СЕНСОРНЫЕ СИСТЕМЫ, 2020, том 34, № 2, с. 100–106

ЗРИТЕЛЬНАЯ СИСТЕМА

УДК 612.843.621 + 612.844.3

CONTACT LENS WITH IMPLANTED OCCLUDER AS A TOOL FOR ASSESSMENT OF FAR PERIPHERAL VISION IN NATURAL VIEWING CONDITIONS

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Received December 17, 2019; Revised January 09, 2020; Accepted January 23, 2020

The purpose of this research was to assess the perspectives of using contact lens with implanted occluder (CL + O) for far peripheral vision investigation. Contact lens with sufficiently large artificial opaqueness at the center seems to be a proper tool for separation of peripheral visual mechanisms since it prevents any possibility of test stimulus foveating. Earlier studies with similar contact lenses were aimed to mimic vision loss in the case of macular degeneration by means of creating artificial scotoma with relatively small occluders which only "switched off" foveal area and near periphery from visual perception. The task of our study was to separate far peripheral vision using significantly larger occluders in order to provide a possibility to investigate peripheral visual capabilities in natural visual conditions without gaze fixation and division of attention. The calculations based on geometrical optics analysis taking into account the quantitative data available in literature on the human eye structure were used for assessment of the blind zone size created with a given occluder in various experimental conditions in view of proper CL + O choice for experimental sessions. The experimental part of the work included measurements of the blind zone size and position in the visual field varying the occluder diameter and ambient illumination (to change the pupil size). It has been concluded that CL + O is promising for peripheral vision investigations, however, application of CL + O requires thorough control of experimental conditions because the occluded retinal area essentially depends on the individual eye optics and illumination of the experimental scene.

Key words: peripheral vision, vision without fovea, contact lens, implanted occluder, calculation of blind area

DOI: 10.31857/S0235009220020043

INTRODUCTION

Human peripheral vision is usually studied in conditions of gaze fixation when visual attention is divided between the presented peripheral test object and the fixation stimulus at the center of the visual field. Such unnatural and uncomfortable conditions inevitably cause substantial difficulties in the assessment of potential capabilities of peripheral vision. Firstly, keeping central fixation means limitation of the test stimulus drift over the retina, whereas, for optimal perception of the peripheral stimuli, the drift should be enhanced (Yarbus, Rozhkova, 1977). Secondly, forced gaze stabilization requires special efforts to suppress natural oculomotor activity, i.e. to prevent normal voluntary saccadic movement to the peripheral object. Thirdly, at the cognitive level, mental resources have to be distributed between the two tasks thus reducing the potential quality of the peripheral test stimulus analysis.

Our idea to study peripheral vision in conditions of excluding foveal visual mechanisms by means of shading central part of the retina was based on the investigation performed more than 40 years ago (Yarbus, Rozhkova, 1977) with the aid of famous suction caps proposed and widely used by Yarbus for eye movement recording and retinal image stabilization (Yarbus, 1967). To study "pure peripheral vision", Yarbus elaborated a suction cap with a miniature transparent screen (attached to it on thin holders) that allowed pasting central occluders of various sizes preventing central vision. The main advantage of such device was a possibility to achieve complete shielding of the central retina and free observation of the peripheral visual field. However, any experiments with suction cap on the eye implied that the subject's eyelids had to be fixed keeping the eye wide open. Because of this, subjects usually felt significant discomfort that made duration of the experimental sessions too short for detailed quantitative investigations. In our present study,

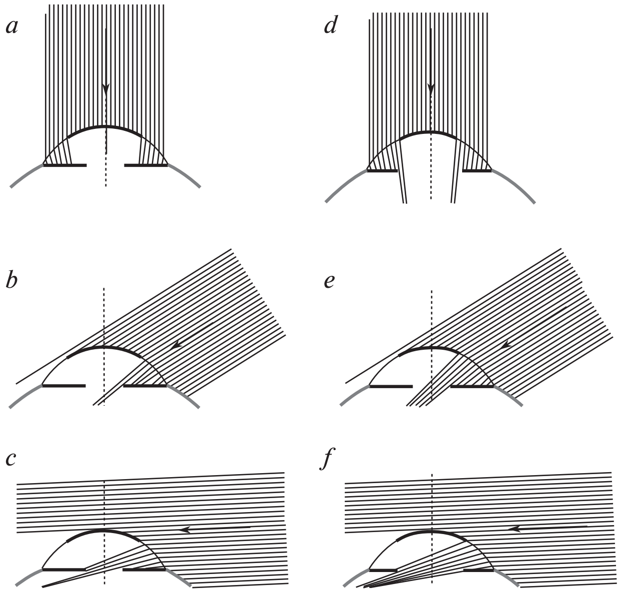

Fig. 1. The schemes showing the light rays of different directions entering the eye in presence of central occluders of two different sizes: in (*a–c*) occluder is larger than in (*d–e*).

instead of Yarbus's suction cap, we used special contact lens with implanted opaque occluder at its center (CL + O).

To our knowledge, the idea of using contact lens with implanted central occluder was firstly published in the paper (Walonker, Diddie 1981). This short paper only contained technical details while the results of practical using similar devices appeared later (Sivak et al., 1985; Sivak, MacKenzie, 1990; Czoski-Murray et al., 2009; Nau, 2012; Butt et al., 2015; Klee et al., 2018; Almutleb et al., 2018; Rozhkova et al., 2019b). Sivak with coauthors used this technique for studying lateralization of visual input and integration of visual information and motor output in reaching and grasping. Main interest of most other researchers was to simulate age-related macular degeneration (AMD) and central scotoma. In particular, the paper of Almutleb with coauthors concerned the conditions necessary to mimic absolute central scotoma. The authors examined geometric optics relationships for predicting dependence of scotoma size on diameters of the opaque center and the eye pupil. They concluded that, in order to mimic central scotoma, one should have the contact lens with the opaque center larger than the entrance pupil of the eye and, therefore, this simulation tool could be ineffective at low levels of illumination when the pupil size could become too large.

In our own paper (Rozhkova et al., 2019b), we presented the results of CL + O application for studying color vision at far periphery of the visual field – in the range of eccentricities from 60 to 95°. However, in this paper, we omitted many technical details focusing attention on some principally interesting findings related to color perception. Here, we tried to compensate for the brevity of our previous technical description: in the first part of the paper, we presented the results of optics analyses and discussed their usage for conducting adequate studies of peripheral vision and correct interpretation of experimental data. In the second part of the paper, we presented experimental data on peculiarities of observation in conditions of wearing CL + O.

GEOMETRICAL OPTICS ANALYSIS

Some basic conclusions concerning usage of contact lens with implanted occluder could be drawn from the results of calculations based on geometrical optic analysis and quantitative data available in literature for the human eye optics parameters.

Figure 1 shows how the light rays of various directions enter the eye in presence of central occluder. The series of the schemes illustrates the cases of observing a point light source positioned on perimetric arc (with radius of about 330 mm) at various eccentricities. Taking into account a typical human corneal diameter (10–12 mm), one could estimate that the angle between the middle and extreme rays falling onto the cornea edges from the point source wouldn't exceed 1.1° (cornea angular size in this conditions). For this reason, all beams of light are pictured as consisted of parallel rays. As one can see, in the case of moderate sizes of the occluder and the pupil (Fig. 1, a–c), for the zero eccentricity of the light source (paraxial rays), the occlusion is complete (or absolute), while with increasing eccentricity, more and more amount of light could enter the eye through the circular slit between the edges of the occluder and the pupil. It's evident that, in the cases of relatively small occluder or large pupil size (compared with the occluder size), complete occlusion is impossible even for the central stimuli (Fig. 1, d–e).

The extension of the central blind zone created by means of a given occluder could be assessed by simple calculations based on tracing the light rays from their falling on the corneal surface to entering the eye pupil. In Fig. 2, a schematic drawing of the anterior part of the human eye with CL + O is shown which is sufficient for such calculations.

Similar scheme was presented earlier in the paper (Almutleb et al., 2018; Fig. 1), however, the rays drawn in the published illustration seemed to be impossible and hindered adequate interpretation. In our scheme, cornea is traditionally considered as a thin spherical wall of the anterior eye chamber and we used the radial lines of this sphere to indicate the directions normal to the eye surface. It's noteworthy that the nodal point of the schematic human eye with the diameter of 24.5 mm is situated quite near the center of this sphere: according to the commonly accepted model, the distance of the nodal point from the retina is 16.7 mm and, therefore, 24.5 – 16.7 = 7.8 mm from the anterior eye surface (Katz, Kruger, 2006). Corneal curvature radius R and the anterior chamber depth H (ACD) are constant parameters to be taken either from description of the schematic eye or from investigation of the subject's eye. The pupil size (radius R_p) and the size of the occluder (radius R_o and its angular size in corneal sphere θ) are varying parameters depending on experimental conditions. The margins of the blind zone created by the occluder in the visual field are determined by the extreme light rays entering the eye along the lines connecting the edges of the occluder and the pupil. In the section of the eye shown in Fig. 2, the angle between such a ray and corresponding corneal radius is denoted as φ. To find this ray deviation from the direction orthogonal to the corneal surface before refraction (angle ψ), one should use refraction law: $n = \dfrac{\sin\psi}{\sin\varphi}$, where n – the ratio of refractive indexes at the two sides of the eye surface.

The resulting eccentricity β of the blind zone margins in the visual field is given by the formula:

$$\beta = \theta + \psi = \theta + \arcsin(n * \sin\varphi) \qquad (1)$$

In order to express β in known parameters, one could use additional relations evident from the scheme in Fig. 2:

$$\theta = \arcsin\frac{R_o}{R}, \qquad (2)$$

$$\varphi = \mathrm{arctg}\frac{R_o - R_p}{h} - \theta, \qquad (3)$$

where h is distance between the plane of the pupil and the occluder base level and it can be expressed as:

$$h = H - R * (1 - \cos\theta) \qquad (4)$$

After all substitutions, the final formulae for the eccentricity of the blind zone edge could be written as follows:

$$\beta = \theta + \arcsin\left\{n * \sin\left[\mathrm{arctg}\frac{R_o - R_p}{h}\right]\right\} \qquad (5)$$

Besides the two parameters of the eye (R – radius of the corneal curvature, H – the anterior chamber depth – ACD**)** and the occluder radius R_o which, in any experimental session, could be considered as approximately constant, the formulae contains the term R_p – radius of the pupil – which essentially depends on illumination level and should be measured for each experimental conditions. The simplest way to do this is to use a frontal photo of the eye shot with infrared camera. However, in this case, it's necessary to make some corrections because, unlike the remaining open eye surface, the pupil and the iris are captured through the corneal lens. Calculation of correction coefficient is based on finding the light rays which, after refraction at the corneal surface, go from the extreme points of the pupil to the camera at right angle to the plane of the pupil and iris, i.e. parallel to the eye axis and the axis of the camera.

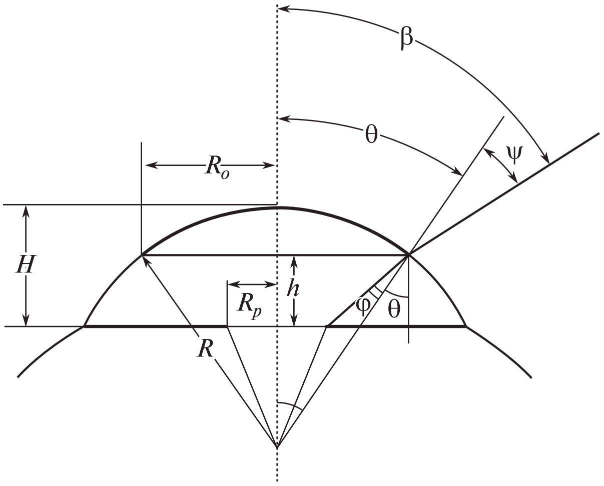

Fig. 2. Schematic drawing of the anterior part of the human eye with CL + O used for calculation of the eccentricity β of the blind area margin.

The sets of the curves calculated to demonstrate dependence of the blind zone size on the individual eye parameters and the occluder diameter are shown in Fig. 3. Two columns of graphs correspond to different values of the parameters R and H, respectively.

The left column shows dependence of the blind zone (scotoma) diameter on the occluder diameter for several pupil sizes (2, 4, 6, and 8 mm). The three sets of curves were obtained for three different values of the corneal radius (6.2, 7.8, and 8.8 mm) with one and the same value of ACD (3.1 mm). The data on corneal radius ranges were taken from (Mashige, 2013; Zhang, 2015). The calculated curves demonstrate steeper increase of the occluded area with increasing the occluder size in myopic eyes and complete absence of blind areas when the occluder diameter is close to the pupil size.

The right column contains the graphs showing dependence of the blind zone diameter on the pupil diameter for several sizes of the occluder (2, 4, 6, 8, and 10 mm in diameter). All three sets of curves were obtained for the same radius of the cornea (7.8 mm, typical of emmetropic eyes) and three different values of ACD: middle value 3.1 mm and the extreme values 2.0 and 4.2 mm taken from (Feng at al., 2011) containing big data set collected in many countries.

Not all combinations of parameters taken for these calculations might be realistic. Anyway, the results presented in Fig. 3 demonstrate a possibility of significantly different sizes of blind areas in different subjects with the same occluders. Therefore, the experimental data of each subject should be analyzed taking into account his/her individual parameters.

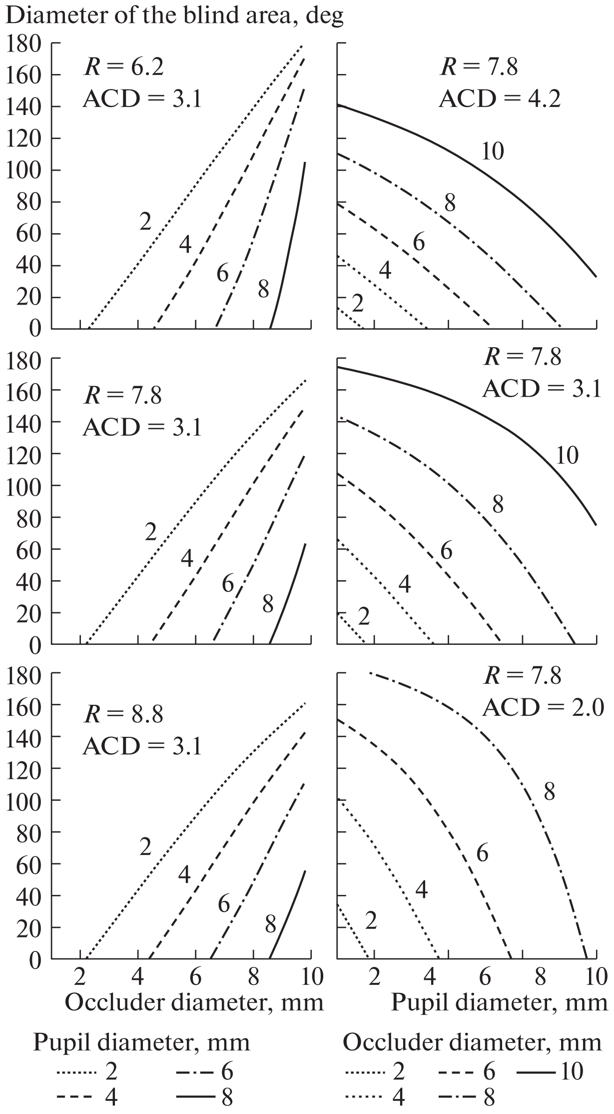

Fig. 3. Calculated sets of the curves showing dependence of the blind area diameter on the occluder diameter and individual eye parameters.

EXPERIMENTAL STUDIES

METHODS

The experimental studies were carried out in accordance with the Helsinki Declaration of 1975. Prior to testing, a written informed consent was obtained from each subject. The experimental procedure was approved by the ethics boards of IITP RAS and Helmholtz NMRC of Eye Diseases.

Subjects

The subjects were 5 volunteers (27–47 years old): 3 males and 2 females with normal vision according to the standard clinical tests.

Contact lenses

The contact lenses (CL) with occluder (CL + O) were manufactured in the Department of contact correction (Helmholtz NMRC of Eye Diseases) taking into account individual eye parameters of each subject. In essence, our CL + O were of a standard type widely used for everyday wearing. The implanted opaque occluders were coated by several layers of a black paint similar to the paints employed for picturing color iris on CL for actors and all those who wish. The number of layers was increased until CL + O provided complete “blindness” in the occluded area.

The occluder size was varied from 6 to 12 mm in diameter; in all cases, the occluders were large enough to overlap the pupil area completely. In each case, the exact positions of the blind area margins in the visual field were verified because they depended on the angle of the individual visual axis deviation from the optical axis (angle α) and might be influenced by somewhat asymmetric position of the CL + O after attachment and by other conditions of the experiment.

Measurements of eye parameters

In all subjects, refractive state of the eyes and the corneal curvature were assessed using autokeratorefractometer Huvitz MRK-3000.

To measure the pupil size during the experiments, the photos of the subject’s eyes were obtained with a modified web-camera (IR-cut filter was replaced by IR-pass filter) in conditions of additional infrared illumination of the eye with 940 nm LED.

Experimental procedure

The purpose of the experimental session was to compare the size of the blind area in the visual field (visual scotoma) created with CL + O and the data of corresponding calculations taking into account individual parameters of the subject’s eye and illumination level. Measurements of the blind zone size were performed on the perimeter in conditions of varying illumination of the eyes from 40 to 700 lx. A white cylindrical screen was mounted along the perimetric arc to present the black test stimuli on white background. Test stimuli were two thin black pencil-like vertical bars (diameter 7 mm, length 150 mm) with flickering red LED on the upper end. The subject was seated in such a way that his/her eye with CL + O appeared to be at the center of the perimeter. The subject’s task was to place the bars on both sides of the blind zone to indicate its size. The additional instruction was to direct and keep both visual axes at miniature fixation point (red LED in a small tube) in the center of the perimetric arc checking this state by means of the eye free from CL + O.

RESULTS

It appeared that, initially, most subjects performed the task unsatisfactorily because of difficulties with keeping stable fixation of the eyes in the course of positioning the two test bars simultaneously on both sides of the blind area. This negative result revealed the necessity of modifying the experimental procedure for better outcome. Moreover, evidently, certain period of learning was required.

Luckily, one of our subjects had time for such learning and we could collect sufficient amount of information for the analysis. The experimental data obtained in this subject and corresponding results of calculations are presented in Fig. 4. For Fig. 4 *a*, the calculated curves were obtained using individual eye parameters of the subject for the cases of CL + O with 5 different occluder diameters: 2, 4, 6, 8, and 10 mm. The circles show experimental data only obtained with the occluder of 6 mm in diameter and these data appeared to fall quite near the calculated curve corresponding to such occluder size. This coincidence could be considered as an indication of adequacy of our calculations. Though this subject was also examined with smaller and larger occluders, we can’t present complete sets of data for these cases because of visual discomfort hindering subject performance. For instance, even with occluder of 8 mm, the conditions of viewing were not satisfactory for measurements. As one can judge from Fig. 4 *b*, with such occluder, in the cases of high and moderate illumination levels suitable for an accurate measurements, the pupil diameter was 2–4 mm, according to Fig. 4 a, and the blind area was too large. Actually, in the graph Fig. 4 *a*, the area of favorable conditions for successful experiments is rather limited and, naturally, in different subjects, these areas are different.

Retrospective analysis of the incomplete data obtained in other subjects indicated that the occluders were not optimal in view of providing good conditions necessary for measurements. This means that the experiments with CL + O require a thorough preliminary investigation of the subject’s eye optics for choosing a proper combination of the occluder diameter and the illumination level.

It should be mentioned that, presenting the experimental data of subject NV, we used total diameters of the occluded areas and didn’t indicate that, in all experimental conditions, the blind areas were asymmetric, the temporal margin eccentricity being significantly larger than the nasal one. The difference was equal approximately to 24° and was relatively stable (23.95 ± 0.86). It seems likely that, in part, this asymmetry can be explained by the angle between visual and optical axes – the angle α – which should cause the difference of 2α between temporal and nasal margin eccentricities. However, in subject NV, this angle was estimated as close to 5° and corresponding difference should be about 10°. Therefore, it is inevitable to consider also other causes of the blind area asymmetry. To date, this issue had not been studied properly.

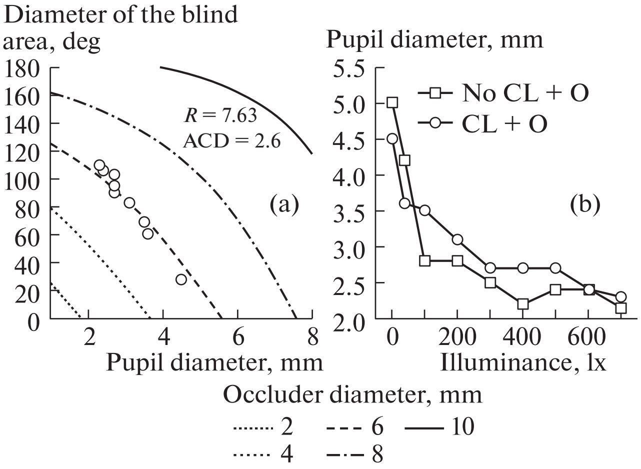

Fig. 4. The quantitative data obtained for the subject NV:
a – results of calculating and measuring the size of the blind area;
b – dependence of the pupil size on illumination level.

In (Chateau et al., 1996), the authors described clinical measurements of pupil diameter and lens position relative to the pupil in group of presbyopes (112 subjects) using special ring-marked soft contact lenses. It had been found that lens position was generally decentered from the pupillary axis, usually in inferior temporal direction. Decentration depended on luminance level, mean horizontal decentration being ranged from 0.34 mm at 50 cd/m^2 to 0.48 mm at 350 cd/m^2.

In (Young et al., 1997), the authors assessed 8 soft lenses models from various manufacturers. Besides many lens parameters they measured lens centration relative to limbus (30 subjects) in two conditions – static fit and dynamic fit. It had been found that all lenses had systematic decentration. Static fit horizontal decentration ranged from –0.8 mm (temporal) to 0.5 mm (nasal) with mean –0.047 mm. Static fit vertical centration ranged from –2.0 mm (inferior) to 2.0 mm (superior) with mean 0.02 mm. The typical movement seen with a well fitting lens was approximately 0.3 mm and the range in mean lens post-blink movement was relatively wide (0.28–0.48 mm).

The main conclusions from our experiments: (1) successful investigations of peripheral vision with CL + O require thorough choice of the occluder size taking into account individual eye parameters; (2) learning seems to be inevitable for obtaining reliable data in such experiments and, therefore, it’s unrealistic to collect many data in a short time.

DISCUSSION AND CONCLUSIONS

The attempts to study peripheral vision in conditions not requiring gaze fixation led to developing the approaches defined in literature as “vision without a fovea”, “switching central vision off”, “pure peripheral vision”, “imitation of central scotoma”. In principle, two different techniques were proposed: physical and virtual occlusion of the central retina. The first approach implied shielding the central retinal area with an opaque occluder attached to the eye thus providing free observation of real test objects at the periphery of the visual field without forced gaze fixation. The second approach implied computer-aided deleting (or darkening) the part of optical image projected onto the central retinal area from the display on the basis of correlating the image area to be deleted with instant eye positions via an eye-tracker (Lingnau, 2005; Marmor, Marmor, 2010; Jordan et al., 2012). At first glance, this noninvasive technique seems to be very promising and universal. However, the varieties of visual tasks suitable for investigation in this case are rather limited due to presentation of the test stimuli on displays.

In contrast, the first method has no limitations as concerned the variety of test stimuli – both various real objects and displayed images can be used – but it requires special optical devices attached to the viewing eye. Luckily, nowadays, there is no need to employ uncomfortable suction caps since they can be substituted with contact lens.

The advantages of using CL + O were briefly described in our poster at the ECVP’2018 (Rozhkova et al., 2019a) and will be discussed in more detail elsewhere. In particular, in perimetric experiments, shielding a large central area of the visual field by means of CL + O technique leads to decreased tendency of turning the viewing eye to the peripheral stimuli and guarantees eccentricity of the viewed stimulus location not less than that of the occluder edge. In studies of blind peripheral retina contribution to assessment of ambient illumination for color constancy mechanisms, CL + O helps varying the balance between the flows of light entering the eye through the pupil and through the eye tunics.

Among the shortcomings of CL + O technique the following three seem to be the most essential:

(1) The size of the shaded area depends not only on the occluder diameter but also on the individual eye optics and the ambient luminance indicating the necessity of additional measurements for proper description of viewing conditions.

(2) The pupil diameter is permanently changing during observation and depends on physical parameters of the scene and the emotional influence of the stimuli. The amplitude of possible “pupil pulsations” has to be taken into consideration since the pupil size is one of the main parameters determining the size of occluded area in the case of wearing CL + O.

(3) The lens can slip over the cornea changing the position of the occluded area in the visual field; such slippage should be prevented or taken into consideration.

A general conclusion is that application of contact lens with implanted occluders seems to be promising for certain studies of human peripheral vision but require thorough control and description of experimental conditions and individual visual characteristics of subjects.

ACKNOWLEDGEMENTS

We are greatly indebted to our colleagues Nadezhda Vasilyeva, Maria Gracheva and Anna Kazakova for their help and participation in our experiments.

DISCLOSURES

The authors declare no conflicts of interest.

FUNDING

Research was partially funded by Russian Foundation for Fundamental Investigations (19-015-00396A).

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Контактная линза с имплантированным окклюдером как средство для оценки дальнего периферического зрения в естественных условиях

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Целью данной работы была оценка перспектив использования контактной линзы с имплантированным окклюдером (КЛ + О) для исследования дальнего периферического зрения. Контактная линза с достаточно большим окклюдером представляется подходящим средством для выделения периферических зрительных механизмов, поскольку она исключает возможность переводить тестовое изображение на фовеа. Более ранние исследования с подобными контактными линзами имели целью имитировать потерю зрения в случаях макулярной дегенерации путем создания искусственной скотомы при помощи относительно малых окклюдеров, “выключающих” из восприятия только фовеа и ближнюю периферию. Задачей нашей работы было выделение дальнего периферического зрения путем использования окклюдеров значительно большего размера, обеспечивающих возможность исследовать потенциальные способности периферического зрения в естественных условиях без фиксации взора и раздвоения внимания. Результаты расчетов, проведенных нами на основе геометрической оптики и имеющихся в литературе данных о параметрах глаз человека, были использованы для оценки величины слепой зоны, создаваемой заданным окклюдером в различных условиях эксперимента, что необходимо для выбора КЛ + О, подходящих для конкретного исследования. Экспериментальная часть работы включала измерение размеров слепой зоны и ее позиции в поле зрения в условиях варьирования диаметра окклюдера и уровня внешнего освещения (для изменения диаметра зрачка). Сделано заключение, что КЛ + О является перспективным средством для исследования периферического зрения, однако его применение требует тщательного контроля условий эксперимента, поскольку область окклюзии на сетчатке существенно зависит от индивидуальных особенностей глазной оптики и освещения экспериментальной сцены.

Ключевые слова: периферическое зрение, зрение без фовеа, контактная линза, имплантированный окклюдер, расчет слепой зоны