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The state and dynamics of the wavefront of the eye in children with different refractions engaged in regular sport activities (badminton)

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*The paper is **aimed** at comparing the level of aberrations, structure of the wavefront, and its response to cycloplegia in children with different refractions before they started practicing badminton regularly and after a year's duration of this practice. **Material and methods.** 40 children (80 eyes) with refractive errors from +6.63 to -6.75 D (average -1.28 ± 2.28 D) aged 7 to 11 years (average 9.24 ± 1.06 years) were examined before the practice, 6 months after practice start (38 children, 72 eyes) and after 1 year of badminton playing (27 children, 54 eyes). All patients underwent wavefront aberrometry before and after cycloplegia on an OPD-Scan III (Nidek) aberrometer. We analyzed Zernike coefficients up to the 12th order inclusive: vertical and horizontal slope (tilt 1, tilt 2), vertical and horizontal trefoil (trefoil 6, trefoil 9), vertical and horizontal coma (coma 7, coma 8), spherical aberration (SA), mean square deviation from the ideal wavefront (RMS). **Results.** SA in myopia was found to be negative, in hyperopia positive; Tilt 1, Tilt 2, Trefoil 9, Coma 7 in myopia were significantly higher, and Coma 8 significantly lower than in hyperopia. The slope of the wavefront (Tilt 1, Tilt 2) in cycloplegia falls significantly in hyperopic eyes and does not change in myopic ones. The latter fact points to insufficient tension of Zinn ligaments in the myopic eye. Regular badminton practice results in significant changes in wavefront aberrations, indicating a strengthening of the ligaments of the lens and the normalization of the ciliary muscle tone. **Conclusions.** The structure of the wavefront in children with different refractions shows significant differences. Badminton helps strengthen the ligaments of the lens.*

Keywords: myopia, aberrations, badminton.

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In recent decades, the incidence of myopia is steadily growing, claiming 30 to 40% of young people in Russia, USA, and Europe, and 70 to 96% in South-East Asia [1–5].

According to the data of Aron Dashevsky, children aged 4 to 7 years must normally have hyperopic refraction (ca 1.0 D) [6]. Regretfully, increasing visual work, the computerization of all life aspects of modern children, increasing requirements of new programs at school, reduction of physical exercise and physical inactivity bring about early emmetropization occurring at the age of 4–6 ears and the onset of myopia of schoolchildren. In recent years, the development of acquired myopia tends to be explained, more and more often, by insufficient physical activity, especially open air activity. To minimize the pathogenic impact of adverse environmental factors, sports activities are recommended.

Badminton is an ideal sport that harmoniously combines tracing a moving object (accommodation training), head and torso turns (hemodynamics strengthening), deep breathing (blood oxygenation).

According to modern views, not only hereditary predisposition but also environmental factors, and above all, optical errors in the formation of a retinal image, play a significant role in the development of acquired myopia. It has been shown by experiments that both the central and the peripheral hyperopic defocus stimulate eye growth and myopization of refraction. In its turn, image focusing on the retina is determined by the accuracy (adequacy) and stability of the accommodation response, as well as by aberrations of the wavefront of the eye. These aberrations are closely related with the accommodation and the peripheral refraction. On the one hand, the aberrations determine the quality of the retinal image and stimulate its focusing. As is known, the negative spherical aberration (SA) and the coma stimulate the accommodation response; in its turn, the accommodation stress increases the negative SA [8, 9].

On the other hand, the high level of aberrations, in particular, of the positive Sa, increases the depth of the focus area, facilitates near visual work without accommodation participation (the so-called pseud-accommodation) and may reduce the accommodation response, which leads to an accommodation lag and the formation of hyperopic defocus on the retina.

M. Collins и C. Wildsoet [10] suggested that individual aberrations, such as SA, may violate the emmetropization process. They believed that the negative SA induces the myopic eye growth while the positive SA slows it down. A number of papers report high values of the 4th, 5th and higher order aberrations (HOA) in myopic subjects as compared to emmetropes [11]. The eyes that revealed rapid myopia progression showed a higher level of both total HOAs and root mean square of the ideal wavefront, and 3rd order aberrations and the coma than the eyes with slow myopia progression [12–15].

SA change in myopia is associated with the lens change during eye growth [16, 17]. A higher level of aberrations reducing the quality of the retinal image may play a role in myopia development [13, 18, 19].

Contrariwise, certain studies report a lower level of 4th order aberrations [10], SA [20–22], 3th and higher-order aberrations [20, 23, 24] in myopi eyes as compared to emmetropic ones. Yet other studies do not see differences in wavefront parameters in different refraction groups [25–28].

Under natural conditions, there exists a physiological tone of accommodation, which is enabled by the balance of sympathetic and parasympathetic innervation [29]. Mainly due to this tone, the internal optics of the eye tends to for corneal aberrations, which leads to a decrease in total (ophthalmic) HOAs and an improvement in the retinal image. In children and young people with myopia and hyperopia, the total HOAs are lower than the retinal ones [30, 31].

Wavefront changes are revealed under cycloplegia as compared to non-cycloplegic conditions [32].

Of special interest is the result of comparison of wavefront aberrations and their changes occurring under cycloplegia in myopic and hyperopic eyes. According to our previous data, the level of tilt1, horizontal trefoil and vertical coma aberrations under natural conditions with the pupil width of 3 mm are significantly higher in myopia than in hyperopia, whilst their changes in response to cycloplegia are substantially lower or completely absent. We believe that these features can be associated with the state of the ligamentous apparatus of the lens and the ciliary muscle. An increased level of aberrations associated with the tilt of the lens, its shift, decentration of the optical elements of the eye may be an evidence of a weak ligament tension (possibly associated with the excessive tone of the ciliary muscle). This is also confirmed in cycloplegia: changes in the tone of the ciliary muscle, the tension of the Zinn ligaments and the position of the lens in myopia are insufficient for significant changes in the wavefront [33].

In addition to the accommodation and the central defocus, aberrations play an important role in the formation of the peripheral retinal defocus. A number of studies report that the positive SA contributes to the formation of relative peripheral myopia, while the negative SA is instrumental in the onset of hyperopia. Both the experimental and the clinical observations clearly indicate the inhibitory effect of myopic defocus on the process of myopia progression [34].

The above facts explain an increasing interest to eye wavefront studies which is noted in the literature in recent years. The role of aberrations in postnatal refractogenesis appears to be indisputable but the results of numerous studies are ambiguous. The association of the total level of aberrations with the refraction, myopia progression and accommodation lag is confirmed in some papers but unconfirmed in others.

The **PURPOSE** of this work was a comparative analysis of the level of aberrations, the structure of the wavefront, its response to cycloplegia in children with various refractions before they started practicing badminton regularly and after a year's duration of this practice.

MATERIAL AND METHODS

40 children (80 eyes) aged 7 to 11 years (average 9.24 ± 1.06 years) with refractive errors from +6.63 to -6.75 D (average -1.28 ± 2.28 D) were examined. Of these, 34 chidlren (67 eyes) were myopic: 26 children (51 eyes) had low myopia, 6 children (12 eyes) with moderate myopia and 2 children (4 eyes) with high myopia. The remaining 13 eyes belonging to 7 children were hyperopic or emmetropic. From the total cohort of patients, a group with spasm and habitually excessive accommodation strain (HEAS) was isolated that counted 11 children (20 eyes), of which 7 eyes of 4 children were myopic, 6 eyes of 3 children were hyperopic and 7 eyes of 4 children were emmetropic.

6 months after badminton practice start, 38 children (76 eyes) were examined, and after 1 year of regular badminton playing 27 children (54 eyes) aged 8 to 12 (average 9.42 ± 1.10 years) with various refraction levels (averagely -1.62 ± 1.81 D) underwent through examination. Of the 54 eyes, 46 eyes belonging to 23 children were myopic: 37 eyes of 19 children had low myopia, 7 eyes of 4 children had moderate myopia, and 2 eyes of 1 child had high myopia. Again, in the total cohort of patients, a group of 7 children (14 eyes) with spasm and HEAS was identified: 3 children (6 eyes) were myopic, 2 children (4 eyes) were hyperopic and 2 children (4 eyes) were emmetropic.

All patients underwent wavefront aberrometry in a darkened room before and after medical cycloplegia: 1% cyclopentolate dehydrochloride was used twice, with an interval of 10 minutes. Aberrometry was performed 40 minutes after the first instillation on an OPD-Scan III (Nidek) aberrometer. Since the action of cycloplegics is accompanied by mydriasis, which increases the level of many aberrations, we analyzed the wavefront before and after instillation of cyclopentolate with a fixed pupil width in order to assess the impact of cycloplegia alone, and not that of mydriasis. Aberrations were analyzed with a pupil width of 3 mm both without cycloplegia and under cycloplegic conditions (in the latter case, with the option of selecting a 3 mm zone). We analyzed Zernike coefficients up to the 12th order inclusive: vertical and horizontal slope (tilt 1, tilt 2), vertical and horizontal trefoil (trefoil 6, trefoil 9), vertical and horizontal coma (coma 7, coma 8), spherical aberration (SA), and root mean square (RMS) deviation.

Badminton was practiced according to the technique proposed by Valery Turmanidze [35].

RESULTS AND DISCUSSION

As is seen from the analysis of the tables 1–4, the following aberrations show statistically significant differences in myopia and hyperopia: SA, tilt 1, tilt 2, trefoil 9, and coma 7 are higher in myopia than in hyperopia, whilst coma 8 is 10 times lower. SA has negative values in myopia and positive values in hyperopia.

The response to cycloplegia is very specific, too. Both in myopia and hyperopia, SA showed a shift towards positive values: in the first case, the negative SA showed a 2-fold reduction while in the second case the positive SA increased.

In spasm and HEAS, the positive SA showed a 5-fold (!) increase. These changes fall within the changes of lens shape under cycloplegia: the lens is flattening and the refractive power of the central region is decreasing (table 2).

The waverfron slope (tilt 1, tilt 2) in hyperopic eyes under cycloplegia decreased (tilt 2 showed a 25-fold decrease!) while in myopic eyes it showed a statistically insignificant (1.5-fold) reduction or even an increase. Trefoil 9 showed a 5-fold increase in hyperopia under cycloplegia and remained unchanged in myopia (tables 1–3).

The above changes of the listed aberrations that occur in response to cycloplegia and are associated with the wavefront slope agree with those we reported earlier and are consistent with the proposed explanation [33]. The tension of the Zinn ligaments under cycloplegic in hyperopic eyes is sufficient for the change in the shape and position of the lens but it is insufficient for myopia, which is obviously caused by weak ligamentous apparatus and/or habitually excessive tone of the ciliary muscle.

The changes of the waverfront in response to cycloplegia in eyes with HEAS and accommodation spasm were ambivalent. The spherical aberration and tilt 1 behaved in the same way as in the hyperopic eyes (which they indeed were, on average): namely, the former increased 5 times toward the positive values (conforming to lens flattening) and the letter was decreasing (tables 1, 2).

Tilt 2, trefoil 6, trefoil 9 showed no significant changes in response to cycloplegia (tables 1–3).

Coma 7 in patients with HEAS and spasm had negative values as in hyperopia (in myopia the values were

Table 1. Wavefront structure in children with various refractions before and after badminton workouts: RMS and Tilt 1 (M ± σ)

Refraction	RMS						Tilt 1					
	before		after 6 months		after 1 year		before		after 6 months		after 1 year	
	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia
Averaging over the group n = 54	0.1788 ± 0.1000	0.19833 ± 0.10000	0.23178 ± 0.15000	0.19167 ± 0.09000	0.08621 ± 0.03000	0.08164 ± 0.03000	0.00839 ± 0.03000	0.0091 ± 0.0600	0.0125 ± 0.0600	0.0096 ± 0.0600	0.0146 ± 0.0600	0.0184 ± 0.0600
Myopia n = 46	0.1822 ± 0.1000	0.19545 ± 0.11000	0.22764 ± 0.15000	0.195 ± 0.090	0.08187 ± 0.03000	0.081 ± 0.030	0.011834 ± 0.060000*	0.0149 ± 0.0600*	0.0182 ± 0.0600*	0.0202 ± 0.0600*	0.0219 ± 0.0500*	0.0167 ± 0.0600*
Low myopia n = 37	0.1631 ± 0.0800	0.18343 ± 0.08000	0.22389 ± 0.17000	0.18257 ± 0.08000	0.08187 ± 0.03000	0.081 ± 0.020	0.0186 ± 0.0600*	0.0134 ± 0.0600*	0.015 ± 0.060*	0.0189 ± 0.0500*	0.0219 ± 0.0600*	0.0167 ± 0.0500*
Moderate myopia n = 7	0.2943 ± 0.1500	0.28857 ± 0.16000	0.25143 ± 0.08000	0.27143 ± 0.13000	0.079 ± 0.030	0.08333 ± 0.03000	0.03486 ± 0.05000*	0.0247 ± 0.0700*	0.0304 ± 0.0900*	0.0264 ± 0.0800*	0.0062 ± 0.0600*	0.0033 ± 0.0600*
High myopia n = 2	0.125 ± 0.050	0.08 ± 0.03	0.21 ± 0.10	0.145 ± 0.060	0.0465 ± 0.0100	0.066 ± 0.000	-0.044 ± 0.030	0.007 ± 0.010	0.032 ± 0.010*	0.021 ± 0.100*	0.015 ± 0.010*	0.0135 ± 0.0700*
Hyperopia and emmetropia n = 8	0.20 ± 0.08	0.25 ± 0.05	0.22 ± 0.03	0.23 ± 0.10	0.068 ± 0.020	0.0735 ± 0.0200	-0.0528 ± 0.040	-0.0423 ± 0.0600	-0.0383 ± 0.0400	-0.049 ± 0.060	-0.059 ± 0.040	-0.0428 ± 0.0700
Spasm and pseudomyopia n = 14	0.1613 ± 0.0900	0.18615 ± 0.05000	0.23 ± 0.14	0.14923 ± 0.05000	0.13 ± 0.04	0.08767 ± 0.02000	-0.0134 ± 0.0300	0.005 ± 0.040	-0.0069 ± 0.0500	-0.0169 ± 0.0300	0.019 ± 0.040	0.0427 ± 0.0600

Note. n — number of eyes; * — p < 0.05 — significant with respect to patients with hyperopia and emmetropia; ** — p < 0.05 — significant with respect to parameters before cycloplegia.

Table 2. Wavefront structure in children with various refractions before and after badminton workouts: Tilt 2 and spherical aberrations (M ± σ)

Refraction	Tilt 2						SA					
	before		after 6 months		after 1 year		before		after 6 months		after 1 year	
	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia
Averaging over the group n = 54	0.0306 ± 0.2900	0.0217 ± 0.2900	-0.0157 ± 0.0400	-0.0139 ± 0.0400	-0.015 ± 0.0500	-0.0269 ± 0.0400	-0.0198 ± 0.1400	-0.00926 ± 0.15000	0.003019 ± 0.010000	0.021981 ± 0.050000	0.002458 ± 0.040000	0.001071 ± 0.050000
Myopia n = 46	0.0383 ± 0.3200*	0.0263 ± 0.3200*	-0.0174 ± 0.0400	-0.0185 ± 0.0400*	-0.0209 ± 0.0500	-0.0172 ± 0.0400	-0.02545 ± 0.16000*	-0.01405 ± 0.16000*	0.00175 ± 0.01000	0.013977 ± 0.040000	-0.00253 ± 0.04000*	0.001333 ± 0.050000
Low myopia n = 37	-0.0031 ± 0.0400	-0.0169 ± 0.0400*	-0.0139 ± 0.0400	-0.0096 ± 0.0400	-0.0209 ± 0.0500	-0.0172 ± 0.0300	-0.0022 ± 0.0100*	0.0122 ± 0.0400	0.001857 ± 0.010000	0.013971 ± 0.050000	-0.00253 ± 0.04000*	0.001333 ± 0.050000
Moderate myopia n = 7	0.2703 ± 0.8000*	0.242 ± 0.820*	-0.0247 ± 0.0300	-0.0554 ± 0.0600	-0.0072 ± 0.0700	-0.0703 ± 0.0600	-0.14814 ± 0.40000*	-0.14914 ± 0.40000*	0.001571 ± 0.010000	0.018143 ± 0.020000	0.0182 ± 0.0400	-0.004 ± 0.040
High myopia n = 2	-0.0495 ± 0.0100	-0.0525 ± 0.0100	-0.0085 ± 0.0900	0.027 ± 0.020	-0.0465 ± 0.0400	-0.032 ± 0.030	-0.003 ± 0.010*	-0.0005 ± 0.0100*	0.0005 ± 0.0100	-0.0005 ± 0.0100	-0.0155 ± 0.0100	-0.037 ± 0.030
Hyperopia and emmetropia n = 8	-0.002 ±0.03	-0.0008 ±0.05**	-0.0028 ±0.02	-0.0002 ±0.04**	0.0115 ±0.04	0.0073 ±0.03**	0.00725 ±0.01	0.025 ±0.02**	0.0075 ±0.01	0.0445 ±0.04**	0.0035 ±0.01	0.01075 ±0.01**
Spasm and pseudomyopia n = 14	0.0049 ± 0.0400	0.0022 ± 0.0400	-0.0045 ± 0.0300	0.0067 ± 0.0300	-0.0003 ± 0.0500	-0.0110 ± 0.0300	0.004 ± 0.010	0.023077 ± 0.050000**	0.006385 ± 0.010000	0.060923 ± 0.090000**	0.0596 ± 0.0700	0.003333± 0.080000**

Note. n — number of eyes; * — p < 0.05 — significant with respect to patients with hyperopia and emmetropia; ** — p < 0.05 — significant with respect to parameters before cycloplegia

Table 3. Wavefront structure in children with various refractions before and after badminton workouts: Trefoil 6 and Trefoil 9 (M ± σ)

Refraction	Trefoil 6						Trefoil 9					
	before		after 6 months		after 1 year		before		after 6 months		after 1 year	
	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia
Averaging over the group n = 54	-0.0274 ± 0.0500	-0.02376 ± 0.04000	-0.031 ± 0.060	-0.0118 ± 0.0400	-0.01813 ± 0.04000	-0.02093 ± 0.04000	0.023593 ± 0.260000	0.027963 ± 0.26000	-0.00407 ± 0.03000	-0.00419 ± 0.03000	-0.01167 ± 0.03000	0.002571 ± 0.030000
Myopia n=46	-0.0259 ± 0.0500	-0.0208 ± 0.0400	-0.02607 ± 0.05000	-0.01075 ± 0.04000	-0.01753 ± 0.04000	-0.023 ± 0.040	0.034205± 0.280000	0.038909 ± 0.280000	0.000864± 0.030000	-0.00132 ± 0.03000	-0.00187 ± 0.03000	0.005333 ± 0.030000
Low myopia n = 37	-0.0323 ± 0.0500	-0.02437 ± 0.04000	-0.03071 ± 0.05000	-0.01651 ± 0.04000	-0.01753 ± 0.04000	-0.023 ± 0.040	-0.01023 ± 0.03000	-0.00083 ± 0.03000*	-0.00177 ± 0.03000	-0.00077 ± 0.02000*	-0.00187 ± 0.03000	0.005333 ± 0.030000*
Moderate myopia n = 7	-0.0039 ±0.05	-0.00957 ±0.06	-0.00814 ±0.05	0.022143 ±0.03	-0.0086 ±0.05	0.000333 ±0.04	0.258571 ±0.7	0.251143 ±0.71*	-0.00014 ±0.02	0.000714 ±0.06*	-0.0256 ±0.04	0.006667 ±0.05*
High myopia n = 2	0.0085± 0.0100	0.0025 ± 0.0100*	-0.0075 ± 0.0400	-0.025 ± 0.0100	-0.009 ± 0.020	0.0015 ± 0.0600	0.0265 ± 0.0400	-0.0085 ± 0.0100	0.0505 ± 0.0200*	-0.018 ± 0.020	-0.0065 ± 0.0100	-0.0055 ± 0.0300
Hyperopia and Emmetropia n = 8	-0.0353 ± 0.0100	-0.04025 ± 0.04000	-0.03725 ± 0.02000	-0.0345 ± 0.0002	-0.036 ± 0.030	-0.04675 ± 0.02000	-0.00875 ± 0.04000	-0.04025 ± 0.05000	-0.0175 ± 0.0300	-0.01275 ± 0.01000	-0.0145 ± 0.0300	-0.0145 ± 0.0400
Spasm and pseudomyopia n = 14	-0.0236 ± 0.0400	-0.03154 ± 0.04000	-0.03469 ± 0.07000	-0.00538 ± 0.03000	-0.00467 ± 0.04000	-0.003 ± 0.050	-0.01769 ± 0.04000	-0.00292 ± 0.04000	-0.01646 ± 0.04000	-0.00492 ± 0.03000	-0.0347 ± 0.0400	0.002667 ± 0.030000

Note. n — number of eyes; * — p < 0.05 — significant with respect to patients with hyperopia and emmetropia; ** — p < 0.05 — significant with respect to parameters before cycloplegia.

Table 4. Wavefront structure in children with various refractions before and after badminton workouts: Coma 7 and Coma 8 (M ± σ)

Refraction	Coma 7						Coma 8					
	before		after 6 months		after 1 year		before		after 6 months		after 1 year	
	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia	before cycloplegia	after cycloplegia
Averaging over the group n = 54	0.001407 ± 0.020000	0.002963± 0.020000	0.005481 ± 0.020000	0.006389 ± 0.030000	0.005792± 0.020000	0.008214± 0.020000	-0.00015 ± 0.02000	-0.0022 ± 0.0300	-0.00481 ± 0.01000	-0.00256 ± 0.01000	-0.00329 ± 0.02000	-0.00793 ± 0.01000
Myopia n = 46	0.004023 ± 0.020000*	0.004545± 0.020000*	0.006977 ± 0.020000*	0.009795 ± 0.030000*	0.008533± 0.020000*	0.007556 ± 0.020000*	0.000205 ± 0.030000	-0.00236 ± 0.03000	-0.0052 ± 0.0100	-0.00348 ± 0.01000*	-0.005 ± 0.020	-0.005 ± 0.010
Low myopia n = 37	0.004343 ± 0.010000*	0.004457± 0.020000*	0.006657 ± 0.010000*	0.0064 ± 0.0200*	0.008533± 0.020000*	0.007556± 0.020000*	-0.0018 ± 0.0100	-0.00509 ± 0.01000	-0.00429 ± 0.01000	-0.00197 ± 0.01000	-0.005 ± 0.010	-0.005 ± 0.010
Moderate myopia n = 7	0.007714 ± 0.020000*	0.004857± 0.020000*	0.007571 ± 0.030000*	0.027143 ± 0.070000*	0.0018 ± 0.0100*	0.001 ± 0.020*	0.014714± 0.060000*	0.008714 ± 0.070000*	-0.00714 ± 0.01000	-0.00843 ± 0.01000	-0.0004 ± 0.0200	-0.02133 ± 0.03000
High myopia n = 2	-0.0145 ± 0.0100	0.005 ± 0.000*	0.0105 ± 0.0100*	0.0085 ± 0.0300*	0.007 ± 0.000*	0.007 ± 0.020*	-0.0155 ± 0.0100	0.0065 ± 0.0100	-0.0145 ± 0.0300	-0.0125 ± 0.0100	-0.0035 ± 0.0200	-0.008 ± 0.010
Hyperopia and emmetropia n = 8	-0.0185 ± 0.0100	-0.0145 ± 0.0200	-0.01325 ± 0.02000	-0.014 ± 0.020	-0.02 ± 0.02	-0.01025 ± 0.02000	-0.00225 ± 0.01000	-0.00375 ± 0.02000	-0.0015 ± 0.0100	0.00025 ± 0.01000	0.0045 ± 0.0100	0.00125 ± 0.01000
Spasm and pseudomyopia n = 14	-0.00369 ± 0.01000	0.002385± 0.010000	0.000308 ± 0.020000	-0.00185 ± 0.01000	0.008667± 0.010000	0.015 ± 0.020	0.001154± 0.010000	0.000231 ± 0.010000	-0.00108 ± 0.01000	0.001538 ± 0.010000	-0.00207 ± 0.02000	-0.00333 ± 0.01000

Note. n — number of eyes; * — p < 0.05 — significant with respect to patients with hyperopia and emmetropia; ** — p < 0.05 — significant with respect to parameters before cycloplegia.

positive); after cycloplegia, it increased 8 times and transferred to positive values. In all other groups, it remained unchanged (see table 4).

The values of Coma 8 in patients with HEAS were conform to those in hyperopia. After cycloplegia, these aberrations showed a more significant reduction than in other groups – they sank 4.5 times (in hyperopia there was a 1.5-fold decrease and in myopia, a 3.5-fold decrease), see table 4.

On the whole, it can be concluded that the wavefront structure of the eyes in HEAS and accommodation spasm corresponded to the true refraction of these eyes, i.e. to hyperopia. At the same time, the response of the wavefront to cycloplegia in these eyes differed from the response shown both by myopic and hyperopic eyes.

After regular badminton workouts, statistically significant changes of a number of eye wavefront aberrations were observed. The total aberrations (RMS) did not show a significant change but after a year they fell in all groups, which can be assessed as an increase in vision quality. In myopia, SA showed a 20-fold decrease and transferred to positive values, which means that it approached the state of hyperopic eyes. After a year, a 10-fold reduction of SA level against the initial values was still observable (see table 1).

Changes of tilt 1 were unstable and by the end of the year of workouts its values return to the initial ones. In myopia, Tilt 2 dropped 2.5 times after 6 months, and the values remained the same after a year. In hyperopia, Tilt 2 did not change after 6 months but after a year it showed a sharp increase with a transfer to positive values. In HEAS and spasm, Tilt 2 decreased by the end of the year but the response to cycloplegia was paradoxical: it showed a 25-fold increase (see tables 1, 2).

Trefoil 6 did not change after a year of practice in hyperopia but it showed a 1.7-fold decrease in myopia, which was accompanied by the emergence of a response to cycloplegia (the indicator dropped 2 times after cycloplegia). An even more pronounced response to cycloplegia was observed after 6 months in the groups of HEAS and spasm: trefoil 6 dropped 5 times. After a year, the level of this aberration dropped 4.5 times as compared to the initial value (see table 3).

Trefoil 9 reduced 12 times in myopic patients after 6 months and developed a previously absent response to cycloplegia. The changes persisted after a year. In spasm and HEAS, these aberrations increased during the year but developed a response to cycloplegia similar to that in myopia: a 5-fold increase with the transfer from negative to positive values was observed (see table 3).

No statistically significant changes of Coma 7 under natural conditions were observed after 6 months in any group. Only in HEAS and spasm, a response to cycloplegia was observed, which consisted in a 6-fold increase of Coma 7 with positive values transferring to negative ones. After a year, Coma 7 values increased 3 times in this group with respect to the initial values. In hyperopia, no changes were observed either before or after cycloplegia (see table 4).

Coma 8 values showed an even higher reduction after a year in patients with myopia, HEAS and spasm, demonstrating the transfer to negative values; no response to cycloplegia was present. In hyperopic eyes, the changes of Coma 8 aberrations were opposite: their level showed an even higher increase, with a transfer to positive values, and the response to cycloplegia was pronounced: it showed a 3.5-fold decrease (see table 4).

It can thus be concluded that after regular badminton practice, the eyes with myopia, HEAS or spasm showed statistically significant changes of wavefront aberrations, which can be associated with the strengthening of the ligamentous apparatus of the lens and the normalization of ciliary muscle tone. First of all, the changes consisted in a shift of spherical aberrations from negative values (when the center of the optical system shows a more powerful refraction than the periphery) to positive values (the periphery refracts stronger than the center. Such an effect is an undeniable evidence of lens flattening, which, in its turn, is associated with the elimination of the hypertone of the ciliary muscle and with increased tension of Zinn ligaments.

A reduction of the wavefront slope (Tilt 2), vertical and horizontal trefoil and horizontal coma (coma 8), i.e. the aberrations associated with the mismatch and irregularity of the elements of the optical system can also be attributed to the strengthening of the ligamentous apparatus of the lens.

The appearance of a previously absent response to cycloplegia, namely wavefront changes in Zinn ligaments under the influence of cycloplegic agents is an even clearer indication of this fact (see table 2–4).

CONCLUSIONS

The structure of the wavefront in children with various refractions shows a statistically significant difference. In particular, SA is negative in myopia anf positive in hyperopia; Tilt 1, Tilt 2, Trefoil 9, Coma 7 in myopia is significantly higher and Coma 8 is significantly lower than in hyperopia.

The wavefront slope (Tilt 1, Tilt 2) under cycloplegia significantly decreases in hyperopic eyes and does not change in myopic ones. The latter indicates insufficient tension of Zinn ligaments.

After regular badminton workouts, statstically significant changes are revealed in wavefront aberrations, which is an evidence of the strengthening of the ligamentous apparatus of the lens and the normalization of the tone of the ciliary muscle.

References

1. *Katargina L.A., Tarutta E.P.* Medical-social significance of the disorders of accommodation: Accommodation: a guide for physicians. Moscow; 2012: 9–12 (In Russian).
2. *Jonas J.B., Xu L., Wei W.B., Wang Y.X., et al.* Myopia in China: a population-based cross-sectional, histological, and experimental study. Lancet. 2016; 388 (Oct. Suppl 1): S 20. doi: 10.1016/S0140-6736(16)31947-X
3. *Matamoros E., Ingrand P., Pelen F., et al.* Prevalence of myopia in France: a cross-sectional analysis. Medicine. 2015; 94 (45 November). doi: 0.1097/MD.0000000000001976

4. *McCullought S.J., O'Donoghue L., Saunders K.J.* Six year refractive change among white children and young adults: evidence for significant increase in myopia among white UK Children. PLoS ONE. 2016; 11(1): e0146332. https://doi.org/10.1371/journal.pone.0146332
5. *Williams K.M., Verhoeven V.J.M., Cumberland P., et al.* Prevalence of refractive error in Europe: the European Eye Epidemiology (E3) Consortium. Eur. J. Epidemiol. 2015; 30(4): 305–15. doi: 10.1007/s10654-015-0010-0
6. *Dashevsky A.I.* New methods of studying the optical system of the eye and the development of its refraction. Kiev; 1956 (In Russian).
7. *Yastrebtseva T.A., Chuprov A. A., Plotnikova Yu.A.* Indicators of general, cerebral and regional hemodynamics in schoolchildren 13–15 years with myopia. Vestnik oftal'mologii. 2002; 5: 12–5 (In Russian).
8. *Theagarayan B., Radhakrishnan H., Allen P.M., Calver R.I., Rae S.M.* The effect of altering spherical aberration on the static accommodative response. Ophthal. Physiol. Opt. 2009; 29 (1): 65–71. doi.org/10.1111/j.1475-1313.2008.00610.x
9. *Allen P.M., Radhakrishnan H., Rae S., Calver R.I., Theagarayan B.P.* Aberration control and vision training as an effective means of improving accommodation in individuals with myopia. Invest. Ophthalmol. Vis. Sci. 2009; 50: 5120–9. doi:10.1167/iovs.08-2865
10. *Collins M.J., Wildsoet C.F.* Optical treatment method. Australia: Queensland University of technology. Brisbane (Australia); 2000.
11. *Buehren T., Collins M.J.* Accommodation stimulus-response function and retinal image quality. Vision Research. 2006; 46 (10): 1633–45. doi.org/10.1016/j.visres.2005.06.009
12. *Zhang N., Yang X., Zhang W., Liu L., Dong G.* Relationship between higher-order aberrations and myopia progression in schoolchildren. A retrospective study. Int. J. Ophthalmol. 2013 18; 6 (3): 295–9. doi: 10.3980/j.issn.2222-3959.2013.03.07
13. *He J.C., Sun P., Held R., et al.* Wave-front aberrations in eyes of emmetropic and moderately myopic schoolchildren and young adults. Vis. Res. 2002; 42: 1063–70. doi.org/10.1016/S0042-6989(02)00035-4
14. *Zadok D., Levy Y., Segal O., et al.* Ocular higher-order aberrations in myopia and skiascopic wavefront repeatability. J. Catar. Refract. Surg. 2005; 31 (June): 1128–32. doi.org/10.1016/j.jcrs.2004.10.075
15. *Kirwan C., O'Keffe M., Soeldner H.* Higher-order aberrations in children. Am. J. Ophthalmol. 2006; 141 (1 Jan.): 67–70. doi.org/10.1016/j.ajo.2005.08.031
16. *Philip K., Sankaridurg P., Holden B., Ho A., Mitchell P.* Influence of higher-order aberrations and retinal image quality in myopisation of emmetropic eyes. Vision Research. 2014; 105: 233-43.
17. *Hartwig A., Atchison D. A., Radhakrishnan H.* Higher-order aberrations and anisometropia. Curr. Eye Res. 2013; 38 (1): 215–29. doi: 10.3341/kjo.2014.28.1.66
18. *Paquin M. P., Hamam H., Simonet P.* Objective measurement of optical aberrations in myopic eyes. Optometry and Vision Science. 2002; 79: 285–91.
19. *He Ji.C., Sun P., Held R., Thorn F.* Wavefront aberrations in eyes of emmetropic and moderately myopics schoolchildren and young adults. Vis. Research. 2002; 42: 1063–70. doi.org/10.1016/S0042-6989(02)00035-4
20. *Kwan W.C., Yip S.P., Yap M.K.* Monochromatic aberrations of the human eye and myopia. Clinical and Experimental Optometry. 2009: 92 (3): 304–12. doi:10.1111/j.1444-0938.2009.00378.x
21. *Carkeet A., Luo H.D., Tong L., Saw S.M., Tan D.* Refractive error and monochromatic aberrations in Singaporean children. Vision Research. 2002; 42 (14): 1809–24. doi.org/10.1016/S0042-6989(02)00114-1
22. *Marcos S., Barbero S., Llorente L.* The sources of optical aberrations in myopic eyes. Invest. Ophthalmol. Vis. Sci. 2002; 43 (13 Dec.): 1510.
23. *Martinez A. A., Sankaridurg P. R., Naduvilath T. J., Mitchell P.* Monochromatic aberrations in hyperopic and emmetropic children. Journal of Vision. 2009; 9 (1): 21–14. doi:10.1167/9.1.23
24. *Thapa D., Fleck A., Lakshminarayanan V., Bobier W.R.* Ocular wavefront aberration and refractive error in pre-school children. Journal of Modern Optics. 2011 Nov; 58 (19–20): 1681–19. doi: 10.1080/09500340.2011.564316
25. *Atchison D.A., Lucas S.D., Ashman R., et al.* Refraction and aberration across the horizontal central 10 degrees of the visual field. Optom. Vis Sci. 2006 Apr; 83 (4): 213–21. doi:10.1097/01.opx.0000214382.75847.c4
26. *Cheng H., Barnett J.K., Vilupuru A.S., et al.* A population study on changes in wave aberrations with accommodation. J. Vis. 2004; 4: 272–80. https://doi.org/10.1167/4.4.3
27. *Bao J., Le R., Wu J., et al.* Higher-order wavefront aberrations for populations of young emmetropes and myopes. J. Optom. 2009; 2 (1): 51–8. doi:10.3921/joptom.2009.51
28. *Porter J., Guirao A., Cox I.G., Williams D.R.* The human eye's monochromatic aberrations in a large population. J. Opt. Soc. Am. 2001; A18: 1793–803. doi.org/10.1364/JOSAA.18.001793
29. *Gilmartin B.* A review of the role of sympathetic innervations of the ciliary muscle in ocular accommodation. Ophthalmic. Physiol. Opt. 1986; 6 (1): 23–37.
30. *He J.C., Burns S.A., Marcos S.* Monochromatic aberrations in the accommodated human eye. Vision Res. 2000; 40 (1): 41–8. doi.org/10.1016/S0042-6989(99)00156-X
31. *Hiraoka T., Miyata K., Nakamura Y., et al.* Influences of cycloplegia with topical atropine on ocular higher-order aberrations. Ophthalmology. 2013; 120 (1): 8–13. doi: 10.1016/j.ophtha.2012.07.057
32. *Carkeet A., Velaedan S., Tan Y.K., Lee D.Y., Tan D.T.* Higher order ocular aberrations after cycloplegic and non-cycloplegic pupil dilation. J. Refract. Surg. 2003; 19 (3): 316–20. doi.org/10.3928/1081-597X-20030501-08
33. *Tarutta E.P., Arutyunyan S.G., Smirnova T.S.* Wavefront aberrations in children with myopia and hyperopia before and after cycloplegia. Russian Ophthalmological Journal. 2017; 10 (3): 78–83. (In Russian). https://doi.org/10.21516/2072-0076-2017-10-3-78-83
34. *Tarutta E., Khodzhabekyan N., Filinova O., Milash S., Kruzhkova G.* Long-term effects of optical defocus on eye growth and refractogenesis. Pomeranian J. Life Sci. 2016; 62 (1): 25–30.
35. *Turmanidze V.G., Tarutta E.P., Shakrai S.M.* Badminton against myopia. Instructional Manual. Moscow: Kuchkovo Pole Publishers. 2017.

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