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Biomechanical parameters of the fibrous capsule of the eyeball in pseudoexfoliative glaucoma in comparison with primary open-angle glaucoma

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ABSTRACT

BACKGROUND: Pseudoexfoliation syndrome is currently considered as a systemic disorder of the connective tissue metabolism with the accumulation in all corneal cell layers of pseudoexfoliation syndrome deposits, which disrupt corneal morphology and biomechanics.

AIM: to study the features of biomechanical parameters of the fibrous capsule of eyes in primary open-angle glaucoma (POAG) in comparison with those in pseudoexfoliative glaucoma (PEG).

MATERIALS AND METHODS: We compared 65 eyes with POAG and 77 eyes with PEG aged under 80 years. The control group consisted of 18 healthy eyes. Biomechanical indicators were compared, such as: DA Ratio, Integr. Radius, SP-A1, SSI, BGF, biomechanically corrected intraocular pressure (bIOP) obtained with Pentacam (Oculus) and CorVis ST.

RESULTS: Patients with PEG were elder (68.013 ± 0.75 years) in contrast to POAG patients (60.03 ± 1.05 years) (p = 0.001), had a thinner central retinal thickness (CRT) — 543.99 ± 3.9 μm versus 559.33 ± 4.4 μm in those with POAG (p = 0.010). The IOP level did not differ between groups, and no correlation with CRT was detected. Indicators of corneal stiffness: DA ratio Integr. Radius did not differ between POAG, PEG and control group. The SP-A1 parameter also did not differ between POAG and PEG patients, while there were differences between PEG patients and the control group (p = 0.046). Moreover, in eyes with POAG, SP-A1 directly correlates with IOP Po (p = 0.001) and CRT (p = 0.001), in those with PEG — p = 0.001 and p = 0.001, respectively. The SSI index in PEG was higher and amounted to 1.38 ± 0.03 versus 1.27 ± 0.03 in POAG (p = 0.013), while it correlated with age only in the case of PEG (p = 0.007). A correlation between SSI and CTR was also revealed — in POAG (p = 0.018), in PEG (p = 0.001). In PEG, BGF shows higher values (25.92 ± 2.3) than in POAG (17.71 ± 2.2; p = 0.010). BGF has no correlation with age (p = 0.094 and p = 0.737 for POAG and PEG, respectively), depends on CRT (p = 0.001 and p = 0.027, respectively), on bIOP (p = 0.001 and p = 0.001, respectively), and on SP-A1 (p = 0.009 and p = 0.001, respectively). The only parameter that was higher in PEG than in POAG was SSI, which did not correlate with the BGF indicator (p = 0.642 and p = 0.327, respectively).

CONCLUSIONS: We did not find any fundamental differences in biomechanics between PEG and POAG, which could explain the significant rates of progression of PEG. Based on our data, it is obvious that the eye with PEG differs from that with POAG being more rigid, even at similar IOP values.

Keywords: primary open-angle glaucoma; pseudoexfoliative glaucoma; central corneal thickness; tonometry; corneal-compensated pressure; biomechanical properties of the fibrous capsule of the eye.

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Биомеханические показатели фиброзной оболочки глазного яблока при псевдоэксфолиативной глаукоме в сравнении с первичной открытоугольной глаукомой

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АННОТАЦИЯ

Актуальность. Псевдоэксфолиативный синдром на сегодняшний день рассматривают как системное нарушение метаболизма соединительной ткани с накоплением депозитов псевдоэксфолиативного материала во всех слоях клеток роговицы, которые нарушают её морфологию и биомеханику.

Цель — изучить особенности биомеханических показателей фиброзной оболочки глаз при первичной открытоугольной глаукоме (ПОУГ) в сравнении с псевдоэксфолиативной глаукомой (ПЭГ).

Материалы и методы. Сравнили 65 глаз с ПОУГ и 77 глаз с ПЭГ у пациентов в возрасте до 80 лет. Группа контроля составила 18 здоровых глаз. Сравнивали биомеханические показатели, такие как: DA Ratio, Integr. Radius, SP-A1, SSI, BGF, биомеханически скорректированное внутриглазное давление (bIOP) по данным Pentacam (Oculus) и CorVis ST.

Результаты. Пациенты с ПЭГ были старшего возраста (68,013 ± 0,75 года) в отличие от пациентов с ПОУГ (60,03 ± 1,05 года, p = 0,001), имели более тонкую центральную толщину роговицы (ЦТР) — 543,99 ± 3,9 мкм против 559,33 ± 4,4 при ПОУГ, p = 0,010. Уровень внутриглазного давления не различался между группами, корреляции с ЦТР не выявлено. Показатели жёсткости роговицы DA Ratio, Integr. Radius не различались между пациентами с ПОУГ, ПЭГ и контрольной группой. Параметр SP-A1 также не различался между ПОУГ и ПЭГ, при этом есть различия между ПЭГ и группой контроля (p = 0,046). При этом в глазах с ПОУГ SP-A1 прямо коррелирует с внутриглазным давлением P_0 (p = 0,001) и ЦТР (p = 0,001), при ПЭГ — p = 0,001 и p = 0,001 соответственно. Индекс SSI при ПЭГ выше и составил 1,38 ± 0,03 против 1,27 ± 0,03 при ПОУГ (p = 0,013), при этом коррелировал с возрастом только в случае ПЭГ (p = 0,007). Выявлена также корреляция SSI и ЦТР — при ПОУГ (p = 0,018) и ПЭГ (p = 0,001). При ПЭГ BGF демонстрирует более высокие значения (25,92 ± 2,3), чем при ПОУГ (17,71 ± 2,2; p = 0,010). BGF не взаимосвязан с возрастом (p = 0,094 и p = 0,737 при ПОУГ и ПЭГ соответственно), зависит от ЦТР (p = 0,001 и p = 0,027 соответственно), bIOP (p = 0,001 и p = 0,001 соответственно) и SP-A1 (p = 0,009 и p = 0,001 соответственно). Единственный параметр — SSI, который при ПЭГ был выше, чем при ПОУГ, не коррелировал с показателем BGF (p = 0,642 и p = 0,327 соответственно).

Выводы. Принципиальных отличий по биомеханике при ПЭГ и ПОУГ, которые бы объяснили значительные темпы прогрессирования ПЭГ, мы не получили. На основании наших данных очевидно, что глаз при ПЭГ отличается от ПОУГ большей ригидностью даже при сходных значениях внутриглазного давления.

Ключевые слова: первичная открытоугольная глаукома; псевдоэксфолиативная глаукома; центральная толщина роговицы; тонометрия; роговично-компенсированное давление; биомеханические свойства фиброзной оболочки глаза.

Как цитировать

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ЭКО•ВЕКТОР

BACKGROUND

Pseudoexfoliation syndrome (PEX) is a genetic age-related disease characterized by the formation and deposition of abnormal fibrillary extracellular aggregates in the anterior segment [1]. Today, it is considered a systemic disorder of connective tissue metabolism, as PEX deposits have been detected in internal organs such as the liver, kidneys, heart, brain meninges, and skin [2]. There is available data on morphological changes in all corneal layers in eyes with PEX. Eyes with PEX are documented to have deposits of pseudoexfoliative material on the endothelium, significantly lower cell density in the basal epithelium, anterior and posterior stroma, and endothelium compared with the control values [3]. Corneal biomechanics were previously found to be altered in PEX. Bi-directional applanation pneumotonometry (Ocular Response Analyzer, ORA, USA) revealed decreased corneal hysteresis and corneal resistance factor in eyes with PEX and pseudoexfoliative glaucoma (PEG) compared with healthy eyes. In a retrospective review, Ayala [4] found decreased corneal hysteresis in eyes with PEG compared with eyes with primary open-angle glaucoma (POAG) [4]. Demonstrated changes in the anterior segment, in particular in the cornea, may be caused by an extracellular matrix abnormality and indicate a change in the entire cornea and sclera. If scleral fibroblasts are similarly reduced or altered in patients with PEX, structural changes in the entire cornea and sclera may occur. This finding is significant, as changes in the mechanics of the peripapillary sclera and lamina cribrosa have been shown to affect optic nerve defects with increased intraocular pressure (IOP) [5]. PEX is currently considered one of the common causes of development and progression of open-angle glaucoma. PEG is one of the leading causes of blindness and visual impairment worldwide and more progressive compared with POAG [6].

The *study aimed* to evaluate and compare fibrous tunic biomechanics in POAG and PEG.

METHODS

We analyzed data of 65 eyes with compensated POAG and 77 eyes with PEG in patients under 80 years (Table 1).

The control group included 18 healthy eyes of patients aged 37 ± 1.93 years without glaucoma or any signs of PEX, with an anteroposterior axis not exceeding 24.00 mm. The mean anteroposterior axis was 23.29 ± 0.13 mm, and mean central corneal thickness (CCT) was 566.89 ± 6.3 μm.

Diagnostic examination for glaucoma included visometry, tonometry, pachymetry, gonioscopy, optical coherence tomography (Cirrus HD-OCT 5000, Carl Zeiss, Germany), standard automated perimetry (Tomey AP1000, Germany) as per the Glaucoma Screening program. he biometric eye parameters were evaluated using IOLMaster 700 (Carl Zeiss, Germany). Standard non-contact tonometry was performed using Reichert 7CR (USA) and included measurement of corneal compensated pressure.

Corneal tomography and biomechanical parameters were assessed using Oculus (Pentacam, USA) and Corvis ST (Oculus GmbH, Germany), respectively.

The following biomechanical parameters were evaluated:

- DA ratio defined as deformation amplitude of the central corneal apex divided by an average of the deformation 2 mm either side of center (nasal and temporal). It indicates the degree of corneal stiffness. The stiffer the cornea (more resistant to deformation) is, the lesser the values are scattered in the center and 2-millimeter zone and the lower DA ratio is (inverse correlation).
- Integr. radius (R) is the corneal radius integrated in concavity or reversed integrated corneal radius of curvature. The following parameters are calculated: central corneal radius of concave curvature, reversed radius ($1/R$), and the area under it; then the radius-time curve is plotted. This area is called the integrated radius. The lesser the indentation (stiff cornea),

Table 1. Main characteristics of the patients' group
Таблица 1. Основные характеристики группы пациентов

Parameter		Primary open-angle glaucoma	Pseudoexfoliative glaucoma
Sex	Men	15 (22.5%)	31 (40%)
	Women	50 (76.5%)	46 (60%)
Glaucoma	Early-stage	35 (53%)	31 (40%)
	Moderate	13 (20%)	23 (30%)
	Advanced	12 (18%)	15 (19.5%)
	End-stage	5 (8%)	7 (9.5%)

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the larger the indentation radius, which means that the reversed radius is smaller. In other words, the stiffer the cornea, the lower this value.

- SP-A1 is a stiffness parameter for quantifying corneal resistance to deformation, defined as the ratio of pressure to the cornea to displacement of the corneal apex from the undeformed state to first applanation, which is measured in mmHg/mm. This parameter is determined by using displacement of the corneal apex from the undeformed state to first applanation and indicates corneal resistance to deformation. It reflects corneal stiffness and internal biomechanics and depends on IOP and CCT [7].

In addition to numerical values of three biomechanical parameters presented above (DA ratio, integr. radius, and SP-A1), the study protocol also includes standard deviation (SD) of the reference mean. SD close to 0 means average stiffness and indirectly indicates tolerant IOP. Negative and positive SDs represent increased and decreased tissue stiffness, respectively.

Stress-strain index (SSI) is a stress and strain index that characterizes corneal stiffness. This index was set at 1.0 for the average experimental behavior of the corneal tissue in a 50-year-old patient. Higher SSI indicates higher corneal stiffness, and vice versa. SSI is a corrected biomechanical index independent of IOP or CCT. It is based on the input and output parameters of numerical simulation of CCT, biomechanically-corrected IOP, and stiffness parameter (SP) at maximum corneal concavity. The index is used to assess the internal material stiffness (corneal tissue) [8].

BGF is a biomechanical glaucoma factor, a parameter characterizing the risk of glaucoma with low IOP. It is used in screening for low-tension glaucoma. The obtained BGF values are correct only in case of normal IOP (high IOP gives a minimal value). The presented scale shows the following grading: <0.25 = no risk of glaucoma, 0.25–0.5 = minimal risk of glaucoma, and >0.5 = high risk of low-tension glaucoma.

Statistical analysis of the obtained results was performed using SPSS v.16.0 standard software package for Windows and included data processing using methods of dispersion statistics with calculation of the means, standard deviations, and mean errors. Normality of sample distribution was determined using the Kolhomonov-Smirnov and Shapiro–Wilk tests. The parameters with normal distribution are shown as $M \pm m$, where M is the mean, and m is the mean error.

RESULTS AND DISCUSSION

The main comparative characteristics of the groups are presented in Table 2.

Table 2 shows that the compared POAG and PEG groups were age heterogeneous, which once again demonstrates that age is the main risk factor for development and progression of PEX. Numerous studies have confirmed that the disease is more common in older people, with peak prevalence in patients over 80 years old [1, 9]. Significant differences in CCT were identified. Supposedly, they are related to age, as the groups differ in this parameter; however, analysis of correlation between CCT and age found that p values were 0.084 and 0.615 in patients with POAG and PEG, respectively. Therefore, other non-age related causes of corneal tissue changes should be considered.

Pronounced corneal changes were detected in eyes with PEX. One non-Russian study demonstrated that eyes with PEX had significantly lower cell density in the basal epithelium, stroma, and endothelium, less dense and more tortuous subbasal nerves, and reduced corneal sensitivity compared with healthy eyes [10].

A recent review by Palko et al. [11] showed a clear relationship between corneal changes and PEX, which tends to increase in patients with PEG. The authors concluded that corneal parameters such as endothelial cell and subbasal nerve cell density can be considered as clinical PEX biomarkers to assess the disease severity and determine the risk of progression from PEX to PEG [11].

Our previous study of corneal endothelium status in PEX based on endothelial microscopy revealed differences in corneal endothelial cell density (ECD) and mean endothelial cell area between eyes with and without PEX. Interestingly, ECD decreased depending on glaucoma stage and

Table 2. Differences in age and morphometric parameters of the eye in patients with pseudoexfoliative glaucoma and those with primary open-angle glaucoma

Таблица 2. Различия в возрасте и морфометрических показателях глаза у пациентов с псевдоэксфолиативной глаукомой и первичной открытоугольной глаукомой

Parameter	Primary open-angle glaucoma	Pseudoexfoliative glaucoma	Significance of difference between the groups, p
Age, years	60.03 ± 1.05	68.013 ± 0.75	0.001
Central corneal thickness, µm	559.33 ± 4.4	543.99 ± 3.9	0.010
Anteroposterior axis, mm	23.39 ± 0.17	23.64 ± 0.12	0.157

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age, with the highest value in patients of 40–50 years old (2722.75 ± 63.05 cells/mm^2); in patients of 81–90 years old, ECD decreased to 1872.67 ± 417.29 cells/mm^2 [12].

In this study, we analyzed IOP in eyes with POAG and PEG (Table 3).

Table 3 shows that IOP based on standard non-contact tonometry and biomechanically-corrected IOP (bIOP) do not differ between the groups. But CCT differed between the groups, so we decided to check correlation between these parameters. In patients with POAG, correlation between CCT and P_0 IOP was detected (p = 0.02), but not between bIOP and CCT (p = 0.569). In patients with PEG, there was no correlation between CCT and both types of IOP (p = 0.128 and p = 0.249, respectively). BIOP in patients with POAG did not differ from that in the control group (p = 0.264), whereas the differences were significant in patients with PEG (p = 0.010). Moreover, positive direct correlation between age and bIOP was found in patients with POAG (p = 0.041), but not in patients with PEG (p = 0.423).

An analysis of biomechanical parameters of the fibrous tunic provided the data presented in Table 4. Table 4 shows that there were no differences in corneal stiffness between the compared groups, as DA ratio and integr. radius did not differ between patients with POAG or PEG and the control group.

Authors from India obtained similar data. They compared data of 132 naive eyes, including 44 with PEG, 42 with POAG, and 46 healthy eyes. The compared biomechanical corneal parameters included corneal deflection speed, applanation length, deformation amplitude (DA), maximum distance, and radius of curvature. The authors concluded that the biomechanical corneal parameters measured using Corvis ST did not differ between eyes with PEG or POAG and healthy eyes after IOP correction [13]. A study of eyes with PEX, PEX and ocular hypertension, or PEG and healthy eyes made a similar conclusion that as PEG is high-pressure glaucoma, corneal biomechanics may not play an important role in its diagnosis and pathogenesis [14].

SP-A1 indicating stiffness of the entire fibrous tunic also did not differ. However, there were significant differences between patients with PEG and the control group (p = 0.046), whereas the difference was not significant

Table 3. Comparison of IOP levels obtained by standard non-contact tonometry and biomechanically corrected IOP in primary open-angle glaucoma and pseudoexfoliative glaucoma

Таблица 3. Сравнение уровня внутриглазного давления, полученного методом стандартной бесконтактной тонометрии, и биомеханически скорректированного при псевдоэксфолиативной глаукоме и первичной открытоугольной глаукоме

Parameter	Primary open-angle glaucoma	Pseudoexfoliative glaucoma	Significance of difference between the groups, p	Control group
P_0 IOP, mmHg	20.83 ± 1.18	21.04 ± 0.86	0.885	18.35 ± 0.73
bIOP, mmH	18.21 ± 0.85	18.76 ± 0.64	0.598	16.37 ± 0.56

Note. IOP P_0, intraocular pressure, measured by standard non-contact tonometry; bIOP, IOP taking into account the biomechanical properties of the fibrous capsule of the eye.

Примечание. ВГД P_0 — внутриглазное давление, измеренное методом стандартной бесконтактной тонометрии; bIOP — внутриглазное давление с учётом биомеханических свойств фиброзной оболочки глаза.

Table 4. Biomechanical characteristics of the fibrous capsule of the eye in patients with POAG as compared with those with PEG

Таблица 4. Биомеханические характеристики фиброзной оболочки глаза у пациентов с первичной открытоугольной глаукомой в отличие от псевдоэксфолиативной глаукомы

Parameter	Primary open-angle glaucoma	Pseudoexfoliative glaucoma	Significance of difference between the groups, p	Control group (n = 18)
DA Ratio	4.07 ± 0.09	4.01 ± 0.07	0.624	4.02 ± 0.08
Integr. radius (R), mm	7.495 ± 0.23	7.455 ± 0.16	0.883	7.63 ± 0.23
SP-A1, mmHg/mm	128.32 ± 2.9	128.93 ± 2.64	0.877	115.64 ± 6.77
SSI	1.27 ± 0.03	1.38 ± 0.03	0.013	1.21 ± 0.05
BGF	17.71 ± 2.2	25.92 ± 2.3	0.010	7.44 ± 1.31

Note. DA Ratio, the ratio between the amplitude of deformation of the cornea at the apex and in the 2-millimeter zone; Integr. Radius (R), radius of the cornea inscribed in a concave surface; SP-A1, difference between the strength of the air pulse on the surface of the cornea and the biomechanically corrected IOP; SSI, stress-strain index, BGF, biomechanical glaucoma factor.

Примечание. DA Ratio — соотношение между амплитудой деформации роговицы на вершине и в 2-миллиметровой зоне; Integr. Radius (R) — радиус роговицы, вписанный в вогнутую поверхность; SP-A1 — разность между силой воздушного импульса на поверхности роговицы и биомеханически скорректированным внутриглазным давлением; SSI — индекс напряжения-деформации; BGF — биомеханический глаукомный фактор.

in patients with POAG (p = 0.055). SP-A1 is known to be dependent on IOP and CCT in healthy eyes. The analysis of correlations in eyes with POAG found that SP-A1 directly depended on P_0 IOP (p = 0.001) and CCT (p = 0.001; Fig. 1), whereas in eyes with PEG, p values were 0.001 and 0.001, respectively (Fig. 2). As patients with PEG in our sample have thinner cornea, we can assume that patients with PEG and similar SP-A1 have stiffer fibrous tunic.

Table 4 also shows that SSI in PEG is higher than in POAG, which indicates increased eye rigidity. This parameter is known to correlate with age, which is significant for patients over 50 years old and healthy eyes [8]. And higher SSI in PEG compared with POAG may be explained by the fact that patients with PEG are older. An analysis found highly significant correlation between SSI and age in patients with PEG (p = 0.007) and no such relationship in patients with POAG (p = 0.355) There is evidence that SSI in healthy eyes does not depend on CCT; however, this relationship was observed in our sample, and p values were 0.018 and 0.001 in POAG and PEG, respectively. There was no correlation between SSI and bIOP in the POAG and PEG groups (p = 0.998 and p = 0.529, respectively). We obtained very interesting data demonstrating correlation between SSI and age in PEG. On the one hand, this suggested an increase in SSI with age and, on the other hand, a direct dependence on CCT, which assumes higher SSI with increased CCT. However, in our study, patients with PEG had lower CCT and higher SSI compared with patients with POAG, which obviously indicates an increase in SSI resulting from higher corneal stiffness and older age. Higher corneal stiffness is considered to reflect higher peripapillary scleral stiffness and, consequently, greater vulnerability of the optic nerve head [15].

Our early clinical observations showed that the less rigid the fibrous tunic (SD of biomechanical parameters is positive), the higher the BGF. Interestingly, BGF was higher in patients with PEG than with POAG. To explain this finding, we investigated the correlation between BGF and other possibly affecting parameters (Table 5).

High BGFs in PEG could not be explained by age, although patients in this group were older. CCT was also not the reason, as it is lower in PEG and, therefore, lower BGF was expected in this group. BIOP and SP-A1 could not explain the finding, as these parameters did not differ between patients with POAG and PEG, although they correlated with BGF. And SSI was higher in the PEG group, but was not related to BGF (Table 5). Higher biomechanical factor in PEG seems to be associated with other parameters that we have not investigated.

In this study, we did not find any fundamental differences in biomechanics between patients with PEG and POAG, which would explain the significant PEG progression rate compared with POAG. Faster progression of the disease seems to more associated with damage to the vascular wall caused by PEX and impaired vascularization of the optic nerve and retina. Studies comparing density of the macular and peripapillary vasculature using optical coherence tomography angiography (OCTA) in 36 eyes with POAG and 34 eyes with PEG showed that PEG eyes had lower density of surface macular vessels, especially in the parafoveal region. Foveal avascular zone area was larger in PEG than in POAG; as most parameters

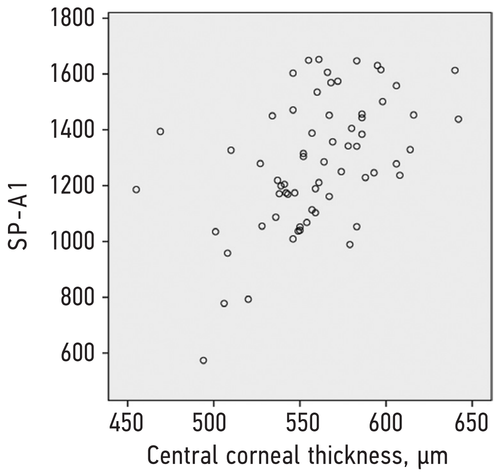

Fig. 1. Dependence of the stiffness parameter of the fibrous capsule of the eyeball SP-A1 on the central corneal thickness in primary open-angle glaucoma

Рис. 1. Зависимость параметра жёсткости фиброзной оболочки глазного яблока SP-A1 от центральной толщины роговицы при первичной открытоугольной глаукоме

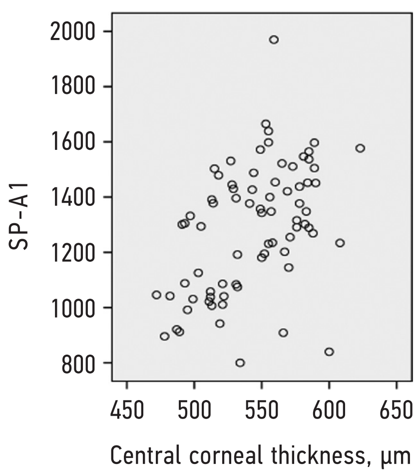

Fig. 2. Dependence of the stiffness parameter of the fibrous capsule of the eyeball SP-A1 on the central corneal thickness in pseudoexfoliative glaucoma

Рис. 2. Зависимость параметра жёсткости фиброзной оболочки глазного яблока SP-A1 от центральной толщины роговицы при псевдоэксфолиативной глаукоме

Table 5. Correlations indicator between the biomechanical glaucoma factor and various indicators that may influence its value in patients with POAG and PEG

Таблица 5. Корреляции между биомеханическим глаукомным фактором и различными показателями, возможно оказывающими влияние на его значение у пациентов с первичной открытоугольной глаукомой и псевдоэксфолиативной глаукомой

Parameter	Primary open-angle glaucoma	Pseudoexfoliative glaucoma
Age	$p = 0.094$	$p = 0.737$
Central corneal thickness	$p = 0.001$	$p = 0.027$
Anteroposterior axis	$p = 0.175$	$p = 0.096$
bIOP	$p = 0.001$	$p = 0.001$
SP-A1	$p = 0.009$	$p = 0.001$
SSI	$p = 0.642$	$p = 0.327$

Note. bIOP, IOP taking into account the biomechanical properties of the fibrous capsule of the eye, SP-A1, difference between the strength of the air pulse on the surface of the cornea and the biomechanically corrected IOP; SSI, stress-strain index, BGF, biomechanical glaucoma factor.
Примечание. bIOP — внутриглазное давление с учётом биомеханических свойств фиброзной оболочки глаза; SP-A1 — разность между силой воздушного импульса на поверхности роговицы и биомеханически скорректированным внутриглазным давлением; SSI — индекс напряжения-деформации; BGF — биомеханический глаукомый фактор.

in radial peripapillary blood flow, vessel density in PEG was lower than in POAG [16]. In another study, the authors compared 26 eyes with POAG and 23 eyes with PEG using OCTA and found that mean perfusion density in the superficial perifoveal plexus was significantly lower in eyes with PEG than in eyes with POAG. However, mean parameters of capillary perfusion in the superficial peripapillary plexus and foveal avascular zone size did not differ between the groups. This study concluded that the glaucoma severity is crucial for density of peripapillary and macular perfusion, not the glaucoma type [17]. Moghimi et al. [18] found the thinned lamina cribrosa in patients with PEX without glaucoma compared with the age-matched control group using enhanced depth imaging spectral-domain OCT [18]. Kim et al. [19] revealed that although IOP and glaucoma severity were similar in the two groups, the lamina cribrosa was significantly thinner in eyes with PEG compared with eyes with POAG, indicating a possible change in the structure of the posterior segment in patients with PEX [19].

CONCLUSION

In our study, patients with PEG were significantly older ($p = 0.001$) than patients with POAG. The groups were also CCT heterogeneous; it was lower in the PEG group (543.99 ± 3.9 μm) than in the POAG group (559.33 ± 4.4 μm; $p = 0.010$), and this finding was not age-related.

IOP based on standard non-contact tonometry and biomechanically-corrected IOP (bIOP) did not differ between the groups, which was not CCT-related. However, bIOP in patients with POAG and in the control group did not differ ($p = 0.264$), whereas the difference was significant in patients PEG ($p = 0.010$).

The analysis of fibrous tunic stiffness did not show any differences in corneal stiffness in the study groups, as DA ratio and integr. radius did not differ between patients with POAG or PEG and the control group. SP-A1 also did not differ between patients with POAG and PEG, whereas there were significant differences between patients with PEG and the control group ($p = 0.046$), and the difference was not significant in patients with POAG ($p = 0.055$). The analysis of relationship in eyes with POAG found that SP-A1 directly correlated with P_0 IOP ($p = 0.001$) and CCT ($p = 0.001$), and in eyes with PEG, p values were 0.001 and 0.001, respectively. As patients with PEG in our sample have thinner cornea, we can assume that patients with PEG and equal SP-A1 have stiffer fibrous tunic.

Stress-strain index (SSI) in patients with PEG (1.38 ± 0.03) was higher than in patients with POAG (1.27 ± 0.03; $p = 0.013$), which indicates increased eye rigidity. The analysis found significant correlation between SSI and age in PEG ($p = 0.007$) and no such relationship in POAG ($p = 0.355$) Evidence has been obtained that SSI in healthy eyes does not depend on CCT; however, this relationship was observed in our sample, and p values were 0.018 and 0.001 in POAG and PEG, respectively.

The analysis revealed that BGF was higher in patients with PEG (25.92 ± 2.3) than in patients with POAG (17.71 ± 2.2; $p = 0.010$). The analysis to explain the data obtained demonstrated that BGF was not age-related ($p = 0.094$ and $p = 0.737$ for POAG and PEG, respectively).

Positive correlation with CCT was found in POAG and PEG ($p = 0.001$ and $p = 0.027$, respectively), which suggested lower BGF in PEG in our study. BIOP also correlated with BGF ($p = 0.001$ and $p = 0.001$ for POAG and PEG, respectively), but bIOP did not differ between the groups. We also revealed that BGF was dependent on SP-A1, but the latter did not differ between patients with POAG and PEG. SSI was the only parameter that was higher in PEG than in POAG and did not correlate with BGF ($p = 0.642$ and $p = 0.327$, respectively). Higher biomechanical factor in PEG seems to be associated with other parameters that we have not investigated.

CONCLUSION

In this study, we did not find any fundamental differences in biomechanics between patients with PEG and POAG, which would explain the significant PEG progression rate compared with POAG. Our data clearly demonstrated that eyes with PEG were more rigid than eyes with POAG even with similar IOP.

ADDITIONAL INFO

Authors' contribution. All authors made a substantial contribution to the conception of the study, acquisition, analysis, interpretation of data for the work, drafting and revising the article, final approval of the version to be published and agree to be accountable for all aspects of the study. Personal contribution of each author: A.V. Malyshev, research concept, scientific editing, final approval of the manuscript; A.S. Apostolova, research development and design, collection and processing of material, writing of the text, final approval of the manuscript; A.A. Sergienko, statistical processing, writing of the text, translation of the text; A.F. Teshev, collection and processing of material, bibliography; G.Yu. Karapetov, text editing, preparation of illustrations; M.K. Ashkhamakhova, preparation of illustrations, technical editing; B.N. Khatsukova, bibliography, technical editing.

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