

Comparison of Pneumatometry and Transpalpebral Tonometry Measurements of Intraocular Pressure during Scleral Lens Wear

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SIGNIFICANCE: As scleral lens wear becomes more common, understanding the impact of these lenses upon ocular physiology is critically important. Studies on the effect of scleral lens wear upon intraocular pressure (IOP) have used different instruments and have reported conflicting results.

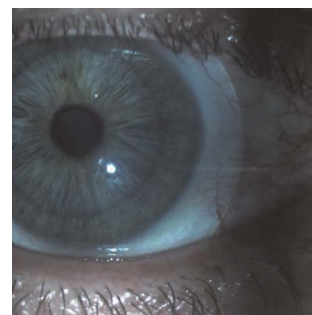
PURPOSE: The purpose of this study was to compare assessment of IOP during scleral lens wear using pneumatometry and transpalpebral tonometry.

METHODS: Twenty healthy subjects wore a small-diameter (15.2 mm) and a large-diameter (18.0 mm) scleral lens on the right eye, each for 1 hour in randomized order. IOP was assessed with pneumatometry and transpalpebral tonometry on both eyes before lens application, immediately after lens application, after 1 hour of lens wear, and immediately after lens removal. Paired *t* test compared mean IOP in the study eye to the control eye. Repeated-measures ANOVA was performed to take instrumentation, lens diameter, and their interaction into account in an analysis of the change in IOP in the study eye.

RESULTS: Mean peripheral IOP measured with pneumatometry was not significantly different from baseline at any subsequent measurement. Measurements with transpalpebral tonometry, however, were significantly different during scleral lens wear immediately after application and after 1 hour of wear with both diameter lenses ($P < .005$), but were not significantly different after either sized lens was removed. Repeated-measures ANOVA revealed that the instrument used to measure IOP was a significant factor in IOP changes found during lens wear ($P \leq .001$).

CONCLUSIONS: Assessment of IOP during scleral lens wear varies based upon the instrument that is used. Although further studies are clearly needed to further elucidate this issue, clinicians should continue to monitor optic nerve structure and function in scleral lens wearers, as they do in all patients.

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Potential effects of scleral lenses on ocular physiology, including aqueous humor dynamics, are not well understood. The possibility that scleral lenses might cause elevation of intraocular pressure (IOP) was first suggested by Huggert^{1,2} in the 1950s and later by Miller and Carroll³ and Miller et al.⁴ in the 1960s. In Miller and colleagues⁴ article, the force needed to remove a scleral lens from the ocular surface was referred to as “cling.” It was suggested that this force could create induced pressure upon the eye, thus altering IOP. Increased IOP during scleral lens wear was suggested as a possible cause of corneal epithelial edema because edema was reported to have a more rapid onset in glaucoma patients who wore scleral lenses.³ More recently, McMonnies and Boneham⁵ reported that an increase in IOP occurs as a result of digital force applied to the temporal sclera and suggested that scleral lens tightness could cause such an indentation, therefore altering IOP.⁶

Assessment of IOP during scleral lens wear is complicated by the fact that the lens completely covers the cornea, making it impossible to use any traditional method of IOP measurement that requires access to that tissue, including Goldmann tonometry. Measuring IOP immediately before lens placement and then again

immediately after lens removal provides some idea of the effects of scleral lens wear on aqueous dynamics. Studies have been conducted comparing IOP before and after scleral lens wear with mixed results.^{7,8} However, pre-lens and post-lens measurement of IOP cannot definitively answer the fundamental question of what happens to IOP during lens wear. In addition to recognizing the possibility that IOP could normalize very shortly after lens removal, the process of applying or removing a lens from the ocular surface has been shown to cause a transient shift in IOP.⁹ A recent study evaluated IOP after application and after removal of a scleral lens with a central fenestration, which allowed for use of a rebound tonometer.¹⁰ However, this instrument cannot be used with a typical non-fenestrated lens. Fortunately, there are several instruments that allow for IOP assessment through conjunctival and scleral tissue. Pneumatometry uses a probe with a small membrane tip that is propelled by a force of air to measure IOP either on the cornea or the conjunctiva.¹¹ Use of pneumatometry has been described for a number of eye conditions in which the IOP cannot be reliably measured on the central cornea.^{11–13} Although peripheral IOP as measured by the pneumatometer has been found to be higher than central IOP

measured with the instrument, it has been correlated to central IOP and thus has been suggested as a reasonable alternative to central IOP measurements.¹⁴ Transpalpebral tonometry measures the elastic resistance of the eye to the ballistic tonometer through the upper eyelid and sclera. During measurement, the instrument must be held vertically because it relies upon gravity to depress the internal weight. The patient must therefore be positioned with his/her head tilted back at approximately a 45° angle while eyes move into downgaze to maintain fixation on a target straight in front of the patient. The upper lid is retracted by the operator, and measurement is made behind the lash line through the eyelid and superior sclera.¹⁵

Several studies have reported conflicting results on the effects of short periods of scleral lens wear on IOP in young healthy patients. In a group of 29 healthy subjects, Nau et al.¹⁶ found no significant change in mean IOP as measured by pneumatonometry with 2 hours of 15.0 mm lens wear. Michaud et al.¹⁷ measured IOP using transpalpebral tonometry in 21 subjects wearing both 15.0- and 18.0-mm-diameter scleral lenses for an average of 4.5 hours and found that mean IOP increased significantly during lens wear. The conflicting results reported in studies using different methods and measurement instruments have made it impossible to draw definitive conclusions regarding the effects of scleral lens wear on IOP. Rather, these results require that we examine the differences between the instruments used to measure IOP during lens wear. Given that the results of such studies will influence practice patterns, particularly for patients who need scleral lenses but either have glaucoma or are at risk of the disease, determination of the most appropriate method for obtaining these data is needed.

The purpose of this study was to compare IOP during scleral lens wear as measured by peripheral pneumatonometry and transpalpebral tonometry, with two different lens diameters, over the course of 1 hour of scleral lens wear in healthy subjects.

METHODS

This study used a prospective, repeated measures, crossover design. It was reviewed and approved by the Illinois College of Optometry Institutional Review Board. Twenty healthy participants 18 years or older with no prior scleral lens use were recruited. Each participant had a screening examination to identify any significant ocular surface disease (i.e., corneal abrasion, corneal staining greater than grade 1) or ocular hypertension (by history of increased IOP or measured Goldmann IOP of >20 mmHg), which would exclude them from the study. Participants who wore contact lenses were instructed to not wear their lenses to the study visit, to ensure the minimum washout required after soft lens wear was achieved before the beginning of the study.¹⁸

During the screening evaluation, the right eye of each participant was fit with both a small 15.2-mm-diameter (Onefit 2.0; Blanchard Contact Lens Inc., Manchester, NH; “small lens”) and a large 18.0-mm-diameter (BostonSight Scleral; BostonSight, Needham, MA; “large lens”) scleral lens, according to the manufacturer’s recommended fitting guides. Standard diagnostic lenses from diagnostic fitting sets were used for the study visit, and potential subjects needed to demonstrate adequate central clearance (250 to 400 μm), limbal clearance (50 to 100 μm), and haptic alignment without significant blanching or compression with a diagnostic lens to participate in the study. No lenses were placed on the left eye because that eye would serve as the control during the study. A single investigator (JSH) assessed all lenses to verify that

adequate centration, reasonable haptic alignment, and complete corneal clearance were achieved.

Participants were randomized as to whether the small- or large-diameter lens would be worn first during the study visit, with half wearing the smaller-diameter lens first. Investigators applied and removed all lenses to ensure that minimal pressure was placed on the globe during lens application and removal. All lenses were filled with nonpreserved saline (LacriPure; Menicon, Nagoya, Japan) for application. Participants were asked to avoid prolonged eye closure during lens wear but were otherwise allowed to carry out normal activities.

IOP measurements were obtained using pneumatonometry (Model 30 Classic Pneumatometer, Reichert; Ophthalmic Instruments, Depew, NY) and transpalpebral tonometry (Diaton; BiCom, Inc., Long Beach, NY). Three measurements, for each time point, were acquired with both instruments on each eye and were averaged for analysis. One investigator (CBN) acquired all pneumatonometry measurements, and another investigator (JSH) acquired all transpalpebral tonometry measurements.

One drop of proparacaine was instilled in each eye before central IOP measurement. Central and peripheral pneumatonometer measurements were obtained with the patient facing forward with an erect head position. The subjects were then asked to tilt their heads back at approximately a 45° angle to approximate the head posture required for transpalpebral measurements, and pneumatonometry was repeated. IOP was then measured using transpalpebral tonometry, with head tilt described previously.

The first scleral lens was placed on the right eye, and measurements were repeated, with the exception of the central IOP with pneumatonometry on the study eye (as the cornea was covered by the scleral lens). The lens was worn for 1 hour, and these IOP measurements were repeated. The study lens was then removed, and all measurements, now including central pneumatonometry, were immediately repeated on the study eye only. The second study lens was placed on the right eye, and the measurement sequence was repeated. An illustration of the study design is in Fig. 1.

Comparisons of mean IOP of the study eye and the control eye were conducted utilizing paired *t* tests, as established in previous IOP studies.^{16,19–21} To evaluate the effect of scleral lens diameter and the instrument used as well as interactions between these factors on the change in IOP, two-factor repeated-measures ANOVA was used for each time point. Single *t* tests were used to determine if the changes in IOP from baseline were significant for all combinations of lens diameter and instrument. In addition, paired *t* tests were used to compare the mean change in IOP in the study eyes and control eyes.

The repeatability of each instrument was assessed using the three measurements taken at each time point.²² Peripheral pneumatonometry was compared with transpalpebral tonometry by Bland-Altman analysis.²³

RESULTS

Twenty subjects participated in this study. Average ± standard deviation age was 29 ± 9 years (range, 20 to 57 years), with 5 males and 15 females. Sixteen subjects were habitual soft lens wearers, and none were current corneal gas permeable lens wearers.

Study Eye Compared with Control Eye

Analysis of Mean IOP (Study Eye versus Control Eye)

Mean IOP measured by central pneumatonometry with head erect was significantly higher in the study eye than the control

eye at baseline (21.6 ± 3 vs. 20.6 ± 2 mmHg, $P = .02$). Central pneumatonometry was performed in the control eye 1 hour after the lens was applied to the study eye; central pneumatonometry was performed in the study eye immediately after lens removal. In comparing these measurements, there was no statistical difference in mean IOP between control and study eyes after small lens removal (20.5 ± 2 vs. 20.0 ± 2 mmHg, $P = .4$) or after large lens removal (21.1 ± 2 vs. 20.3 ± 2 mmHg, $P = .09$).

Comparison of Peripheral and Corneal IOP with Pneumatometry (Study Eye versus Control Eye)

Peripheral IOP was consistently higher than central IOP for all measurements with the pneumatometer ($P < .001$). Table 1 summarizes mean IOP in the study eye and control eye as measured by pneumatometry in both head positions for each lens at each time point.

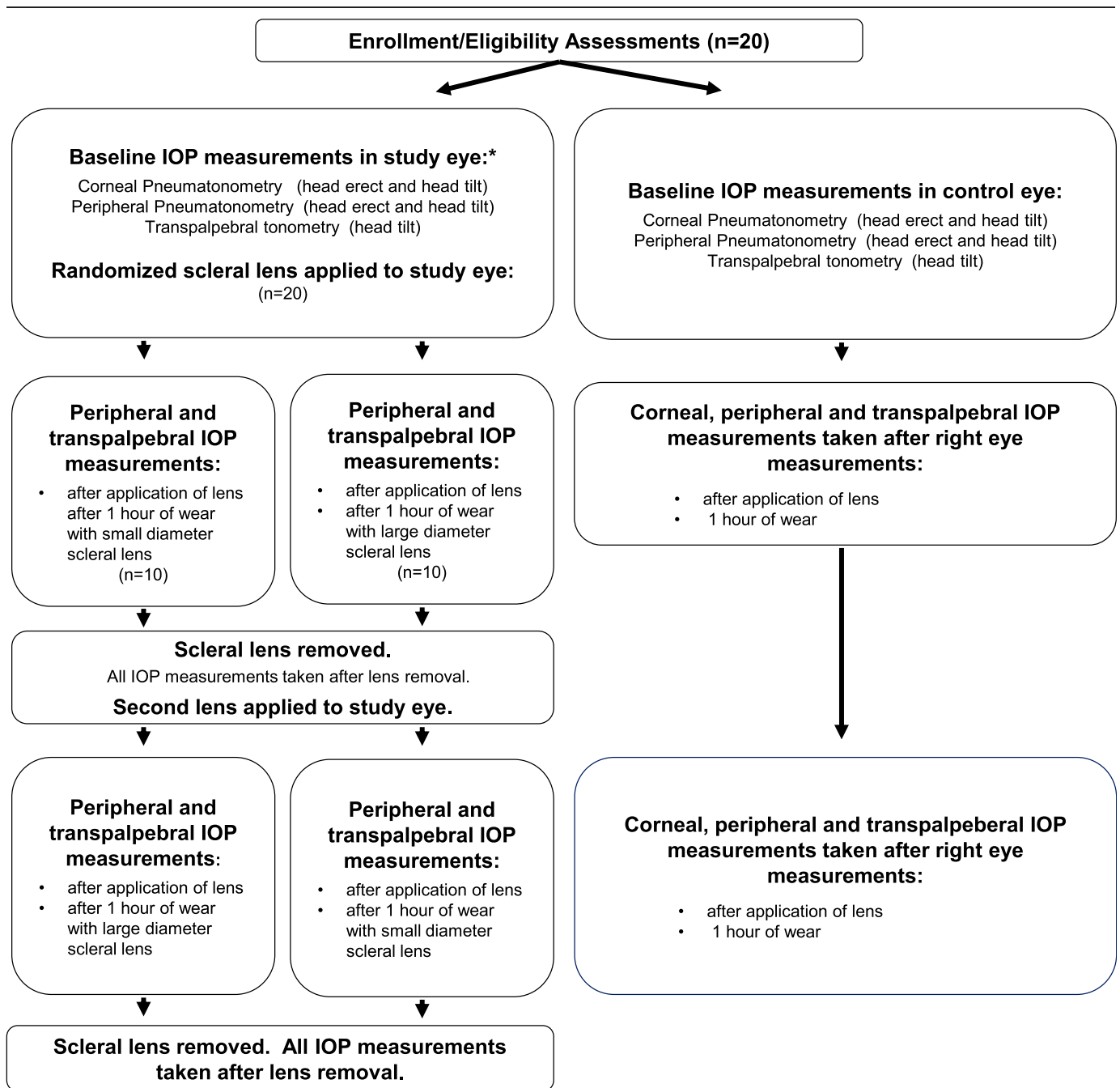


FIGURE 1. Study design for assessing IOP with scleral lens wear using two different diameter lenses and two different instruments. *The study eye was the right eye. IOP measurements were also taken in the left eye to be used as a control eye. Corneal IOP measurements were also taken of the control eye after lens application and 1 hour of wear in the study eye.

TABLE 1. Mean ± standard deviation IOP for each measurement

	Study eye					Control eye				
	Pneumatometry				Transpalpebral tonometry	Pneumatometry				Transpalpebral tonometry
	Central	Peripheral	Central	Peripheral		Central	Peripheral	Central	Peripheral	
	Head erect		Head tilt		Head tilt	Head erect		Head tilt		Head tilt
Baseline	21.6 ± 2.9	27.0 ± 5.4	20.0 ± 2.4	25.4 ± 3.4	7.9 ± 2.4	20.6 ± 2.4	27.5 ± 5.4	19.8 ± 2.4	26.7 ± 5.1	7.5 ± 1.9
15.2-mm lens applied	—	26.6 ± 5.1	—	25.4 ± 4.0	12.3 ± 5.2*	20.3 ± 2.4	25.9 ± 3.2	19.4 ± 2.4	25.7 ± 4.0	7.9 ± 2.5
15.2-mm lens worn 1 h	—	28.7 ± 5.6	—	26.3 ± 3.8	12.3 ± 5.4*	20.0 ± 2.4	25.5 ± 3.9	19.1 ± 2.2	24.9 ± 3.3	7.7 ± 2.9
15.2-mm lens removed	—	25.1 ± 3.1	—	24.4 ± 3.7	8.6 ± 3.6	—	—	—	—	—
18.0-mm lens applied	—	26.5 ± 4.5	—	25.3 ± 4.0	12.9 ± 4.9*	20.2 ± 1.6	25.2 ± 3.5	19.0 ± 2.0	25.0 ± 4.0	7.4 ± 2.7
18.0-mm lens worn 1 h	—	27.5 ± 7.2	—	26.3 ± 3.6	13.4 ± 4.7*	20.3 ± 2.4	26.3 ± 3.7	19.4 ± 1.7	24.5 ± 3.8	7.9 ± 2.3
18.0-mm lens removed	—	27.8 ± 5.4	—	25.2 ± 3.6	9.0 ± 3.3	—	—	—	—	—

Peripheral IOP measurements are higher than central IOP measurements for both head postures (erect and tilted). Transpalpebral tonometry-measured IOP is lower than all pneumatometry measurements.

Comparison of Tonometers (Study Eye versus Control Eye)

Using peripheral pneumatometry, comparison of average IOP, in head erect position, between the study eye and control eye revealed no significant differences before lens application (27.0 ± 5 vs. 27.5 ± 5 mmHg, $P = .6$), after application of the small lens (26.6 ± 5 vs. 25.9 ± 3 mmHg, $P = .5$) or after small lens removal (25.1 ± 3 vs. 25.5 ± 4 mmHg, $P = .6$), but IOP in the study eye was statistically higher after 1 hour of small lens wear (28.7 ± 6 vs. 25.5 ± 4 mmHg, $P = .02$). There was not a statistically significant difference in average peripheral IOP with pneumatometry between study and control eyes with the large-diameter lens after application (26.5 ± 5 vs. 25.2 ± 4 mmHg, $P = .3$), after 1 hour of lens wear (27.5 ± 7 vs. 26.3 ± 4 mmHg, $P = .5$), or after removal (27.8 ± 5 vs. 26.3 ± 4 mmHg, $P = .2$).

Average IOP measured by transpalpebral tonometry revealed no statistically significant difference between the study eye and control eye before lens application (7.9 ± 2 vs. 7.5 ± 2 mmHg, $P = .1$) or after small lens removal (8.6 ± 4 vs. 7.7 ± 3 mmHg, $P = .1$), but was statistically significant after large lens removal (9.0 ± 3 vs. 7.9 ± 2 mmHg, $P = .04$). There was a significant difference during both small lens wear (after application of small lens, 12.3 ± 5 vs. 7.9 ± 3 mmHg, $P < .001$; after 1 hour of wear, 12.3 ± 5 vs. 7.7 ± 3 mmHg, $P < .001$) and large lens wear (after application, 12.9 ± 5 vs. 7.4 ± 3 mmHg, $P < .001$; after 1 hour of wear 13.4 ± 5 vs. 7.9 mmHg, $P < .001$).

Analysis of Change in Mean IOP (Study Eye)

Because of minimal difference between peripheral pneumatometry values with head erect versus head tilted, further analyses used

data gathered in head erect position only; this position is most commonly used for pneumatometry. Average IOP eye measured by peripheral pneumatometry was significantly different than IOP measured by transpalpebral tonometry for all time points ($P < .001$). Therefore, mean change in IOP enabled better comparison between the instruments. Measurements made after lens application, with 1 hour of wear, and after lens removal are compared with baseline in the study eye (Table 2).

A two-factor repeated-measures ANOVA was performed to examine the effect of the instrument used and lens diameter on the mean change in mean IOP measurements when comparing baseline to each time point in the study eye. An interaction term with the diameter and instrumentation was included in the assessment. In assessing the mean change in IOP between baseline and immediately after lens application, the only factor showing a significant influence on the change in IOP was the instrument used ($F_2 = 22.2$, $n = 2$, $P < .001$), whereas lens diameter ($F_1 = 0.5$, $n = 2$, $P = .8$) and the interaction of the diameter and instrument ($F_1 = .1$, $P = .7$) were not significant. The instrument used was also a significant factor in the mean change in IOP found after 1 hour of wear in the study eye ($F_1 = 12.2$, $n = 2$, $P = .001$), whereas lens diameter ($F_1 < 0.01$, $n = 2$, $P > .96$) and the diameter and instrument interaction ($F_1 = 1.1$, $P = .4$) were not significant. The change in IOP post-lens removal was not significantly affected by instrument ($F_1 = 3.4$, $n = 2$, $P = .07$), lens diameter ($F_1 = 4.07$, $n = 2$, $P = .05$), or the interaction of instrument with lens diameter ($F_1 = 2.3$, $P = .3$).

To further explore the differences in instrumentation found with ANOVA, single t tests were completed. In comparison with baseline, no significant differences in the change in mean IOP as measured

TABLE 2. Mean change in IOP (mmHg) from baseline, with percent change from baseline

Scleral lens worn	Time point	Peripheral pneumatonometry (head erect)		Peripheral pneumatonometry (with head tilt)		Transpalpebral tonometry	
		IOP change from baseline (mmHg)	Percent change from baseline	IOP change from baseline (mmHg)	Percent change from baseline	IOP change from baseline (mmHg)	Percent change from baseline
15.2-mm-diameter scleral lens	Study eye post-lens insertion	-0.4 ± 3.5	-0.7%	0.0 ± 3.4	0.5%	4.4* ± 5.2	65.4%
	Control eye post-lens insertion	-1.6 ± 3.6	-4.0%	-1.0 ± 4.3	-2.7%	0.5 ± 1.8	1.9%
	Study eye after 1 h of wear	1.7 ± 3.6	7.3%	0.9 ± 3.9	4.2%	4.4* ± 5.1	64.8%
	Control eye after 1 h	-2.0 ± 3.6	-6.0%	-1.8 ± 4.1	-5.3%	0.3 ± 2.1	1.4%
18.0-mm-diameter scleral lens	Study eye post-lens insertion	-2.0 ± 4.4	-5.3%	-1.0 ± 2.1	-3.9%	0.7 ± 3.1	12.4%
	Study eye after 1 h of wear	0.5 ± 6.9	3.6%	0.9 ± 3.7	4.4%	5.5* ± 4.0	75.3%
	Control eye after 1 h	-1.2 ± 4.4	-2.2%	-2.2 ± 4.5	-7.1%	0.5 ± 2.0	1.8%
	Study eye post-lens removal	0.8 ± 4.0	4.0%	-0.2 ± 3.1	-0.2%	1.1 ± 2.6	16.3%
	Control eye post-lens insertion	-2.3 ± 3.5	-6.7%	-1.7 ± 3.7	-5.4%	-0.1 ± 2.1	-0.3%

The largest mean change in IOP using peripheral pneumatonometry during lens wear is after 1 hour of small-diameter lens wear with IOP increasing 1.7 mmHg (7.3%). Overall, minimal changes in pneumatonometry are measured. The largest mean change in IOP during lens wear with transpalpebral tonometry is with 1 hour of large lens wear, with an increase of 5.5 mmHg (75.3%). None of the measurements with the pneumatonometer, during or after lens wear, are significantly different from baseline. All measurements with lens wear are significantly different from baseline with transpalpebral tonometry but return to near baseline after lens removal. *Denotes a statistically significant increase from baseline.

by peripheral pneumatonometry were found for lenses of either diameter (15.2 mm: after lens application [-0.4 mmHg], $P = .6$; after 1 hour of lens wear [1.7 mmHg], $P = .05$; after lens removal [-2.0 mmHg], $P = .06$; 18.0 mm: after lens application [-0.8 mmHg], $P = .7$; after 1 hour of wear [0.5 mmHg], $P = .8$; after lens removal [0.9 mmHg], $P = .4$). In contrast, significant differences in the change in IOP with lens wear were found with both lenses by transpalpebral tonometry (15.2 mm: after lens application [4.4 mmHg], $P = .001$; after 1 hour of wear [4.4 mmHg], $P = .001$; 18.0 mm: after lens application [5.0 mmHg], $P < .001$; after 1 hour of lens wear [5.5 mmHg], $P < .001$). When the scleral lens was removed from the eye, IOP as measured by transpalpebral tonometry returned nearly to baseline (15.2 mm: after lens removal [0.7 mmHg], $P = .3$; 18.0 mm: after lens removal [1.1 mmHg], $P = .08$). Table 2 summarizes the mean changes in IOP for the study eye and the control eye as measured by both peripheral pneumatonometry and transpalpebral tonometry (Fig. 2).

In summary, there were no changes in IOP that were statistically different from zero with any of the peripheral pneumatonometry findings. Changes in IOP found with the transpalpebral tonometer from baseline to after lens application and after 1 hour of lens wear were significantly different from zero for both lens diameters. These data confirmed the earlier paired t test findings comparing the control eye and the study eye.

This was validated further by comparing changes in the study eye to those in the control eye. All comparisons wearing either diameter scleral lens were statistically significant ($P < .0001$) when

measured by transpalpebral tonometry. Comparisons when changes were measured with peripheral pneumatonometry were not statistically significant except for one case. This single difference occurred with the small-diameter lens at 1 hour of wear and was the result of a reduction in the mean IOP in the control eye.

Repeatability and Comparison of Instruments

Assessment of the repeatability of the instruments used in the study was completed using the method described by Bland and Altman.²² The repeatability values are shown in Table 3.

A direct comparison of peripheral pneumatonometry and transpalpebral tonometry using the three measurements taken with each instrument at baseline can be viewed in Bland-Altman plots (Fig. 3).

DISCUSSION

In this study, IOP during scleral lens wear measured with peripheral pneumatonometry did not significantly differ from baseline. However, IOP measured by transpalpebral tonometry rose significantly in the study eye while a scleral lens was being worn but returned nearly to baseline immediately upon lens removal. Statistical analysis of factors that could potentially account for these differences suggest that the instrument used to measure IOP is the source of disparity between these results.

Using peripheral pneumatonometry, the maximum mean change in IOP during scleral lens wear was 1.7 mmHg (6%) after 1 hour of

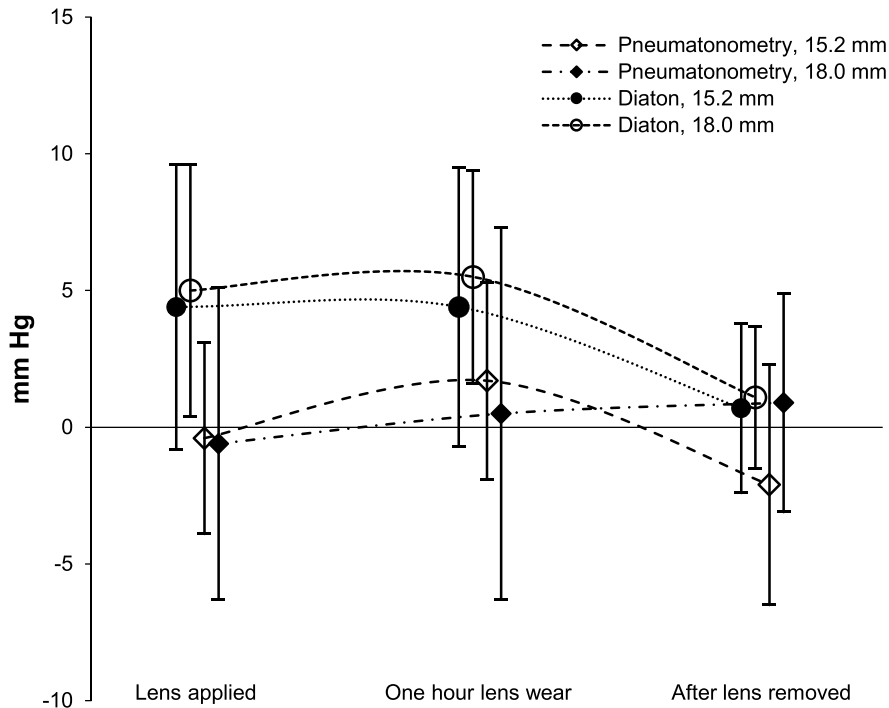


FIGURE 2. Mean change in IOP (mmHg) from baseline, comparing lens diameters. There was a decrease in mean IOP after initial lens application in pneumatometry with both the small-diameter (−0.4 mmHg, −2%) and large-diameter (−0.8 mmHg, −3%) lenses. The small-diameter lens had the largest increase in mean IOP change with 1 hour of wear (1.7 mmHg [6%] vs. 0.5 mmHg [2%]). After lens removal, the mean change in IOP from baseline decreased after small lens removal (−2.1 mmHg, −8%) and after large lens removal (0.9 mmHg, 3%). Mean changes in IOP measured with the transpalpebral tonometer have a dramatic increase during lens wear. With the small-diameter lens, mean IOP was increased from baseline 4.4 mmHg (56%) both immediately after lens application and with 1 hour of lens wear. After small lens removal, mean IOP was again close to baseline (0.7 mmHg difference, 9%). There was an even higher increase in IOP with large lens wear. Immediately after lens application, mean IOP increased (5.0 mmHg, 63%) and remained elevated with 1 hour of wear (5.5 mmHg, 70%). After lens removal, there was again a return to near baseline, with a mean of 1.1 mmHg (14%).

small-diameter lens wear; all changes in mean IOP with or after lens wear were within the 2- to 3-mmHg range of variability considered acceptable for Goldmann applanation tonometry.²⁴ In contrast, the minimum change in mean IOP measured using transpalpebral tonometry during lens wear was 55% (4.4 mmHg) immediately after application of the small-diameter lens. Maximum mean IOP change as measured by transpalpebral tonometry was 70% (5.5 mmHg) after 1 hour of large lens wear. The mean changes measured by transpalpebral tonometry during lens wear are greater than the clinically accepted 2 to 3 mmHg of variability in IOP measured with a Goldmann tonometer, in contrast to the results found with peripheral pneumatometry.

To further determine why IOP measurements differ in this study, understanding the validation of these instruments is imperative. Studies comparing corneal pneumatometry to Goldmann applanation tonometry report that the relationship slope between the instruments is similar; therefore, the instrument corresponds well to the criterion standard for IOP measurement.¹¹ Although the pneumatometer is calibrated to measure IOP on the cornea, it is possible to obtain measurements on the conjunctival tissue that overlies the sclera. In some clinical scenarios, corneal IOP cannot be measured, but IOP assessment is essential for long-term management. For example, patients who have undergone corneal prosthesis placement are at risk of glaucoma, but IOP obviously cannot be measured through the implanted PMMA material. For this reason, previous studies have examined the relationship between central

and peripheral IOP using pneumatometry. These studies have shown correlation between central IOP and peripheral IOP, although peripheral measurements are uniformly higher than corneal assessments by 8 to 9 mmHg.^{14,25} Even though peripheral IOP is generally higher than central IOP as measured with this device, the correlation between the two measurements allows us to assume that changes in IOP found peripherally will correlate well to values that would be obtained with central IOP assessment. Our results were consistent with those reported previously; average peripheral pneumatometry was approximately 6.5 mmHg higher than average central corneal IOP.

TABLE 3. Measurement error and repeatability of peripheral methods of measuring IOP

	Peripheral pneumatometry (forward facing)	Peripheral pneumatometry (with head tilt)	Palpebral tonometry
Measurement error	1.6 mmHg	1.5 mmHg	0.9 mmHg
Repeatability	4.4 mmHg	4.3 mmHg	2.6 mmHg
Repeatability divided by mean	20%	20%	30%

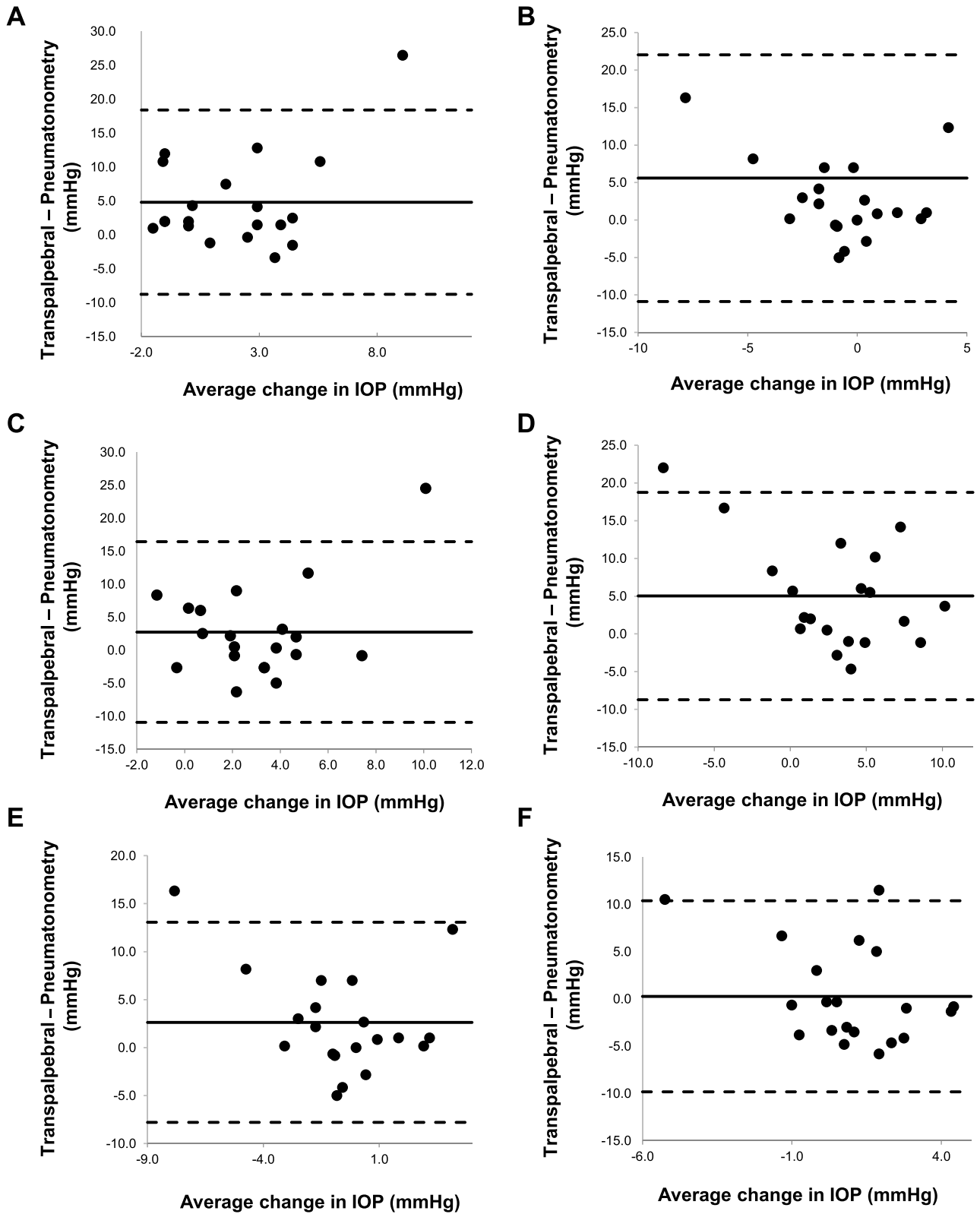


FIGURE 3. Bland-Altman plots of changes in IOP with transpalpebral tonometry and peripheral pneumatonometry. Plots A, C, and E are for the 15.2-mm scleral lens, and plots B, D, and F are for the 18.0-mm scleral lens. Plots A and B compare the change in IOP measurements from baseline until immediately after the lens was applied. Plots C and D compare change in IOP from baseline to immediately after 1 hour of lens wear. Plots E and F show the change in IOP from baseline to after lens removal. The solid line represents the bias, and the upper and lower dashed lines represent the upper and lower 95% limits of agreement.

However, they are generally accepted as a reasonable clinical alternative to standard IOP assessment.

Transpalpebral tonometry was introduced within the past 15 years. Studies that compared the transpalpebral tonometry to Goldmann tonometry found that the average \pm standard deviation transpalpebral IOP was 0.53 ± 3.24 mmHg lower than that which was measured with Goldmann applanation tonometry in normal patients; however, it is not recommended for diagnostic purposes because of underestimation of low measurements and overestimation of high measurements.²⁶ Although transpalpebral tonometry is considered an acceptable screening tool, it is not a replacement for Goldmann tonometry because considerable asymmetry has been noted over the range of IOP values measured.^{26–29}

The large changes in IOP found when wearing scleral lenses measured by transpalpebral tonometry in this study did not correspond to the measurements obtained with peripheral pneumatonometry; this compels further consideration of factors that may contribute to these differences. The transpalpebral tonometer was somewhat less repeatable in this study; however, this does not explain why the IOP findings were greatly different when a lens was on the eye compared with when no lens was worn. Transpalpebral tonometry requires that the head be tilted back, with the eyes in relative downgaze. Neck extension has been shown to increase IOP.³⁰ To account for the possible effect of head position on IOP, we obtained pneumatonometry measurements both with head erect and head tilted but found no difference in IOP associated with head position. Compression of conjunctival and episcleral tissue occurs during scleral lens wear and is most pronounced in the superior quadrant.³¹ It is possible that this tissue compression may decrease tissue elasticity immediately adjacent to the lens haptic, which could help to explain elevated IOP readings during scleral lens wear with the transpalpebral tonometry. However, Alonso-Caneiro et al.³¹ reported that compression of tissue may persist for more than 3 hours after scleral lens removal. Delayed resolution of compression does not explain our observation of an immediate return to baseline IOP as measured by transpalpebral tonometry after lens removal. One might therefore conclude that conjunctival compression does not influence IOP, but additional studies need to be done to understand any effects of both

short- and long-term effects of conjunctival compression on the fluid dynamics of the drainage angle. Lid tension may also affect transpalpebral tonometry; measurement may be elevated if an already-tight lid is stretched over a scleral lens. Indeed, a previous study concluded that eyelids may buffer the findings of the transpalpebral tonometer differently depending on IOP levels or even aging of the eyelids.²⁶ Finally, it may be difficult to determine the location of the edge of the scleral lens haptic beneath the eyelid; artificially elevated IOP measurements may result from any interference of the lens haptic. In our experience, measurement directly over the lens haptic resulted in a dramatically elevated reading; however, it is possible that mildly elevated measurements could be obtained if any portion of the plunger of the transpalpebral tonometer was impeded by the edge of the lens.

CONCLUSIONS

Differences in the instrument used to measure IOP may account for the conflicting results reported in previous studies of IOP during scleral lens wear. Assessment of IOP using pneumatonometry agreed with results presented by Nau et al.,¹⁶ and transpalpebral tonometry yielded IOP measurements that resemble those reported by Michaud et al.¹⁷ Given the robust body of literature that reports reasonably strong agreement between pneumatonometry and Goldmann tonometry and the relatively wide acceptance of peripheral pneumatonometry as an alternative to standard IOP measurement in specialty corneal practices, we suspect that peripheral assessment of IOP using pneumatonometry in this study accurately represented this value during scleral lens wear. We recognize, however, that pneumatonometry is not readily available in many practices. Although the Diaton is relatively inexpensive and easy to use, this study was not able to confirm that transpalpebral tonometry provides an accurate assessment of IOP during scleral lens wear. Given the challenges in accurately assessing IOP during scleral lens wear, it may be necessary to explore other ocular parameters that can serve as surrogate assessments of changes in IOP.

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REFERENCES

- Huggert A. Increase of the Intraocular Pressure when Using Contact Glasses. *Acta Ophthalmol* 1951;29:475–81.
- Huggert A. The Intraocular Pressure in Glaucomatous Eyes, Following the Use of Contact Lenses. *Acta Ophthalmol (Copenh)* 1953;31:141–52.
- Miller D, Carroll JM. Corneal Edema and Scleral Lenses. *Int Ophthalmol Clin* 1968;8:623–35.
- Miller D, Carroll JM, Holmberg A. Scleral Lens Cling Measurement. *Am J Ophthalmol* 1968;65:929–30.
- McMonnies CW, Boneham GC. Experimentally Increased Intraocular Pressure Using Digital Forces. *Eye Contact Lens* 2007;33:124–9.
- McMonnies CW. A Hypothesis That Scleral Contact Lenses Could Elevate Intraocular Pressure. *Clin Exp Optom* 2016;99:594–6.
- Vincent SJ, Alonso-Caneiro D, Collins MJ. Evidence on Scleral Contact Lenses and Intraocular Pressure. *Clin Exp Optom* 2017;100:87–8.
- Aitsebaomo A, Wong-Powell J, Miller W, et al. Influence of Scleral Lens on Intraocular Pressure. *J Contact Lens Res Sci* 2019;22(3):e1–9.
- Khan JA, LaGreca BA. Tono-Pen Estimation of Intraocular Pressure through Bandage Contact Lenses. *Am J Ophthalmol* 1989;108:422–5.
- Cheung SY, Collins MJ, Vincent SJ. The Impact of Short-term Fenestrated Scleral Lens Wear on Intraocular Pressure [published online February 19, 2020]. *Cont Lens Anterior Eye* 2020. doi:10.1016/j.clae.2020.02.003.
- Wittenberg S. Evaluation of the Pneuma-tonometer. *Am J Optom Physiol Opt* 1978;55:337–47.
- Magalhaes OA, Aldave AJ. Scleral Pneumatometry in Penetrating Keratoplasty: A Clinical Study. *Cornea* 2017;36:1200–5.
- Lee JH, Sanchez LR, Porco T, et al. Correlation of Corneal and Scleral Pneumatometry in Pediatric Patients. *Ophthalmology* 2018;125:1209–14.
- Kuo DS, Ou Y, Jeng BH, et al. Correlation of Serial Scleral and Corneal Pneumatometry. *Ophthalmology* 2015;122:1771–6.

15. Lam AK, Lam CH, Chan R. The Validity of a Digital Eyelid Tonometer (Tgdc-01) and Its Comparison with Goldmann Applanation Tonometry—a Pilot Study. *Ophthalmic Physiol Opt* 2005;25:205–10.
16. Nau CB, Schornack MM, McLaren JW, et al. Intraocular Pressure After 2 Hours of Small-diameter Scleral Lens Wear. *Eye Contact Lens* 2016;42:350–3.
17. Michaud L, Samaha D, Giasson CJ. Intra-ocular Pressure Variation Associated with the Wear of Scleral Lenses of Different Diameters. *Cont Lens Anterior Eye*. 2019;42:104–10.
18. Recep OF, Hasiripi H, Vayisoglu E, et al. Accurate Time Interval in Repeated Tonometry. *Acta Ophthalmol Scand* 1998;76:603–5.
19. Hamilton-Maxwell K, King N. Modern Disposable Hydrogel Contact Lens Removal Has a Minimal Effect on Intraocular Pressure. *Ophthalmic Physiol Opt* 2015; 35:231–5.
20. Roddy GW, Viker KB, Winkler NS, et al. Stanniocalcin-1 Is an Ocular Hypotensive Agent and a Downstream Effector Molecule That Is Necessary for the Intraocular Pressure-lowering Effects of Latanoprost. *Invest Ophthalmol Vis Sci* 2017;58:2715–24.
21. Kazemi A, McLaren JW, Kocczynski CC, et al. The Effects of Netarsudil Ophthalmic Solution on Aqueous Humor Dynamics in a Randomized Study in Humans. *J Ocul Pharmacol Ther* 2018;34:380–6.
22. Bland JM, Altman DG. Measurement Error. *BMJ* 1996;312:1654.
23. Bland JM, Altman DG. Statistical Methods for Assessing Agreement between Two Methods of Clinical Measurement. *Lancet* 1986;1:307–10.
24. Whitacre MM, Stein R. Sources of Error with Use of Goldmann-type Tonometers. *Surv Ophthalmol* 1993; 38:1–30.
25. Kapamajian MA, de la Cruz J, Hallak JA, et al. Correlation between Corneal and Scleral Pneumatometry: An Alternative Method for Intraocular Pressure Measurement. *Am J Ophthalmol* 2013;156:902–6.e1.
26. Li Y, Shi J, Duan X, et al. Transpalpebral Measurement of Intraocular Pressure Using the Diaton Tonometer versus Standard Goldmann Applanation Tonometry. *Graefes Arch Clin Exp Ophthalmol* 2010;248:1765–70.
27. Sandner D, Bohm A, Kostov S, et al. Measurement of the Intraocular Pressure with the “Transpalpebral Tonometer” Tgdc-01 in Comparison with Applanation Tonometry. *Graefes Arch Clin Exp Ophthalmol* 2005; 243:563–9.
28. Troost A, Specht K, Krummenauer F, et al. Deviations between Transpalpebral Tonometry Using Tgdc-01 and Goldmann Applanation Tonometry Depending on the IOP Level. *Graefes Arch Clin Exp Ophthalmol* 2005; 243:853–8.
29. Troost A, Yun SH, Specht K, et al. Transpalpebral Tonometry: Reliability and Comparison with Goldmann Applanation Tonometry and Palpation in Healthy Volunteers. *Br J Ophthalmol* 2005;89:280–3.
30. Arora N, McLaren JW, Hodge DO, et al. Effect of Body Position on Epscleral Venous Pressure in Healthy Subjects. *Invest Ophthalmol Vis Sci* 2017;58:5151–6.
31. Alonso-Caneiro D, Vincent SJ, Collins MJ. Morphological Changes in the Conjunctiva, Episclera and Sclera Following Short-term Miniscleral Contact Lens Wear in Rigid Lens Neophytes. *Cont Lens Anterior Eye* 2016; 39:53–61.