Cross-sectional Study

Comparing corneal biomechanics and intraocular pressure between healthy individuals and glaucoma subtypes: A cross-sectional study

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ABSTRACT

Background: The utilization of corneal biomechanical features in evaluating glaucoma and its progression has received particular attention. The severity of corneal biomechanical changes can play an essential role in response to medical or surgical treatment. The present study evaluated the biomechanical features of the cornea in glaucoma patients in different subtypes and compared them with the normal condition.
Methods: In this cross-sectional study, glaucoma patients and healthy individuals were referred to the tertiary hospital in 2021. Both eyes underwent a complete ophthalmologic examination, intraocular pressure measurement, and corneal biomechanical parameters using Corvis and ORA devices. Finally, data from both groups were compared.
Results: Based on the ORA evaluation, Lower CRF and CH were seen in glaucoma patients. In the Corvis evaluation, minor differences were observed in glaucoma as increased pachy, radius, and pachy slope, and decreased HC deformation amplitude, HC deflection amplitude, HC deflection area, deflection amplitude max, dArc length max, max inverse radius, and integrated radius. Lower ACD and higher CCT differentiated PACG from others. Lower CCT and higher C/D and WTW indicated NTG. Based on ORA, the highest CRF and CH were related to PACG and the lowest related to PEXG. In contrast, based on Corvis, higher pachy and radius and lower max inverse radius and integrated radius were specified for PACG. PEXG also had the highest values of the last two parameters.
Conclusion: Evaluation of corneal biomechanical parameters and other indicators can be beneficial in assessing the status and severity of glaucoma and distinguishing between disease subtypes.

1. Introduction

Glaucoma is a slow progressive neuropathy of the optic nerve due to the degeneration of retinal ganglion cells. It is defined by the optic nerves' specific appearance and visual field disturbances. Glaucoma is the second leading cause of blindness and the leading cause of irreversible blindness worldwide [1,2]. Although various factors are associated with the pathogenesis of this disease, the exact mechanism needs to be further understood and studied. Intraocular pressure is a primary modifiable risk factor in this disease, playing an essential role in disease management and treatment [3].

Biomechanical evaluation of the cornea is crucial for assessing the glaucoma condition. Corneal biomechanics can be indicators of whole eye biomechanics [4]. Also, corneal biomechanical differences affect intraocular pressure measurement more than corneal thickness and curvature [5,6]. Additionally, refractive corneal surgery to correct ametropia and astigmatism has become increasingly common, leading to significant structural and biological changes in the cornea [7]. Therefore, the assessment of corneal biomechanics and intraocular pressure can help diagnose, treat, and assess the procedural outcomes of glaucoma patients. This study aimed to determine the biomechanics of the cornea and intraocular pressure with and without biomechanics correction and compare them between glaucoma patients and healthy individuals.

2. Materials and methods

This cross-sectional study was conducted on glaucoma patients

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referred to the clinics of a teaching hospital and tertiary referral center in 2021. All subjects were over 18 years old and had BCVA> 1/10. Also, sex and age-matched healthy individuals were included in the study as a control group. The study excluded those with a history of ocular surgery other than uncomplicated cataract surgery, poor cooperation during imaging, corneal pathology, contact lens use, media opacity, optic nerve neuropathy except glaucoma, ocular perfusion disorder, hyperopia or myopia >5, astigmatism >3, or spherical equivalent out of range −6 to +4. The eligible patients were categorized into five subgroups: 1) normal group with intraocular pressure <21, normal nerve head examination (C/D < 0.6, asymmetric C/D, no bleeding and pit), normal RNFL, and normal visual field, 2) normal-tension glaucoma group with intraocular pressure <21, abnormal nerve head examination, RNFL defects, and reliable visual field defects compatible with RNFL defects in at least two visual fields, 3) open-angle glaucoma group with intraocular pressure >21, open-angle in gonioscopy, abnormal nerve head examination, RNFL defects, and reliable visual field defects compatible with RNFL defects in at least two visual fields, 4) closed-angle glaucoma group with intraocular pressure >21, closed-angle in gonioscopy, abnormal nerve head examination, RNFL defects, and reliable visual field defects compatible with RNFL defects in at least two visual fields, and 5) pseudoexfoliation glaucoma with intraocular pressure >21, abnormal nerve head examination, RNFL defects, and reliable visual field defects compatible with RNFL defects in at least two visual fields.

First, demographic information and brief clinical history were obtained from all participants. Then, the two eyes underwent a complete ophthalmological examination such as auto refractometry, retinoscopy, visual acuity measurement with Snellen chart with and without correction, anterior segment examination with a slit lamp, gonioscopy, posterior segment examination (fundus and nerve head) after opening pupils with a 90-degree lens, and intraocular pressure measurement with a Goldmann applanation tonometry placed on the eye before any manipulation. The pressure of the Goldmann device was adjusted to 10 mmHg before each measurement. The biometry of the eye was also measured by IOLMaster 700 (Carl Zeiss Meditec, Jena, Germany), and the central corneal thickness was measured by SP 100 Handy pachymeter (Tomey, Nagoya, Japan). Also, intraocular pressure and corneal biomechanical parameters were measured with both Corvis ST (Oculus, Wetzlar, Germany) and ORA (Reichert Inc., Depew, New York) devices. Measurements were taken in the sitting position. All measurements were taken to eliminate pressure fluctuations during the day and night from 9 a.m. to 2 p.m. All technicians of the devices were the same during the study.

We presented data using the mean, standard deviation, median, range, frequency, and percentage. To compare groups when considering the possible correlation of measurements in bilateral subjects, we used Generalized Estimating Equation (GEE). Another GEE model was used to adjust for the effect of possible confounders. We used the Sidak method to compensate for multiple comparisons. All statistical analyses were performed by SPSS version 23.0 software for Windows (IBM, Armonk, New York). P-values less than 0.05 were considered statistically significant.

This research was carried out in compliance with the Helsinki Declaration and was approved by the ethical committee at Tehran University of Medical Sciences(IR.TUMS.FARABIH.REC.1400.005).

This study is fully compliant with the STROCSS criteria www.strocss guideline.com [8].

3. Results

In total, 229 eyes studied in this study were classified into five distinct groups: 1) healthy and non-glaucoma control group (70 eyes), 2) PEXG glaucoma group (26 eyes), 3) PACG glaucoma group (46 eyes), 4) POAG glaucoma group (66 eyes), and 5) NTG glaucoma group (21 eyes). Concerning baseline characteristics, patients with glaucoma and the control group (Table 1) showed no difference in sex distribution, but

Table 1
Baseline characteristics in glaucoma and healthy groups.

Characteristics	Healthy group (70 eyes)	Glaucoma group (159 eyes)	P value
Male gender, %	42.9%	55.3%	–
Mean age, year	51 ± 14	63 ± 9	<0.001
BCVA	0.9 ± 0.2	0.7 ± 0.2	<0.001
Axial Length, mm	22.98 ± 0.88	23.16 ± 0.95	0.977
ACD, mm	3.17 ± 0.53	3.14 ± 0.63	0.528
CCT, mm	540 ± 35	521 ± 33	0.016
IOP (Goldmann), mmHg	14 ± 3	15 ± 4	0.027
C/D ratio	0.42 ± 0.19	0.60 ± 0.23	<0.001
WTW, mm	12.0 ± 0.5	11.8 ± 0.4	0.006

glaucoma patients had a higher mean age than the control group. Also, the mean BCVA was significantly higher in the healthy group. Regarding other features, no significant difference in mean axial length and ACD was observed between the two groups, but the mean CCT, IOP GAT, C/D, and WTW showed a significant difference between the two groups.

According to Table 2, the mean IOPg was 17.3 ± 4.2 and 16.0 ± 4.3 in healthy and glaucoma groups, respectively, showing no difference between the two groups (p = 0.136). The mean IOPcc was 17.2 ± 3.6 and 17.9 ± 4.5, respectively, showing no difference between the two groups (p = 0.274). However, the mean CRF was 11.1 ± 2.3 and 9.4 ± 2.1, respectively, significantly lower in the glaucoma group (p < 0.001). Similarly, the mean CH was 10.6 ± 1.9 and 9.0 ± 2.2, respectively, significantly lower in the glaucoma group (p < 0.001).

Concerning the Corvis parameters between the two groups (Table 3), glaucoma patients had a lower radius, lower pachy slope, higher HC Deformation Amp., higher HC Deflection Amp., higher HC Deflection Area, higher Deformation Amp Max, higher Deflection Amp Max[mm], higher dArc Length, higher DA ratio Max(2 mm), higher inverse radius max, and higher integrated radius than healthy individuals, but there was no difference between the two groups in the other parameters evaluated.

Regarding baseline characteristics, no difference was seen in sex distribution between the glaucoma subgroups and the control group (Table 4). Although the mean age was lower in the control group than in the glaucoma subgroups, no difference was observed between different glaucoma subgroups. Also, controls had a much higher mean BCVA than glaucoma subgroups, attributed to the PEXG and POAG subgroups, but no significant difference was found between the glaucoma subgroups. The mean axial length and ACD were higher in the healthy group than in glaucoma patients. It seems that the PACG subgroup was responsible for such a result, as there were significantly lower ACD and axial length values in the PACG subgroup than in the healthy group and other glaucoma subgroups.

Interestingly, the mean ACD was lower in the PEXG subgroup than in the POAG subgroup, possibly due to applying zonulysis in PEX. The CCT level was much higher in the control group than in the glaucoma subgroups, attributed to the NTG subgroup. Also, this index was significantly higher in the PACG subgroup and lower in the NTG subgroup than in other groups. The mean IOP GAT was not significantly different due to drug treatment of glaucoma patients, and the highest value was revealed in the POAG subgroup. Also, the mean C/D was much lower in the control group than in the glaucoma subgroups, attributed to the NTG

Table 2
Comparing ORA parameters in glaucoma and healthy groups.

Characteristics	Healthy group (70 eyes)	Glaucoma group (159 eyes)	P value	Adjusted P value
IOPg, mmHg	17.3 ± 4.2	16.0 ± 4.3	0.136	0.057
IOPcc, mmHg	17.2 ± 3.6	17.9 ± 4.5	0.274	0.683
CRF, mmHg	11.1 ± 2.3	9.4 ± 2.1	<0.001	<0.001
CH, mmHg	10.6 ± 1.9	9.0 ± 2.2	<0.001	0.001

Table 3
Comparing Corvis parameters in glaucoma and healthy groups.

	Healthy group (70 eyes)	Glaucoma group (159 eyes)	P value	Adjusted P value
IOP [mmHg]	19.1 ± 3.9	17.8 ± 3.4	0.116	0.014
Pachy [μm]	527 ± 37	514 ± 35	0.063	0.118
bIOP[mmHg]	18.4 ± 3.3	17.3 ± 3.1	0.075	0.033
Deformation Amp. Max [mm]	0.95 ± 0.1	1.01 ± 0.1	0.009	0.009
A1 Time [ms]	7.63 ± 0.58	7.45 ± 0.52	0.107	0.011
A1 Velocity [m/s]	0.12 ± 0.02	0.12 ± 0.02	0.088	0.006
A2 Time [ms]	20.96 ± 0.39	21.01 ± 0.45	0.598	0.018
A2 Velocity [m/s]	−0.24 ± 0.04	−0.25 ± 0.04	0.282	0.147
HC Time [ms]	16.21 ± 0.46	16.16 ± 0.47	0.501	0.352
Peak Dist. [mm]	4.8 ± 0.3	4.93 ± 0.29	0.125	0.095
Radius [mm]	9.74 ± 1.85	9.06 ± 1.48	0.034	0.011
A1 Deformation Amp. [mm]	0.13 ± 0.01	0.13 ± 0.01	0.617	0.200
HC Deformation Amp. [mm]	0.95 ± 0.10	1.01 ± 0.11	0.006	0.004
A2 Deformation Amp. [mm]	0.40 ± 0.08	0.40 ± 0.08	0.792	0.054
A1 Deflection Length [mm]	2.3 ± 0.18	2.26 ± 0.19	0.209	0.115
HC Deflection Length [mm]	6.11 ± 0.45	6.28 ± 0.46	0.067	0.236
A2 Deflection Length [mm]	2.9 ± 0.57	2.96 ± 0.73	0.490	0.727
A1 Deflection Amp. [mm]	0.09 ± 0.01	0.09 ± 0.01	0.710	0.048
HC Deflection Amp. [mm]	0.80 ± 0.11	0.86 ± 0.12	0.007	0.055
A2 Deflection Amp. [mm]	0.11 ± 0.02	0.11 ± 0.02	0.434	0.331
Deflection Amp. Max [mm]	0.81 ± 0.11	0.88 ± 0.11	0.002	0.021
Deflection Amp. Max [ms]	15.64 ± 0.43	15.57 ± 0.56	0.263	0.880
Whole Eye Movement Max [mm]	0.31 ± 0.08	0.31 ± 0.08	0.795	0.084
Whole Eye Movement Max [ms]	21.86 ± 1.05	21.85 ± 0.93	0.766	0.969
A1 Deflection Area [mm^2]	0.18 ± 0.03	0.18 ± 0.03	0.186	0.127
HC Deflection Area [mm^2]	2.80 ± 0.53	3.09 ± 0.55	0.012	0.049
A2 Deflection Area [mm^2]	0.256 ± 0.055	0.250 ± 0.062	0.503	0.250
A1 dArc Length [mm]	−0.017 ± 0.005	−0.018 ± 0.004	0.290	0.518
HC dArc Length [mm]	−0.142 ± 0.024	−0.146 ± 0.025	0.372	0.843
A2 dArc Length [mm]	−0.024 ± 0.009	−0.025 ± 0.011	0.897	0.165
dArc Length Max [mm]	−0.159 ± 0.027	−0.171 ± 0.034	0.020	0.150
Max Inverse Radius [mm^-1]	0.139 ± 0.018	0.157 ± 0.022	<0.001	0.001
DA Ratio Max (1 mm)	1.57 ± 0.07	1.58 ± 0.06	0.453	0.379
DA Ratio Max (2 mm)	3.91 ± 0.43	4.12 ± 0.43	0.012	0.079
Pachy Slope [μm]	42.95 ± 10.82	38.40 ± 11.56	0.045	0.165
ARTh [μm]	506.7 ± 112.8	527.1 ± 166.4	0.341	0.769
Integrated Radius [mm^-1]	5.84 ± 0.97	6.57 ± 1.15	<0.001	<0.001
SP A1	129.5 ± 19.8	126.0 ± 18.7	0.575	0.069
SSI	1.424 ± 0.199	1.366 ± 0.251	0.227	0.048
CBI	0.223 ± 0.236	0.282 ± 0.278	0.229	0.271

and POAG subgroups. This parameter had the highest value in the NTG subgroup, significantly higher than those in the PACG and PEXG subgroups. The mean WTW was higher in the healthy group than in the glaucoma subgroups. The PACG subgroup showed lower values than the others, significantly different from the NTG subgroup.

Based on Table 5, the mean IOPg and IOPcc were not different between the healthy and different glaucoma subgroups. The mean CRF and CH were significantly higher in the control group than in the glaucoma subgroups, which was also significant in each subgroup with the healthy group, except for the CRF index between the PACG and healthy groups. However, after adjustment for age, Goldmann pressure, central corneal thickness, diabetes mellitus, latanoprost medication, keratometry, and axial length were significantly different. In addition, after adjusting for these variables, there was a significant difference between the NTG subgroup and the healthy group in the CRF parameter and the PEXG, POAG, and NTG groups with the healthy group in the CH parameter. Among the subgroups, the highest and lowest CRF and CH values were in the PACG and PEXG subgroups, respectively, but none was significant.

As shown in Table 6, according to Corvis, the main differences between the glaucoma subgroups and the control group were related to pachy, peak distance, radius, HC Deformation Amp., HC Deflection Amp., HC Deflection Length, HC Deflection Area, Deformation Amp. Max, Deflection Amp. Max, DA Ration Max (2 mm), Max inverse radius, integrated radius, and SSI. After adjustment for age, Goldman's pressure, corneal thickness, diabetes, latanoprost, axial length, and keratometry, only maintained Pachy, Radius, HC Deformation Amp., Max Inverse Radius, and Integrated their significance.

The mean pachy and radius indices were lower in the PEXG, POAG, and NTG subgroups than in the control group; it was much higher in the PACG subgroup than in other subgroups and the control group. Max inverse radius and integrated radius were much higher in the glaucoma subgroups than in the normal group. Nevertheless, the endo-parameter was lower in the PACG subgroup than in the other glaucoma subgroups.

4. Discussion

The utilization of corneal biomechanical features in evaluating glaucoma and its progression has received particular attention. Some changes in corneal biomechanical parameters are specific to the subtypes of the disease. Moreover, the severity of corneal biomechanical changes can play an essential role in response to the medical or surgical treatment of such patients. In the present study, we evaluated the biomechanical features of the cornea, compared them with the normal condition, and then evaluated these features in different subtypes of glaucoma.

We found a significant difference in some biomechanical features of the cornea compared to the healthy condition, so higher CRF and CH were observed in glaucoma patients (regardless of glaucoma subtype). These findings were based on the ORA evaluation. However, in the Corvis evaluation, more minor differences were observed, including increased pachy, radius, and Pachy Slope and decreased HC Deformation Amp., HC Deflection Amp., HC Deflection area, Deflection Amp Max, dArc Length Max, Max Inverse Radius, and Integrated Radius. These changes were in line with CCT, IOP GAT, C/D, and WTW changes, as also identified in previous studies. Tracking the routine parameters and biomechanical changes and their trends can effectively assess the glaucoma severity or response to treatment rate. In a 2020 study by Vinciguerra et al. in the United Kingdom, corneal biomechanics interfered in the measurement of intraocular pressure, and they were the risk factors for the development or progression of NTG glaucoma [9]. In a 2022 meta-analysis of published articles on the biomechanical status of the cornea in glaucoma patients, Catania et al. showed that the cornea in patients with POAG had far lower values of concavity, deformation amplitude, higher concavity radius, and much lower peak distance compared to healthy individuals. These patients also had slower loading phases and lowered maximal concavity times than healthy individuals

Table 4
Baseline characteristics in different disease subgroups.

Characteristics	Healthy (70 eyes)	PEXG (26 eyes) (p value)[a]	PACG (46 eyes) (p value)[a]	POAG (66 eyes) (p value)[a]	NTG (21 eyes) (p value)[a]	P value[b]
Male gender, %	42.9	69.2	41.3	63.6	42.9	–
Mean age, year	51 ± 14	68 ± 9 <0.001	63 ± 8 <0.001	62 ± 10 <0.001	63 ± 10 0.006	<0.001
BCVA	0.9 ± 0.2	0.7 ± 0.2 0.007	0.8 ± 0.2 0.059	0.7 ± 0.2 0.009	0.7 ± 0.2 0.073	<0.001
Axial Length, mm	22.98 ± 0.88	23.21 ± 0.91 1.000	22.47 ± 0.68 0.002	23.40 ± 0.95 0.728	23.79 ± 0.69 0.111	<0.001
ACD, mm	3.17 ± 0.53	2.99 ± 0.35 0.643	2.68 ± 0.42 <0.001	3.43 ± 0.66 0.325	3.29 ± 0.54 1.000	<0.001
CCT, mm	540 ± 35	517 ± 33 0.124	532 ± 25 0.999	522 ± 37 0.599	502 ± 22 <0.001	<0.001
IOP (Goldmann), mmHg	14 ± 3	14 ± 4 0.999	15 ± 4 0.792	16 ± 3 0.057	14 ± 2 1.000	0.053
C/D ratio	0.42 ± 0.19	0.54 ± 0.26 0.279	0.54 ± 0.19 0.095	0.62 ± 0.23 <0.001	0.77 ± 0.16 <0.001	<0.001
WTW, mm	12.0 ± 0.5	11.6 ± 0.4 0.068	11.6 ± 0.3 (0.001)	11.8 ± 0.5 (0.617)	12.1 ± 0.4 1.000	<0.001

[a] Compared to healthy group.
[b] Comparing between groups.

Table 5
Comparing ORA parameters in different disease subgroups.

Characteristics	Healthy (70 eyes)	PEXG (26 eyes) (p value) * (Adjusted p value) *	PACG (46 eyes) (p value) * (Adjusted p value) *	POAG (66 eyes) (p value) * (Adjusted p value) *	NTG (21 eyes) (p value) * (Adjusted p value) *	P value **	Adjusted P value
IOPg, mmHg	17.3 ± 4.2	15.5 ± 4.2 0.897 0.572	17.1 ± 4.8 1.000 0.958	15.7 ± 4.1 0.587 0.082	15.3 ± 3.9 0.559 0.932	0.182	0.077
IOPcc, mmHg	17.2 ± 3.6	18.4 ± 5.3 0.956 1.000	18.4 ± 4.7 0.836 0.951	17.4 ± 4.1 1.000 0.968	17.7 ± 4.0 1.000 1.000	0.588	0.109
CRF, mmHg	11.1 ± 2.3	8.6 ± 2.1 <0.001 0.014	10.1 ± 2.0 0.389 0.028	9.4 ± 2.1 0.002 0.007	8.9 ± 1.9 0.001 0.395	<0.001	0.006
CH, mmHg	10.6 ± 1.9	8.2 ± 2.6 0.001 0.065	9.4 ± 1.8 0.024 0.029	9.0 ± 2.3 0.002 0.241	8.6 ± 1.9 <0.001 0.474	<0.001	0.019

*Compared to healthy group.
** Comparing between groups.

[10]. Also, in the study by Wei et al., in 2021, the NTG group had significantly lower values of deformation amplitude than healthy controls [11].

We successfully differentiated between the disease subtypes based on the corneal biomechanical features. Lower ACD and higher CCT could differentiate between the PACG subtype and other glaucoma subtypes. Lower CCT and higher C/D and WTW indicated the NTG subtype. Based on ORA measurements, the highest CRF and CH were related to PACG and the lowest to PEXG, which can be useful in differentiating between glaucoma subtypes. In contrast, based on Corvis measurements, higher pachy and radius parameters and lower max inverse radius and integrated radius could help distinguish PACG from other subtypes. At the same time, the PEXG subtype had the highest values of the last two parameters.

As the corneal biomechanical features affect intraocular pressure measurement more than corneal thickness, Corneal biomechanics can be indicators of whole eye biomechanics, and evaluation of the corneal Biomechanical parameters is essential for assessing the glaucoma condition and the effects Of IOP on the optic nerve.

These results lead us to two important conclusions. First, tracking corneal biomechanical changes along with routine indicators can be very helpful in distinguishing between different subtypes of glaucoma. Second, although ORA and Corvis do not lead to similar results, both can help better differentiate between glaucoma subtypes.

Our study however had some innate limitations. First, the nature of the study was retrospective, thus there was a possibility that some patient information may be missed. Second, the numbers of patients included in subgroups were not the same. In final, the small sample size of the study made it possible to reduce the study power, and therefore further studies with a larger sample size are needed in the future.

5. Conclusion

Evaluation of corneal biomechanical parameters and other indicators can be instrumental in assessing the status and severity of glaucoma and distinguishing disease subtypes.

Further studies about the utilization of corneal biomechanical features and LC characters and the relations between them are needed. as the quality of LC cannot be evaluated directly, the assessment of corneal biomechanics made it possible to distinguish the LC features and pathogenesis of this disease and exact mechanism.

Provenance and peer review

Not commissioned, externally peer-reviewed.

Ethical approval

This research was carried out in compliance with the Helsinki Declaration and was approved by the ethical committee at Tehran

Table 6
Comparing Corvis parameters in different disease subgroups.

	Healthy (70 eyes)	PEXG (26 eyes) (p value) * (Adjusted p value) *	PACG (46 eyes) (p value) * (Adjusted p value) *	POAG (66 eyes) (p value) * (Adjusted p value) *	NTG (21 eyes) (p value) * (Adjusted p value) *	P value **	Adjusted P value
IOP [mmHg]	19.3 ± 2.9	17.6 ± 3.6 (0.906) (0.618)	18.6 ± 3.8 (1.000) (0.201)	17.8 ± 3.4 (0.703) (0.127)	16.9 ± 2.1 (0.073) (0.634)	0.072	0.143
bIOP [mmHg]	18.4 ± 3.3	17.0 ± 3.3 (0.880) (0.821)	17.4 ± 3.5 (0.951) (0.257)	17.5 ± 3.1 (0.842) (0.413)	16.8 ± 1.9 (0.202) (0.846)	0.249	0.257
Pachy [μm]	527 ± 37	508 ± 38 (0.304) (0.367)	532 ± 31 (0.999) (1.000)	507 ± 34 (0.230) (0.014)	500 ± 28 (0.065) (0.650)	0.001	0.001
Deformation Amp. Max [mm]	0.95 ± 0.10	1.01 ± 0.11 (0.557) (0.510)	0.98 ± 0.09 (0.999) (0.229)	1.02 ± 0.11 (0.069) (0.035)	1.03 ± 0.10 (0.176) (0.883)	0.022	0.064
A1 Time [ms]	7.63 ± 0.58	7.40 ± 0.55 (0.893) (0.579)	7.56 ± 0.57 (1.000) (0.160)	7.43 ± 0.51 (0.686) (0.099)	7.29 ± 0.33 (0.071) (0.595)	0.072	0.117
A1 Velocity [m/s]	0.12 ± 0.02	0.13 ± 0.02 (0.213) (0.089)	0.12 ± 0.02 (0.996) (0.160)	0.12 ± 0.02 (0.882) (0.143)	0.12 ± 0.02 (1.000) (0.980)	0.220	0.060
A1 Deformation Amp. [mm]	0.13 ± 0.01	0.13 ± 0.01 (1.000) (1.000)	0.13 ± 0.01 (1.000) (0.331)	0.13 ± 0.01 (0.997) (0.997)	0.13 ± 0.01 (0.863) (1.000)	0.515	0.148
A1 Deflection Amp. [mm]	0.09 ± 0.01	0.09 ± 0.01 (1.000) (0.646)	0.09 ± 0.01 (1.000) (0.600)	0.09 ± 0.01 (0.967) (0.407)	0.09 ± 0.01 (1.000) (0.985)	0.582	0.311
A1 Deflection Length [mm]	2.30 ± 0.18	2.22 ± 0.19 (0.547) (0.394)	2.31 ± 0.21 (1.000) (0.823)	2.25 ± 0.16 (0.794) (0.795)	2.27 ± 0.20 (1.000) (1.000)	0.303	0.342
A1 Deflection Area [mm²]	0.18 ± 0.03	0.17 ± 0.03 (0.225) (0.495)	0.18 ± 0.03 (1.000) (0.434)	0.18 ± 0.03 (0.924) (0.991)	0.18 ± 0.03 (1.000) (1.000)	0.217	0.073
A1 dArc Length [mm]	−0.017 ± 0.005	−0.017 ± 0.003 (1.000) (0.967)	−0.019 ± 0.004 (0.807) (0.995)	−0.018 ± 0.003 (0.997) (1.000)	−0.018 ± 0.004 (1.000) (1.000)	0.652	0.553
A2 Time [ms]	20.96 ± 0.39	20.98 ± 0.61 (1.000) (0.995)	20.96 ± 0.54 (1.000) (0.196)	21.03 ± 0.35 (0.998) (0.182)	21.10 ± 0.31 (0.868) (0.611)	0.683	0.167
A2 Velocity [m/s]	−0.24 ± 0.04	−0.25 ± 0.05 (1.000) (1.000)	−0.24 ± 0.05 (1.000) (0.826)	−0.25 ± 0.04 (0.831) (0.543)	−0.26 ± 0.05 (0.905) (1.000)	0.517	0.381
A2 Deformation Amp. [mm]	0.40 ± 0.08	0.39 ± 0.09 (1.000) (0.973)	0.43 ± 0.09 (0.768) (0.591)	0.40 ± 0.07 (1.000) (0.497)	0.39 ± 0.07 (1.000) (0.916)	0.376	0.379
A2 Deflection Amp. [mm]	0.11 ± 0.02	0.11 ± 0.02 (0.986) (0.899)	0.11 ± 0.02 (1.000) (0.994)	0.11 ± 0.02 (0.884) (0.978)	0.11 ± 0.02 (1.000) (1.000)	0.568	0.342
A2 Deflection Length [mm]	2.90 ± 0.57	2.88 ± 0.89 (1.000) (1.000)	2.96 ± 0.77 (1.000) (1.000)	2.99 ± 0.64 (0.991) (0.964)	2.96 ± 0.72 (1.000) (0.997)	0.912	0.695
A2 Deflection Area [mm²]	0.256 ± 0.055	0.240 ± 0.067 (0.897) (0.777)	0.258 ± 0.065 (1.000) (0.993)	0.244 ± 0.063 (0.989) (0.899)	0.263 ± 0.047 (1.000) (1.000)	0.489	0.388
A2 dArc Length [mm]	−0.024 ± 0.009	−0.026 ± 0.019 (1.000) (1.000)	−0.025 ± 0.010 (1.000) (0.995)	−0.024 ± 0.008 (1.000) (0.451)	−0.024 ± 0.008 (1.000) (0.851)	0.921	0.462
Peak Dist. [mm]	4.80 ± 0.30	4.93 ± 0.29 (0.981) (1.000)	4.81 ± 0.28 (1.000) (0.684)	4.96 ± 0.30 (0.381) (0.338)	5.06 ± 0.20 (0.012) (0.904)	0.002	0.185
Radius [mm]	9.74 ± 1.85	8.64 ± 1.52 (0.163) (0.035)	9.61 ± 1.58 (1.000) (0.887)	8.86 ± 1.31 (0.107) (0.016)	8.95 ± 1.47 (0.828) (0.901)	0.020	0.010
HC Time [ms]	16.21 ± 0.46	16.12 ± 0.57 (1.000) (1.000)	16.28 ± 0.42 (0.998) (0.829)	16.13 ± 0.47 (0.980) (1.000)	16.03 ± 0.46 (0.925) (1.000)	0.363	0.695
HC Deformation Amp. [mm]	0.95 ± 0.10	1.03 ± 0.13 (0.287) (0.218)	0.98 ± 0.09 (0.999) (0.182)	1.02 ± 0.11 (0.070) (0.014)	1.03 ± 0.10 (0.178) (0.724)	0.014	0.033
HC Deflection Amp. [mm]	0.80 ± 0.11	0.89 ± 0.12 (0.189) (0.812)	0.82 ± 0.10 (1.000) (0.678)	0.87 ± 0.12 (0.087) (0.365)	0.91 ± 0.10 (0.009) (0.792)	0.001	0.382
HC Deflection Length [mm]	6.11 ± 0.45	6.23 ± 0.40 (0.991) (1.000)	6.15 ± 0.45 (1.000) (0.988)	6.32 ± 0.49 (0.418) (0.748)	6.54 ± 0.36 (0.001) (0.412)	0.001	0.074
HC Deflection Area [mm²]	2.80 ± 0.53	3.18 ± 0.56 (0.269) (0.919)	2.91 ± 0.52 (1.000) (0.464)	3.11 ± 0.56 (0.213) (0.546)	3.33 ± 0.45 (0.005) (0.552)	0.003	0.334
HC dArc Length [mm]	−0.142 ± 0.024	−0.141 ± 0.022 (1.000) (0.819)	−0.149 ± 0.026 (0.911) (0.984)	−0.144 ± 0.023 (1.000) (1.000)	−0.150 ± 0.031 (0.998) (1.000)	0.644	0.102
Whole Eye Movement Max [mm]	0.31 ± 0.08	0.30 ± 0.09 (1.000) (0.896)	0.33 ± 0.09 (0.977) (0.846)	0.30 ± 0.08 (1.000) (0.754)	0.29 ± 0.07 (1.000) (0.987)	0.766	0.585
Whole Eye Movement Max [ms]	21.86 ± 1.05	21.83 ± 0.89 (1.000) (0.998)	21.95 ± 0.73 (1.000) (0.999)	21.67 ± 1.09 (0.955) (0.971)	22.27 ± 0.66 (0.498) (0.681)	0.065	0.029
Deflection Amp. Max [mm]	0.81 ± 0.11	0.91 ± 0.12 (0.111) (0.678)	0.84 ± 0.10 (0.999) (0.392)	0.90 ± 0.11 (0.016) (0.070)	0.92 ± 0.1 (0.010) (0.852)	<0.001	0.110
Deflection Amp. Max [ms]	15.64 ± 0.43	15.50 ± 0.70 (0.972) (0.996)	15.52 ± 0.53 (0.842) (1.000)	15.58 ± 0.55 (0.999) (1.000)	15.71 ± 0.50 (1.000) (1.000)	0.508	0.746
dArc Length Max [mm]	−0.159 ± 0.027	−0.167 ± 0.025 (0.924) (1.000)	−0.170 ± 0.031 (0.644) (0.667)	−0.172 ± 0.038 (0.469) (0.895)	−0.174 ± 0.037 (0.816) (0.995)	0.234	0.463
DA Ratio Max (1 mm)	1.57 ± 0.07	1.59 ± 0.05 (0.800) (0.990)	1.56 ± 0.07 (1.000) (0.995)	1.58 ± 0.06 (0.973) (0.939)	1.58 ± 0.07 (1.000) (1.000)	0.307	0.650
DA Ratio Max (2 mm)	3.91 ± 0.43	4.22 ± 0.44 (0.131) (0.728)	3.98 ± 0.40 (1.000) (0.814)	4.14 ± 0.43 (0.163) (0.530)	4.25 ± 0.48 (0.272) (0.991)	0.017	0.478

Table 6 (*continued*)

	Healthy (70 eyes)	PEXG (26 eyes) (p value) * (Adjusted p value) *	PACG (46 eyes) (p value) * (Adjusted p value) *	POAG (66 eyes) (p value) * (Adjusted p value) *	NTG (21 eyes) (p value) * (Adjusted p value) *	P value **	Adjusted P value
ARTh [μm]	506.7 ± 112.8	501.2 ± 182.1 (1.000) (0.996)	531.9 ± 159.3 (0.994) (1.000)	545.7 ± 164.3 (0.788) (0.998)	484.8 ± 172.1 (1.000) (0.980)	0.517	0.609
Pachy Slope [μm]	42.95 ± 10.82	39.30 ± 15.56 (0.999) (0.678)	39.61 ± 11.47 (0.972) (0.996)	36.78 ± 9.25 (0.049) (0.983)	39.95 ± 13.30 (1.000) (0.362)	0.087	0.233
Max Inverse Radius [mm^-1]	0.139 ± 0.018	0.168 ± 0.026 (<0.001) (<0.001)	0.149 ± 0.018 (0.087) (0.398)	0.158 ± 0.022 (<0.001) (0.003)	0.158 ± 0.018 (0.003) (0.028)	<0.001	<0.001
Integrated Radius [mm^-1]	5.84 ± 0.97	6.98 ± 1.22 (0.003) (<0.001)	6.22 ± 1.13 (0.779) (0.040)	6.60 ± 1.06 (0.010) (0.001)	6.75 ± 1.19 (0.159) (0.104)	<0.001	<0.001
SP A1	129.5 ± 19.8	124.8 ± 16.8 (0.998) (0.652)	130.8 ± 15.8 (0.999) (0.889)	125.0 ± 20.9 (1.000) (0.215)	120.0 ± 17.6 (0.750) (0.998)	0.291	0.216
SSI	1.424 ± 0.199	1.324 ± 0.253 (0.910) (0.392)	1.465 ± 0.253 (0.968) (0.920)	1.312 ± 0.215 (0.137) (0.167)	1.366 ± 0.301 (1.000) (0.997)	0.026	0.170
CBI	0.223 ± 0.236	0.326 ± 0.278 (0.675) (0.811)	0.195 ± 0.227 (1.000) (1.000)	0.287 ± 0.278 (0.974) (0.691)	0.411 ± 0.338 (0.641) (0.963)	0.106	0.365

*Compared to healthy group.
** Comparing between groups.

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Author contributions

1-R.Z.: editing the final manuscript
2- M.H.Z.: collecting data, writing, corresponding
3- Y.E.: collecting data
4- GH.F.: collecting data
5- M.T.: collecting data and editing
6- A.R.E: data analysis

Registration of Research Studies

Name of the registry:
Iran National Committee for Ethics in Biomedical Research
Unique Identifying number or registration ID: **IR.TUMS.FARABIH.REC.1400.005**
Hyperlink to your specific registration (must be publicly accessible and will be checked): IR.TUMS.FARABIH.REC.1400.005).

Guarantor

Mohammad Hossein Zamani.

Consent

All the patients signed the informed consent form. A copy of the written consent is available for review by the Editor-in-Chief of this journal on request

Declaration of competing interest

Nothing to declare.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.amsu.2022.104677.

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