Results of a study on the stress-strain behavior of the cornea in polarized light under conditions of visual work

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Background: *Near visual work causes redistribution of internal stresses in the cornea, leading to a change in the shape and parameters of the interference patterns observed on the cornea in polarized light.*
Purpose: *To assess the effect of various types of visual load on the extraocular muscles (EOM) in children and adolescents on the basis of characteristics of the interference patterns observed on the cornea in polarized light.*
Material and Methods: *The interference patterns observed on the cornea in polarized light were studied in children and adolescents before and after they performed a visual load task which consisted in either working with texts printed on paper at different parameters of convenience for reading (97 individuals) or playing Tetris on a smartphone (58 adolescents). A symmetry coefficient K was calculated for the quantitative assessment of changes in interference pattern parameters induced by visual load.*
Results: *Performing a visual load task which consisted in working with texts printed on paper resulted in a significant increase in asymmetry between the actions of the EOM in 60% to 73% of children; this was indicated by the values of a symmetry coefficient K which were twofold to six-fold higher than normal. Performing a visual load task which consisted in playing Tetris on a smartphone resulted in an increase in asymmetry between the actions of the EOM in 64% of adolescents.*
Conclusion: *Our research confirmed that studies on the stress-strain behavior of the cornea in polarized light are promising for assessing the effect of various types of visual load on the function of EOM.*

Introduction

Progress in medical diagnostics is largely due to advances in other fields, e.g., biophysics which studies physical features of biological systems of various levels of organization. The use of polarized light in studies of biological systems allows not only investigating in detail their structure through improved image quality, but also investigating the stress-strain behavior of biological objects. The use of biophysical methods in ophthalmology has had a long history and is associated with the structural features and physical properties of the eye and ocular components.

David Brewster [1] in the early 19th century was the first to study the cornea in polarized light. He described the interference pattern generated by the living cornea in polarized light. In the 20th century, many researchers also observed this pattern, but there was no agreement regarding its origin and major properties [2-7]. Felix Zandman [8], American physicist, in 1966 was the first to note the photoelastic origin of the corneal interference pattern and the role of intraocular pressure (IOP) and extraocular muscles (EOM) in the formation of this pattern. He supposed that corneal interference patterns of healthy individuals and patients differ from each other, but it was not clear what makes this difference and how it can be used in medical diagnostics.

Studies on the cornea in polarized light in patients with strabismus [4, 9-14] and at various IOP levels in patients with glaucoma [15, 16] allowed identifying the major physical features of these interference patterns. It has been demonstrated that, in any pathology of the EOM, a change in the shape of interference pattern occurs, which has an effect on the geometrical parameters of these muscles [10-12, 14]. Studies on the shapes of interference patterns at various IOP levels demonstrated that an IOP increased above 25 mmHg resulted in the curvature of the sides of interference diamond. The induced interference patterns at an IOP above 30 mmHg appeared almost as concentric circles [17, 18].

The visual environment of humans (especially, children and adolescents), has become much more complicated recently due to the appearance of numerous novel visual information carriers [19, 20] like mobile phone screens, graphics pads, PC displays, electronic books, etc. There is a substantial difference in the principle of image formation between electronic and printed carriers of visual information, which affects the visual system. In addition, printed publications for children and adolescents vary in quality and do not always conform to hygiene standards. On the other hand, visual function worsening has been seen in children and adolescents, and the number of patients with accommodation, myopia and strabismus has been increasing. One may argue that it is carriers of visual information that contribute to visual function worsening in the population [19, 21].

Near visual work requires some redistribution of the efforts of the EOM for convergence of both visual axes on the fixation object as well as keeping them in this position for a long time. These features of visual work result in the redistribution of internal stresses in the cornea, leading to changes in the shape of interference pattern. A symmetry coefficient K was introduced for the quantitative assessment of changes in interference pattern parameters induced by visual load [22]. The response of the EOM to visual load depends on the baseline anatomical and functional status of these muscles, and may take a form of a symmetrical increase in efforts of relevant muscles of both eyes leading to a symmetrical redistribution of internal stresses in the cornea of either eye. Under conditions unfavorable for visual work (too little objects, the objects arranged closely to the eyes, inadequate desktop illumination, prolonged visual work, etc.) or in the presence of anatomical and functional differences between the eyes, which is very common, asymmetry in the function of the visual system increases, leading to a change in parameters of interference patterns for the right and left eyes.

The development of objective methods for visual system assessment in the course of prolonged visual activity will enable assessing the quality of printed publications and electronic data carriers for children and adolescents, and developing and changing work-rest modes for various age categories and various conditions of the visual system.

The results of studies on the stress-strain behavior of the cornea in health and disease have enabled identifying the interference-pattern features that might be used in the diagnosis of certain conditions of the eye and visual system.

The methodology used previously for determining interference-pattern parameters was rather cumbersome, thus limiting their application in clinical practice and research.

Advances in information technologies have opened new prospects for applications of polarized light in studies on the stress-strain behavior of the cornea. The automation of the process for creating and processing corneal interference patterns [17, 18, 20] enabled simplifying the determination of their parameters, thus creating favorable conditions for the introduction of polarized light diagnostic techniques into clinical practice.

The purpose of this work was to assess the effect of various types of visual load on the extraocular muscles in children and adolescents on the basis of characteristics of the interference patterns observed on the cornea in polarized light.

Material and Methods

The interference patterns observed on the cornea in polarized light were studied in children and adolescents before and after they performed a visual load task which consisted in either working with texts printed on paper at different parameters of convenience for reading (97 individuals) or playing Tetris on a smartphone (58 adolescents).

The paper text of the first task was printed in accordance with age requirements (10-point font), whereas that of the second task was printed at a small font size (7-point font). The visual load task for the paper test was to find and cross out certain letters.

The texts consisted of standard textual components which were developed based on Cyrillic letter frequencies in standard texts [22]. Each textual component had 200 characters (four lines of 50 characters) and could be copied within the text in order to modify the amount of text load. Each study subject was proposed to perform a visual load task with a specified number of characters in the text in accordance with age requirements (Table 1).

The children and adolescents who participated in the study of the effect of visual load on the state of the EOM underwent an eye examination. Study subjects included emmetropes, mild myopes and mild hypermetropes. Individuals with astigmatism, strabismus, or moderate to severe refractive errors were excluded.

A Web camera equipped with an illuminator and Polaroid unit as well as special software for interactive parameterization of interference patterns was used for documentation and determination of informative parameters of interference patterns [17, 18, 23].

Fig. 1 presents a photograph and schemes of interference patterns for the norm, with specification of interference pattern parameters normalized to the mean corneal diameter. Interference pattern parameters normalized to the mean corneal diameter allow taking into consideration the scale of interference pattern images which may vary due to variability either in the size of the cornea on in the conditions used to document the pattern.

The relative sizes of interference diamond diagonal segments specified on the schemes (Fig. 1) indicate a sufficient symmetry of interference patterns, which is not always observed. In most normal individuals, there is some asymmetry between the actions of the EOM of the right and left eyes. Near visual work may result in either a significant increase in this asymmetry or a more symmetrical action of the muscles.

A symmetry coefficient K was calculated for quantitatively assessing the impact of visual work on the extraocular muscles. The calculation procedure was as follows. First, parameters of interference patterns were determined. Second, the difference between lengths of matched interference diamond diagonal segments for the right and left eyes was determined both before and after visual work task was performed. Third, these differences were summed up, and thus we obtained the integrative indices characterizing symmetry or asymmetry between the actions of the EOM of the right and left eyes before (K1) and after (K2) performing the visual work task. Finally, a symmetry coefficient was calculated using the following equation:

$$K = [(K2-K1)/K1]\cdot 100\%,$$

where K1 and K2 are the integrative characteristics of asymmetry before and after, respectively, the visual load task was performed.

If the calculated symmetry coefficient was less or equal to 20%, the stress exhibited by the muscles when performing the visual load task was believed to be within a normal range, and the visual load did not cause a substantial transformation in the visual system. If the calculated symmetry coefficient was negative, it was believed that the system functioned more symmetrically before than after the visual load task was performed, and, consequently, the visual load task was also within a normal range. If the calculated symmetry coefficient was positive and was above 20%, it was believed that the visual load caused a substantial asymmetry between the actions of the EOM of the right and left eyes, which was an unfavorable sign.

Descriptive statistics was used to process the quantitative parameters of interference patterns. Non-parametric Wilcoxon test and Pearson's Chi Square test were employed to determine significant differences. Statistical analyses were conducted using Statistica 13.3 (StatSoft, Tulsa, OK, USA) software.

Results

Table 2 presents the results of calculation of a symmetry coefficient for the actions of the EOM for children and adolescents of various age groups performing two types of visual load task which consisted in working with texts printed on paper in a normal size font (type 1) or low size font (type 2).

Based on the results presented in Table 2, it is noteworthy that there were both positive and negative symmetry coefficient values in each type of visual load task and in each age group. This indicates two variants of a change in EOM tone: an increase in asymmetry between the actions of the EOM of the right and left eyes after performing a visual load task in positive K values, and a more symmetric action of the muscles in negative K values.

It may be noted that both types of visual load caused an increase in asymmetry of EOM action almost twice more frequently than an increase in symmetry of EOM action. Both visual load type 1 (with a normal size font) and visual load type 2 (with a low size font) could result in an increase in asymmetry of EOM action. This should be taken into consideration when teaching a child early to read or having a child to play computer games or miniature games, because this type of visual load can cause asymmetric EOM action. Prolonged use of unfavorable visual loads may result in perpetuation of asymmetric EOM action, leading to the onset of strabismus (especially in genetically susceptible individuals, in the presence of congenital abnormality in extraocular muscle structure, or in heterophoria).

In addition, the positive symmetry coefficient values were at least twice greater than negative symmetry coefficient values practically in each age group, i.e., asymmetry of EOM action was more apparent than symmetry of EOM action which developed as a result of visual work.

Table 2 demonstrates that a more symmetric EOM action was seen much more rarely than a symmetric EOM action after a visual loaf task was performed.

We also used a symmetry coefficient to assess the impact of playing Tetris on a smartphone for 45 minutes on the EOM in 58 adolescents of 15 to 16 years.

The symmetry coefficient was negative (i.e., playing the game resulted in a more symmetric EOM action) in 21 subjects (36 ± 6.6%). The mean value for the negative coefficient was 114%. An increase in EOM action asymmetry was significantly more common ($\chi 2=7.89$; $p < 0.05$) than a more symmetric EOM action and was seen in 37 subjects (64 ± 6.6%). Absolute value of the positive coefficient K was 50.2% and was lower that absolute value of the negative coefficient K. We found that the visual load task performed by adolescents resulted in an increase in asymmetry in 64% of subjects. This may be associated with the fact that, because in this age group, the visual system was not completely mature yet, performing a visual load task with suboptimal visual parameters resulted in an increase in EOM action asymmetry.

Discussion

In children, the visual system develops under the influence of visual environment, which has become more aggressive in recent years. Interestingly, the term of "visual aggressive environment" has appeared in the literature [24]. On the other hand, recent studies have noted the worsening of visual functions in children and adolescents.

In this connection, developing objective methods for assessing the function of the visual system and its components is important.

Studies on the stress-strain behavior of the cornea allow determining the anatomical and functional status of the EOM [10-12]. Moreover, if performed in the course of prolonged visual work, these studies will allow assessing EOM state changes occurred under the influence of visual load.

The results of the current study enabled noting patterns in changes in symmetry of EOM action. Among children of 6 to 10 years and adolescents of 11 to 12 years, after performing two types of visual load task (working with texts printed on paper in a normal size font and low size font), the patterns of changes in symmetry of EOM action included an increase in the amount of asymmetry and an increase in the number of subjects with asymmetry (Table 2).

Among the older age group (adolescents of 13 to 15 years), the percentages of those with symmetry of EOM action and those with asymmetry of EOM action were almost equal after performing the above types of visual load task. This indicates that, with an increase in age (and, correspondingly, an increase in the maturation of the visual system), visual load causes less apparent changes.

The Tetris game which was used in a visual load task for adolescents is difficult for visual perception. In addition, in this game, tiny objects and an externally imposed pace of interaction are used. After performing a visual load task associated with playing the Tetris game, an increase in asymmetry of EOM action was seen in 64% of the subjects. This was comparable with the results after working with texts printed on paper in a low size font (Table 2), although the asymmetry was less apparent than after working with texts.

Our studies demonstrated that interference pattern parameters are promising for assessing the effect of various types of visual load on the function of EOM. Such studies are relevant for two reasons. First, anatomical and functional EOM asymmetry between the eyes in the absence of strabismus has been reported in a significant percentage of children and adolescents [25]. This asymmetry is compensated by the compensation reserves present in the visual system. The amount of compensation, if excessive, causes a compensation breakdown, potentially leading to the development of visual pathology. Second, the revealed patterns of changes in symmetry of the actions of the EOM may be employed while assessing the influence of the effect of the use of an information carrier and the duration of this use on the visual system in various age groups.

Conclusion

First, among the younger age groups of the participants, after performing two types of visual load task (working with texts printed on paper in a normal size font and low size font), the pattern of changes in symmetry of EOM action included an increase in the amount of asymmetry. This should be taken into consideration when teaching a child early to read or having a child to play computer games or miniature games, because this type of visual load can cause asymmetric EOM action. In addition, prolonged use of high visual loads may result in perpetuation of asymmetric EOM action, leading to the onset of strabismus.

Second, with an increase in age (and, correspondingly, an increase in the maturation of the visual system), visual load causes less apparent changes in the function of the EOM. In addition, among the older age group, the percentages of those with symmetry of EOM action and those with asymmetry of EOM action were almost equal after performing the visual load task.

Finally, our research confirmed that studies on the stress-strain behavior of the cornea in polarized light are promising for assessing the effect of various types of visual load on the function of EOM.

Further studies on the effect of various types of visual load on the function of EOM in children and adolescents at different states of the visual system are warranted.

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Conflict of Interest Statement:
The authors declare no conflict of interest which could influence their opinions on the subject or the materials presented in the manuscript.

Table 1. Amount of visual load specified for various age groups

Age group (years)	Amount of visual load expressed in the number of text characters
Children of junior school age (6 -10 years)	2000-4000
Children of middle school age (11-12 years)	4000-6000
Children of older school age (13-15 years)	4000-6000

Table 2. Distribution of subjects based on the symmetry coefficient K

Age group, years	Type of text	Range of values for symmetry coefficient K	Percentage value of coefficient K (frequency expressed as percentage from the number of subjects in the group)
6-10 (n=33)	first	K>0	106 (60±8,5)
		K <0	53 (40±8.5)*
	second	K>0	98 (73±7.7)
		K <0	46 (27±7.7)*
11-12 (n=25)	first	K>0	132 (67±9.5)
		K <0	45 (33±9.5)*
	second	K>0	90 (68±9.3)
		K <0	40 (32±9.3)*
13-15 (n=39)	first	K>0	96 (51±8.0)
		K <0	46 (49±8.0)
	second	K>0	88 (65±7.6)
		K <0	48 (35±7.6)*

Note: *, significant difference in frequency between positive and negative values of symmetry coefficient K for the relevant age group ($p < 0.05$); n, number of subjects in the group

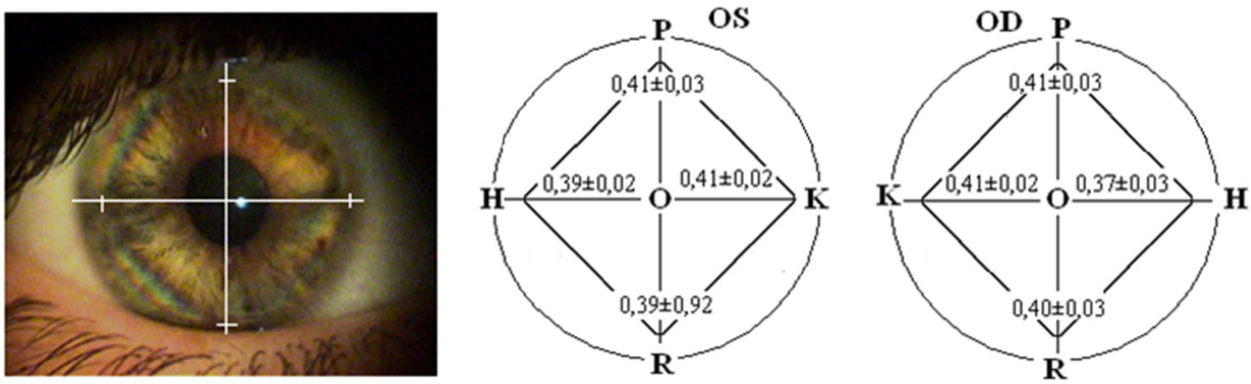

Fig. 1. Interference pattern photograph and interference pattern schemes for the normal right and left eyes