DESCRIPTION

Method for measuring the intraocular scattering that affects different ocular media of the eye and computer program products thereof

Field of the Invention

The present invention generally concerns non-invasive methods used for measuring the intraocular scattering. In particular, the invention concerns a method, and computer program products, for measuring the intraocular scattering that affects different ocular media of the eye, particularly the cornea, the anterior chamber and the crystalline lens.

Background of the invention

Vision has a direct impact on society and people's quality of life. Amongst all the visual aspects, spatial vision is one of the key points that affect vision quality and depends on the image quality that is formed on the retina and on the post-processing in the visual pathways and in the brain. The retinal image is affected by three optical phenomena: diffraction, aberrations and diffusion. In particular, the diffusion induces a luminous veil superimposed on the retinal image, which reduces its contrast.

Several techniques have been proposed to determine the light scattered in the eye. Traditionally, the visual deficiency due to scattering has been assessed by means of clinical psychophysical tests such as a contrast sensitivity chart with or without a glare source. Currently, there exist commercial instruments specialized in measuring intraocular scattering, such as the C-Quant (Oculus GmbH, Germany) [1, 2]. There are also some methods that are related to the assessment of backscattered light, such as the slit lamp or the Scheimpflug camera [3]. However, this light never reaches the retina and, therefore, does not directly affect vision. Recently, robust techniques have also been proposed for measuring the intraocular scattering that directly affects the image of the retina objectively, such as the conventional double-pass technique that uses a point light source, such as the HDA (Visiometrics, Spain) [4, 5], or combined with the projection of an extended source, such as in the Sigma [6].

Some patents and/or patent applications are also known in the state of the art.

Patent US-B2-9498114 discloses a system for determining biomechanical properties of the corneal tissue wherein Purkinje images are used. In this patent, the image analysis is carried out to analyse the X-Y dimension and carry out a rotational tracking of the eye.

Patent US-B2-9101292 describes electronics and certain algorithms to drive, control and process the data from a sequential wavefront in real time and other subsets associated with the wavefront sensor. In this case, the Purkinje images are used to determine the transverse position of the eye, not for calculating the scattering of different parts of the eye.

Patent US-B2-7654668 discloses a method and a device for detecting the spatial position of the optical axis of the eye of an animal or human subject and for centring a reference system relative to the optical axis. In this case, Purkinje images are used to analyse the corneal reflection, for which the maximum light intensity of the image is taken into account. Unlike the present invention, no analysis of the scattering is carried out in order to know the diffusion associated with each part of the eye.

On the other hand, in [7] an instrument is disclosed that uses the fourth Purkinje image to measure the scattering of the anterior segment of the eye. In this case, unlike the present invention, to create the Purkinje images an object is not used with certain areas that allow light to pass to a greater or lesser degree, nor are the contributions of the corneal and the crystalline lens diffusion separated to know the scattering associated with each ocular medium based on a measurement of distribution of light in the images. To measure the scattering in [7], a saturated image is compared with an image without saturation.

In the scientific article described in [8], a technique is described for measuring the ocular optical quality using the third Purkinje image to extract information about the roughness of the anterior surface of the crystalline lens, not information of the diffusion.

Therefore, there exists the need of new, non-invasive analysis methods capable of objectively measuring the intraocular scattering separating the scattered light caused by different parts of the eye, essentially the cornea, the anterior chamber and the crystalline lens.

References:

[1] Fransen L et al. ‘Compensation Comparison Method for Assessment of Retinal Straylight’, Investigative Ophthalmology & Visual Science February, 47, 768-776 (2006).

[2] Coppens JE et al. ‘Reliability of the compensation comparison stray-light measurement method’, Journal of Biomedical Optics 11, 034027 (2006).

[3] Vivino MA et al. ‘Development of a Scheimpflug slit lamp camera system for quantitative densitometric analysis’, Eye 7, 791-798 (1993).

[4] Artal P et al. ‘An Objective Scatter Index Based on Double-Pass Retinal Images of a Point Source to Classify Cataracts’, PLoS ONE 6(2):e16823 (2011).

[5] Vilaseca M et al. ‘Grading nuclear, cortical and posterior subcapsular cataracts using an objective scatter index measured with a double-pass system’, British Journal of Ophthalmology, 96, 1204-1210 (2012).

[6] Sahin O et al. 'Optical Measurement of Straylight in Eyes with Cataract', Journal of Refractive Surgery, 32, 12 (2016).

[7] Bueno JM et al. 'Purkinje imaging system to measure anterior segment scattering in the human eye', Optics Letters, 32, 3447-3449 (2007).

[8] Navarro R et al. 'Optical quality of the eye lens surfaces from roughness and diffusion measurements', Journal of the Optical Society of America A, 3, 228-234 (1986).

Disclosure of the Invention

The present invention provides in a first aspect a method for measuring the intraocular scattering that affects different ocular media of the eye, which comprises, as well as the known methods in the field, radiating, by means of a light source, a light beam on at least one eye (for example, a patient's eye); and capturing, by a camera, a series of Purkinje images of the eye after the reflection of said light beam in each media change of said eye, including the corneal surfaces and the crystalline lens surfaces.

Said light beam, prior to its impingement on said eye, passes through an object, preferably opaque, which includes areas that allow light to pass to a greater or lesser degree, so that light is received in the eye in a series of clear and dark distinct areas.

Unlike known methods, the proposed method also comprises calculating the associated intraocular scattering, separately, to each of the different media of the eye through the processing, by a computing system that includes one or more processors and at least one memory, of the series of captured Purkinje images, wherein the processing includes carrying out a measurement of the light distribution in two or more of the Purkinje images.

Alternatively, the proposed method, instead of radiating the patient's eye, even though this radiation is non-invasive for the patient, can begin with the storage, in a database (or a memory), of the Purkinje images obtained by said camera. Thereafter, the method would carry out the calculation of the associated intraocular scattering as has been described in the previous paragraph.

In a first embodiment, the measurement of the light distribution comprises carrying out a contrast measurement of the Purkinje images.

In a second embodiment, the measurement of the light distribution comprises carrying out a Fourier Transform of the Purkinje images.

In a third embodiment, the measurement of the light distribution comprises analysing contrast changes that occur at different spatial frequencies of the opaque object.

Preferably, according to the proposed method, said series of Purkinje images comprises four different images, a first one relating to a first corneal surface, a second one relating to a second corneal surface, a third one relating to a first crystalline lens surface and a fourth one relating to a second crystalline lens surface. Likewise, in an embodiment, the processing is only carried out for said third and fourth images.

In an embodiment, particularly when the eye suffers from cataracts, said capture of the series of Purkinje images shows that between the third and the fourth images a phantom image appears due to the cataracts. In this case, the method also comprises carrying out a correction of the third Purkinje image by carrying out a contrast adjustment, for example linear or quadratic, of the third Purkinje image removing the contribution relative to said phantom image.

In an embodiment, said object comprises a number of grooves, which can have equal or different dimensions. For example, said grooves can include two mutually parallel grooves, between which another two mutually coaligned grooves are arranged, spaced a certain distance and perpendicular to the former. In another embodiment, said object comprises a liquid crystal device, for example a screen, which is illuminated with a light source.

Other embodiments of the invention that are disclosed herein also include computer program products for carrying out the steps and operations of the proposed method in the first aspect of the invention. More in particular, a computer program product is an embodiment that has a computer-legible medium that includes computing program instructions coded therein, which, when executed in at least one processor of a computing system, cause the processor to carry out the operations indicated herein as embodiments of the invention.

Brief description of the drawings

The previous and other features and advantages will be fully understood from the following detailed description of embodiments, which merely have an illustrative and non-limiting character, with reference to the attached drawings, in which:

Fig. 1 shows a schematic view of a system used to implement the proposed method according to an embodiment of the present invention.

Fig. 2 is a flow diagram that illustrates an embodiment of the proposed method.

Fig. 3 illustrates an example of the Purkinje images in a healthy eye (with low diffusion). P1 and P2 are superimposed and P1 is saturated so as to observe P3 and P4 correctly.

Fig. 4 shows (image on the left) an eye with the ghost Purkinje image GPI beside the third Purkinje image P3. The intensity profile of the ghost image corresponding to the dotted line is shown in the image on the right side. The maximum intensity of this profile according to an embodiment of the present invention is used to calculate the P3' contrast.

Fig. 5 is a dispersion and corresponding linear regression (R^2) diagram obtained according to an embodiment of the present invention for the contrast of the third Purkinje image P3 based on the maximum pixel value within of the phantom image GPI beside the third Purkinje image P3.

Detailed description of several embodiments

The present invention provides a non-invasive method for measuring the intraocular diffusion that separately affects different ocular media of a patient's eye 1, essentially the cornea, the anterior chamber and the crystalline lens, measuring the contribution of each part of the eye.

Fig. 1 shows an embodiment of the system used to implement the proposed method. According to this embodiment, the system comprises a light source 10, such as a xenon lamp, a camera 11, for example a digital camera, an opaque object 12, and a computing system 20 that includes one or more processors and at least one memory and that is operatively connected to said camera 11. Likewise, the system may also comprise a database (or a memory), not shown, for storing the images obtained by said camera 11.

In an embodiment, the light beam produced by the light source 10 is projected on the opaque object 12 that includes a number of areas that allow light to pass to a greater or lesser degree in order to create the profile of the Purkinje images (see Fig. 3). Likewise, the opaque object 12 has a diffuser in the inner side (the closest one to the light source 10) and in the outer side (the closest one to the eye 1) so that said areas act as a light source with uniform intensity.

In order to form the Purkinje images, there is a filter, between the light source 10 and the object, preferably a high-pass one with a cut-off frequency of 760 nm (not shown). The function of the filter is to allow infrared light to pass keeping visible light from reaching the retina, and therefore, avoiding the contraction of the pupil. The light that reaches the eye 1 is reflected on each medium change there is in the eye 1, creating four Purkinje images: a first one formed by the first surface of the cornea P1, a second one by the second surface of the cornea P2, a third one by the first surface of the crystalline lens P3 and a fourth one by the second surface of the crystalline lens P4.

Said camera 11 is coupled to a telecentric lens that provides the adequate depth of field for capturing all the Purkinje images simultaneously (Fig. 3) and compensates for the distortion of the objects based on their position. In order to aim and fix the patient's sight, a fixation test is used, in particular a very low intensity LED 13, so as to avoid the patient's pupil contraction. The system can incorporate another high-pass filter with a cut-off frequency of 760 nm (not shown either) in front of the telecentric lens so as to keep light from the LED 13 (fixation test) from reaching the camera 11.

The system also incorporates two stepper motors that allow positioning the light source 10 and the opaque object 12, as well as the camera 11 in the correct position relative to the eye 1.

Preferably, the opaque object 12 comprises a number of grooves that can have the same or different dimensions (non-limiting, since the opaque object 12 may alternatively comprise a liquid crystal device, such as a screen). For example, the grooves may be arranged so that there are two mutually parallel grooves, between which another two mutually coaligned grooves are arranged, spaced a certain distance and perpendicular to the former.

Referring now to Fig. 2, an embodiment of the proposed method is shown therein. According to this embodiment, the method comprises, radiating, step 201, by means of said light source 10, a light beam on the eye 1, wherein said light beam, before its impingement on said eye, passes through the opaque object 12, so that light is received in the eye in a series of clear and dark distinct areas. Thereafter, the camera 11 captures, step 202, the Purkinje images of the eye 1. Finally, step 203, the associated intraocular diffusion is separately calculated for each of the different media of the eye 1 through processing, by the computing system 20, of the captured Purkinje images, wherein the processing includes carrying out a distribution measurement of the light in two or more of the Purkinje images.

In an alternative embodiment, instead of carrying out step 201, the method comprises storing the Purkinje images captured by the camera 11 in said database (or memory) and then carrying out step 203, as has been previously described.

Preferably, the measurement of the light distribution is carried out through the contrast measurement of the Purkinje images. In this case, once the Purkinje images are captured, their intensity profiles are analysed. As can be seen in Fig. 3, the images are shown in a grey scale, which means that each pixel has an associated value. The greater this value is, the more intensity has been received in the pixel during the image acquisition time. Simply put, the scattering phenomenon can be explained as the trajectory change of the photons due to the interaction with particles. Then, the method starts with the hypothesis that, due to the scattering, a portion of the light will be deviated and will reach the central part. That is, the more diffusion there is, more light from the grooves will reach the central part, thereby reducing contrast.

To quantify the contrast (or scattering), the following Michelson equation can be used:

$$Contrast = \frac{\mathrm{I}\max - \mathrm{I}\min}{\mathrm{I}\max + \mathrm{I}\min}$$

wherein, Imax and Imin represent the maximum and minimum intensity, respectively. To calculate the contrasts, for example, the average of the maximum and minimum intensities may be calculated.

In another embodiment, the contrast may even be carried out with maxima and minima at different distances (varying the spatial frequency) and observing how the contrast changes based on the spatial frequency.

In another embodiment, the measurement of the light distribution comprises carrying out a Fourier Transform of the Purkinje images.

Preferably, the Purkinje image processing is only carried out for such third and fourth images. The hypothesis behind this is that the third Purkinje image P3 is affected by the light scattered in the cornea (and also in the anterior chamber), whereas the fourth Purkinje image P4 is affected by the previous scattering sources, as well as by that produced within the crystalline lens. In any case, the proposed method can process others of the Purkinje images or even all the images for measuring the intraocular scattering that affects the different ocular media.

On the other hand, the experimental results show that the contrast of the third Purkinje image is somehow affected by cataracts existing in the eye, which means that it carries information about the scattering of the crystalline lens and not only by the diffusion caused in the cornea and in the aqueous humour. The reason for this is that the formation of a cataract implies changes in the refraction index within the crystalline lens, which, in some cases, may cause additional internal reflections, that is, an additional Purkinje image, or several of them, causing a ghost image to appear between the third and fourth Purkinje images P3 and P4.

For this reason, in an embodiment, the proposed method also comprises compensating for said ghost Purkinje image GPI based on the calculation of a new contrast P3’ in which the influence of said ghost image GPI is subtracted from the contrast of the third Purkinje image P3 so that P3’ is independent from the cataract.

To remove the light of the ghost image GPI from the calculated contrast of the third Purkinje image P3, those patients whose eyes show the ghost image GPI, that is, those with cataracts, are selected in the first place.

Then, the highest pixel value is preferably measured corresponding to the ghost image GPI (see Fig. 4 for a particular embodiment). It should be noted that, instead of calculating the highest pixel value corresponding to the ghost image GPI, all of the pixels of said image might alternatively be measured or even another type of correction function might be applied. As has been previously stated, in most cases the ghost image GPI is proximate to the third Purkinje image P3, although in others it can appear between the third P3 and fourth P4 Purkinje images.

Fig. 5 represents a dispersion graph of the raw contrast of the third Purkinje image P3 based on the maximum intensity of the ghost image GPI (GPI max I) as well as the corresponding adjustment, linear in this particular case, according to an embodiment of the present invention. As can be observed, a linear correlation exists between both parameters (r=0.683), which indicates that the contrast of the third Purkinje image P3 is really affected by the light distribution of the ghost image GPI.

According to this particular embodiment, using the linear adjustment (P3=a·(GPI max I) + b), calculating the contrast of P3' from the raw contrast of the third Purkinje image P3 is achievable in order to remove the contribution of the ghost image GPI, that is, the cataract contribution, in the latter in the following way:

$$P3' = P3 - a\cdot(\text{GPI max I}) \qquad \text{Eq. 1}$$

wherein: P3' is the compensated contrast, P3 is the raw contrast, *a* is the slope found in the linear regression and GPI max I is the maximum pixel value found in the light distribution of the ghost image GPI next to the third Purkinje image P3.

The proposed invention may be implemented in hardware, software, firmware or any combination thereof. If it is implemented in software, the functions may be stored or coded as one or more instructions or code in a computer-legible medium.

The computer-legible medium includes a computer storage medium. The storage medium may be any medium available that can be accessed by a computer. By way of example, and not limitation, such computer-legible media may comprise RAM, ROM, EEPROM, CD-ROM or another optical disc storage, magnetic disk storage or other magnetic storage devices, or any other medium that may be used to carry or store desired program code in the form of instructions or data structures and which can be accessed by a computer. Disk and disc, as used herein, include compact discs (CD), laser disc, optical disc, digital versatile disc (DVD), flexible disk and Blu-ray disc, where the disks normally reproduce data magnetically, whereas the discs reproduce data optically with lasers. Combinations of the foregoing should also be included within the scope of computer-legible media. Any processor and storage medium may reside in an ASIC. The ASIC may reside in a user terminal. As an alternative, the processor and the storage medium may reside as discrete components in a user terminal.

As used herein, the computer program products that comprise computer-legible media include all forms of computer-legible media except, insofar that medium is considered not to be non-established transitory propagation signals.

The scope of the present invention is defined in the attached claims.

CLAIMS

1. A method for measuring the intraocular scattering that affects different ocular media of the eye, the method comprising:

   a) radiating, by means of a light source (10), a light beam on at least one eye (1), wherein said light beam prior to its impingement on said eye (1) goes through an opaque object (12) that includes certain areas that allow light to pass to a greater or lesser degree, so that light is received on the eye (1) in a series of clear and dark distinct areas; and
   b) capturing, by a camera (11), a series of Purkinje images of the eye (1) after the reflection of said light beam in each media change of said eye (1), including the corneal surfaces and the crystalline lens surfaces,

   the method being **characterised in that** it further comprises c) calculating the associated intraocular scattering, separately, to each of the different media of the eye through the processing, by a computing system (20), of said series of captured Purkinje images, wherein the processing includes carrying out a measurement of the light distribution in two or more of the Purkinje images.

2. The method according to claim 1, wherein the measurement of the light distribution comprises carrying out a contrast measurement of the Purkinje images.

3. The method according to claim 1, wherein the measurement of the light distribution comprises carrying out the Fourier Transform of the Purkinje images.

4. The method according to claim 1, wherein the measurement of the light distribution comprises analysing certain contrast changes that occur at different spatial frequencies of the opaque object (12).

5. The method according to any of the previous claims, wherein said series of Purkinje images comprises four different images, a first one pertaining to a first surface of the cornea, a second one pertaining to a second surface of the cornea, a third one pertaining to a first surface of the crystalline lens and a fourth one pertaining to a second surface of the crystalline lens, and in that said processing is only carried out for said third and fourth images.

6. The method according to claim 5, wherein said eye (1) suffers from cataracts, a ghost image between the third image and the fourth image being produced in addition to said series of Purkinje images, the method further comprising carrying out a correction of the

third Purkinje image, said correction comprising carrying out a contrast adjustment of the third Purkinje image removing the contribution relative to said ghost image.

7. The method according to any of the previous claims, wherein the opaque object (12) comprises a number of grooves having identical or different dimensions, and providing said areas that allow light to pass to a greater or lesser degree.

8. The method according to claim 7, wherein said grooves include two mutually parallel grooves, between which another two mutually coaligned grooves are arranged, spaced a certain distance and perpendicular to the former.

9. The method according to any of claims 1 to 6, wherein the opaque object (12) comprises a liquid crystal device including a screen, which provides said areas that allow light to pass to a greater or lesser degree.

10. A computer program product that includes code instructions that, when executed in a processor of a computing system, implement step c) of claim 1.

ABSTRACT

Method and computer program products for measuring the intraocular scattering that affects different ocular media of the eye

The method comprises radiating a light beam on an eye, wherein said light beam, prior to its impingement on said eye, passes through an opaque object with certain areas that allow light to pass to a greater or lesser degree, so that light is received on the eye in clear and dark distinct areas; capturing a series of Purkinje images of the eye after the reflection of the light beam in each media change of the eye, including the corneal surfaces and the crystalline lens surfaces; and calculating the intraocular scattering associated, separately, to each of the different media of the eye through the processing of the captured Purkinje images by carrying out a measurement of the light distribution in two or more of the Purkinje images.

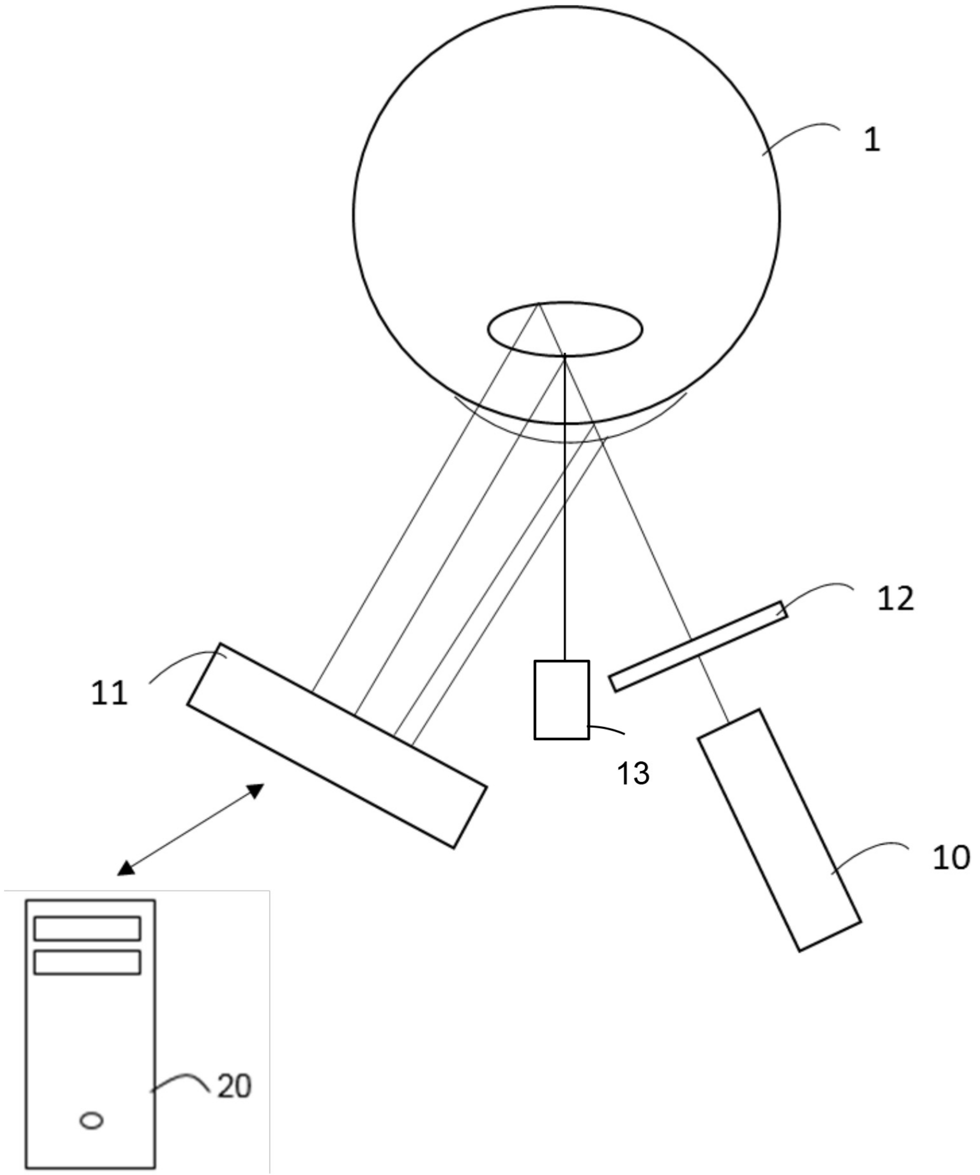

Fig. 1

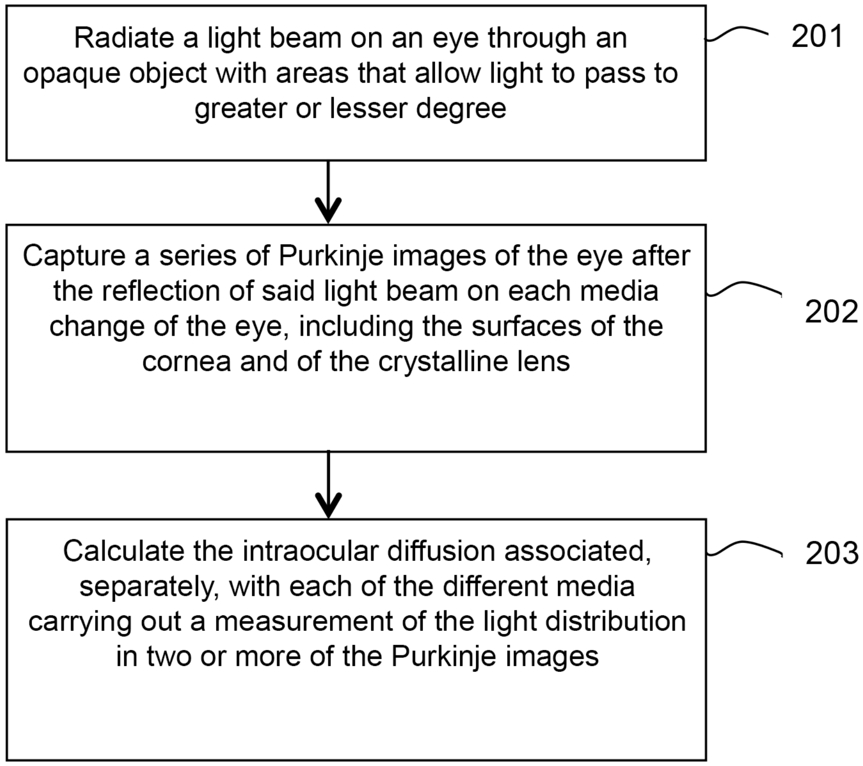
Radiate a light beam on an eye through an opaque object with areas that allow light to pass to greater or lesser degree
201
Capture a series of Purkinje images of the eye after the reflection of said light beam on each media change of the eye, including the surfaces of the cornea and of the crystalline lens
202
Calculate the intraocular diffusion associated, separately, with each of the different media carrying out a measurement of the light distribution in two or more of the Purkinje images
203

Fig. 2

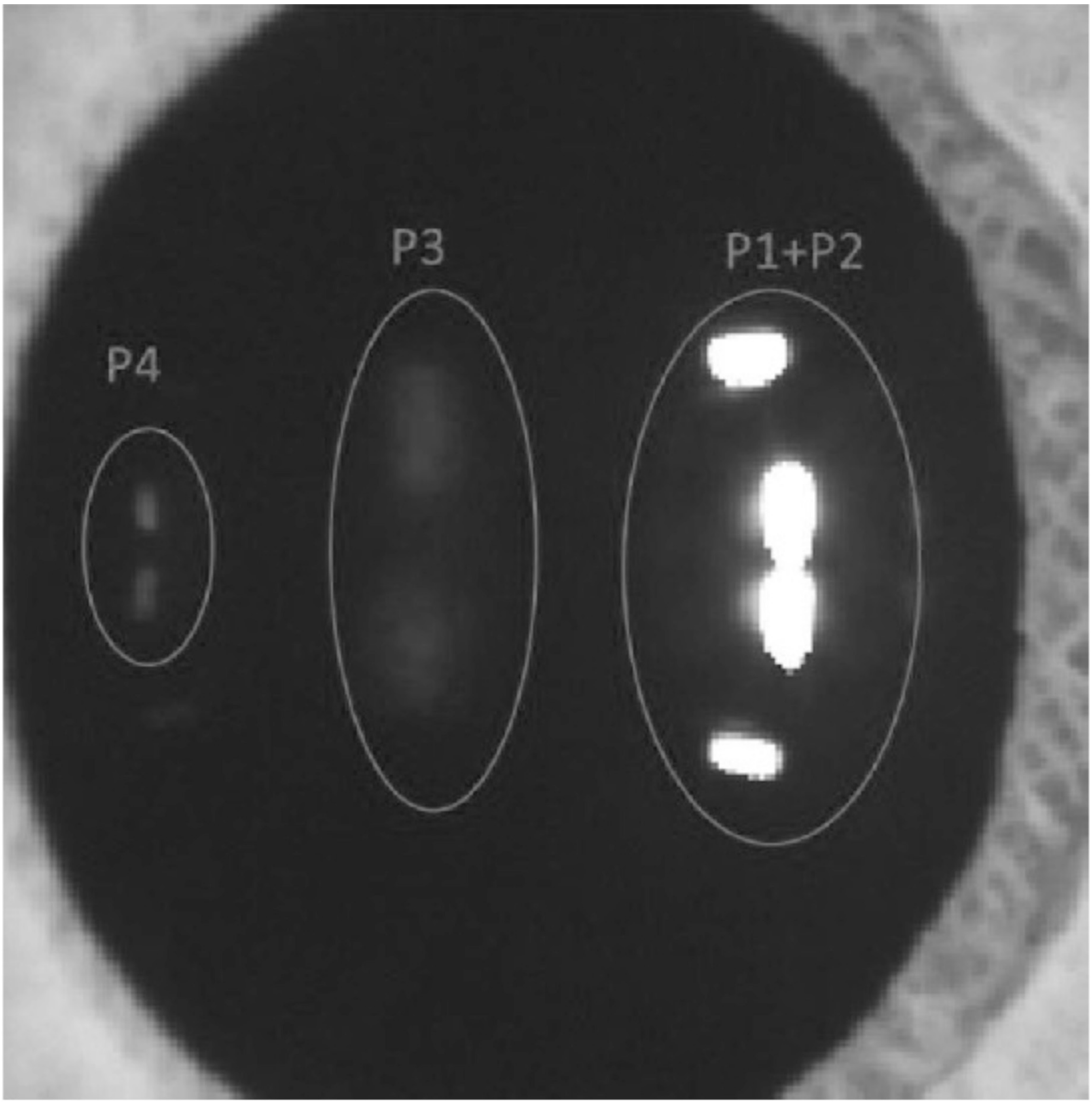

Fig. 3

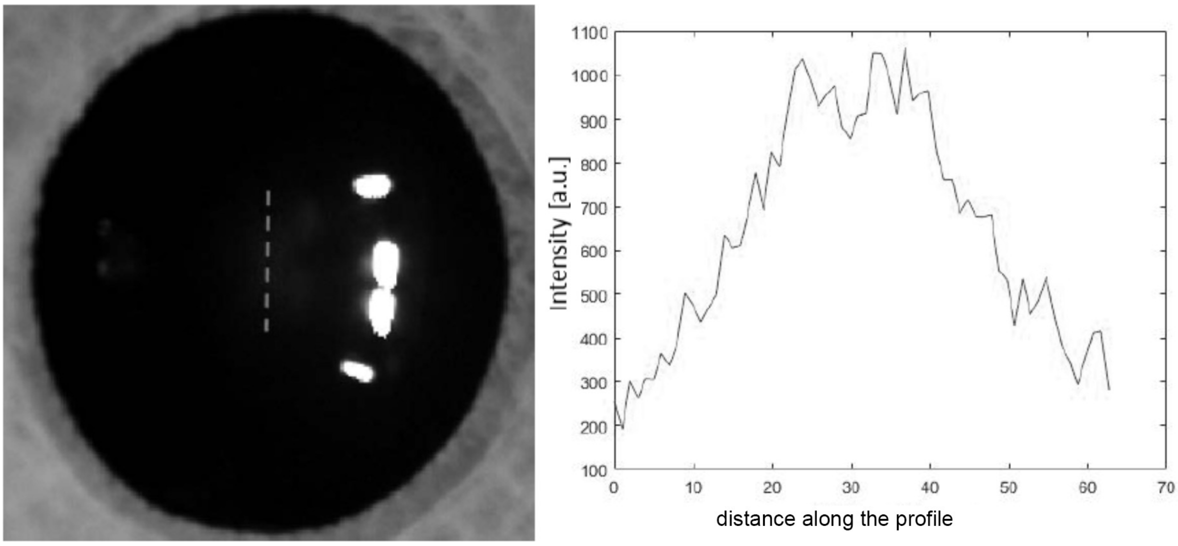
Intensity [a.u.]
1100
1000
900
800
700
600
500
400
300
200
100
0
10
20
30
40
50
60
70
distance along the profile

Fig. 4

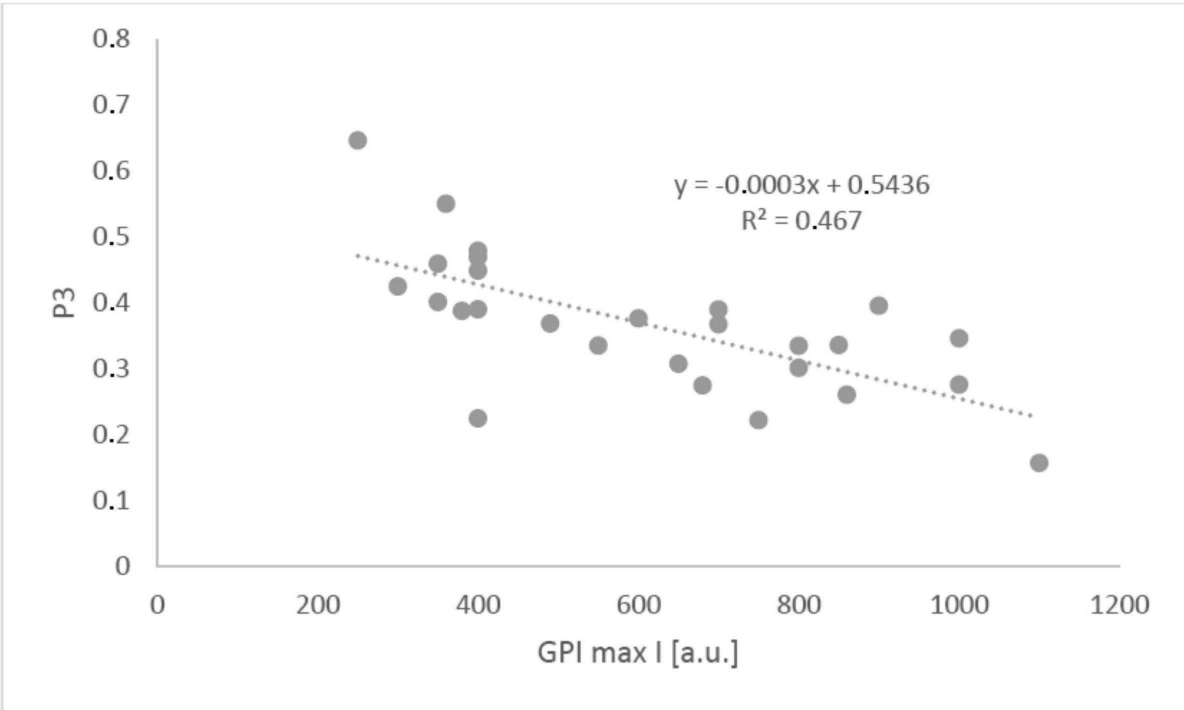
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
P3
y = -0.0003x + 0.5436
R² = 0.467
0
200
400
600
800
1000
1200
GPI max I [a.u.]

Fig. 5