



Exploring the links between contact lens comfort, osmolarity and lid wiper staining



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ABSTRACT

Purpose: Contact lens discomfort remains poorly understood, not least due to lack of associations between clinical signs and symptoms. This study aimed to explore the relationships between osmolarity, comfort and lid wiper epitheliopathy in contact lens wear.

Methods: Twenty subjects participated in a randomized, cross-over study where comfilcon A and lotrafilcon A lenses were each worn for 10 days separated by a 7 days washout period. Tear and contact lens osmolarity, ocular symptoms including comfort, tear stability and production, and lid wiper epitheliopathy were measured. **Results:** Comfort and tear stability decreased and upper lid wiper staining and foreign body sensation increased with lens wear. These were not affected by lens type. A reduction in tear production was seen after 10 days of comfilcon A lens wear. High proportions of lid wiper epitheliopathy were observed at the upper (range 65%–85%) and lower (range 90%–100%) lid margins. Tear and contact lens osmolarity were unaffected by lens wear or type. Contact lens osmolarity was associated with comfort ($r = 0.45$, $p = 0.009$). Tear osmolarity moderately correlated with tear stability ($r = -0.53$, $p = 0.014$) and tear production ($r = -0.44$, $p = 0.012$) but not with lid wiper staining.

Conclusions: A relationship between comfort and contact lens osmolarity and between tear osmolarity and tear stability and production were found, however, this study was unable to demonstrate an association between comfort and tear osmolarity or lid wiper epitheliopathy. Further studies using contact lenses with a wider range of comfort responses are warranted to investigate these associations further.

1. Introduction

Contact lens wearers are much more likely to report discomfort than spectacle wearers and non wearers (emmetropes) [1–6], with dryness being the most commonly reported symptom [7]. The ocular symptom “end of day dryness” is most particularly noticed in contact lens wearers [1,3,5] and discomfort due to dryness remains the single largest cause of discontinuation of contact lens wear [8,9]. The underlying causes of contact lens discomfort, however, remain poorly understood, not least due to lack of associations between clinical signs and symptoms of the condition [10–16].

Understanding of the etiology of contact lens discomfort is limited [17,18]. The lid margin contains stratified squamous epithelial cells [19,20]. An alteration of those epithelial cells, staining with fluorescein, rose bengal or lissamine green, has been coined lid wiper epitheliopathy [21,22]. Lissamine green is a synthetic acidic organic food dye, recommended for visualising damage to the ocular surface [23–25]. Lissamine green shares a similar staining profile to rose bengal

in dry eye [26], however it's improved tolerability may make it favourable in clinical practice. Upper lid margin staining (lid wiper epitheliopathy) has been identified as a sign which is more prevalent in symptomatic contact lens wearers and in dry eye patients than their asymptomatic counterparts [22,27–32]. Although lower lid wiper staining is more frequently observed than upper lid wiper staining in non wearers [33], its relevance to contact lens discomfort is uncertain. Such lid wiper staining must be differentiated from the narrow Marx's line that normally stains on lower and upper lids [34–36]. Visualisation of the line is most evident with lissamine green, as the green dye is vivid amongst the pink hue of the tarsal conjunctiva. The frequency of contact lens discomfort mandates further research into lid wiper staining in contact lens wearers, given the potential high diagnostic yield. To date, very few studies have investigated lid wiper staining during lens wear or specifically examined links between signs and symptoms of contact lens discomfort [37–39].

Similarly, tear osmolarity measured in situ [40] has in recent years been suggested to have the best ability to detect, classify and monitor

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dry eye disease [41–43]. Elevated tear osmolarity is thought to cause stress to the ocular surface and induce an inflammatory cascade, and has also been shown to negatively affect ocular surface cells [44–46]. Symptomatic contact lens wearers often present with a hyperosmolar tear film [47,48]. Elevated contact lens osmolarity has also been associated with decreased comfort [49]. There remain conflicting results as to tear osmolarity's correlation with the other signs and symptoms of dry eyes and its ability to accurately detect dry eye disease. Further evidence is needed to support the association between osmolarity and contact lens discomfort.

Considering the findings described above together, it was proposed that a relationship between tear and contact lens osmolarity, contact lens comfort (or discomfort), and surface damage to the upper lid wiper region may exist. The aim of this study was therefore to explore the relationships between osmolarity (tear and contact lens), ocular symptoms and lid wiper staining. More specifically, the hypotheses of the study were that (1) upper lid wiper staining will be associated with increased contact lens and tear osmolarity; (2) upper lid wiper staining will be associated with increased contact lens discomfort; and (3) increased contact lens and tear osmolarity will be associated with increased contact lens discomfort.

2. Methods

A prospective double-masked cross-over randomised clinical study was designed where participants wore two lens types. Each lens type was worn bilaterally for a period of 10 days. For lid wiper staining, a standard deviation of 0.7 grade and a clinically relevant effect size of half a grade yielded a calculated sample size of 17. Similarly, a standard deviation of 50 mmol/kg and a clinically relevant effect size of 50 mmol/kg yielded a sample of 10 for contact lens osmolarity. Based on this, a sample size of 20 was determined to be sufficient to demonstrate differences both in lid wiper staining and in contact lens osmolarity, with an allowance for dropouts. Twenty participants wore lotrafilcon A (24% water content, 8.6 mm basecurve, 13.8 mm diameter, DK 140; CIBA Vision, Duluth, GA) and comfilcon A (48% water content, 8.6 mm basecurve, 14.0 mm diameter, DK 128; Cooper Vision, Pleasanton, CA) bilaterally for 10 days each, with a seven day washout period before each lens type. The lens materials above were chosen based on prior findings [49] to maximise the range of contact lens osmolarity used for this study. In this previous study, the contact lens osmolarity of lotrafilcon A was highest of eight lenses at 386 mmol/kg; comfilcon A was chosen as the second material for this study based on its higher water content and expected lower contact lens osmolarity.

Inclusion criteria comprised a vision correctable with contact lenses. Participants were not screened for a history of prior symptoms of ocular discomfort (with or without contact lenses), as this was not an exclusion criterion for the study. However, participants were excluded if they required the use of any ocular eye drops other than unit dose saline rewetting drops during the study period or if they had any contraindications to contact lens wear or had worn lenses in the past seven days. Some participants were therefore occasional or past contact lens wearers that may have previously experienced contact lens discomfort; all participants refrained from lens wear for at least seven days prior to commencing the study. Participants were required to attend the clinic for three visits: one initial visit, one follow-up visit after the first lens wear period, and one follow-up visit after the second lens wear period. At the initial visit, baseline measurements were collected and trial contact lenses of the two lens materials involved in the study fitted, placed in identical containers by a study coordinator not involved in the data collection and marked as pair "1" and "2" according to a computer generated random code. Participants were dispensed with their first pair of lenses according to randomisation and instructed to wear lenses for a minimum of eight hours per day and for up to 10 days. Participants were instructed to remove, clean, store and disinfect their lenses daily with AOSept[®] Plus (CIBA Vision, Duluth, GA). Unit dose

saline was provided for rinsing prior to insertion if needed. Participants were discouraged from using saline for rewetting purposes, and had to stop any usage at least 2 h prior to their follow-up visit. To ensure participants adhered to the 7-day washout period, participants were required to collect their second pair of lenses after the wash-out period.

Participants were instructed to wear their lenses when attending their follow-up visits (visits 2 and 3). The baseline and follow-up visits were conducted at approximately the same time in the afternoon to minimize differences in measurements due to diurnal variations. Comfort, dryness, foreign body sensation and burning/stinging were assessed at baseline and prior to lens removal at the follow-up visits using a numerical rating scale and the question "Please rate the following sensation on a scale from 1 to 100, where 1 represents severe sensation and 100 represents perfect or no sensation at all". Lens awareness was assessed using the same scale at the follow-up visits only.

Tear film osmolarity was measured using an in situ osmometer (TearLab[™] Osmolarity System (TearLab Corporation, San Diego, CA)). Participants were asked to look up and care was taken not to pull the eyelid so as to not break the tear lake. Tear stability was assessed non-invasively using a handheld Keeler Tearscope-plus (Keeler, Windsor, Berkshire, United Kingdom) in conjunction with a slit lamp biomicroscope as previously described [50]. To measure non-invasive tear film break-up time for the precorneal (baseline visit) and prelens (follow-up visits) tear film, subjects were asked to blink twice normally and then to keep their eyes open until the first spot of drying could be observed. Tear film stability was measured as the time (in s) between the last blink and the first random tear break-up or discontinuity in the tear film. Tear film production was assessed using the phenol red thread test (Zone Quick, Showa Yakuhim Kako Ltd, Japan) as previously described [51]. Subjects were instructed to look upwards and blink normally throughout the test. Gently pulling the lower lid away from the ocular surface, the bent part of the thread was placed underneath the lower lid approximately 1 mm from the temporal fornix. A stopwatch was used to measure 15 s, after which the lower lid was gently pulled down and the thread removed. Tear production was recorded as the length of the thread (including the 3 mm bend) that had changed colour from the original yellow to red after 15 s. These measurements were conducted with the contact lenses in place.

Contact lens osmolarity was measured indirectly using a vapour pressure osmometer (Vapro[®] Wescor (5520), Inc. Logan, Utah, USA) and previously described methods [49]. Briefly, contact lenses were removed with gloves, weighed on an electronic balance and placed in 200 mL of phosphate buffered saline with an osmolarity of 100 mmol/kg. The difference in contact lens weight between after removal from the eye and after 16 h of dehydration in an oven at 105 °C, and the contact lens induced change in the equilibrating solution over two hours was used to calculate contact lens osmolarity.

The in situ osmometer used to determine tear film osmolarity measures the "osmolarity" of a sample, with the units expressed in milliosmoles per liter, whereas the vapour pressure osmometer used to determine contact lens osmolarity measures "osmolality", with the units expressed in millimoles per kilogram. The difference in osmolarity and osmolality is minimal [40,52] and thus, for clinical purpose in the context of this study, the two terms can be considered equivalent. The term "osmolarity" has been used for maintaining consistency.

Staining of the upper and lower lid wiper was assessed following contact lens removal, using OPGreen lissamine green strips (Ophthalmics Unlimited, India). A solution was prepared by dipping a pre-impregnated strip for one minute in 200 µL of sterile saline (0.9% NaCl, Astra Zeneca, NSW, Australia) as previously described [33,34]. A standardised 40 µL volume of the resulting lissamine green solution was instilled into the lower conjunctival sac of each eye using a calibrated micropipette and sterile tips. This corresponds to a lissamine green solution with a concentration of approximately 3.5% [34]. Patients were instructed to gently close and rotate their eyes. Upper and lower lid staining were graded using a simplified, previously validated, single

scale where 0 = no staining, 1 = mild staining, 2 = moderate staining, and 3 = severe staining in 0.5 steps, which was termed “subjective rating” [34]. In a previous study involving 22 patients, lid margin staining was graded by a single experienced investigator using Korb’s grading scale where length and width gradings were averaged [21,22], as well as with the simplified rating scale described above; gradings were conducted in a masked fashion on digital photographs at the conclusion of data collection [34]. Use of a simple subjective rating yielded similar results to that of the Korb’s scale [21,22,53], justifying its adoption as a method of collection for this study. It was necessary to evert the upper lid and gently pull out the lower lid to assess staining.

All procedures were in accordance with the Helsinki Declaration of 1975, as revised in 2013. Ethics approval was obtained from the institutional ethics committee and informed consent from all participants prior to conducting the study. Statistical analysis was carried out using SPSS for Windows Version 22 (SPSS for Windows, Chicago, IL). For tear osmolality, the measurement from the eye with the highest value was used because intereye variability has been found to be associated with an increased severity of dry eye [41]. For all other variables, data from the two eyes of each participant were averaged. Data were tested for normality of distribution using Shapiro-Wilk after testing after outliers. Outliers were identified through the calculation of z-scores and application of a 99% confidence interval. In the case of removal of an outlying data point, removal was applied to that specific variable only, and not to the subject’s complete visit data. Repeated-measures ANOVA were conducted to look for the effect of lens type and time on ocular symptoms, osmolality (tear and contact lens), and tear stability and production. Friedman test was used to look for the effect of lens type and time on upper and lower lid wiper staining grade. P-values were adjusted for multiple testing. Associations between ocular comfort and tear film osmolality and other variables were tested using linear mixed model ANOVA to adjust for intra-subject correlation. Each covariate was tested individually and visit was used as a factor to account for differences between visits (differences between lens wear and no lens wear and between lens types). Similarly, to explore the associations between contact lens osmolality and other variables, linear mixed model ANOVA was used, with contact lens osmolality as the dependent variable. Again, each covariate was tested individually. R values were calculated using the slope of the covariate and the standard deviations of the dependent variable and the covariate obtained from the linear mixed model. Statistical significance was set at 5% for each test variable.

3. Results

Fifteen females and 5 males aged 29.1 ± 4.8 years old were enrolled and completed the study. No adverse events occurred during the study period and no discontinuations of lens wear or major breaches of protocol were reported. The median and interquartile ranges for ocular symptoms at the baseline visit and with each lens type are shown in Fig. 1. Compared to no lens wear baseline, lens wearers reported a significant decrease in comfort (baseline 91 ± 13 , lotrafilcon A 81 ± 19 , comfilcon A 83 ± 16 ; $p = 0.03$) and an increase in foreign body sensation (baseline 96 ± 10 , lotrafilcon A 90 ± 10 , comfilcon A 85 ± 15 ; $p = 0.04$) after 10 days wear. However, there were no differences in subjective ratings between lens types for comfort ($p = 0.38$), foreign body sensation ($p = 0.23$), or lens awareness ($p = 0.50$). Lens wearers also reported no significant changes in dryness ($p = 0.44$) or burning/stinging ($p = 0.14$) compared to no lens wear baseline or between lens types ($p > 0.05$).

The mean and standard deviations for tear variables and contact lens osmolality at baseline and with each lens type are shown in Table 1. There was no effect of lens wear on tear film osmolality, and both, contact lens osmolality ($p = 0.16$) and tear film osmolality ($p = 0.63$) were independent of lens type (Table 1). Tear stability was significantly reduced by lens wear ($p < 0.001$) but there was no effect

of lens type ($p > 0.05$). Tear production was significantly reduced during wear of comfilcon A lenses compared to baseline or lotrafilcon A values ($p = 0.01$).

The median and interquartile ranges for lid wiper epitheliopathy (upper and lower) at the baseline visit and with each lens type are shown in Fig. 2. Upper lid staining or lid wiper epitheliopathy increased significantly during daily wear of lotrafilcon A and comfilcon A lenses ($p < 0.05$) (Fig. 2). Whilst lower lid staining was more pronounced than upper lid staining at baseline, it did not significantly change with lens wear ($p = 0.31$). Lens type did not impact the levels of lid wiper epitheliopathy seen during lens wear ($p > 0.05$). All participants displayed lower lid margin staining in one or both eyes at both the lens wearing visits and all but one participant had lower lid staining at the baseline visit. Six participants (30%) had no upper lid staining or lid wiper epitheliopathy at the baseline visit whilst only 3 (15%) and 1 (5%) participant had no upper lid staining following 10 days wear of comfilcon A and lotrafilcon A lenses, respectively.

Associations between variables were tested using a linear mixed model to account for intra-subject correlations and the effects of lens wear and lens type. Calculated r values and p-values are shown in Table 2. There were no associations between ocular comfort and upper (Fig. 3, right) or lower lid wiper staining, or any tear film variables (Table 2). Contact lens osmolality was positively associated with ocular comfort ($r = 0.45$, $p = 0.009$, Fig. 3 left) but not with upper or lower lid wiper staining or any tear variables (all $p > 0.05$). There was no association between tear film osmolality and upper (Fig. 4, top left) or lower lid wiper staining (all $p > 0.05$), however, tear osmolality was negatively correlated with tear stability ($r = -0.53$, $p = 0.014$) (Fig. 4, top right) and tear production ($r = -0.44$, $p = 0.012$) (Fig. 4, bottom left).

4. Discussion

Contact lens discomfort was recently defined as “a condition characterised by episodic or persistent adverse ocular sensations related to lens wear, either with or without visual disturbance, resulting from reduced compatibility between the contact lens and the ocular environment, which can lead to decreased wearing time and discontinuation of contact lens wear” by the Tear Film and Ocular Surface Society (TFOS) Workshop on Contact Lens Discomfort [18]. Accordingly, contact lens wear was associated with a significant reduction in comfort and increased symptoms of foreign body sensation in this study (Fig. 1). This agrees with the bulk of the published contact lens literature [17]. The TFOS Workshop also proposed that contact lens discomfort be classified into discomfort that can be attributed to contact lens factors or environment factors [18]. The chosen design allowed for investigation of the interactions between the contact lens factors “material”, “design” and “fit” (including contact lens osmolality) and the environment factors “ocular environment” (including lid wiper staining and tear osmolality) and contact lens discomfort, albeit with more than one parameter modified by the lens change from comfilcon A to lotrafilcon A at the one time.

An association between lid wiper staining and osmolality or contact lens discomfort could not be demonstrated in this study. Whilst upper lid staining increased during lens wear (Fig. 2), there were no differences between lens types with regards to upper lid staining, contact lens discomfort or tear osmolality (Table 1). To the best of our knowledge, this is the first prospective longitudinal cohort evaluation of the effect of lens wear on lid wiper staining. This study involved wear of two silicone hydrogel lenses that differed in more than one parameter, with different water content, dehydration, ionicity, centre thickness, oxygen transmissibility, wettability, modulus, hysteresis and friction coefficient [54,55]. It appears, however, that these differences in the inherent properties of the material did not equate to marked differences in the lid wiper staining appearance and that soft lens wear of any type may lead to significant increases in upper lid wiper staining. The high proportion of participants already displaying lid wiper staining at the

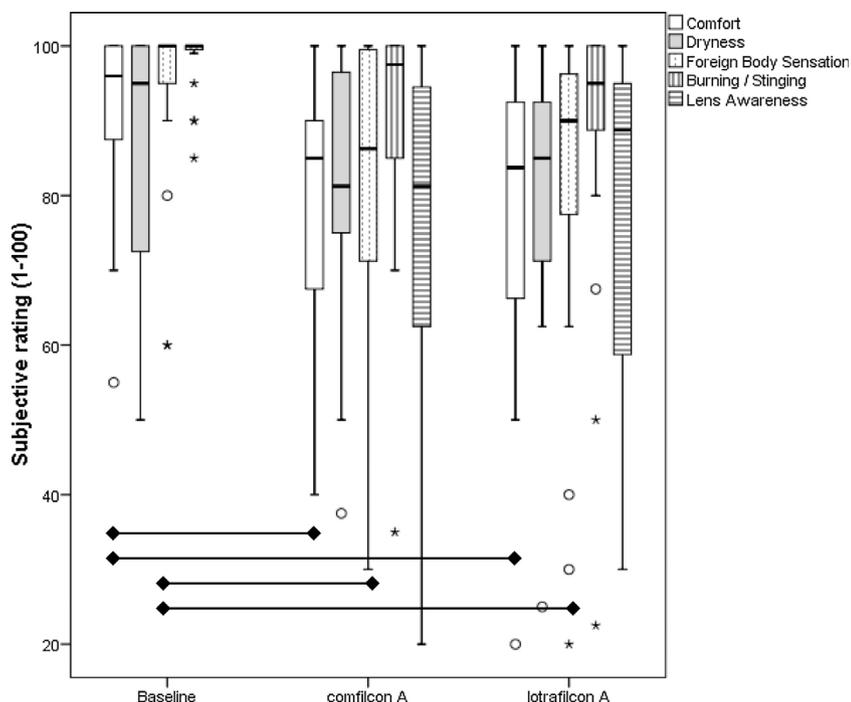


Fig. 1. Effect of lens wear on the ocular symptoms comfort (white bars), dryness (grey bars), foreign body sensation (dotted bars), burning/stinging (vertical patterned bars) and lens awareness (horizontal patterned bars) using a 1–100 subjective rating scale where 1 = severe sensation and 100 = perfect or no sensation at all. Horizontal lines indicate significant differences attributable to lens wear ($p < 0.05$). Comfort decreased and foreign body sensation increased ($p < 0.05$) following 10 days wear of lenses. There were no differences between the two lens types in any symptoms including lens awareness ($p > 0.05$). Baseline measurements were conducted prior to any lens wear, following a 7 days wash-out period.

Table 1
The effect of lens wear on tear characteristics and contact lens osmolarity.

	Baseline	Comfilcon A	Lotrafilcon A	p-value
Tear osmolarity (mOsmol/L)	296.7 ± 9.4	296.8 ± 9.8	299.1 ± 10.4	0.63
Tear stability (seconds)	15.5 ± 5.9*†	9.9 ± 5.5*	7.5 ± 3.1†	< 0.001
Tear production (mm)	21.6 ± 5.7†	17.4 ± 6.0*†	19.9 ± 7.5*	0.01
Contact lens osmolarity (mmol/kg)	n/a	346.5 ± 40.1	375.2 ± 75.0	0.16

* and † indicate significantly different variables after post-hoc testing.

non lens wearing baseline visit (70%) may have somewhat restricted the study’s ability to demonstrate a change during lens wear, although increases in the level of upper lid wiper staining should still have been detectable. A study involving 365 daily wearers of six types of soft or rigid gas permeable contact lenses similarly could not demonstrated any effect of lens type on upper lid staining [37]. Similarly, lens type had no effect on lid staining patterns in a study involving 40 participants wearing each of two lens types [39]. Conversely, a study of 236 participants found that lid staining was frequent, seen in 85% of habitual soft lens wearers, and could be impacted by lens type but not lens care solution [38]. A relationship between contact lens discomfort and lid staining could not be demonstrated in the same study [38]. Intrinsic patient related factors such as contact lens deposition may also have had an impact [54]. Shearing stress generated by inadequate lubrication between the region of the upper lid that contacts the globe during blink and the ocular surface has been suggested to be the cause of the characteristic lid wiper epithelium staining in non wearers [56]. The findings presented in this study support the notion that wearing of contact lenses further increases such interactions, causing more severe staining. Rewetting agents are increasingly used in contact lens formulations, packaging solutions and eyedrops, in an attempt to prevent drying of the tear film and reduce the likelihood of high surface tension and shear stress between the contact lens and the ocular surface. A study recently showed significant reductions in lid wiper staining during lens wear with use of one type of contact lens wetting eyedrop

(carboxymethylcellulose and hyaluronic acid) but not the other (carboxymethylcellulose only) [37]. Participants in the current study were allowed the use of unit dose saline rewetting drops only and this is unlikely to have had any lasting effect on the surface friction and interactions described above. A moderate correlation ($r = 0.41$) between tear osmolarity and upper lid wiper staining in non wearers has previously been demonstrated [33] but this finding could not be replicated in the present study, even at the baseline visit where no lenses were worn. The study’s sample size may have been insufficient. It is possible that the presence of the contact lens and its effect on the lid wiper region have overridden the previously demonstrated relationship.

This study confirmed the significant impact of wearing contact lenses on tear stability, irrespective of the lens characteristics [50,57–60]. In this study, a decrease in tear production was observed during lens wear but this was significant only for the comfilcon A lenses (Table 1). This is in contrast to the bulk of the published literature which, as recently reviewed by the TFOS Workshop on Contact Lens Discomfort, suggests that tear turnover rate is largely unaffected by contact lens wear [60]. Previously demonstrated differences in tear production between individuals who have different “tolerances” to wear of contact lenses may have confounded the results of this study [61].

The significant relationship previously reported between contact lens discomfort and upper lid wiper staining could not be replicated [28,30,31], even though the study was powered to detect such differences. A recent meta-analysis of the relationship between upper lid wiper staining and contact lens comfort using data extracted from six studies found no association between these two variables [32]. However, the study’s ability to detect differences may have been hampered by the relative lack of difference in the amount of upper lid staining induced by the two lens types used in this research. It is likely that factors such as accumulation of lens deposits and unmeasured differences in material properties of the two lens types used in the study [54] such as water content and lubricity may confound this relationship.

In contrast to the current finding of no change in tear osmolarity during contact lens wear, two recent studies recently reported a possible slight increase in tear osmolarity during lens wear [16,62]. Similarly to this study’s findings, a cross-sectional study comparing 28 tolerant and 16 intolerant contact lens wearers to 34 controls found no

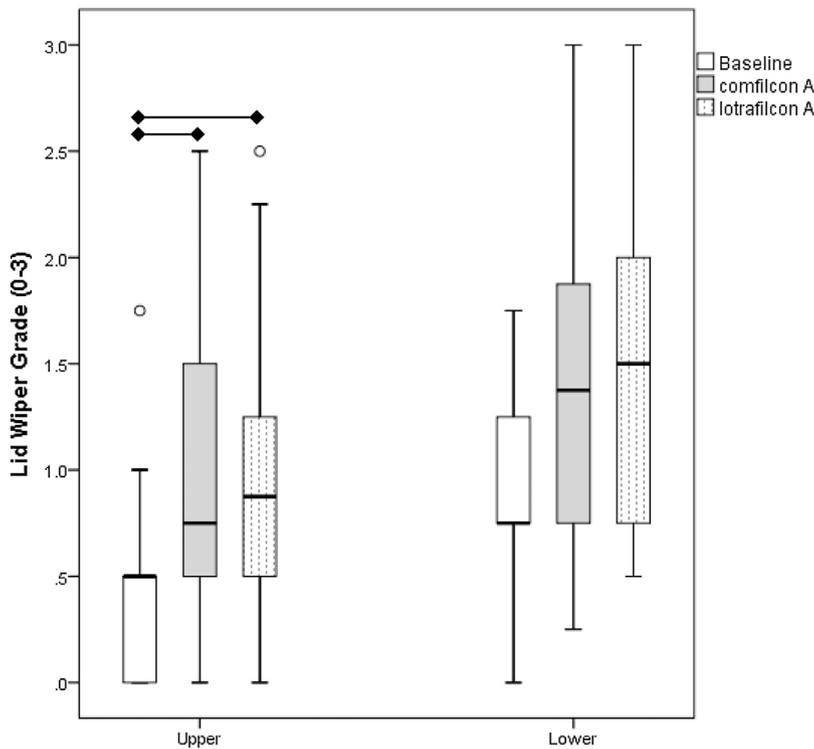


Fig. 2. Upper and lower lid wiper grade (0–3) at baseline (white bars) and after 10 days wear of comfilcon A (grey bars) and lotrafilcon A (dotted bars) lenses. Horizontal lines indicate significant differences attributable to lens wear ($p < 0.05$). Wear of both lens types increased upper lid wiper staining ($p < 0.05$) but there were no differences in effect between the two lens types ($p > 0.05$). Lower lid staining was frequently observed without lens wear and was not significantly impacted by lens wear. Baseline measurements were conducted prior to any lens wear, following a 7 day wash-out period.

Table 2
Associations between comfort, contact lens osmolarity and tear osmolarity and other variables. Associations were tested using linear mixed model. Values listed in bold are significant.

Variable	r	p-value
<i>Associations between comfort and</i>		
Contact lens osmolarity	0.45	0.009
TF osmolarity	-0.13	0.238
Tear stability	0.35	0.056
Tear production	0.01	0.974
Upper lid wiper staining	-0.08	0.593
Lower lid wiper staining	0.11	0.437
<i>Associations between contact lens osmolarity and</i>		
Tear osmolarity	-0.004	0.976
Tear stability	0.011	0.938
Tear production	-0.083	0.486
Upper lid wiper staining	0.006	0.969
Lower lid wiper staining	0.023	0.866
<i>Associations between tear osmolarity and</i>		
Tear stability	-0.53	0.014
Tear production	-0.44	0.012
Upper lid wiper staining	0.02	0.91
Lower lid wiper staining	0.24	0.128

effect of lens wear on tear osmolarity [63], however lens removal one hour prior to tear osmolarity measurements may have confounded these results. The recent TFOS Workshop on Contact Lens Discomfort

highlighted the conflicting reports on the effect of contact lens wear on tear osmolarity currently existing in the published literature [60]. The lack of availability of low tear volume osmolarity instrumentation [40] until very recently may only partially explain these inconsistencies. It has been speculated that regional differences in osmolarity values across the ocular and contact lens surfaces might also be significantly higher [64] than what is measured by the in situ instrument at the tear meniscus. The relationship between tear osmolarity and lens wear warrants further investigation with appropriately designed and powered studies.

In this study, ocular comfort was positively associated with contact lens osmolarity. These findings are unexpected and in contrast to a previous study. In a previous study, a difference in contact lens osmolarity of 50 mmol/kg was required in order to affect the ocular comfort by 5 on a scale from 1 to 100 [49]. The relatively narrow range of contact lens osmolarities reached in this study might have contributed to those results. The study period of 10 days versus the 6 h of wear used in the previous study may also partially explain these differences as factors other than contact lens osmolarity (e.g. accumulation of lens deposits) are more likely to come into play with longer wear time. Further studies using contact lenses with a wider range of contact lens osmolarity and comfort responses are warranted to investigate and clarify these associations further.

Tear osmolarity negatively correlated with tear production and stability in this study. The physical presence of a contact lens in the tear

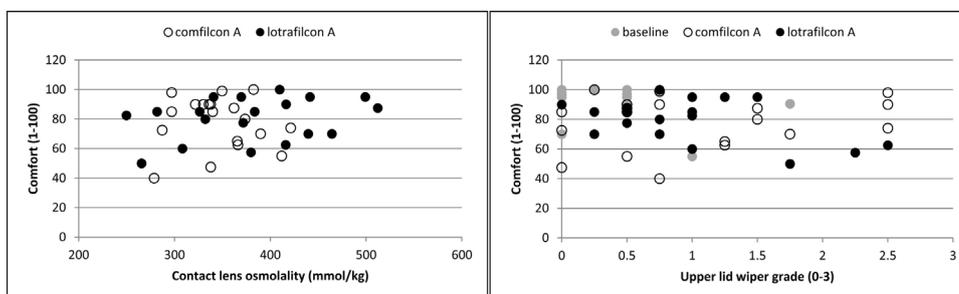


Fig. 3. Associations between ocular comfort and other factors were tested using linear mixed model with lens type as a factor. Contact lens osmolarity (left) was associated with ocular comfort ($p = 0.009$); upper lid wiper staining (right) was not associated with ocular comfort ($p > 0.05$). Refer to Table 2 for correlation values.

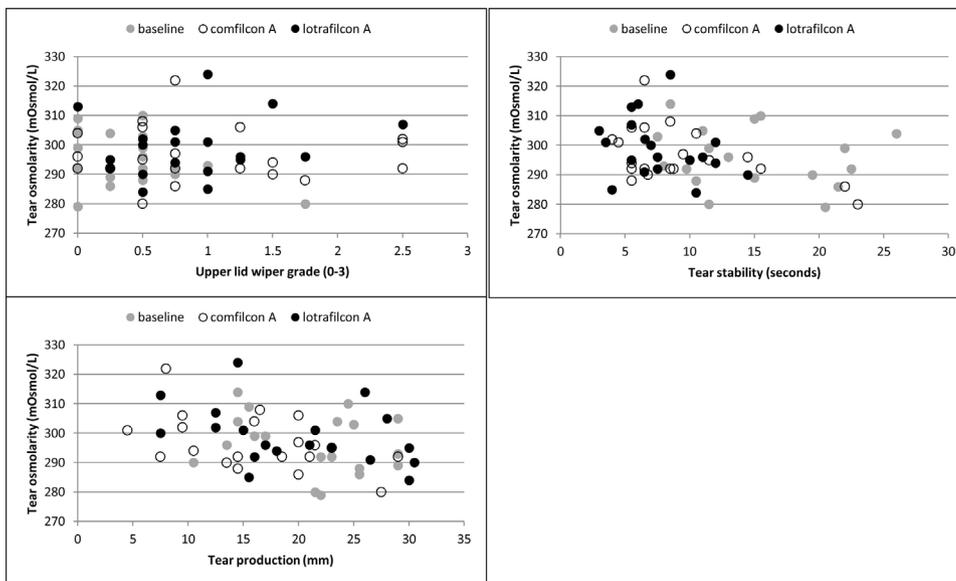


Fig. 4. Associations between tear osmolarity and other factors were tested using linear mixed model with lens type as a factor. Upper lid wiper staining was not associated with tear osmolarity (top left). Tear stability (top right) and tear production (bottom left) were negatively correlated with tear osmolarity ($p < 0.05$). Refer to Table 2 for correlation values.

film is thought to lead to reduced tear production due to reduced corneal sensitivity and excessive evaporation due to a disrupted tear film and reduced tear stability [60]. Excessive evaporation, potentially leading to decreased stability of the tear film and decreased tear production are recognised to cause tear film hyperosmolarity, triggering ocular surface inflammation [65].

In this study, lower lid wiper epitheliopathy was routinely observed with and without lens wear in an overwhelming majority of participants. Similar differences in the frequency of staining of the upper and lower lid wiper have previously been reported in a group of non lens wearers [33] and it was postulated that they were caused by different mechanisms. The findings from the current study support the presence of physiological lower lid staining associated with pooling of tears in the lower lid tear lake leading to prolonged exposure to the dye and any damaging chemicals (e.g. pro-inflammatory cytokines) normally present in the tear film.

This robust study used a double-masked, cross-over, randomized design and aligned with the recommendations on trial design from the TFOS Workshop on Contact Lens Discomfort [66]. A strength of the study was that the potential for the contact lens factors “wear” and “lens care” and of the environment “patient factors” (inherent and modifiable) to impact contact lens discomfort was controlled through the use of the cross-over study design. Validated instruments like the Contact Lens Dry Eye Questionnaire [67] or its short form CLDEQ8 [68] were unavailable at the time the study was carried out and could therefore not be used. For that reason, the possibility that several study participants may not report suffering from “contact lens discomfort” or “episodic or persistent adverse ocular sensations” cannot be excluded, as this was not specifically sampled. Use of a 1 to 100 rating scale as recommended by the TFOS Workshop on Contact Lens Discomfort is nevertheless appropriate [66]. A future study could be strengthened by specifically sampling end of day symptoms of dryness and discomfort, as these have been suggested to play a role in the interaction between the contact lens, its friction characteristics and the lid wiper [28,54]. The contact lens’ impact on tear osmolarity may be regional and require sampling of the tear film at the center of the cornea; this is not possible with the current instrument, with which sampling must occur at the lower tear meniscus.

In summary, although a relationship between a number of signs (tear osmolarity, stability and production) was found, associations between signs and symptoms of ocular discomfort including lid wiper epitheliopathy and contact lens osmolarity remained elusive. However, further studies using contact lenses with a wider range of comfort

responses are warranted to investigate these interactions further.

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References

- [1] J.J. Nichols, C. Ziegler, G.L. Mitchell, K.K. Nichols, Self-reported dry eye disease across refractive modalities, *Invest. Ophthalmol. Vis. Sci.* 46 (2005) 1911–1914.
- [2] C. Vajdic, B.A. Holden, D.F. Sweeney, R.M. Cornish, The frequency of ocular symptoms during spectacle and daily soft and rigid contact lens wear, *Optom. Vis. Sci.* 76 (1999) 705–711.
- [3] C.G. Begley, R.L. Chalmers, G.L. Mitchell, K.K. Nichols, B. Caffery, T. Simpson, et al., Characterization of ocular surface symptoms from optometric practices in North America, *Cornea* 20 (2001) 610–618.
- [4] K. Dumbleton, B. Caffery, M. Dogru, S. Hickson-Curran, J. Kern, T. Kojima, et al., The TFOS International Workshop on Contact Lens Discomfort: report of the subcommittee on epidemiology, *Invest. Ophthalmol. Vis. Sci.* 54 (2013) TFOS20–TFOS36.
- [5] R.L. Chalmers, C.G. Begley, Dryness symptoms among an unselected clinical population with and without contact lens wear, *Cont. Lens Anterior Eye* 29 (2006) 25–30.
- [6] M.J. Doughty, D. Fonn, D. Richter, T. Simpson, B. Caffery, K. Gordon, A patient questionnaire approach to estimating the prevalence of dry eye symptoms in patients presenting to optometric practices across Canada, *Optom. Vis. Sci.* 74 (1997) 624–631.
- [7] C.G. Begley, B. Caffery, K.K. Nichols, R. Chalmers, Responses of contact lens wearers to a dry eye survey, *Optom. Vis. Sci.* 77 (2000) 40–46.
- [8] K. Richdale, L.T. Sinnott, E. Skadahl, J.J. Nichols, Frequency of and factors associated with contact lens dissatisfaction and discontinuation, *Cornea* 26 (2007) 168–174.
- [9] K. Dumbleton, C.A. Woods, L.W. Jones, D. Fonn, The impact of contemporary contact lenses on contact lens discontinuation, *Eye Contact Lens* 39 (2013) 93–99.
- [10] H. Pult, C. Purslow, P.J. Murphy, The relationship between clinical signs and dry eye symptoms, *Eye* 25 (2011) 502–510.
- [11] A. Galor, W. Feuer, D.J. Lee, H. Florez, V.D. Venincasa, V.L. Perez, Ocular surface parameters in older male veterans, *Invest. Ophthalmol. Vis. Sci.* 54 (2013) 1426–1433.
- [12] G. Julio, S. Lluch, G. Cardona, A. Fornieles, D. Merindano, Item by item analysis strategy of the relationship between symptoms and signs in early dry eye, *Curr. Eye Res.* 37 (2012) 357–364.

- [13] K.K. Nichols, J.J. Nichols, G.L. Mitchell, The lack of association between signs and symptoms in patients with dry eye disease, *Cornea* 23 (2004) 762–770.
- [14] B.D. Sullivan, L.A. Crews, E.M. Messmer, G.N. Foulks, K.K. Nichols, P. Baenninger, et al., Correlations between commonly used objective signs and symptoms for the diagnosis of dry eye disease: clinical implications, *Acta Ophthalmol.* 92 (2014) 161–166.
- [15] G. Young, R. Chalmers, L. Napier, J. Kern, C. Hunt, K. Dumbleton, Soft contact lens-related dryness with and without clinical signs, *Optom. Vis. Sci.* 89 (2012) 1125–1132.
- [16] S.P. Chen, G. Massaro-Giordano, M. Pistilli, C.A. Schreiber, V.Y. Bunya, Tear osmolarity and dry eye symptoms in women using oral contraception and contact lenses, *Cornea* 32 (2013) 423–428.
- [17] J.J. Nichols, M.D. Willcox, A.J. Bron, C. Belmonte, J.B. Ciolino, J.P. Craig, et al., The TFOS International Workshop on Contact Lens Discomfort: executive summary, *Invest. Ophthalmol. Vis. Sci.* 54 (2013) TFOS7–TFOS13.
- [18] K.K. Nichols, R.L. Redfern, J.T. Jacob, J.D. Nelson, D. Fonn, S.L. Forstot, et al., The TFOS International Workshop on Contact Lens Discomfort: report of the definition and classification subcommittee, *Invest. Ophthalmol. Vis. Sci.* 54 (2013) TFOS14–TFOS19.
- [19] E. Knop, N. Knop, A. Zhivov, R. Kraak, D.R. Korb, C.A. Blackie, et al., The lid wiper and muco-cutaneous junction anatomy of the human eyelid margins: an in vivo confocal and histological study, *J. Anat.* 218 (2011) 449–461.
- [20] I. Jalbert, M. Madigan, M. Shao, J. Ng, J. Cheng, D. Wong, et al., Assessing the human lid margin epithelium using impression cytology, *Acta Ophthalmol. (Copenh.)* 90 (2012) 547–552.
- [21] D.R. Korb, J.V. Greiner, J.P. Herman, E. Hebert, V.M. Finnemore, J.M. Exford, et al., Lid-wiper epitheliopathy and dry-eye symptoms in contact lens wearers, *CLAO J.* 28 (2002) 211–216.
- [22] D.R. Korb, J.P. Herman, J.V. Greiner, R.C. Scaffidi, V.M. Finnemore, J.M. Exford, et al., Lid wiper epitheliopathy and dry eye symptoms, *Eye Contact Lens* 31 (2005) 2–8.
- [23] M. Norn, Lissamine green. Vital staining of cornea and conjunctiva, *Acta Ophthalmol.* 51 (1973) 483–491.
- [24] D.R. Korb, J.P. Herman, V.M. Finnemore, J.M. Exford, C.A. Blackie, An evaluation of the efficacy of fluorescein, rose bengal, lissamine green, and a new dye mixture for ocular surface staining, *Eye Contact Lens* 34 (2008) 61–64.
- [25] P. Hamrah, F. Alipour, S. Jiang, J.-H. Sohn, G.N. Foulks, Optimizing evaluation of Lissamine Green parameters for ocular surface staining, *Eye* 25 (2011) 1429–1434.
- [26] L.M. Machado, R. Castro, B. Fontes, Staining patterns in dry eye syndrome: rose bengal versus lissamine green, *Cornea* 28 (2009) 732–734.
- [27] M. Berry, H. Pult, C. Purslow, P.J. Murphy, Mucins and ocular signs in symptomatic and asymptomatic contact lens wear, *Optom. Vis. Sci.* 85 (2008) E930–E938.
- [28] D.R. Korb, J.V. Greiner, J.P. Herman, E. Hebert, V.M. Finnemore, J.M. Exford, et al., Lid-wiper epitheliopathy and dry-eye symptoms in contact lens wearers, *CLAO J.* 28 (2002) 211–216.
- [29] D.R. Korb, J.P. Herman, C.A. Blackie, R.C. Scaffidi, J.V. Greiner, J.M. Exford, et al., Prevalence of lid wiper epitheliopathy in subjects with dry eye signs and symptoms, *Cornea* 29 (2010) 377–383.
- [30] H. Pult, P.J. Murphy, C. Purslow, A novel method to predict the dry eye symptoms in new contact lens wearers, *Optom. Vis. Sci.* 86 (2009) E1042–E1050.
- [31] H. Pult, C. Purslow, M. Berry, P.J. Murphy, Clinical tests for successful contact lens wear: relationship and predictive potential, *Optom. Vis. Sci.* 85 (2008) E924–E929.
- [32] N. Efron, N.A. Brennan, P.B. Morgan, T. Wilson, Lid wiper epitheliopathy, *Prog. Retin. Eye Res.* 53 (2016) 140–174.
- [33] B. Golebiowski, K. Chim, J. So, I. Jalbert, Lid margins: sensitivity, staining, meibomian gland dysfunction, and symptoms, *Optom. Vis. Sci.* 89 (2012) 1443–1449.
- [34] N. Delaveris, U. Stahl, M. Madigan, I. Jalbert, Do lissamine green strips from various manufacturers perform equally? *Clin. Exp. Optom.* 94 (2011) 613–614.
- [35] D.R. Korb, C.A. Blackie, Marx's line of the upper lid is visible in upgaze without lid eversion, *Eye Contact Lens* 36 (2010) 149–151.
- [36] M.J. Doughty, T. Naase, C. Donald, L. Hamilton, N.F. Button, Visualisation of Marx's line along the marginal eyelid conjunctiva of human subjects with lissamine green dye, *Ophthalmic Physiol. Opt.* 24 (2004) 1–7.
- [37] J.J. Nichols, C.W. Lievens, M.R. Bloomenstein, H. Liu, P. Simmons, J. Vehige, Dual-polymer drops, contact lens comfort, and lid wiper epitheliopathy, *Optom. Vis. Sci.* 93 (2016) 979–986.
- [38] M.M. Schulze, S. Srinivasan, S.B. Hickson-Curran, D.A. Berntsen, G.F. Howarth, Y. Toubouti, et al., Lid wiper epitheliopathy in soft contact lens wearers, *Optom. Vis. Sci.* 93 (2016) 943–954.
- [39] J. Varikooty, S. Srinivasan, L. Subbaraman, C.A. Woods, D. Fonn, T.L. Simpson, et al., Variations in observable lid wiper epitheliopathy (LWE) staining patterns in wearers of silicone hydrogel lenses, *Cont. Lens Anterior Eye* 38 (2015) 471–476.
- [40] M. Gokhale, U. Stahl, I. Jalbert, In situ osmometry: validation and effect of sample collection technique, *Optom. Vis. Sci.* 90 (2013) 359–365.
- [41] M.A. Lemp, A.J. Bron, C. Baudouin, J.M. Benitez Del Castillo, D. Geffen, J. Tauber, et al., Tear osmolarity in the diagnosis and management of dry eye disease, *Am. J. Ophthalmol.* 151 (2011) 792–798 (e1).
- [42] B.D. Sullivan, L.A. Crews, B. Sonmez, M.F. de la Paz, E. Comert, V. Charoenrook, et al., Clinical utility of objective tests for dry eye disease: variability over time and implications for clinical trials and disease management, *Cornea* 31 (2012) 1000–1008.
- [43] B.D. Sullivan, D. Whitmer, K.K. Nichols, A. Tomlinson, G.N. Foulks, G. Geerling, et al., An objective approach to dry eye disease severity, *Invest. Ophthalmol. Vis. Sci.* 51 (2010) 6125–6130.
- [44] J.P. Gilbard, J.B. Carter, D.N. Sang, M.F. Refojo, L.A. Hanninen, K.R. Kenyon, Morphologic effect of hyperosmolarity on rabbit corneal epithelium, *Ophthalmology* 91 (1984) 1205–1212.
- [45] J.P. Gilbard, R.L. Farris, Tear osmolarity and ocular surface disease in keratoconjunctivitis sicca, *Arch. Ophthalmol.* 97 (1979) 1642–1646.
- [46] J.P. Gilbard, S.R. Rossi, K.L. Gray, L.A. Hanninen, Natural history of disease in a rabbit model for keratoconjunctivitis sicca, *Acta Ophthalmol. Suppl.* 192 (1989) 95–101.
- [47] R.L. Farris, Tear analysis in contact lens wearers, *CLAO J.* 12 (1986) 106–111.
- [48] J.L. Nichols, L.T. Sinnott, Tear film, contact lens, and patient-related factors associated with contact lens-related dry eye, *Invest. Ophthalmol. Vis. Sci.* 47 (2006) 1319–1328.
- [49] U. Stahl, M.D. Willcox, T. Naduvilath, F. Stapleton, Influence of tear film and contact lens osmolality on ocular comfort in contact lens wear, *Optom. Vis. Sci.* 86 (2009) 857–867.
- [50] J. Guillon, M. Guillon, Tear film examination of the contact lens patient, *Optician* 206 (1993) 21–29.
- [51] H. Hamano, M. Hori, T. Hamano, S. Mitsunaga, J. Maeshima, S. Kojima, et al., A new method for measuring tears, *CLAO J.* 9 (1983) 281–289.
- [52] J. Murube, Tear osmolarity, *Ocul. Surf.* 4 (2006) 62–73.
- [53] D.R. Korb, J. Herman, C.A. Blackie, N. Korb, S. Scaffidi, J. Greiner, J. Exford, et al., Prevalence of lid wiper epitheliopathy in subjects with dry eye signs and symptoms, *Cornea* 29 (2010) 377–383.
- [54] L. Jones, N.A. Brennan, J. Gonzalez-Mejome, J. Lally, C. Maldonado-Codina, T.A. Schmidt, et al., The TFOS International Workshop on Contact Lens Discomfort: report of the contact lens materials, design, and care subcommittee, *Invest. Ophthalmol. Vis. Sci.* 54 (2013) TFOS37–TFOS70.
- [55] B.J. Tighe, A decade of silicone hydrogel development: surface properties, mechanical properties, and ocular compatibility, *Eye Contact Lens* 39 (2013) 4–12.
- [56] E. Knop, D.R. Korb, C.A. Blackie, N. Knop, The lid margin is an underestimated structure for preservation of ocular surface health and development of dry eye disease, *Dev. Ophthalmol.* 45 (2010) 108–122.
- [57] J.J. Nichols, G.L. Mitchell, P.E. King-Smith, Thinning rate of the precorneal and prelens tear films, *Invest. Ophthalmol. Vis. Sci.* 46 (2005) 2353–2361.
- [58] E. Faber, T.R. Golding, R. Lowe, N.A. Brennan, Effect of hydrogel lens wear on tear film stability, *Optom. Vis. Sci.* 68 (1991) 380–384.
- [59] D. Alonso-Caneiro, D.R. Iskander, M.J. Collins, Tear film surface quality with soft contact lenses using dynamic-area high-speed videokeratoscopy, *Eye Contact Lens* 35 (2009) 227–231.
- [60] J.P. Craig, M.D. Willcox, P. Argueso, C. Maissa, U. Stahl, A. Tomlinson, et al., The TFOS International Workshop on Contact Lens Discomfort: report of the contact lens interactions with the tear film subcommittee, *Invest. Ophthalmol. Vis. Sci.* 54 (2013) TFOS123–TFOS156.
- [61] M.J. Glasson, F. Stapleton, L. Keay, D. Sweeney, M.D. Willcox, Differences in clinical parameters and tear film of tolerant and intolerant contact lens wearers, *Invest. Ophthalmol. Vis. Sci.* 44 (2003) 5116–5124.
- [62] O. Sarac, C. Gurdal, B. Bostanci-Ceran, I. Can, Comparison of tear osmolarity and ocular comfort between daily disposable contact lenses: hilafilcon B hydrogel versus narafilcon A silicone hydrogel, *Int. Ophthalmol.* 32 (2012) 229–233.
- [63] A. Muselier-Mathieu, A.M. Bron, B. Mathieu, M. Souchier, F. Brignole-Baudouin, N. Acar, et al., Ocular surface assessment in soft contact lens wearers; the contribution of tear osmolarity among other tests, *Acta Ophthalmol.* 92 (2014) 364–369.
- [64] H. Liu, C. Begley, M. Chen, A. Bradley, J. Bonanno, N.A. McNamara, et al., A link between tear instability and hyperosmolarity in dry eye, *Invest. Ophthalmol. Vis. Sci.* 50 (2009) 3671–3679.
- [65] The definition and classification of dry eye disease: report of the Definition and Classification Subcommittee of the International Dry Eye WorkShop (2007), *Ocul. Surf.* 5 (2007) 75–92.
- [66] G. Foulks, R. Chalmers, N. Keir, C.A. Woods, T. Simpson, R. Lippman, et al., The TFOS International Workshop on Contact Lens Discomfort: report of the subcommittee on clinical trial design and outcomes, *Invest. Ophthalmol. Vis. Sci.* 54 (2013) TFOS157–TFOS183.
- [67] J.J. Nichols, G.L. Mitchell, K.K. Nichols, R. Chalmers, C. Begley, The performance of the contact lens dry eye questionnaire as a screening survey for contact lens-related dry eye, *Cornea* 21 (2002) 469–475.
- [68] R.L. Chalmers, C.G. Begley, K. Moody, S.B. Hickson-Curran, Contact lens dry eye questionnaire-8 (CLDEQ-8) and opinion of contact lens performance, *Optom. Vis. Sci.* 89 (2012) 1435–1442.