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Tear film surface quality with rigid and soft contact lenses

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Conflict of Interest

There are no conflicts of interest for any of the authors.

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Abstract

Objectives: To measure tear film surface quality (TFSQ) using dynamic high-speed videokeratoscopy during short-term (8 hours) use of rigid and soft contact lenses.

Methods: A group of fourteen subjects wore 3 different types of contact lenses on 3 different non-consecutive days (order randomized) in one eye only. Subjects were screened to exclude those with dry eye. The lenses included a PMMA hard, an RGP (Boston XO) and a soft silicone hydrogel lens. Three 30 second long high speed videokeratoscopy recordings were taken with contact lenses in-situ, in the morning and again after 8 hours of contact lens wear, both in normal and suppressed blinking conditions. Recordings were also made on a baseline day with no contact lens wear.

Results: The presence of a contact lens in the eye had a significant effect on the mean TFSQ in both natural and suppressed blinking conditions ($p=0.001$ and $p=0.01$ respectively, repeated measures ANOVA). TFSQ was worse with all the lenses compared to no lens in the eye (in the afternoon during both normal and suppressed blinking conditions (all $p<0.05$). In natural blinking conditions, the mean TFSQ for the PMMA and RGP lenses was significantly worse than the baseline day (no lens) for both morning and afternoon measures ($p<0.05$).

Conclusions: This study shows that both rigid and soft contact lenses adversely affect the TFSQ in both natural and suppressed blinking conditions. No significant differences were found between the lens types and materials.

Keywords: Tear film surface quality, rigid contact lens, soft contact lens, dynamic high-speed videokeratoscopy

Word count: 238 (Limit 250)

INTRODUCTION

The frequency of dry eye symptoms is typically higher in contact lens wearers than non-wearers [1-5], with up to 50% of all contact lens wearers reporting some symptoms of dry eye [2]. Contact lenses are known to alter the structure of the tear film by dividing the pre-corneal tear film into pre-lens and post-lens tear film layers. Compared to the natural tear film a variety of changes in the tear film have been noted with the use of contact lenses including an unstable tear film [6], increased evaporation of the tear film [7] and increased tear osmolarity [8, 9].

In general, the tear film quality is subjectively assessed clinically in terms of fluorescein tear break-up time (TBUT), as abnormalities in any of the tear film layers (lipid layer, aqueous layer or mucin layer) results in an unstable tear film causing reduced tear break-up time. As the presence of a contact lens divides the tear film into the pre-lens and post-lens tear film, any break in the pre-lens tear film may not be readily observed due to the presence of the post-lens tear film in the case of rigid gas permeable (RGP) lenses and due to absorption of fluorescein in the case of soft contact lenses, resulting in measurement errors. Therefore, TBUT in contact lens wearers is often measured with non-invasive techniques such as the Tearscope [10], lipid layer interferometry [11-13], wavefront sensing [14, 15], meniscometry [16] or high-speed videokeratoscopy [17]. Using non-invasive techniques to measure tear film also minimises the risk of errors due to change in tear film properties caused by fluorescein [18].

Another technique of estimating the tear film surface quality (TFSQ) using image processing techniques based on the properties of the Placido disk images has been recently developed [19, 20]. This technique differs from previous methods utilising videokeratoscopy to study the tear film, as it derives a dynamic estimate of TFSQ from the Placido disk image rather than from the surface topography. It also overcomes limitations of some of the previous techniques such as sensitivity to eye movements with interferometry, small coverage area with wavefront sensing (in non-contact lens wearing eyes), and errors due to subjective assessment of the tear film with the Tearscope. Lately, this method has been used to quantify the TFSQ in eyes with and without soft contact lenses [21] and has been demonstrated to exhibit good performance in the detection of patients with dry eye [20, 22].

Previous studies have reported no differences in the frequency of dryness symptoms between RGP and soft contact lens wearers compared to non-contact lens users [4, 23]. Alonso Caneiro et al.,[21] found a reduction in TFSQ with hydrogel and silicone hydrogel contact lenses but no statistically significant differences were found between the two lens types. Compared to the large amount of research investigating the influence of soft contact lens wear upon the tear film, there have been relatively few studies reporting changes in tear film stability with rigid contact lenses and comparing it to that with silicone hydrogel contact lenses. Both RGP and polymethyl methacrylate (PMMA) lens wear have also been shown to be associated with a significant reduction in non-invasive TBUT at the 3 and 9 o' clock locations of the conjunctiva [24], however these changes may be related to altered blinking patterns.

Given the relatively small number of reports in the literature on the quality of the tear film with rigid contact lenses using objective, non-invasive techniques, we were interested to assess the quality of tears on the surface of RGP and silicone hydrogel (SiHy) lenses at the start and end of a normal day of lens wear, utilizing high-speed videokeratoscopy measurement techniques. To provide a point of comparison, we also measured the tear film surface quality of the same subjects on a day with no contact lens wear and on a day wearing PMMA contact lenses.

MATERIALS AND METHODS

Subjects

A group of fourteen subjects (age range: 20 to 33 years, mean 27.8 ± 4.0 years, 5 females, 9 males), who were mainly students and staff at Queensland University of Technology participated in this study. All subjects had low corneal astigmatism ($\leq$ 1.5 D corneal cylinder) and exhibited no signs of keratoconus or other ectatic corneal disorders in corneal topography maps acquired using the Medmont E300 videokeratoscope (Medmont Pty. Ltd., Victoria, Australia). A slit-lamp examination was conducted to ensure that all the subjects had a normal anterior segment and ocular health. The subjects were additionally screened for any significant dry eye based on the McMonnies dry eye questionnaire [3], fluorescein tear break-up time, Phenol red thread test (ZONE-QUICK, Showa Yakuhin Kako Co., Ltd. Tokyo, Japan) [25] and fluorescein and lissamine green staining of the ocular surface with staining graded using Efron grading scale [26]. The group mean results from these screening tests are presented in Table 1. The mean fluorescein TBUT of the subjects was slightly less than the normal value, but according to the screening criterion we adopted (and used in many other studies of "normal" tear quality [22, 27]) the subjects were excluded only if they failed 2 or more of the diagnostic dry eye tests. Two of the fourteen subjects were soft contact lens wearers, but they discontinued the use of their lenses at least one month prior to the start of the study. None of the subjects had any history of rigid contact lens wear. All subjects gave written informed consent after explanation of the procedures. The study followed the tenets of the Declaration of Helsinki and was approved by the Queensland University of Technology (QUT) Human Research Ethics Committee.

Instrument

Dynamic high-speed videokeratoscopy was performed using the Medmont E300 high-speed videokeratoscope (HSV), to derive measurements of non-invasive TFSQ. This technique is based on specular reflection of a Placido disk pattern that is reflected from the surface of the tear film on the cornea or anterior contact lens. The quality of the reflected ring pattern depends on the smoothness or regularity of the surface and analysis of the image of the Placido rings provides a nominal value of the TFSQ from 0 (poor) to 1 (perfect) [19, 21, 28].

Lenses

Subjects wore 3 different types of contact lenses on 3 different days, for 8 hours on each day, in their left eye only. Description of the contact lenses that were used is shown in Table 2. The PMMA and RGP lenses were custom ordered from Gelflex Laboratories (Perth, Australia). The optimal back optic zone radius of the rigid lenses was determined after a contact lens fitting trial for each subject. The lenses were fit on the flattest k to obtain an optimal alignment fit for all subjects, which typically showed central alignment, slight mid-peripheral bearing and moderate edge lift. The fluorescein fitting patterns of all the lenses were assessed on both the trial lens fitting day and on the day of lens wear by the same experienced examiner (GT). The lenses supplied by the manufacturer were verified for BOZR, back vertex power, lens diameter and surface quality.

No surface treatment was ordered for the PMMA or RGP lenses and the lenses were stored in Boston conditioning solution (Bausch & Lomb Incorporated, New York, U.S.A.) prior to use by the subject. The silicone hydrogel lens used was the commercially available Bausch and Lomb PureVision lens, which is manufactured with a standard “Performa” surface treatment. In order to convert the silicone components on the lens surface into hydrophilic silicate compounds, this lens is surface treated in a gas plasma reactive chamber [29, 30].

Protocol

Measurements were performed with the contact lens in eye, in the morning (between 8 and 11 am) before inserting the lenses and then repeated in the afternoon (between 4 and 7 pm) just before removal of contact lenses. Baseline measurements were also taken in the morning and in the afternoon, on a day when no contact lens was worn. The order of wear of the different contact lenses was randomized. Ten to 20 minutes of lens settling time was allowed before taking the measurements in the morning. Three sets of 30 second videokeratoscopy recordings were captured both in natural and then under suppressed blinking conditions (6x30 sec in total). Each 30 seconds recording consisted of 25 image frames per second. Thus a total of 750 image frames were captured for each 30 second measurement.

A thorough slit-lamp examination was carried out by the same experienced examiner (GT) before and after each lens wearing session to assess the cornea, bulbar and tarsal conjunctiva. The Efron grading scale [26] was used to grade conjunctival roughness and redness, and corneal and conjunctival staining using both fluorescein and lissamine green dyes. Any corneal edema was documented. Digital slit-lamp images were also captured for records. Any ocular surface changes observed after lens wear were allowed to resolve completely before the next contact lens wearing session.

For each measurement, the subject was positioned in the chin rest of the E300 videokeratoscope and was asked to fixate on the centre of the inner-most ring of the Placido disk. During the natural blinking condition, the subject was asked to blink naturally during the 30 second capture period. During the suppressed blinking condition, the subject was asked to “take a gentle, complete blink and then stop blinking for as long as it was comfortable”. A gap of 3-4 minutes was allowed between the measurements, during which time the subjects could relax and blink naturally. The measurements were taken in the same room, with approximately the same humidity (58.0 ± 5.2%) and temperature (24.9 ± 1.0 ºC) and at approximately the same time of day, for all measurement days (both morning and afternoon). The main room lights were dimmed during the measurements to optimize the videokeratoscope image quality. The data were collected within a 2 month period when the outdoor environmental conditions were similar. Also the subjects were typically university students or staff and therefore spent most of the lens wearing time indoors at the university where the temperature and humidity were well controlled.

Data Analysis

The mean tear film surface quality (TFSQ) was calculated for both the natural and suppressed blinking conditions. Matlab-based custom written image processing techniques were used for analysis of the videokeratoscope images from the inter-blink interval. The details of this method have been described by Alonso-Caneiro et al. [19] However, the technique was modified for the analysis of contact lens images. This modification affected the region of interest (ROI) within which the image containing the Placido ring pattern is estimated. In bare eye conditions, any interference in the ring pattern can either be due to shadows from the eyelashes or poor TFSQ. However, when a lens is inserted into the eye, extra interference can be found in the lens edges or the front optic zone diameter. The interference from the eyelashes is removed by an special image processing procedure [19] , then the centre of the Placido disk is detected and a region of 5.5 mm diameter is extracted to obtain the area of analysis (see Figure 1). The dimension of the area was selected for analysis to ensure that there was no interference from the lens edges or the front optic zone diameter junction in the area of analysis.

The TFSQ is then estimated in the form of a number (ranging from 0 to 1) in the area of analysis using image coherence analysis [21, 31]. The coherence, which is a measurement of the pattern's local orientation, is estimated as 0, when the pattern is poorly oriented (i.e. when the tear film is disrupted and of poor quality) and 1, when the pattern is well oriented (i.e. when the tear film is smooth and of high quality). TFSQ for each image is the average of the coherence measurement in the area of analysis. An average TFSQ for all the Placido disc images in the measurement is then calculated. Images of the Placido disc pattern immediately after and then again a few seconds after blink are illustrated in Figure 1.

For natural blinking conditions the analysis was carried out on all the data for a duration of 30 seconds (excluding frames during blinking and 1 sec following the blink) to derive the mean TFSQ. In order to allow for the tear film to "build-up" [32], a period of one second after each blink was excluded from the analysis of all measurements. For the suppressed blinking condition, the period of analysis (5 seconds) began after the final blink, plus one further second to allow for tear build-up. This led to 5 X 25 image frames to derive the mean TFSQ throughout the 5 seconds. If the subject blinked within the 6 second measurement period, these data were not used, however at least 2 out of the 3 suppressed blinking trials were available for the 11 subjects in the study. A period of 6 seconds was selected for analysis, as the majority of subjects (n=11) had valid data (for at least 2 out of 3 measurements) for this measurement duration. A repeated measures analysis of variance (ANOVA) was used to investigate the statistical significance of changes in TFSQ, with the lens type (3 different types) and time of day (morning and afternoon) as within-subject factors in normal and suppressed blinking conditions. Degrees of freedom were adjusted using the Greenhouse-Geisser correction to prevent any type 1 errors, where violation of the sphericity assumption occurred. Bonferroni adjusted pair-wise comparisons were carried out for individual comparisons.

RESULTS

TFSQ in natural blinking conditions

The group mean TFSQ in natural blinking conditions for the baseline day and with the three different contact lenses are shown in Figure 2. The presence of a contact lens ($p=0.001$, repeated measures ANOVA) had a significant effect on the mean TFSQ in the natural blinking conditions. Mean TFSQ when wearing the PMMA and RGP lenses was significantly worse than the baseline day (with no lens) in both morning and afternoon (all $p<0.05$, pair-wise comparisons). The SiHy lens also led to a significant reduction in TFSQ in the afternoon ($p=0.03$) (relative to baseline) after 8 hours of lens wear, but not at the morning measurement ($p=0.10$). Post hoc testing showed that there was no significant difference between the mean TFSQ of the three contact lenses compared to each other (all p>0.05) (Figure 2). There was a significant difference in the mean change in TFSQ in the afternoon compared to morning for RGP lens which showed a decrease of –0.02 ± 0.03 (p=0.04, pair-wise comparisons).

Blink frequency in natural blinking conditions

The group mean number of blinks per minute (or blink frequency) in natural blinking conditions was calculated for the baseline day and with the three different contact lenses. The time of day had a significant effect (p=0.01, repeated measures ANOVA) on the blink frequency. On the baseline day, the blink frequency was significantly faster in the afternoon compared to morning, with a mean increase of 4.24 ± 5.39 blinks/min (p=0.01). The blink frequency did not change significantly during the day with any of the contact lenses. Although on average, all lenses caused some increase in mean blink frequency compared to baseline morning measurements, these changes in blink frequency associated with lens wear were not statistically significant (all p>0.05).

TFSQ in suppressed blinking conditions

The presence of a contact lens (p=0.01) also had a significant effect on the mean TFSQ under suppressed blinking conditions. The group mean TFSQ in suppressed blinking conditions for the baseline day and with the three different contact lenses in the morning and afternoon is shown in Figure 3. The figure illustrates the mean TFSQ for each second immediately after blinking for up to 6 seconds. The mean TFSQ shows an increase (improvement), in the first second after the blink with all lenses and during baseline measurement, both in the morning (Figure 3 a) as well as the afternoon (Figure 3 b).

The overall mean TFSQ during the 6 second recording for the two rigid lenses as well as SiHy/Soft lens was significantly worse than the baseline day (no lens wear) both in the morning and afternoon (all p<0.05, pair-wise comparisons) (Figure 3). Post hoc testing showed that there was no significant difference between the mean TFSQ of the three contact lenses compared to each other (all p>0.05). There were no significant differences in the suppressed blinking mean TFSQ in the afternoon compared to morning on the contact lens wearing or the baseline days.

There was a clear trend towards reduction in mean change in TFSQ with time over the 5 second period of recording (Figure 3) both in the morning and afternoon (all p<0.05).

Trend of TFSQ with time in suppressed blinking conditions

The different patterns of change in TFSQ during suppressed blinking were further explored in order to better understand the dynamics of the pre-lens tear film. The tear film surface quality generally showed a decrease with time after each blink. While data are presented above for the first 6 seconds after the blink, many subjects were able to suppress blinking for longer durations. Further exploration of the data, subjective observation and classification of the trends in TFSQ during this extended period of 30 seconds revealed four different types of pattern of change in TFSQ over time (see examples in Figure 4 from four representative subjects). In “Type 1” pattern there was a steady decline in TFSQ with time until the end of recording time [Figure 4 (Type 1) & Figure 5]. The second type of trend showed a slower decrease with time followed by a stable TFSQ towards the end of recording time (Figure 4, Type 2). The third trend showed a steep decline in TFSQ in the first few seconds, presumably forcing the subject to blink well before the end of the 30 second recording time (time of last frame from Figure is at 9.84 seconds, Figure 4, Type 3). The fourth and the most unexpected trend was a decline in TFSQ with time for first 7 to 9 seconds after the blink, but then TFSQ begins to improve and gets even better than the baseline values (approaching 1.0) by 12 to 13 seconds before finally stabilising [Figure 4 (Type 4) & Figure 6].

Figures 5 and 6 show representative examples of the type 1 and 4 TFSQ patterns respectively over time and the corresponding Placido disk images at 3 different times. The type 4 trend shown in Figure 6 was seen most commonly with rigid/hard contact lenses compared to the soft lenses and never noticed during baseline measurements (no contact lens) (Table 3).

DISCUSSION

We found that all types of contact lenses (PMMA, RGP and SiHy) reduce the tear film surface quality on the anterior lens surface. The mean TFSQ was worse with all the lenses both in the morning (10 mins after insertion) and afternoon (after 8 hrs wear) compared to measurements on the baseline day and the changes were statistically significant with all the rigid lenses during normal blinking conditions. The SiHy lens also showed a significant reduction in TFSQ in the afternoon after 8 hours of lens wear, but not in the morning just after lens insertion. This is in agreement with previous studies using high speed videokeratoscopy [21, 28] that found significant differences in TFSQ with both hydrogel and SiHy contact lenses compared to baseline after one day of lens wear. The mean TFSQ with the SiHy lens (balafilcon A, FDA group 3, 36%) in this study was 0.83 ± 0.04 in suppressed blinking conditions and 0.85 ± 0.08 in natural blinking conditions (after 8 hours of lens wear), in close agreement with the value of 0.84 ± 0.02 (after one day of lens wear) reported for a silicone hydrogel lens (galyfilcon A, FDA group 1, 47%) during suppressed blinking, in the study by Alonso-Caneiro et al [21]. This is the first study to use dynamic videokeratoscopy to provide a non-invasive, objective measure of TFSQ with rigid lenses and suggests that a similar magnitude of reduction in TFSQ occurs with both PMMA and RGP lenses.

We found no significant differences between the mean TFSQ with the different lenses (i.e. all of the lens materials caused reductions in TFSQ of similar magnitude compared to the baseline) and this is consistent with previous studies of ocular symptoms that have reported no significant differences in the frequency of dryness symptoms between RGP and soft contact lens wearers [4, 23]. It should be noted that the measurements in our current study are from a single day of wear, in subjects who had a clinically normal tear film who had not previously worn rigid lenses. Given that certain complications associated with longer term rigid lens wear (e.g. 3 and 9 o'clock staining), may be related to alterations in the tear film, future studies examining TFSQ using similar non-invasive measurement techniques in longer term contact lens wearers may help to clarify the tear film changes associated with these complications in different rigid lens types. The method of measuring TFSQ described in this study may not be sensitive enough to distinguish differences between lenses, but has shown significant differences between lens wear and baseline (bare eye) conditions.

We also found a reduction in mean TFSQ in the afternoon compared to the morning on the baseline day, and with PMMA and RGP lenses. On the other hand, SiHy lens did not show a reduction in mean TFSQ in the afternoon compared to morning. Studies have shown an increase in severity of dryness symptoms at the end of contact lens wearing time in contact lens wearers of various types (RGP, disposable, frequent replacement, extended wear) [5, 33].

We observed four different patterns of deterioration in TFSQ over the 30 second period of TFSQ measurement in the suppressed blinking conditions. First a gradual linear decrease in TFSQ, second a slower rate of decrease with a stable TFSQ towards the end of recording time, third a rapid decrease in TFSQ to reach minimum after which the subject blinks and the fourth showing an initial decrease until a certain point followed by an improvement to result in TFSQ even better than the baseline. This improvement is unlikely to be a real improvement in TFSQ and appears to be due to the lens surface evenly drying (i.e. the pre-lens tear film completely drying) and effectively then acting as a mirror-like surface. This difference in the pattern of deterioration in TFSQ has not been reported previously. However, earlier studies investigating TFSQ with contact lenses have analysed shorter measurement times (8 seconds) [21] which may not be long enough to reveal the pattern of change identified with a longer analysis period as used in our current study. This pattern was most frequently noticed with rigid/hard lenses and only in a few subjects with silicone hydrogel lenses. A similar finding is sometimes noted in clinical practice when examining RGP contact lens in eye with a slit lamp biomicroscope, when the front surface of the lens shows a full break-up of the tear film. Although it appears that these changes in TFSQ may relate to a complete break-up of the pre-lens tear film, our videokeratoscopy technique does not measure tear film thickness. Further research utilising interferometry based techniques to measure tear film thickness are required to confirm this hypothesis.

In summary, we used a non-invasive technique of estimating TFSQ in a group of subjects with and without contact lens wear of 8 hours. This technique has been used to measure the TFSQ with rigid contact lenses for the first time in this study. A significant decrease in TFSQ was shown with all types of contact lenses (PMMA, RGP and silicone hydrogel) compared to baseline (bare eye) in normal blinking conditions, though no statistically significant differences were noticed between the lens types. In suppressed blinking conditions we also monitored the pattern of change in TFSQ over time to further explore the dynamics of the pre-lens tear film and noted a number of distinctive patterns representing different rates of deterioration of TFSQ. Further analysis of these patterns in future studies may improve our understanding of tear-lens surface interactions. These findings reinforce the need for better contact lens materials and surfaces that provide improved wettability and hydrophilicity in order to improve TFSQ and patient comfort.

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Table 1: Dry eye screening tests, screening criterion and the mean score of the study subjects.

Test	Screening	Mean score ± SD
McMonnies questionnaire	Score ≥ 14	4.29 ± 2.52
Fluorescein TBUT	< 10 sec	7.38 ± 4.44
Phenol red thread test	< 10 mm	19.36 ± 5.30
Corneal fluorescein staining	> 2	0.43 ± 0.55
Corneal lissamine green staining	> 2	0.07 ± 0.27

Table 2: Description of the lenses used in the study.

Parameter	Lens 1	Lens 2	Lens 3
Lens	PMMA	RGP	SiHy
Design (centre)	Spherical	Spherical	Spherical
Design (periphery)	Aspheric	Aspheric	B&L PureVision
Material	PMMA	RGP (Boston XO)	Silicone hydrogel
Power (Dioptre)	–0.50	–0.50	–0.50
Total diameter	9.5	9.5	14.0
FOZD (mm)	8.0	8.0	8.9 (-3.00D)
BOZD (mm)	8.1	8.1	Unknown
Manufacturing	Lathe	Lathe	Cast moulding
Surface treatment	None	None	Performa/Plasma oxidation
Wetting angle	18° [34]	103° [35]	55° [36]

PMMA: polymethyl methacrylate, RGP: rigid gas permeable, SiHy: silicone hydrogel, B&L: Bausch and Lomb, BOZD: back optic zone diameter, mm: millimetres

Table 3: Analysis of recordings which showed an increase in TFSQ with time (Type 4 pattern). A total of 14 subjects, with 3 recordings performed in both morning and afternoon. (Total number of recordings is 84). Pattern of increase in TFSQ is shown in Figure 6.

Lens	Total number of recordings	Number of recordings with an increase in TFSQ	Percentage (%)
Baseline	84	0	0
PMMA	84	57	68
RGP	84	55	65
SiHy	84	16	19

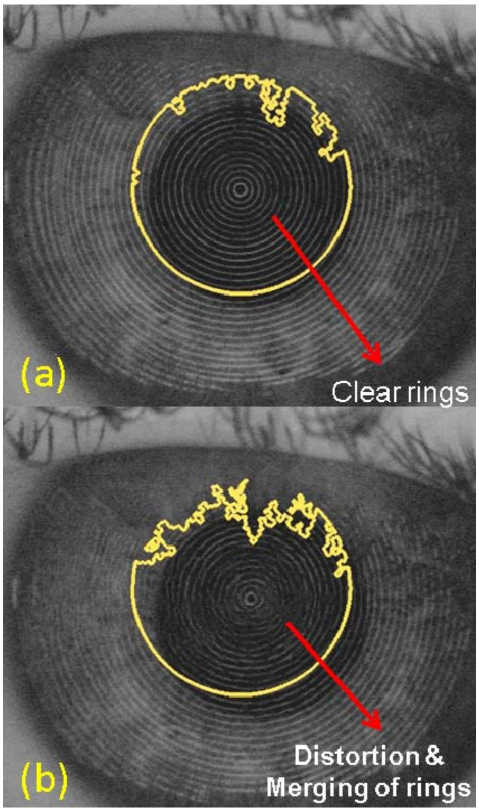

Figure 1: Examples of image frames from high speed videokeratoscopy with an RGP lens on the eye. Images of the Placido disc pattern were acquired (a) immediately after a blink and then again (b) a few seconds after a blink. Panel (b) shows tear break up as distortion of the Placido ring pattern. Yellow lines enclose the dynamic area of analysis, excluding regions of eyelash interference that were identified using frame-by-frame automated software analysis.

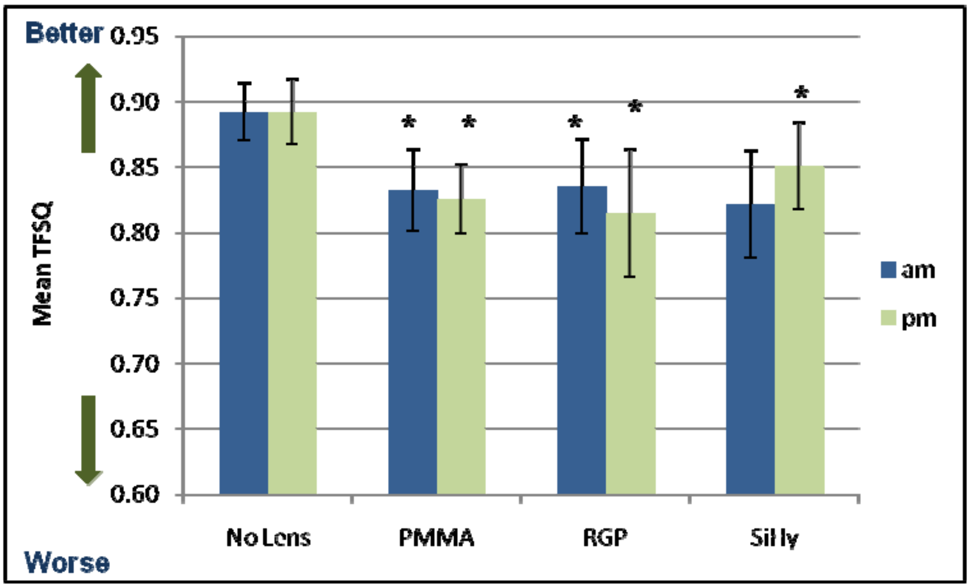

Figure 2: Mean TFSQ in 30 seconds with the three contact lenses and on baseline day (no contact lens), in the morning (am) and afternoon (pm), in natural blinking conditions. The TFSQ is calculated on a scale of 0 to 1 where 0 is very poor and 1 is very good quality. * indicates significant difference ($p<0.05$) compared to the baseline (no lens) condition. Error bars represent standard error of the mean.

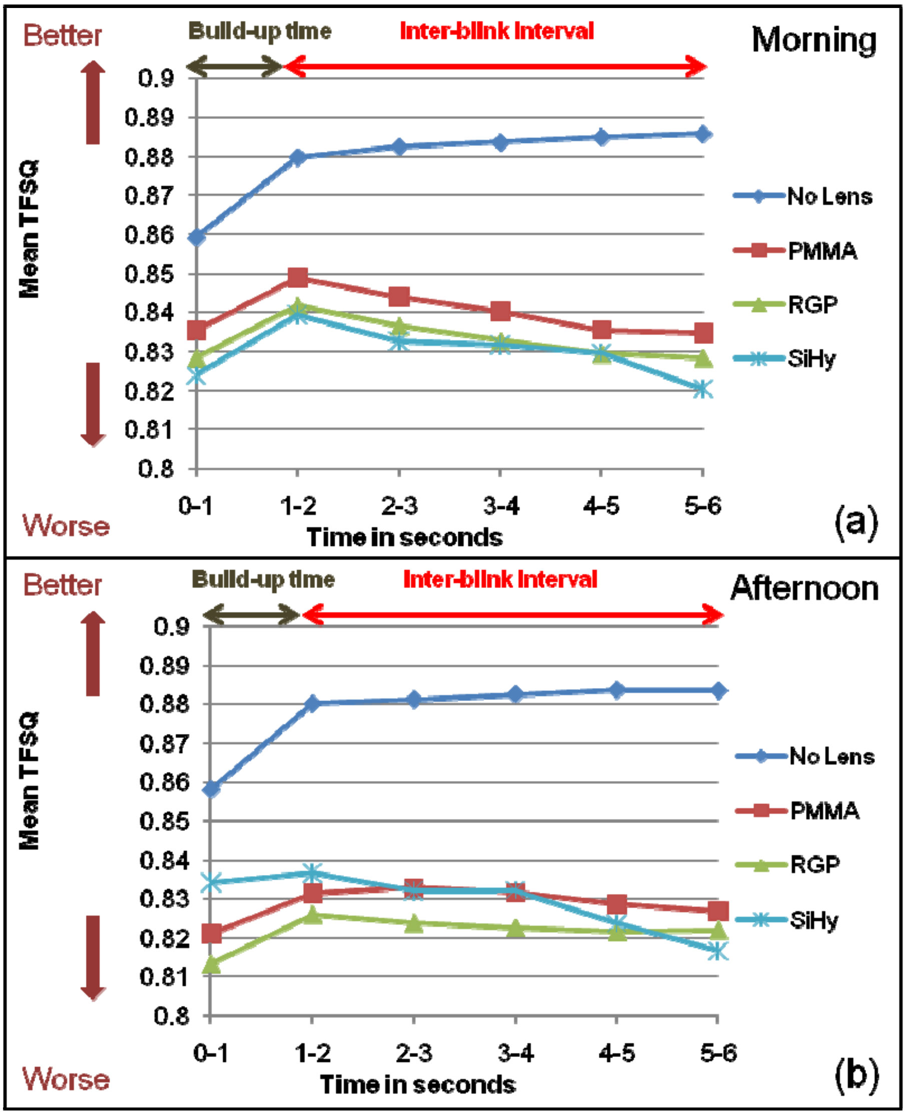

Figure 3: The group mean TFSQ in suppressed blinking conditions with time for the 6 seconds after a blink, for the baseline day and with the three contact lenses in the morning (a) and afternoon (b). The TFSQ values shown are the mean values for the interval from 0 to 1, 1 to 2 (and so on) seconds. Analysis was conducted on the data during the 1 to 6 second inter-blink interval, excluding the first second of tear build-up.

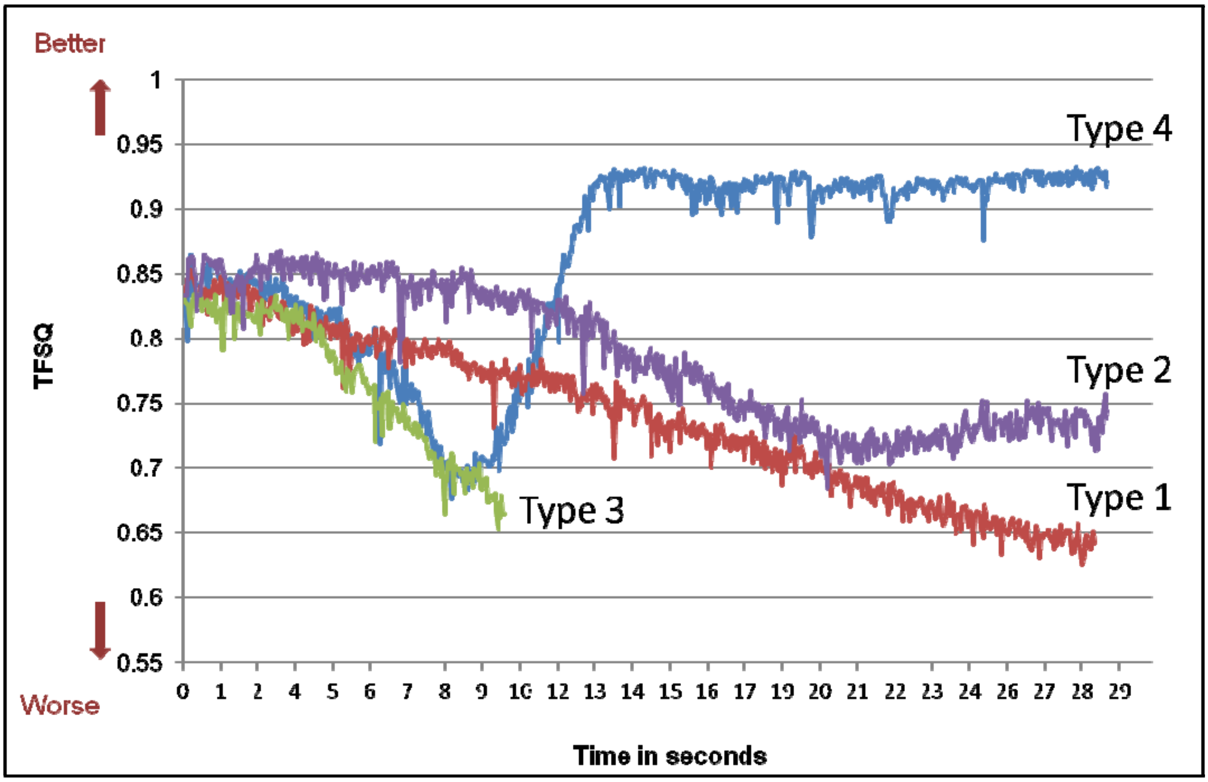

Figure 4: The four different types of representative patterns of TFSQ with time for 30 seconds.

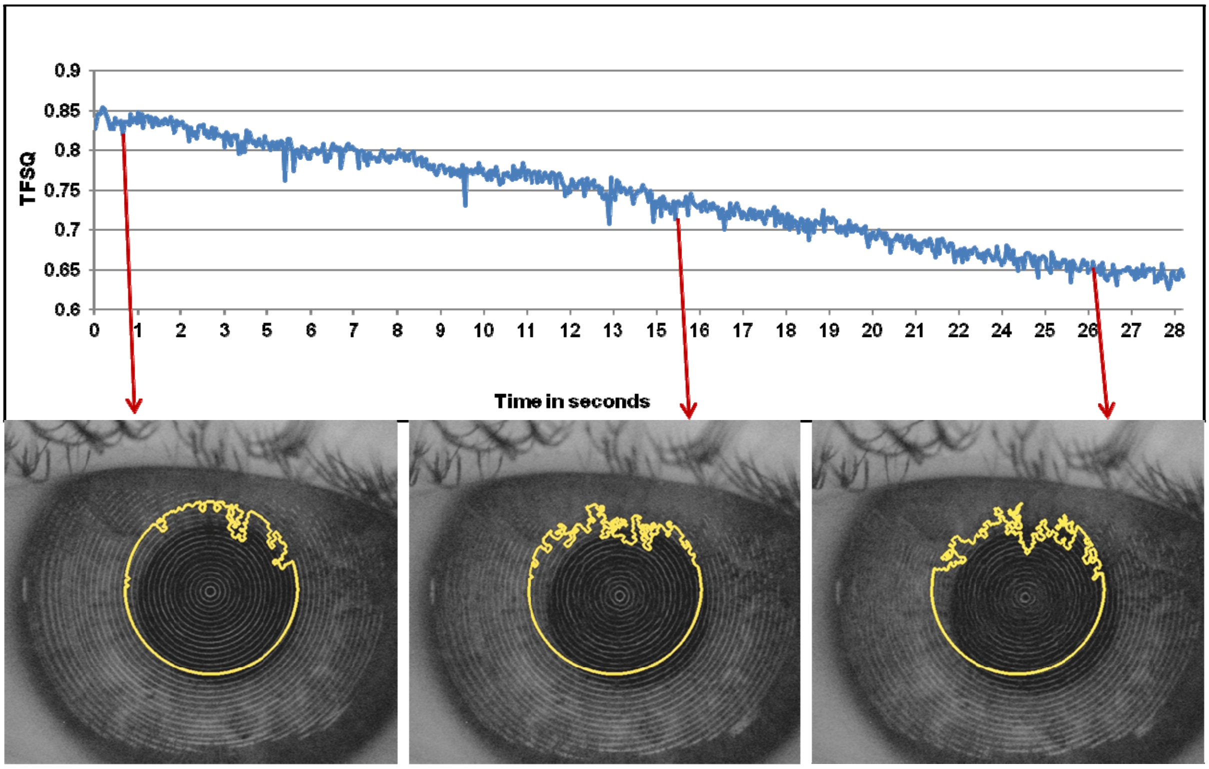

Figure 5: TFSQ over time for a representative subject, showing a slight increase during the first second post-blink (build-up time) and then a steady reduction in TFSQ over time till the end of the measurement (Type 1 pattern). Corresponding Placido disc maps can be seen at the beginning (clear rings), middle (breaks in the ring pattern) and end (severe distortion of the ring pattern) of the measurement. Yellow lines enclose the dynamic area of analysis (regions of eyelash interference are excluded frame-by-frame).

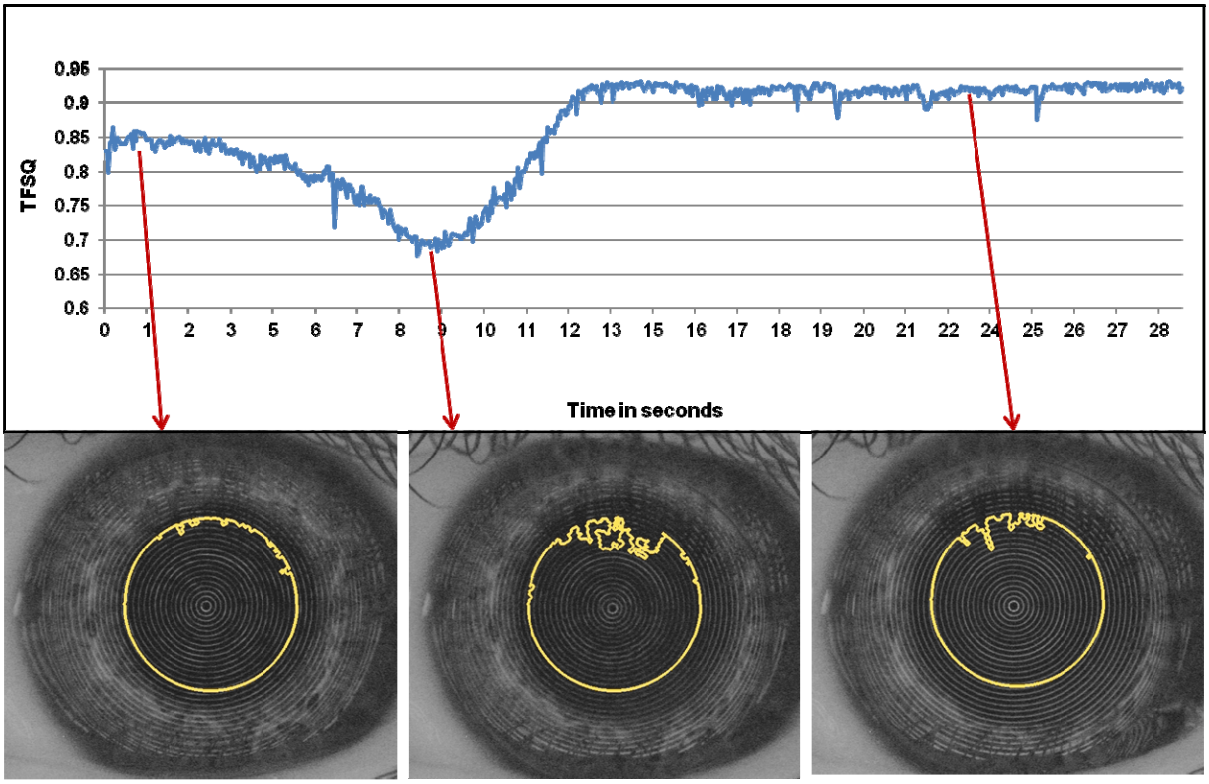

Figure 6: TFSQ over time for a representative subject, showing an increase during first second post-blink, then a reduction is seen with time until a certain point after which TFSQ shows an improvement and reaches a value more than the baseline (Type 4 pattern). Corresponding Placido disc maps can be seen at the beginning (clear rings), middle (few breaks in the ring pattern) and end (very clear and regular ring pattern) of the measurement. This later period seems to correspond to complete drying of the lens surface which now acts like a mirror to produce a high TFSQ score. Yellow lines enclose the dynamic area of analysis.