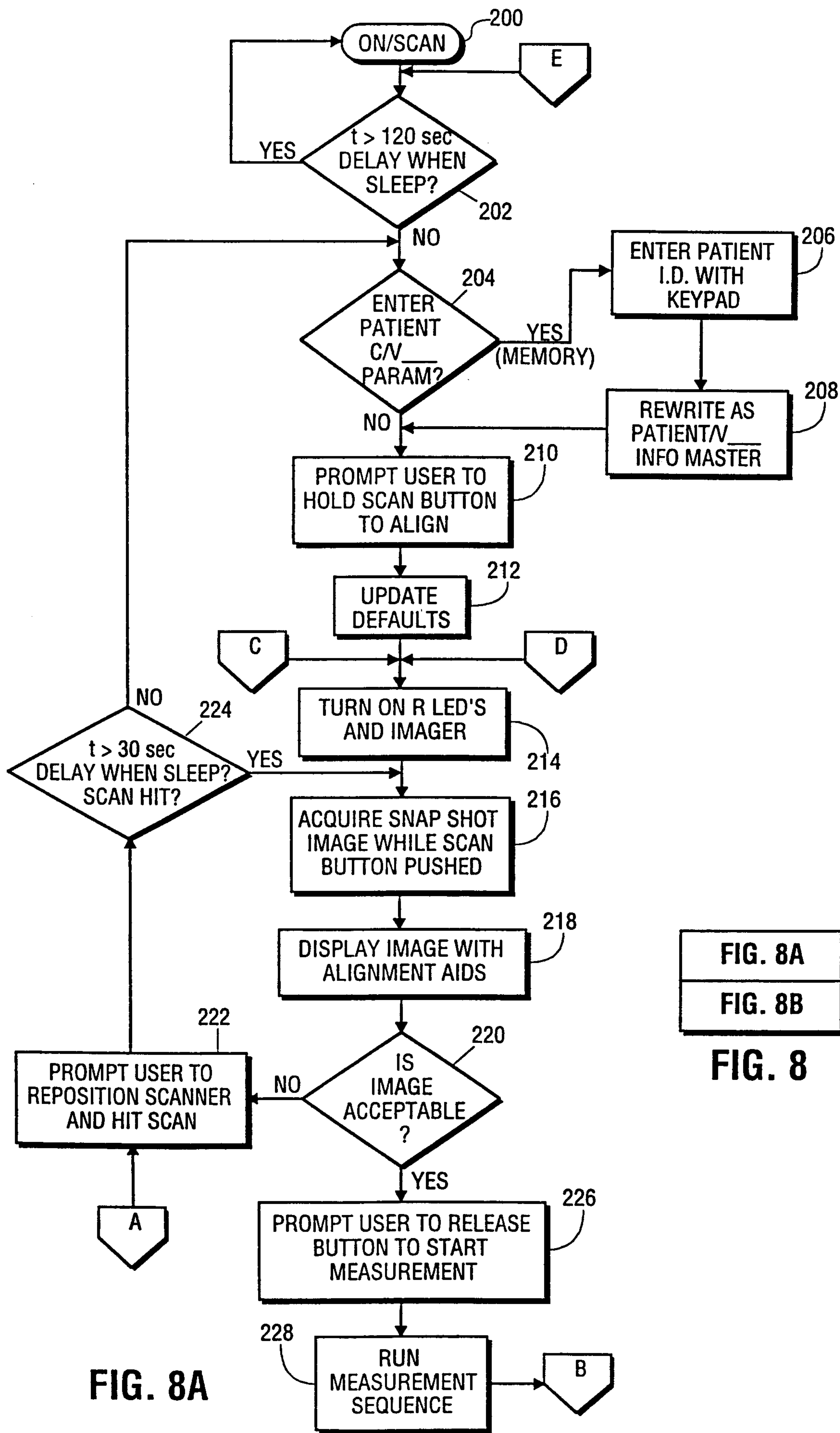


FIG. 8A

FIG. 8A

FIG. 8B

FIG. 8

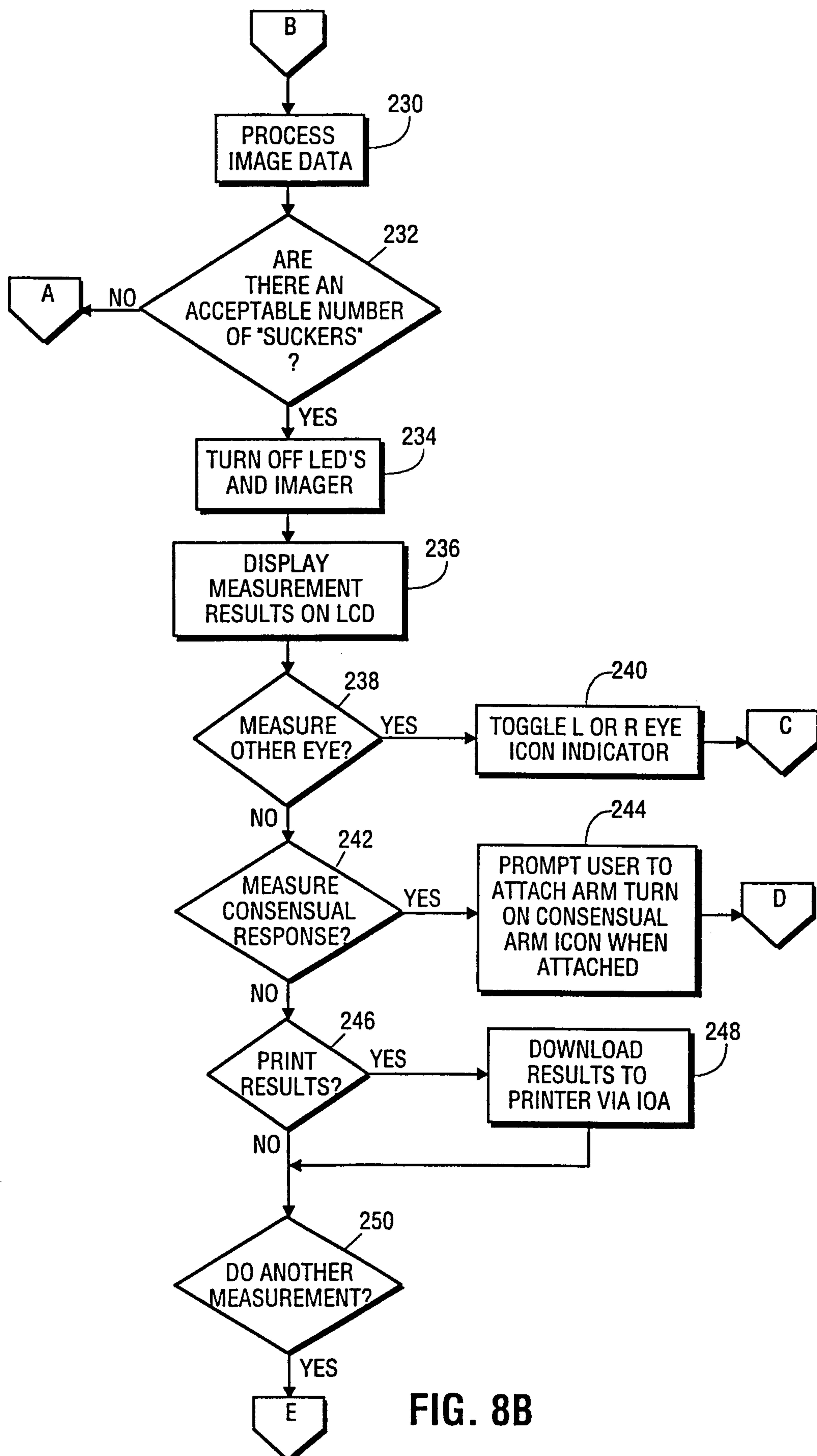


FIG. 8B

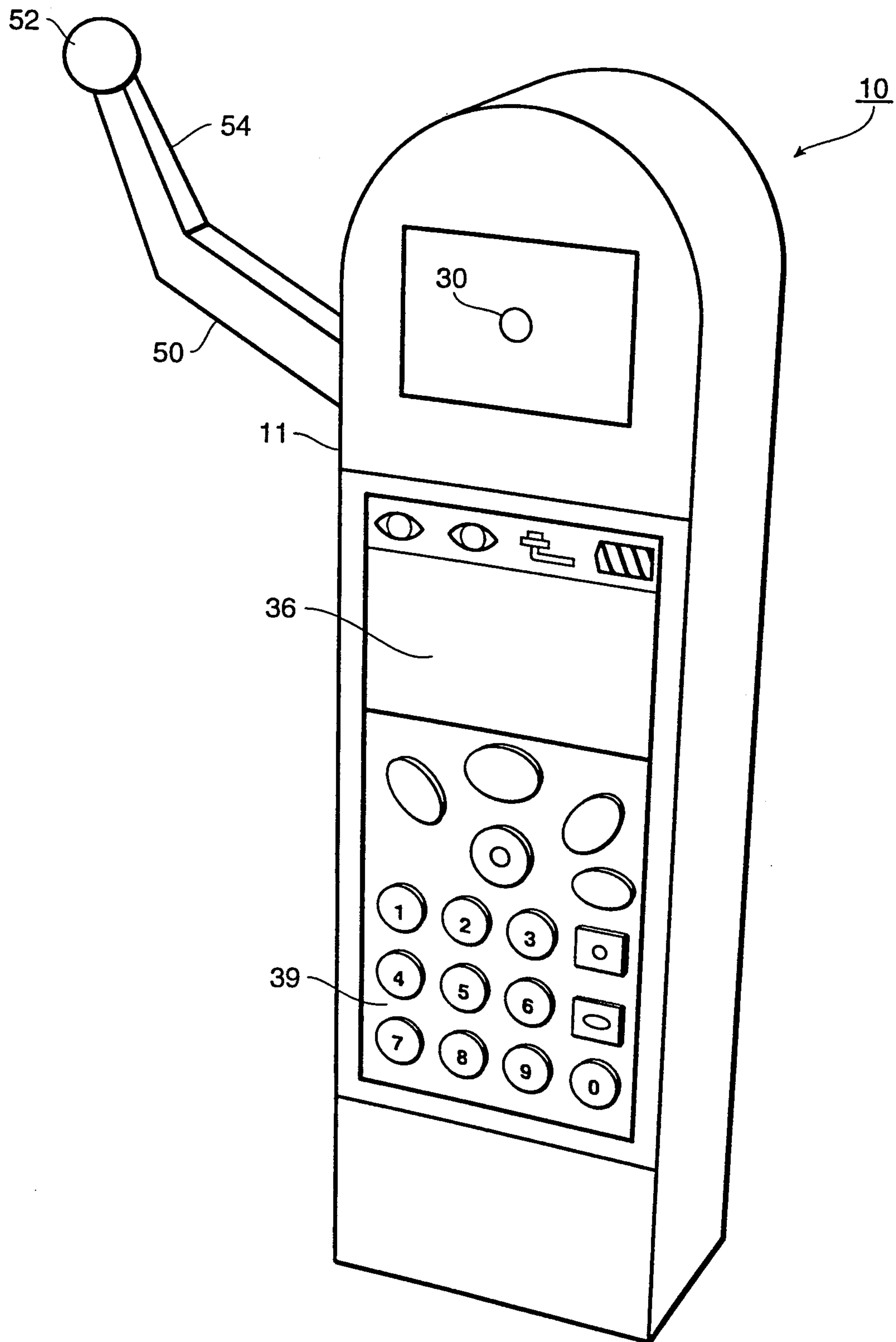


FIG. 9

