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Objective evaluation of static and dynamic behavior of different toric silicone-hydrogel contact lenses

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ABSTRACT

Purpose: The present study aimed to estimate how orientation position, recovery time, and contact lens decentration, associated with visual performance, may vary on several designs of the most recent toric silicone-hydrogel toric contact lenses in two-time different moments.
Methods: To evaluate the toric silicone-hydrogel toric contact lens position and stability, it was conducted with a prospective, observational, randomized, and single-center case series including 95 astigmatic eyes wearing four toric silicone-hydrogel toric contact lenses for two weeks. Orientation and decentration were analyzed with ImageJ software from video-frames extracted with a Python application. Recovery time was evaluated after 45 degrees of inferior-temporal misorientation.
Results: Evaluation of misorientation after 20 min of wear revealed the highest amount for Saphir RX, −20.41 ± 10.84 deg, and lowest for Air Optix Aqua for Astigmatism, −1.43 ± 7.48 deg. The highest horizontal misalignment was found for Air Optix Aqua for Astigmatism, −0.627 ± 0.330 mm, and lowest for Biofinity Toric, 0.004 ± 0.270 mm. Vertical misalignment presented the highest value for Acuvue Vita for Astigmatism, −0.652 ± 0.369 mm, and lowest for Air Optix Aqua for Astigmatism, −0.126 ± 0.231 mm. Recovery time showed the highest amount for Saphir RX, 80.70 ± 33.26 s, and lowest for Biofinity Toric 43.67 ± 23.70 s. Only Air Optix Aqua for Astigmatism presented significant differences after two-week of wear for misorientation ($P = 0.02$) and horizontal misalignment ($P < 0.001$). When pairwise comparisons are made between toric silicone-hydrogel toric contact lenses, significant differences ($P < 0.001$) are found.
Conclusions: Although there was acceptable fitting, based upon decentration, orientation, and recovery with the study contact lenses, the stabilization and profile design used in the Air Optix Aqua for Astigmatism helped to minimize rotation and vertical misalignment. In addition, the peri-ballast and thickness profile of the Biofinity Toric improved rotational recovery and horizontal misalignment compared to the other contact lenses. Finally, lenses with a better fitting profile showed better visual performance.

1. Introduction

Astigmatism is the most prevalent refractive error in the adult population followed by hyperopia and myopia [1–4]. Genetics, the interaction between cornea and eyelids, and the use of near vision are the main etiological factors contributing to astigmatism [1,5,6]. The prevalence of astigmatism increases with age [3], and previous studies reported prevalences from 11.3 to 70 % [1,4]. The estimated world-prevalence of astigmatism is 40.4 % for cylinder powers above 0.5 D [7] and 23.9 % for cylindrical powers higher than 1.0 D [8].

Astigmatism can be treated with surgical procedures, including excimer laser-assisted keratomileusis, photorefractive keratectomy, or femtosecond laser-assisted keratotomy [7]. Although astigmatism is often corrected with reversible methods such as spectacles and rigid or soft contact lenses.

Previous studies identified that up to 47 % of potential contact lens wearers required correction for clinically significant astigmatism (≥0.75 D) [9–13]. Furthermore, it was reported that visual acuity, contrast sensitivity, and subjective preferences after toric soft contact lens wear were similar to those obtained with spectacles [12,14]. Contact lenses may be a reliable option to correct astigmatism, and the most recent toric silicone-hydrogel lenses proved to be a suitable way, better than

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other visual aids or refractive surgery [9,12,15]. Conventional contact lenses sometimes do not provide enough comfort, stability, visual acuity, or contrast sensitivity, and therefore vision care professionals increased the prescription of silicone-hydrogel lenses.

Few previous investigations have evaluated the visual effect of a lens misaligned cylinder concerning the physiologic cylinder of the eye [16–18]. Moreover, there are few studies analyzing misalignment, cylinder axis, and decentration in toric silicone-hydrogel contact lens wearers [11,19,20]. The outcomes of this study could provide new insights into the comparative performance of traditional and new cylinder stabilization designs.

The present study aimed to determine how orientation position, recovery time after inferior-temporal misorientation, and lens decentration may vary on the most recent toric silicone-hydrogel contact lenses within a group of contact lens wearers in two-time different moments, after two weeks of wear. Additionally, the analysis of visual acuity provides implications of the mechanical behavior of the lenses.

2. Methods

To evaluate the static and dynamic performance of last generation toric silicone-hydrogel contact lenses, a prospective, observational, randomized, and single-center case series was conducted with 95 astigmatic eyes wearing four lenses for two weeks. This research followed the tenets of the Declaration of Helsinki and was approved by the Ethics Committee of the University of Santiago de Compostela (A Coruña, Spain). All patients were required to review and sign an informed consent document prior to taking part in the study.

2.1. Inclusion criteria

The present study comprised 50 healthy astigmatic subjects, voluntarily enrolled at the Ocular Surface and Contact Lens Laboratory from the University of Santiago de Compostela. Eligibility criteria included previous contact lens wearers with spherical refractions between −12.00 and +5.00 D and astigmatisms between −2.25 and −0.75 D correctable to 0.00 logMAR (20/20) or better visual acuity. Exclusion criteria included age under 18 years, previous refractive surgery, ocular or systemic diseases, or use of topical medications. Baseline measurements were done after the subject had a one-week washout period without wearing their previous contact lenses.

2.2. Contact lenses and fitting procedures

The contact lenses selected for this study presented four stabilization designs: 1) peri-ballast, Biofinity Toric (BT) (CooperVision, Pleasanton, CA); 2) modified peri-ballast, Air Optix Aqua for Astigmatism (AOAfA) (Alcon Pharmaceuticals Ltd., Geneva, Switzerland); 3) double slab-off design, Acuvue Vita for Astigmatism (AVfA) (Johnson & Johnson Vision, Jacksonville, FL); and 4) prism-ballast, Saphir RX (SRX) (Mark'Ennovy, Madrid, Spain). The main technical characteristics for each lens are summarized in Table 1.

All patients underwent a complete pre-fitting examination, including routine evaluation of tear film, logMAR uncorrected visual acuity, refractive error, logMAR best-corrected visual acuity, slit-lamp biomicroscopy, and corneal topography with particular attention to ocular adverse events. Monocular and binocular high-contrast visual acuity was measured using a Topcon CC-100XP (Topcon, Tokyo, Japan) electronic visual chart at 6 m under mesopic conditions.

The power of contact lenses was calculated with a distometry chart from spectacles refraction, except for SRX, whose power, base curve, and diameter were estimated with a specific calculator. The spherical power of lenses was the closest to the previously calculated sphere when power-range limitation was present. A multipurpose solution All Clean Soft (Avizor Eye Care solutions, Madrid, Spain) was used to preserve the contact lenses, and a saline solution was used before lens insertion.

Table 1
Parameters of the Contact Lenses used in the Study.

Product name	Biofinity Toric	Air Optix Aqua for Astigmatism	Acuvue Vita for Astigmatism	Saphir RX
Manufacturer	CooperVision	Alcon	Johnson & Johnson	Mark'Ennovy
Material	comfilcon A	lotrafilcon B	senofilcon C	filcon v3
Water content (%)	48	33	41	75
Dk (cm^2/s) (mLO_2/mL mmHg)10^{-11}	128	110	129	60
Dk/t (cm/s)/ (mLO_2/mL mmHg)10^{-11}	116	108	103	57
Modulus (MPa)	0.8	1.0	0.77	0.29
Base curve (mm)	8.7	8.7	8.6	6.80 to 9.80
Diameter (mm)	14.5	14.5	14.5	13.00 to 16.00
Sphere range (D)	+10.00 to −10.00	+6.00 to −10.00	+4.00 to −9.00	+30.00 to −30.00
Cylinder range (D)	−0.75 to −5.75	−0.75 to −2.25	−0.75 to −2.25	−0.75 to −8.00
Center thickness at −3.00 D (mm)	0.110	0.102	0.080	0.120
Vertical prism in central 6 mm (Δ)*	0.774	0.524	0.008	≈0.840
Stabilization system	Peri-ballast	Modified peri-ballast	Double slab-off	Prism-ballast
Profile design	Horizontal ISO thickness	Precision Balance 8|4	Blink Stabilized	Streamlined
Manufacturing method	Cast molding	Cast molding	Cast molding	Lathe-cutting

* Mean value for lenses with spherical powers from −6.00D to +3.00 D and a cylindrical power of −1.25 D with 90° and 180° axis.

Each subject did five scheduled visits: 1) an initial screening visit; 2) a lens dispensing and 20 min wearing visit for two initial lenses; 3) a two-week follow-up visit for first and second lenses; 4) a lens dispensing and 20 min wearing visit for two last lenses; 5) a two-week follow-up visit for third and fourth lenses. The subjects fitted two randomized lenses, one in each eye at lens dispensing visit. After 20 min of contact lenses wear, logMAR visual acuity was measured, and subjects were positioned behind the slit-lamp and asked to fixate a mark maintaining primary gaze, thus evaluating orientation position, misalignment, and lens recovery time. Additionally, patients received instructions and phased schedules of contact lens wear, from 2 to 12 h, increasing 2 h per day. After two-week of contact lens scheduled wear, subjects followed the same protocol of the previous visit. The fourth and fifth visits were as second and third visits, respectively, using the two remaining randomized lenses, one in each eye. To avoid possible effects of the first pair of contact lenses, among trials of first-second and third-fourth lenses, subjects had a one-week washout period without wearing contact lenses.

2.3. Contact lens cylinder axis, recovery time, and misalignment

Orientation position and contact lens misalignment were analyzed with ImageJ software (National Institute of Health – Bethesda Softworks, Rockville, MD) from video-frames extracted with an own programmed Python application (Python Software Foundation, Wilmington, DE). Videos were recorded with a Topcon DC-3 biomicroscope (Topcon, Tokyo, Japan), selecting the sharpest frames between two complete blinks.

The orientation position was captured with a narrow-slit beam (≈0.5 mm) at 16× magnification and measured in degrees relative to the vertical axis. Inferior-nasal and inferior-temporal rotation were represented with positive and negative signs, respectively, by convention. Recovery time was measured after manual lens spinning with sterile silicone-tipped tweezers, aligning lens orientation mark with a narrow-slit beam (16× magnification) misorientated 45 degrees inferior-temporally. Time was measured from lens release until the orientation mark reached the final position when no further spin was observed, and while the previously instructed patient blinked approximately 15 times per minute. Lens misalignment was assessed with a wide beam at 10× magnification and measured in millimeters relative to the pupil center. Superior and inferior misalignments were represented with positive and negative signs, respectively, while nasal and temporal misalignments were represented with positive and negative signs, respectively.

Lens misalignment, orientation position, and recovery time were averaged across three repeated measures for each lens and subject.

2.4. Statistical analysis

The Shapiro-Wilk test was implemented to assess the normality of data distribution for all data sets. The ANOVA test evaluated the differences between all groups for normally distributed variables, whereas, the Kruskal-Wallis test assessed non-normally distributed variables. The independent-sample *t*-test was applied to compare two groups with normally distributed variables and the Mann-Whitney *U* test with non-normally distributed variables. For normally and non-normally distributed data, respectively, the Pearson and the Spearman coefficients assessed the correlations among eye and lens parameters. For statistical purposes, *P*-value under 0.05 was considered statistically significant. All statistical analyses ran under SPSS v.24.0 software (IBM Corporation, Armonk, NY).

3. Results

3.1. Sample and refractive data

The current study included 95 eyes of 50 astigmatic patients (40 females and 10 males) with a mean age of 30.56 ± 11.06 years (range: 18–57). Seventy-eight (82.1 %) eyes were myopic (mean −3.85 ± 3.27 D), 15 (15.8 %) were hyperopic (mean +2.15 ± 1.63 D), and 2 (2.1 %) had no spherical ametropia. The average spherical power was −2.82 ± 3.76 D (range: −12.00 to +5.00 D) and the mean cylindrical power was −1.45 ± 0.94 D (range: −2.25 to −0.75 D). All enrolled patients completed the contact lens wear schedule in 15 ± 2.3 days without showing significant adverse events. Table 2 presents a summary of refractive, corneal topography, and palpebral data from each eye group showing no significant differences among fellow eyes.

3.2. Contact lens orientation and recovery time

Evaluation of rotation in the dispensing visit (Table 3) revealed the highest value for SRX (−20.41 ± 10.84 deg) and lowest for AOAfA (−1.43 ± 7.48 deg). The SRX presented the highest misorientation (20.34 ± 10.61 deg), and the AOAfA showed the lowest (6.49 ± 3.86 deg). Recovery time analysis revealed the highest value for SRX (80.70 ± 33.26 s) and the lowest for BT (43.67 ± 23.70 s). When pairwise comparisons were made between lens types, significant differences ($P < 0.001$) were found in all pairs for orientation and absolute orientation position (except BT vs. AVfA), and for recovery time when BT-AOAfA and AVfA-SRX pairs were compared.

The follow-up visit showed the highest misorientation for SRX (−20.22 ± 9.60 deg) and the lowest for AOAfA (−4.81 ± 7.35 deg). The SRX presented the highest absolute misorientation (20.33 ± 9.37 deg), and the AOAfA showed the lowest (6.40 ± 4.99 deg). The AOAfA also revealed the lowest misorientation, near to zero, while BT and AVfA rotated nasally, and SRX temporally in both visits (Fig. 1A). The AVfA (92.12 ± 32.41 s) showed the highest recovery time and BT (41.72 ± 28.81 s) the lowest. Multiple comparisons between groups showed significant differences ($P<0.001$) for orientation and absolute orientation position in all pairs excepting BT vs. AVfA, and for recovery time in all pairs except for AVfA-SRX pair (Fig. 1B).

3.3. Contact lens decentration and misalignments

During the fitting process, all the subjects were managed to avoid any corneal limbus interaction with the contact lens, resulting in a decentration of less than 1.091 mm horizontally and 1.505 mm vertically for the whole sample (Fig. 2).

The dispensing visit (Table 3) showed the highest horizontal misalignment for SRX (−0.565 ± 0.224 mm) and BT (0.004 ± 0.270 mm) the lowest, while the highest absolute horizontal misalignment was obtained for SRX (0.565 ± 0.224 mm) and lowest for BT (0.196 ± 0.156 mm). The highest vertical misalignment was achieved for AVfA (−0.652 ± 0.369 mm) and lowest for AOAfA (−0.126 ± 0.231 mm), while the highest absolute misalignment was found for AVfA (0.660 ± 0.361 mm) and lowest for AOAfA (0.218 ± 0.145 mm). Pairwise comparisons between contact lens groups revealed significant differences ($P < 0.001$) for horizontal and absolute horizontal misalignment in all pairs, except for BT vs. AVfA. Differences were also found for vertical and absolute vertical misalignment in all pairs, excluding the AVfA-SRX pair.

After two weeks of contact lens wear (Table 3), the highest horizontal misalignment was found for SRX (−0.585 ± 0.243 mm) and lowest for BT (−0.057 ± 0.214 mm), while the SRX (0.585 ± 0.243 mm) obtained the highest absolute horizontal misalignment and BT (0.168 ± 0.122 mm) the lowest. The highest vertical misalignment was observed for AVfA (−0.595 ± 0.383 mm) and lowest for AOAfA (−0.108 ± 0.254 mm), while the highest absolute vertical misalignment was found for AVfA (0.646 ± 0.340 mm) and lowest for AOAfA (0.204 ± 0.144 mm). Most lenses showed temporal (Fig. 3A) and inferior (Fig. 3B) center misalignment in both visits, although BT and AOAfA lens centers were concentrated around the horizontal (Fig. 2A) and the vertical axis (Fig. 2B), respectively. Multiple comparisons between groups showed significant differences ($P < 0.001$) for horizontal misalignment in all

Table 2
Biometric Data for 95 Astigmatic Eyes of the Study and Comparisons Pair by Pair.

	Right Eyes (n = 48)		Left Eyes (n = 47)		P[a]
	Mean ± SD	Range	Mean ± SD	Range	
Spherical refractive error (D)	−2.90 ± 3.80	−12.00 to +5.00	−2.74 ± 3.76	−12.00 to +4.75	0.994
Cylindrical refractive error (D)	−1.35 ± 0.90	−2.25 to −0.75	−1.55 ± 1.01	−2.25 to −0.75	0.539
K flat (D)	42.53 ± 1.65	38.87 to 46.49	42.79 ± 1.74	39.00 to 46.25	0.439
K steep (D)	43.89 ± 1.77	40.49 to 48.04	44.15 ± 1.58	41.00 to 48.25	0.537
K steep – K flat (D)	1.35 ± 0.91	0.06 to 3.98	1.36 ± 1.08	0.00 to 4.75	0.947
Corneal eccentricity	0.48 ± 0.13	0.25 to 0.77	0.49 ± 0.11	0.13 to 0.72	0.230
Horizontal Visible Iris Diameter (mm)	12.12 ± 0.44	11.00 to 13.00	12.15 ± 0.46	11.00 to 13.00	0.824
Palbebral aperture (mm)	10.07 ± 0.91	8.27 to 11.71	9.92 ± 0.88	8.33 to 11.99	0.253

[a] Mann-Whitney *U* test.

Table 3
Lens Misalignment, Orientation Position and Temporal Recovery Time (±SD) on Dispensing Visit (1) and Follow-up Visit (2), Comparisons Pair by Pair, and Statistical Significance Between All Lens Types.

	Visit	Mean±SD				Comparisons Pair by Pair	*P*
		BT (1)	AOAfA (2)	AVfA (3)	SRX (4)		
HM (mm)	1	0.004±0.270	-0.627±0.330	-0.026±0.286	-0.565±0.224	1>2[d]; 1>4[d] ;2<3[c]; 2<4[d]; 3>4[d]	<0.001[a]
	2	-0.057±0.214	-0.515±0.177	-0.176±0.256	-0.585±0.243	1<2[c]; 1>4[e]; 2<3[d]; 2>4[c]; 3>4[d]	<0.001[a]
VM (mm)	1	-0.216±0.339	-0.126±0.231	-0.652±0.369	-0.579±0.389	1<2[c]; 1>3[d]; 1>4[e]; 2>3[d]; 2>4[d]	<0.001[a]
	2	-0.302±0.283	-0.108±0.254	-0.595±0.383	-0.563±0.287	1<2[d]; 1>3[c]; 1>4[d]; 2>3[d]; 2>4[d]	<0.001[a]
AHM (mm)	1	0.196±0.156	0.330±0.232	0.228±0.171	0.565±0.224	1<2[c]; 1<4[d]; 2>3[c]; 2<4[d]; 3<4[d]	<0.001[b]
	2	0.168±0.122	0.515±0.177	0.253±0.194	0.585±0.243	1<2[d]; 1<3[c]; 1<4[d]; 2>3[d]; 2<4[c]; 3<4[d]	<0.001[b]
AVM (mm)	1	0.300±0.210	0.218±0.145	0.660±0.361	0.583±0.315	1>2[c]; 1<3[d]; 1<4[e]; 2<3[d]; 2<4[d]	<0.001[b]
	2	0.356±0.231	0.204±0.144	0.646±0.340	0.588±0.281	1>2[c]; 1<3[d]; 1<4[d]; 2<3[d]; 2<4[d]	<0.001[b]
OP (deg)	1	13.46±8.23	-1.43±7.48	14.17±8.27	-20.41±10.84	1>2[d]; 1>4[d]; 2<3[d]; 2>4[d]; 3>4[d]	<0.001[b]
	2	11.78±8.80	-4.81±7.35	14.4±9.73	-20.22±9.60	1>2[d]; 1>4[d]; 2<3[d]; 2>4[d]; 3>4[d]	<0.001[b]
AOP (deg)	1	14.81±7.64	6.49±3.86	14.83±48.65	20.34±10.61	1>2[d]; 1>4[c]; 2<3[d]; 2<4[d]; 3<4[c]	<0.001[b]
	2	13.13±6.56	6.40±4.99	14.73±7.66	20.33±9.37	1>2[d]; 1<4[d]; 2<3[d]; 2<4[d]; 3<4[c]	<0.001[b]
TRT (s)	1	43.67±23.70	52.26±37.14	77.48±29.63	80.70±33.26	1<3[d]; 1<4[d]; 2<3[c]; 2<4[d]	<0.001[b]
	2	41.72±28.81	59.72±24.08	92.12±32.41	85.54±33.26	1<2[d]; 1<3[d]; 1<4[d]; 2<3[d]; 2<4[d]	<0.001[b]

[a] ANOVA test
[b] Kruskal-Wallis test
[c] Independent- sample *t*-test (p<0.05)
[d] Independent-sample *t*-test (p<0.001)
[e] Mann-Whitney *U* test (p<0.001)

BT, Biofinity Toric; AOAfA, Air Optix Aqua for Astigmatism; AVfA, Acuvue Vita for Astigmatism, SRX; Saphir RX; HM, Horizontal Misalignment; VM, Vertical Misalignment; AHM, Absolute Horizontal Misalignment, AVM, Absolute Vertical Misalignment; OP, Orientation Position; AOP, Absolute Orientation Position; TRT, Temporal Recovery Time.

[a]ANOVA test.
[b]Kruskal-Wallis test.
[c]Independent-sample *t*-test ($p < 0.05$).
[d]Independent-sample *t*-test ($p < 0.001$).
[e]Mann-Whitney *U* test ($p < 0.001$).

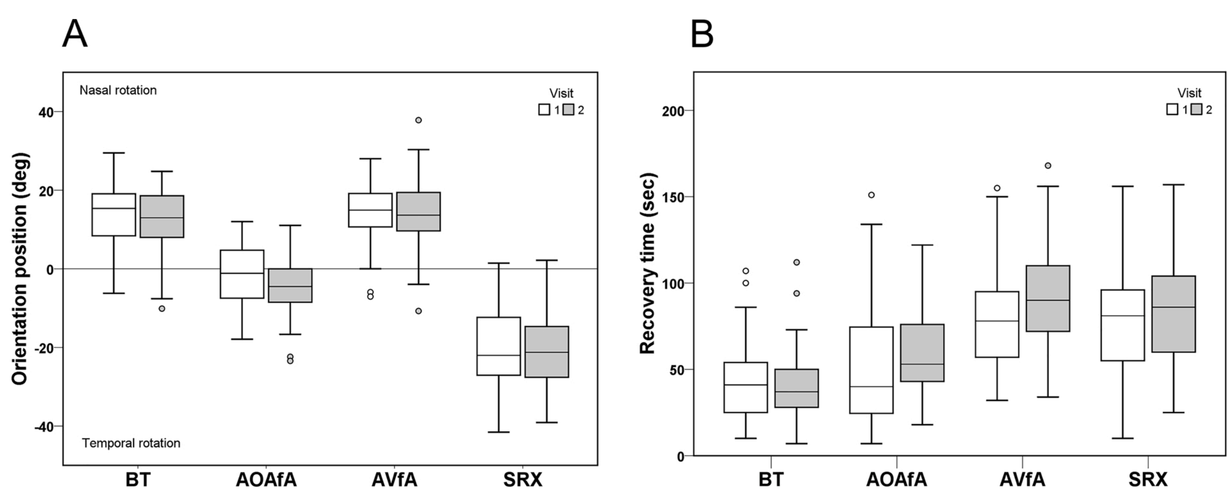

Fig. 1. A) Contact lens orientation position relative to the vertical position, B) Recovery time after 45 deg inferior-temporal contact lens misorientation.BT, Biofinity Toric; AOAfA, Air Optix Aqua for Astigmatism; AVfA, Acuvue Vita for Astigmatism; SRX, Saphir RX.

pairs, except for BT vs. AVfA; for absolute horizontal misalignment in all lenses; and for vertical and absolute vertical misalignment in all pairs excluding AVfA vs. SRX (Fig. 1B).

3.4. *Contact lens orientation, misalignment, and visual acuity*

The interaction of different contact lens designs and visual acuity was significantly different for first and second visits, $P = 0.017$ and $P = 0.048$, respectively (Table 4). Assessment of logMAR visual acuity in dispensing visit showed the highest value for BT (-0.001 ± 0.09) and the lowest for SRX (0.07 ± 0.18). Multiple comparisons analysis presented statistically significant differences in visual acuity for BT-SRX and AVfA-SRX pairs. The follow-up visit presented the highest visual acuity for AOfA (-0.03 ± 0.14), while SRX (0.08 ± 0.25) obtained the lowest. Pairwise comparisons between contact lens significant differences for SRX compared with BT, AOfA, and AVfA.

3.5. *Correlations with ocular parameters and visual acuity*

The correlation analysis between eye and contact lens behavior variables presented five and eight pairs of significant correlations, respectively, for the first and second visits. In the dispensing visit, there

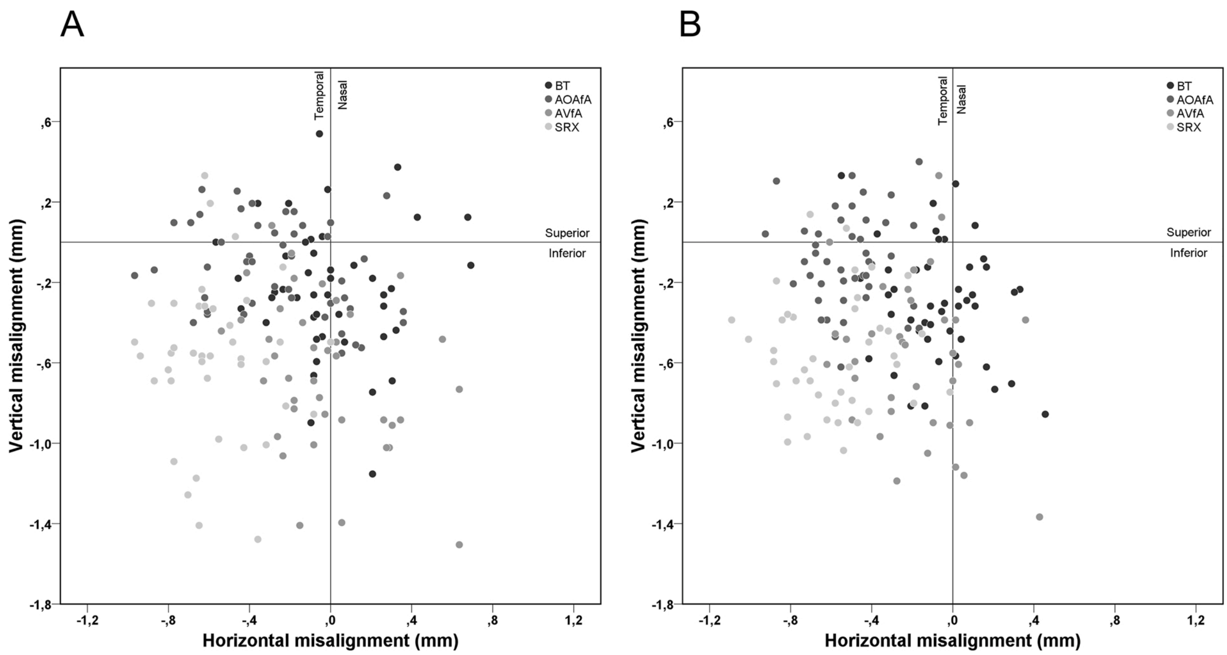

Fig. 2. Contact lens center misalignment relative to the pupil-center for dispensing visit (A) and two-week follow-up visit (B). BT, Biofinity Toric; AOAfA, Air Optix Aqua for Astigmatism; AVfA, Acuvue Vita for Astigmatism; SRX, Saphir RX.

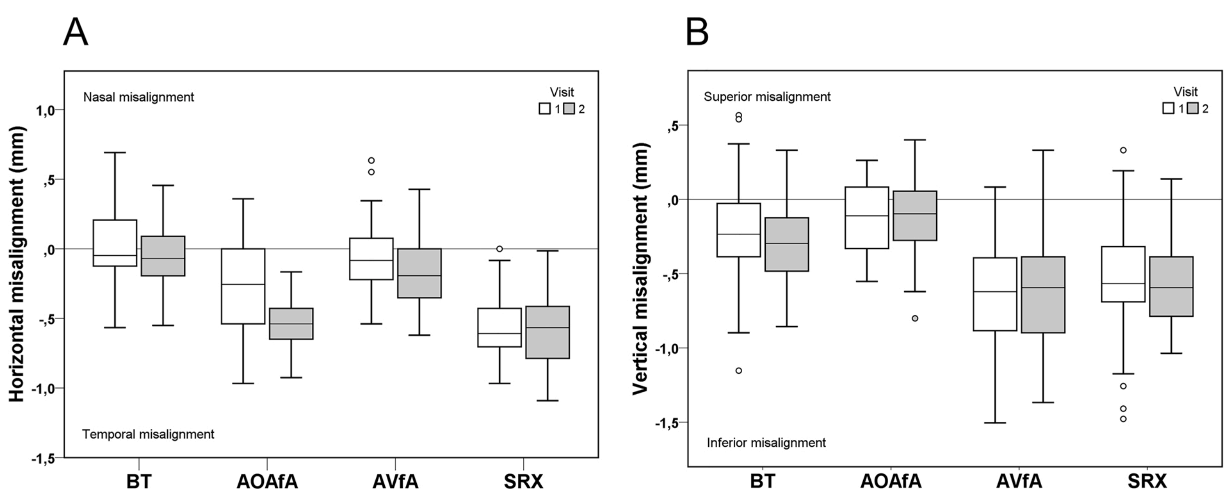

Fig. 3. Contact lens center misalignment relative to the pupil-center on the horizontal axis (A) and the vertical axis (B). BT, Biofinity Toric; AOAfA, Air Optix Aqua for Astigmatism; AVfA, Acuvue Vita for Astigmatism; SRX, Saphir RX.

Table 4
LogMAR Visual Acuity (±SD) on Dispensing Visit (1) and Follow-up Visit (2), Comparisons Pair by Pair, and Statistical Significance Between All Lens Types.

	Mean ± SD					
Visit	BT (1)	AOAfA (2)	AVfA (3)	SRX (4)	Comparisons Pair by Pair	*P*
1	−0.01 ± 0.09	0.02 ± 0.18	0.00 ± 0.18	0.07 ± 0.18	1 > 4[b]; 3 > 4[b]	<0.017[a]
2	−0.01 ± 0.12	−0.03 ± 0.14	−0.01 ± 0.26	0.08 ± 0.25	1 > 4[b]; 2 > 4[b]; 3 > 4[b]	<0.048[a]

BT, Biofinity Toric; AOAfA, Air Optix Aqua for Astigmatism; AVfA, Acuvue Vita for Astigmatism, SRX; Saphir RX.
[a] Kruskal-Wallis test.
[b] Mann-Whitney *U* test.

were significant correlations for 1) BT, between palpebral aperture and absolute horizontal misalignment ($r=-0.424$, $P = 0.004$), and between cylinder power and recovery time ($r=-0.299$, $P = 0.044$); 2) AOAfA, between cylinder power and absolute orientation position ($r=-0.361$, $P = 0.016$), and between visual acuity and orientation position ($r = 0.310$, $P = 0.041$); and 3) SRX, between cylinder power and vertical misalignment ($r=-0.308$, $P = 0.047$). In the follow-up visit, there were significant correlations for 1) BT, between horizontal visible iris diameter and absolute horizontal misalignment ($r=-0.342$, $P = 0.02$), and between visual acuity and horizontal misalignment ($r = 0.341$, $P =$

0.019); 2) AOAfA, between horizontal visible iris diameter and absolute orientation position ($r = 0.405$, $P = 0.006$), and between visual acuity and horizontal misalignment ($r = 0.375$, $P = 0.010$); 3) AVfA, between horizontal visible iris diameter and absolute horizontal misalignment ($r=-0.403$, $P = 0.01$); and 4) SRX, between palpebral aperture and recovery time ($r = 0.311$, $P = 0.048$), between sphere power and horizontal misalignment ($r = 0.327$, $P = 0.034$), and between visual acuity and orientation position ($r=-0.311$, $P = 0.048$).

Taken together, the contact lenses showed significant correlations for horizontal misalignment ($r = 0.217$, $P = 0.043$) and absolute orientation position ($r = 0{,}259$, $P = 0.015$), respictevily, for the dispensing and follow-up visits.

3.6. Inter-session differences

When dispensing and two-week follow-up visits data were compared, the independent-sample *t*-test revealed significant differences only for AOAfA lenses in horizontal (Fig. 3A), absolute horizontal misalignment ($P < 0.001$), and orientation position ($P = 0.02$) (Fig. 1A); and the Mann-Whitney *U* test showed significant differences only in visual acuity (P = 0.003) for AOAfA contact lenses.

4. Discussion

The results of this study demonstrate the implications of toric silicone-hydrogel contact lens design in dynamic and static contact lens behavior. These findings can provide valuable insights to clinicians in contact lens fitting, decreasing procedure time, increasing visual acuity, comfort, visual stability, and contrast sensitivity of toric contact lens wearers.

4.1. Previous studies

Young et al. [11] found the lowest and the highest decentration for prism-ballast lenses (0.4 ± 0.4 and 1.0 ± 0.8), using two prism-ballast, one modified peri-ballast, one double slab-off designs, and a 0–3 misalignment scale. Furthermore, the modified peri-ballast lenses achieved the lowest absolute misorientation (6.0 ± 6.2 deg) and prism-ballast lenses with the highest value (16.3 ± 15.3 and 19.5 ± 12.7 deg), while recovery time showed no significant differences.

Tan et al. [19] found the lowest lens misorientation for two prism-ballasted designs (3 ± 11 deg), and highest for prism-ballast (15 ± 13 deg), while peri-ballast and dynamic stabilization types achieved comparable values. Furthermore, one prism-ballast and one double slab-off lenses presented temporal rotation, while the remaining contact lenses showed nasal misorientation. After 30 degrees of manual temporal misorientation and ten blinks, the lowest misorientation was found for the double slab-off lens (−1 ± 5 deg), and highest for a prism-ballast design (11 ± 3 deg), while the remaining contact lenses showed values between 4 and 9 deg.

Momeni-Moghaddam et al. [20] found the lowest misorientation for the peri-ballast lens (2.25 ± 4.12 deg) and the highest for one prism-ballast lens (8.75 ± 8.56 deg). The peri-ballast lens showed the lowest temporal recovery time (28.50 ± 16.53 s), and the double slab-off lens (94.20 ± 64.95 s) reached the highest. In agreement with Young et al. [11] suggested that subject-related factors with lid anatomy, such as palpebral aperture, tightness, and lids position could be associated with contact lens behavior.

Zikos et al. [21] found that a prism-ballast lens showed temporal rotation (−1.08 ± 4.90 deg), while a double slab-off design lens presented nasal rotation (5.59 ± 7.98 deg).

Jin et al. [22] analyzed the performance of one prism-ballast lens according to eye parameters and found significant correlations between palpebral aperture and orientation position (r = 0.39, $P = 0.03$), between horizontal visible diameter and routine fitting assessments (r=−0.60, $P < 0.001$), between sphere lens power and recovery time (r=0.36, $P = 0.04$), and between cylinder lens power and routine fitting assessments (r=−0.41, $P = 0.02$). In agreement with other researchers noted that refractive errors, horizontal visible iris diameter, corneal topography, lens-related factors, movement after the blink, lens modulus, and stabilization design may handicap contact lens fitting [11,21,23].

4.2. Present study

This research assesses different static and dynamic parameters of four different stabilized toric silicone-hydrogel contact lenses, in two-time different moments, after two weeks of contact lens wear. The results showed that the lens stabilization method and the design parameters can affect misalignment, orientation position, recovery time, and visual acuity [20,22].

4.2.1. Contact lens misorientation and recovery

Modified peri-ballast stabilization design of AOAfA presented the lowest absolute misorientation, in agreement with Young et al. [11]. In addition, the peri-ballast of BT and slab-off design of AVfA showed no significant differences, and the prism-ballast design of SRX achieved the highest rotation, which is not in agreement with Momeni-Moghaddam et al. [20] findings. The temporal misorientation of SRX (prism-ballast) and nasal rotation of AVfA lens (double slab-off) are similar to the results of Zikos et al. [21] and are contrary to the findings of Tan et al. [19]. The differences in orientation position of current and previous studies [11,20], are probably due to the use of customized-power lenses, instead of single-power lenses.

Peri-ballast designs, BT and AOAfA, respectively, showed the lowest recovery time values, while slab-off and prism-ballast achieved the highest values. These results agree with Momeni-Moghaddam et al. [20] and are similar to Young et al. [11] findings, despite this fact, Young et al. found no statistically significant differences between different lens designs. The current study presents discrepancies with Tan et al. [19], who obtained the lowest recovery time for double slab-off lenses, with no statistical differences between peri-ballast and prism-ballast designs. These differences are probably due to the sample characteristics, different contact lens materials, designs, and single-power lenses used in previous studies concerning the current study. Additionally, Tan et al. rotated the lens 30 degrees temporally instead of 45 degrees in the present study.

4.2.2. Contact lens decentration effect

Lens center misalignment can affect different visual outcomes such as visual acuity, binocular vision, visual stability, lens movement, comfort, and presence of limbal trauma [24]. The horizontal misalignment was temporal in all lenses, except for BT, approximately null, probably due to a flattering nasal portion compared to the other quadrants [25,26]. Likewise, all toric contact lenses tend to decenter down, especially with SRX.The two peri-ballast lenses presented lower center misalignment, in agreement with Young et al. [11]. The high SRX displacement could be because of the gravity effect on prism-ballast design [8], thickness profile, manufacturing process, or the personalized base curve of each lens. The AVfA vertical misalignment is probably explained by the slab-off design and the dynamic force squeezing pressure exerted by the upper eyelid [10,27].

It is well known that toric soft contact lenses tend to decenter temporal and inferior as can be seen in the results of this study. Research often attribute this misalignment mainly to the height differences of the cornea and sclera [28]. Usually, the temporal cornea is steeper than the nasal cornea and the nasal sclera is higher than the temporal one [25,26]. Similarly, the inferior sclera tends to be lower than the superior sclera. While corneal and scleral height plays a significant role in lens decentration, the upper lid could as well contribute, but there is not a consensus on the role of the upper lid in toric soft contact lens misalignments. Cui et al. [29] and Young et al. [11] suggested a direct correlation between upper lid proximity to the globe and the resistance to move the eyelid, and consequently, contact lens wearers with greater superior lid tension have more inferior decentration. However, nowadays no studies are comparing upper lid tension and soft contact lens misalignment. On the other hand, polymer properties and design also could be related to toric contact lens behavior [30]. In this way, the selection of the base curve or sagittal height may have some influence. Usually steeper corneas have a greater sagittal height, requiring a lens with a greater sagittal depth, therefore a steeper base curve [28]. In this study, only the SRX lens allowed a selection of base curve, following the guidelines of the manufacturer. Surprisingly, this lens showed the highest displacement and worst recovery time, probably due to the lens design or manufacturing process. The sagittal height is not only related to corneal curvature, it is also associated with corneal asphericity, corneal diameter, and curvature of the corneoscleral area. Conversely, the peri-ballast lenses, with the lowest sagittal height, showed lower center misalignment and recovery time compared to the slab-off lens, which presented the highest sagittal height. This could mean that the global sample had a flatter corneal profile, and thus the more flat and thicker lenses showed a better fitting than the more steep and thinner lens (AVfA). All of these aspects have a fitting influence and should be considered in the selection of the definitive contact lenses for each patient.

4.2.3. Contact lens orientation, misalignment, and visual acuity

The lenses with lower misorientation, AOAfA, and BT, showed higher visual acuity and probably due to the lower crossed cylinder effect concerning the physiologic cylinder of the eye [16,18]. Furthermore, the lenses with lower misalignment showed better visual acuity, this could be explained by the mismatch between optical center and line of sight. Although the optic zone of the lenses is large enough to provide a good-quality image, lenses with a better fitting profile showed high-quality vision, while the worst fitting profile of SRX lenses caused a significant visual acuity loss.

4.2.4. Correlations with ocular parameters and visual acuity

Different results were found for dispensing and follow-up visits, this could be explained by the eye surface or contact lens mechanical changes after two weeks of wear [25,30–32]. The few weak and moderate correlations found along the contact lens designs seem to be not decisive to establish a correlation between analyzed variables and horizontal visible iris diameter, palpebral aperture, or lens power. These results are consistent with those observed in other studies [19,23,27]. These findings are not in agreement with Young et al. [11,33] and Momeni-Moghaddam et al. [20] suggestions, and showed several differences with the results of Jin et al. [22] probably due to the ethnicity of subjects, lens, and study design differences. Visual acuity presented weak correlations with orientation position and horizontal misalignment for all lenses taken together, becoming stronger when are analyzed separately. This is probably due to the crossed cylinder effect of misoriented lenses and the mismatch between the contact lens and eye optical centers, respectively.

4.2.5. Inter-session differences

The dispensing and two-week follow-up visit differences are probably explained by the not enough changes of corneal topography, contact lens properties, or palpebral mechanics for all lenses, except for AOAfA. Surprisingly, the AOAfA increases significantly its mean visual acuity between the first and second visits. This behavior is probably due to the high modulus and corneal reshape over time, which modifies lens centration and rotation [10,30,31].

4.2.6. Limitations

There are possible limitations to this research. The high proportion of females present in the current study is consistent with other previous studies and is explained by the asymmetry present in the contact lens real market [15,22,33]. Additionally, the use of a few contact lens models instead of more, and further materials with different modulus or water content could help to improve the results. Further studies should be conducted to determine the relationship between toric soft contact lens materials and designs with visual implications and eye parameters, unlike eyelid characteristics. Moreover, an additional dynamic analysis could explain the visual acuity differences between contact lens types.

In conclusion, when different toric silicone-hydrogel contact lens designs are compared, the modified peri-ballast and thickness profile present in AOAfA helps reduce lens rotation and vertical misalignment, and the peri-ballast design of BT improves rotational recovery and minimizes horizontal decentration compared to prism-ballast or double slab-off methods. In addition, lenses with a better fitting profile showed better visual performance. These results reflect that contact lens design and material properties can be decisive to determine the final toric soft contact lens fitting.

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Declaration of Competing Interest

The authors report no declarations of interest.

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