Videoonystagmography,
virtual reality,
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PRELIMINARY RESEARCH ON APPLICATION OF VIRTUAL REALITY AS OPTICAL STIMULATION IN VIDEONYSTAGMOGRAPHY

The paper presents a research on the utilization of a virtual reality as means of stimulation during a videonystagmography examination. The main aim of the research was to test whether an optical stimulation generated by means of virtual reality presented in a helmet-mounted display is applicable to the videonystagmography examination. Eye position was recorded by an infrared camera mounted in virtual reality head-set. Visual stimulations were first performed on a LCD display mounted in VR goggles and then on a LCD monitor. Tracking of a moving field was a subject's task. Target horizontal and vertical jumps were used for calibration. Visual stimuli applied were pendulum target movement and moving vertical stripes. The results of tests showed that pupil positions registered during the virtual stimulation were consistent with those registered during the traditional stimulation.

1. INTRODUCTION

Videonystagmography is a technology for vestibular assessment. It consists of a series of tests used to determine the causes of a patient's dizziness or balance disorder. Dizziness and disturbance of equilibrium are ambiguous symptoms that may occur in the process of many diseases [5] [8] [9]. Clinical symptoms that indicate disturbances of the human equilibrium system include dizziness (a subjective symptom) along with objective indicators such as nystagmus (i.e. rapid involuntary movements of eyeballs) as well as unbalanced posture that result from alterations in various groups of muscles. The analysis of the nystagmus effect that has been induced by strictly defined sets of stimuli is considered as one of most reliable methods for evaluation of the equilibrium system [5] [8] [2].

Videonystagmography is based on eye movements observation with the use of an infrared video camera and their subsequent analysis using a dedicated computer application. It is possible to apply different types of stimulation to induce a nystagmus. The essential condition to perform the test is the visibility of the eyeball.

The main aim of the presented research was to test whether an optical stimulation generated on the virtual reality (VR) head-mounted display (HMD)is comparable with traditional methods of the stimulation presented in the human natural environment (not virtual) in this case on a LCD monitor screen. To achieve this, special equipment and software has been developed. VR head set has been constructed so that it allowed for mounting inside an infrared camera for eye

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position tracking and allowing for presentation of visual stimuli either on LCD display placed inside VR goggles or on external LCD monitor.

Early research on the usage of the virtual reality were conducted in the field of vestibular rehabilitation in late ’90s and in early 2000s [17] [19] [1]. Recently researchers returned to this studies [10] [18] [3] in view of a big comeback of the virtual reality technology in many different fields of science as well [12] [14] [13] [15] [6] [24] [25]. Research on application of the virtual reality animations as a stimulation in electronystagmography can be found in [11]. Research on application of the virtual reality animations as a stimulation in videonystagmography was not found.

2. MATERIALS AND METHODS

It was necessary to develop a special piece of equipment to test the usefulness of the virtual reality stimulation in videonystagmography. Functional requirements for the equipment and software were specified below.

2.1. FUNCTIONAL SYSTEM REQUIREMENTS

Functional requirements of the device and software model were determined during the research:

- the device should have the form of goggles,
- it should be possible to remove the LCD display from goggles and perform eyetracking in response to visual stimulation on the external LCD monitor,
- it should be possible to record eye movements without using the LCD display as an optical stimulus,
- the device should be equipped with at least one infrared camera,
- the device should have a backlight system working in the near infrared,
- the device should allow for tracking of at least one eyeball,
- camera frame rate should be in a range of 60 to 120 frames per second.

Functional requirements of the software:

- the software should be able to preview camera output and store it in video files,
- the software should enable calibration of the eye position,
- the software should enable off-line digital image analysis,
- angular resolution of at least 0.5°.

2.2. SYSTEM COMPONENTS SELECTION

Camera selection

The basic criteria for choosing a camera were:

- frame rate of image transfer should be from 60 to 120 frames per second,
- the image resolution of transmitted images at 60 to 120 frames per second should be at least 640 x 480 pixels,
- small dimensions allowing the camera to be mounted inside/on the goggles,
- the ability to change the lens,
- no near infrared filter,

- the ability to control the level of exposure,
- a global snapshot in which all the pixels of the matrix start and finish the exposure at the same time so the entire content of the matrix is read simultaneously, so that sharp images of fast-moving objects are obtained.

The Optitrack solution was finally chosen. The Slim3U camera model met all of the above criteria.

Selection of the lenses

The magnification of the eye image obtained from the camera using the lens provided with the camera was insufficient, therefore, when converting the focal length of the lens into the size of the obtained image, the Lensagon BL8012 lens with the following parameters was selected:

- M12 mounting method,
- sensor 1/3 ”,
- 8 mm focal length,
- aperture 1.2,
- viewing angle (D/H/V) 42.8°, 34.2°, 25.7°,
- infrared filter is missing.

The eye image is directed to the camera via so called hot mirror (mirror with a reflective coating of infrared radiation). Mirror parameters:

- angle of reflection (°): 45,
- IR reflection (%): >90, 750 - 1125 nm,
- dimensions (mm): 50.0 x 50.0,
- thickness (mm): 3.3,
- transmission of visible light (%): >85, 425 - 675 nm,
- type: Hot Mirror,
- wavelength range (nm): 425 - 1150,
- reflective layer: dielectric.

2.3. PRELIMINARY WORK

Research on the optimal arrangement of the object, backlight, the mirror and the camera was conducted on the optical table. An example of the arrangement of objects is shown in Fig.1.

Parameters of the optical table:

- dimensions: 300 x 300 x 15 mm,
- grid of mounting holes: 25 mm.

Finally, the equpiment consisted of an infrared camera, a hot mirror, an acquisition software and virtual reality headset based on smartphone (Fig.2).

2.4. DEVELOPMENT OF BACKLIGHT

The backlight system has been developed in several iterations in various configuration:

- a single IR diode,
- 3 x 3 matrix of IR diodes,
- four IR diodes placed on a circle every 90°,
- eight IR diodes arranged on a circle every 45°,

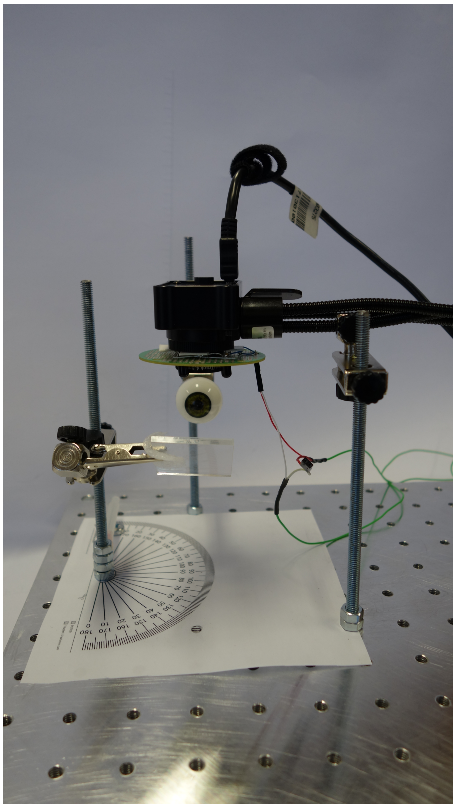


Fig. 1. Optical table with the object, the camera and the mirror and backlight.

Fig. 2. Developed model of the device to record eye movements using a camera working in the near infrared - front view.

The resulting IR illumination consisted of two separate solutions: one for visual stimulation on the inside mounted LCD and another one for stimulation on the external monitor as shown in the Fig. 3. Both used four IR diodes placed on a circle every 90°. When using the inside mounted LCD, IR illuminator was placed on goggle lenses, while when using the external monitor the IR illuminator was slightly bigger in diameter and mounted on a plastic frame inside goggles so that it did not mask the view.

There is an international standard IEC/EN 62471 concerning eye and skin safety for LED lighting products. The standard describes hazard exposure limits. For the cornea and skin, the radiation limit for a time greater than 1000 seconds (16.66 minutes) at temperature of 25°C is $100\frac{W}{m^2}$. The radiation depends on the intensity of radiation (depending on the diode current) and the distance of the IR diode on the eye.

For the retina, the radiation limit depends on the intensity of radiation, the distance of between the eye and the IR diode, the surface of the active (radiating) diode and the length

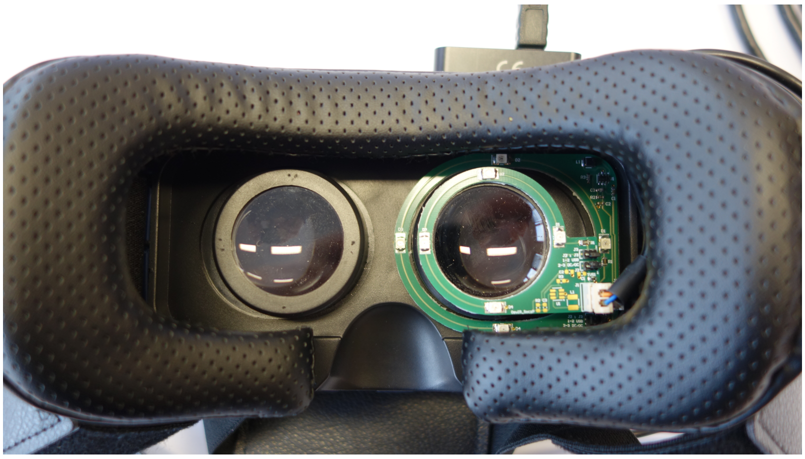


Fig. 3. Developed model of the device to record eye movements using a camera working in the near infrared - rear view.

of the emitted wave. For the distance the diode - the eye of 30 mm and 40 mm and an active diode size of 0.44 x 0.44 mm2, the radiation limit is 60 mW / sr mm2.

In the adopted solution, the radiation values were respectively 1,78 $\frac{W}{m^2}$(cornea and skin) and 2,74 $\frac{mW}{sr*mm^2}$ (retina) for the 5 V supply voltage and the distance of the diode from the eye of 3 cm (the minimum distance).

2.5. IMPLEMENTATION OF SOFTWARE FOR RECORDING AND ANALYZING THE IMAGE OF THE EYEBALL

VNGEyeTrackTest software was developed to support the device model. The main functions of the developed software are: preview of the transmitted image of the eye, registration of the eye image, browsing of registered material, configuration of camera operation parameters, calibration, off-line analysis of the eyeball image.

When the camera is in operation, the online preview is displayed on the computer monitor together with basic camera and recording settings. Camera output is continuously streamed to hard disk. The calibration process for eye position measurement is as follows:

- the person looks at the centre point of the coordinate system for 1 to 2 seconds, the operator determines the so-called centre - angle 0°,
- above described procedure is repeated respectively for the horizontal and vertical directions for angles - 10° and + 10°,
- finally, five reference points are marked on the image of the eye. These reference points, together with eye position extracted from calibration video signal are then used to translate image pixel position to angular values (Fig.4).

2.6. ALGORITHM FOR DETERMINING THE PUPIL CENTRE

Determining of the eye position is performed in two stages and comprises an image preprocessing step and a step of determining the pupil centre. Preprocessing starts with implementing Haar-like feature cascade classifier for findingthe eye is in the image [23] (Fig.5). Then a Gausian Blur is performed on the source image to reduce noise and remove small artefacts.

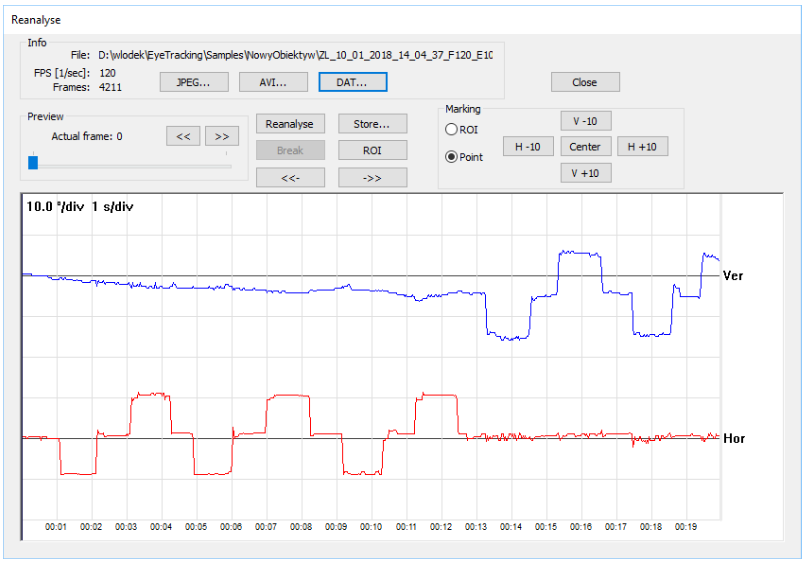


Fig. 4. Software for recording and analyzing registerd eyeball images

Finally, reduction of image artefacts associated with IR lighting is done by filling areas with pixel values above given threshold with average value.

In the first step, the coarse potential position of the pupil (potential pupil region) is detected, shown in the Fig. 6. In this phase, a classification algorithm using the cascade classifier ”Haar-like Feature-based Cascade Classifier” is used to detect the iris and the pupil in the frame of the camera image.

The pupil centre was determined using two methods:

- image binarization method,
- image gradient analysis.

The first method was developed for quasi real-time coarse analysis of the image, the second one for offline reanalysis.

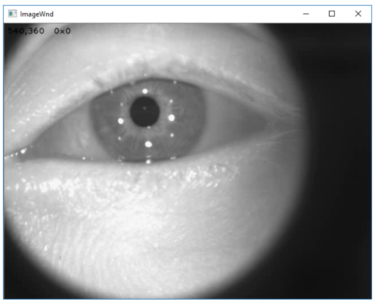


Fig. 5. The original image of an eye

The first one (the quick one) is based on the analysis of the binarized image and the pupil center is determined as a geometry center of the pupil shape. The Otsu binarization method [16] was used.

The basis of the second algorithm for determining the center point of the pupil is to determine the gradient of the potential pupil region, which reflects the vector field of changes in the pixel values in the image. Gradients are calculated for both X and Y axis and the resuling gradient magnitude is obtained..

Mathematical relationship between each potential centre of the iris and all image gradients is defined. Assuming that the iris is a circular object, the optimal centre of this object is found

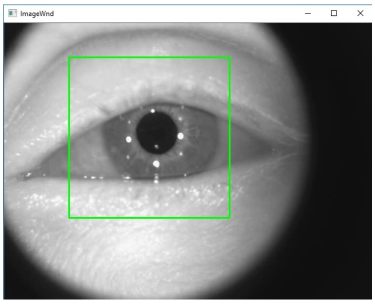


Fig. 6. The eye determined by the Haar-like feature cascade algorithm

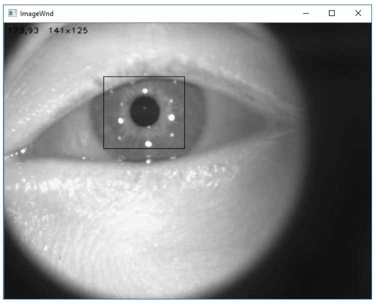


Fig. 7. The narrowed search area of the pupil

a) b)

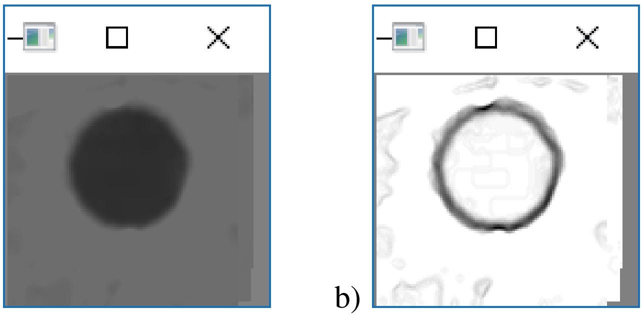


Fig. 8. The pupil image a) after preprocessing, b) after gradient calculation

a) b)

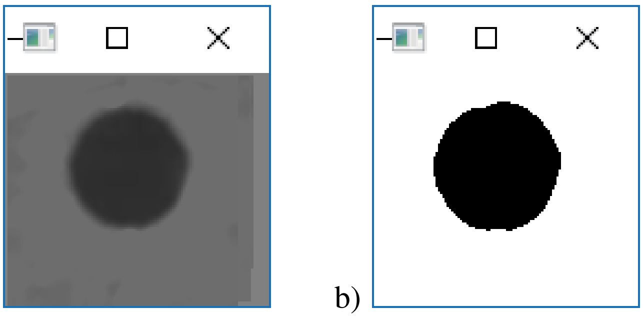


Fig. 9. The pupil image a) after preprocessing, b) after binarizarion

as a point for which the dot products between displacement vectors (formed by potential centre and each other point) and gradient vectors fulfill the defined maximum condition [21].

Before the processing the potential pupil region is narrowed to the area of the pupil defined during the calibration, increased by 30% in both directions as shown in the Fig.7.
Fig.8 and Fig.9 show the pupil image a) after preprocessing and b) after image analysis respectively . In the case of frames in which there is no visible pupil (with a closed eyelid) the pupil position is interpolated.

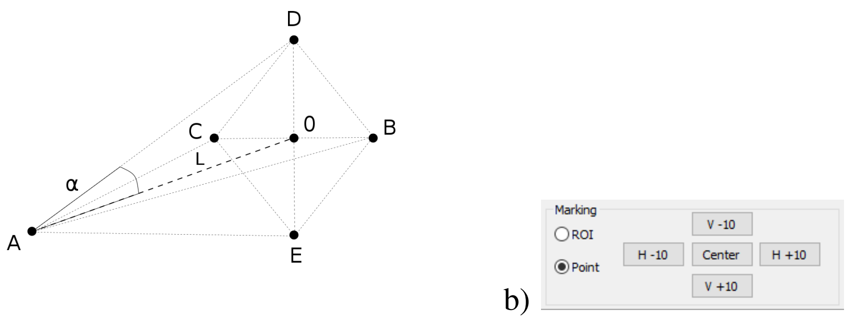
2.7. PREPARATION FOR TESTS

Before each virtual test it was necessary to set a participant's head in a correct position in the virtual space where an animation was displayed. A participant of the experiment fitted two coaxial circles displayed in a virtual reality space in order to set his correct head position . One of the circles was static in the virtual space. The second one was a kind of gaze pointer that followed the movement of the participant's head until it covered the static circle. The correct position of the head was established by the coverage of both circles. After the participant's head had been placed in the correct position it was stabilized not to move.
In presented tests traditional stimulation methods were used. Three traditional animations were prepared: a calibration animation, a pendulum tracking test and moving vertical stripes mimicking a striped rotatory drum for optokinetic test. All these animations were presented on the 30" LCD monitor screen. The participant sat 1 m away from the screen. In order to register eye movement reactions based on vestibulo-oculomotor reflex three virtual animations were worked out. Virtual tests were conducted using stimuli animations prepared for the virtual reality set. All animations for the virtual reality were created with the Unity 3D editor and Blender software [7] [20] [22]. There were following animations: a calibration pre-test animation, a pendulum movement animation and an animation simulating equipment with rotatory chair using optokinetic stimulus superimposed upon round walls.
The tests were carried out in accordance with the procedure:

- a calibration - a determination of an eye angle deflection from the primary position,
- a pendulum tracking test,
- an optokinetic test.

2.8. CALIBRATION

Before the tests, a calibration procedure had been run in order to determine an angle of eyes deflection for further analysis. The traditional calibration was conducted using 30" LCD monitor screen in a darkened room. A calibration was based on tracking points on the Madox cross. In both animations (in a "traditional" and in a virtual one) the calibrating points were lit in a sequence: left-centre-right-top-bottom (C - 0 - B - D - E) as shown in the Fig.10 a). Calibrating points were input by the operator clicking the specified buttons shown in the Fig.10 b).



a) b)

Fig. 10. a) The coordinates points placement in the three dimensional space. Gaze focused on the position "0" is a primary position, b) calibrating points input.

Participant's eyes were situated in the A point. Gaze focused on the position "0" was a primary position. The coordinates of calibration points were given by the formulas: $O(x,y) = (0,0)$, $B(x,y) = (L \cdot sin(\alpha), 0)$, $C(x,y) = ((-1) \cdot L \cdot sin(\alpha), 0)$, $D(x,y) = (0, L \cdot sin(\alpha))$,

$E(x, y) = (0, (-1) \cdot L \cdot sin(\alpha))$, where: α - is an angle between points A and B, A and C, A and D as well as A and E; L is a distance between participant's eyes and Madox cross.

During the experiment, the parameters were as follow: an angle $\alpha = 10°$, the distance $L = 1m$, distances $OB = OD = 17.37cm$, distances $OC = OE = 17.37cm$.

The real distances between a particular objects in the virtual space were mapped to elicit required eyes deflection angle as it had been done in the natural environment. In the Unity 3D editor the distances are represented in Unity units. The default value of 1 Unity unit is 1m for the virtual reality objects creation. Consequently, the object was placed in the distance of 1 Unity unit.

2.9. OPTOKINETIC TESTS

Two optkinetic test were carried out. The first one, a pendulum tracking test was based on a linear pendulum movement following in the range of angles $< -\beta, \beta >$. The angle β was changed from 5° to 10°. A moving object (a sphere) was placed 1m from participant's head at the height of eyes. The frequency of the pendulum ranged from 0.5 to 2Hz. During each test mentioned parameters were constant.

The traditional pendulum tracking test was carried in the same conditions as in calibration process. In the virtual space the coordinates of the sphere position in three dimensional space (x, y, z) were given as follows: $x = sin(\beta)$, $y = 1$, $z = cos(\beta)$,where: β - the angle of deflection of the sphere from the three dimensional position $(x, y, z) = (0, 1, 0)$.

As well as during the calibration process the moving object was placed 1m away from the participant's head.

The second optokinetic test (a rotatating stripes test) was carried out under the same conditions as in the previous one. The participant sat 1m from the monitor. The parameters of an optokinetic test were as follows:

- an angular speed of stripes rotation was 30°/s,
- a stimulus frequency ranged from 0.5 to 2Hz.

The speed, the direction and the stimulus frequency were changed during the test. The virtual simulation of the real equipment used for the second test was prepared as a striped cylinder. A person wearing virtual reality headset was situated inside a virtual rotating striped cylinder [11].

2.10. TECHNICAL ASPECTS

Each frame of the animation is generated in a different time depending on its complexity. A required speed of the animation (e.g. the pendulum movement with the frequency 0.5Hz etc.) was achieved by generating the adequate movement of the sphere determined by the strict time between the successive frames. During the virtual stimulation an angular field of view of a scene equalled 100 ° . All real distances were mapped in the virtual space. Smartphone Huawei Nexux 6 with Anrdoid 8.1 platform was used for tests using virtual reality optical stimulation.

3. RESULTS

30 tests consisting of traditional and virtual tests were conducted. Each deflection of the eye by 10° in the horizontal direction from the starting point 0° was contained in 40 pixels and vertically in 32 pixels of the image on average. This allows to achieve a measurement accuracy for the horizontal direction of 0.25° and 0.3° for the vertical direction in the range of angles

from -10° to + 10°. The accuracy of this order in the field of eye movement analysis is very high. The accuracy of 0.5° in the given range of angles is considered accurate. The test were conducted using Intel Core i7-6700HQ processor and 16 GB RAM memory computer.

In the Table 1 are given results of image processing using both methods binarization with a geometry centre calculation and gradient as well. The average value of the calculation time of a single frame presenting image of the eye was also given. Average values of absolute error and standard deviation values were rounded.

Table 1. The accuracy and calculation time of the pupil centre determining.

Method	Av. value of absolute error [px]	Std deviation [px]	Av. calculation time [ms]
Binarization and a geometry center	2	1	10.2
Gradient	1	1	40.22

Every movie was recorded at 60 frames per second speed. Registered signals were not filtered. After the analysis of aquired signal it was found that corresponding fragments of the signal which were registered in the same conditions (i.e. stimulus angles, speed) were compared with.

As a result of the comparison Pearson correlation coefficients were calculated $(p < 0.05)$ between results obtained using a traditional and virtual stimulation [4]. The results of the comparison are presented in Table 2.

Table 2. The results of the comparison of electronystagmograms registered using traditional and virtual stimulation (the average value of Pearsons correlation coefficient and the standard deviation).

Test	Average value of Pearson correlation coefficient	Standard deviation
Calibration	0.94	0.04
Pendulum tracking	0.92	0.06
Rotating stripes (30 °/s)	0.90	0.05

The comparison of test showed that the stimulation based on the virtual reality is comparable with the traditional stimulation. The Pearson correlation coefficient ranged from 0.94 to 0.90).

4. SUMMARY AND CONCLUSIONS

The research on the application of the virtual reality animations as the optical stimulation in videonystagmography showed that morphology of recordings in the time domain registered during virtual stimulation corresponded to records obtained during traditional stimulation. Eye movment responses registered during virtual stimulation corresponded to records registered during traditional stimulation. The average value of the Pearson correlation coefficient ranged from 0.94 to 0.90 with the standard deviation value ranging from 0.04 to 0.06.

Presented animation did not generate artefacts on the image of the eye.

Gradient method resulted more accurate determining position of the pupil but more time-consuming as well. Gradient method calculation lasted 40.22 ms on average. It is a good solution for signal reanalysis process. Binarization method along with a geometric centre calculation was less accurate and faster(10.2 ms). The time of one frame processing is short enough to use the binaraization method for coarse quasi real-time presentation of a position of the eye. The research shows that an optical stimulation generated in a virtual reality can be used along with the videonystagmography to the extent that was tested.

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