In vitro evaluation of the dehydration characteristics of silicone hydrogel and conventional hydrogel contact lens materials

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Abstract

Purpose: This study investigated the in vitro dehydration performance of silicone hydrogel and conventional hydrogel contact lens materials. Methods: In vitro dehydration was assessed using a gravimetric method. The mass loss over time of Focus Night&Day, PureVision, Optima, Acuvue and Proclear Compatibles was measured as the ambient temperature increased from room temperature to 34 °C under varying airflow and humidity conditions. Results: Dehydration data demonstrated a typical ogival form. The results were best fitted with a double exponential, non-linear regression model, which accounted for at least 99% of the variance. Regardless of material, increased airflow had a greater impact on dehydration rate than increased humidity (P < 0.05). Relative dehydration amounts were strongly correlated with initial water content (r2 = 0.92), with higher water content materials dehydrating to a greater extent. Conclusions: In vitro dehydration studies of conventional and novel silicone-containing hydrogel materials indicated that evaporation rates from materials are predominantly water content related, with only subtle differences between materials of similar water contents being seen. Environmental conditions have a significant impact on in vitro dehydration, with increased airflow having a greater impact than reduced humidity on increasing dehydration rates. In vitro dehydration is closely related to bulk water diffusion rates and, as a result of their low water content, silicone-containing hydrogel materials exhibit low levels of dehydration compared with high water content hydrogel contact lens materials. Further, in vivo studies are necessary to see if the in vitro dehydration behaviour of silicone hydrogel materials is predictive of in-eye performance.

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Keywords: Soft contact lenses; Silicone hydrogel lenses; Dehydration; Gravimetric analysis

1. Introduction

Contact lens “dryness” continues to be a significant problem within the contact lens wearing population. Dry eye symptoms are reported by up to 50% of soft lens wearers [1] with 35% of patients permanently ceasing lens wear due to complications associated with discomfort and dryness [2]. The sensation of “dryness” is a complex subject and is without question related to a variety of factors. One factor to consider is that of lens dehydration, as the subjective symptom of dryness appears to occur more frequently in soft lens wearers whose lenses undergo greater dehydration during open-eye wear [3].

All hydrogel lens materials dehydrate during wear [4–7]. Dehydration is influenced by a number of factors, including the surrounding environment [5,6,8] material water content [6,9] water binding properties [10,11] thickness [12] and wearing period [13]. In addition, significant inter-subject differences exist [6,7]. Potential factors that may explain dehydration-induced discomfort include increased lid-lens interaction through alterations in lens front-surface wettability, alterations in lens fit or the development of epithelial staining due to pervaporation and subsequent desiccation [4,14–16]. Since the maintenance of a wettable surface during lens wear is so critical, a fundamental understanding of the processes which influence wettability and dehydration is essential to the development of new polymers for contact lens usage and the optimisation of existing lens types.

Patients using frequent replacement lenses complain less of dryness than wearers of other lens types [17–19]. This may be due to increased wettability [20] reduced deposition [21] or reduced dehydration. In addition, wearers of recently introduced low water content highly oxygen-permeable silicone hydrogel lenses are less aware of lens-induced dryness than when wearing conventional polymers, particularly at the end of the day [22]. The reasons behind this remain unclear, but may be due to reduced in-eye dehydration, enhanced wettability due to the surface treatment processes required with such materials and/or increased oxygen performance. Quite clearly, further innovative work to investigate
the effects of dehydration on in-eye comfort, wettability and lubricity is required. This will involve the development of novel techniques and the revised application of existing techniques if substantial improvements to our understanding of these complex phenomena are to be achieved.

The water content of hydrogel materials has been traditionally assessed using two methods. The first, based on refractive index [23] has resulted in the production of a hand-held device [24]. This instrument is simple to use in a clinical setting [6,7] but has some inaccuracies [25] due to the fact that it is an indirect method, surface water may impact on the results obtained and the relatively coarse scale is difficult to read. Additionally, low water content silicone-containing hydrogel materials are outside the range of the commercially available device. A more accurate analytical method is based on a gravimetric technique, in which the sample is accurately weighed on a very sensitive balance before and after hydration [25–26].

This paper investigates the rate of dehydration of novel and existing contact lens materials in an in vitro model, in which the environment is systematically controlled. The results obtained provide valuable information about the propensity of these polymers to dehydrate and the potential impact of such bulk hydration on surface wettability and in-eye comfort.

2. Methods

2.1. Lens materials

Five lens types were investigated in this study (Table 1). The centre thickness of commercially available hydrogel lenses varies with water content, with higher water content materials having increased thickness to prevent corneal desiccation [15,16]. All lenses used were ~3.00 D back vertex power, to ensure that differences in material thickness played a minimal role on the degree of dehydration measured [26]. Table 1 lists the manufacturers stated centre thickness as well as the mean centre and mid-peripheral thickness of three lenses of each type, as measured in our laboratory, using a Rehder ET-1 electronic thickness gauge (Castro Valley, CA). The results show that the differences in measured centre thicknesses between the lenses examined were greater than the differences in mid-peripheral thicknesses. The lens discs examined in this study were obtained from the mid-peripheral portion of whole lenses (as described further) and this ensured that the influence of lens thickness on measured dehydration in this experiment were minimised.

2.2. Initial water content measurement

To determine the initial water content of the lenses under test—and to compare them with the manufacturers stated water content—the material water content was assessed using a gravimetric method. The method adopted was the gravimetric analysis outlined in the British Standard relating to the determination of the water content of hydrogels using a microwave oven [29]. A whole lens (~3.00 D) was blotted to remove excess moisture using a slightly dampened Whatman #1 filter paper. This method was chosen following a variety of alternative blotting strategies, including dry Whatman filter paper and various cotton or synthetic cloths. Certain blotting procedures resulted in either too little or too much water being removed from the lens surface or resulted in fibres becoming adherent to the lens material, ultimately producing too great a standard deviation to be a viable alternative. The routine chosen resulted in the least degree of variation and most predictable result and is in agreement with previous studies investigating this factor [30]. Following the blotting process the lens was placed in a pre-weighed glass weighboat and the initial wet/hydrated mass recorded on a digital balance (Sartorius), with an accuracy of ±0.00001 g. The hydrated lens was then placed into a 650 W microwave oven on the “high” setting for 10 min and then cooled in a desiccator containing anhydrous calcium sulphate for 30 min, to ensure total moisture removal. The final dry mass of the lens was then recorded on the balance.

Using the wet and dry measurements, the percent water content was determined using the following definition:

\[
\text{Water content (\%)} = \frac{\text{wet weight} - \text{dry weight}}{\text{wet weight}} \times 100 \quad (1)
\]

A minimum of three runs of all lenses was undertaken to determine a mean and standard deviation.

2.3. Rate of dehydration protocol

In vitro water content was assessed using a thermal analysis technique [26,31]. A TA Instruments STA 1500 (Simultaneous Thermal Analysis) measured the amount and rate of mass change in the contact lens material, both as a function of increasing temperature and isothermally as a function of time, in a humidity-controlled atmosphere. This equipment is used by one of the investigators (LN) on a routine daily basis for materials analysis and characterisation [32–35]. It can be used to characterise any material that exhibits a mass change due to loss or gain of water (or other volatile components). As the sample within the sample pan changes in mass over time, measurements of time, mass and temperature are recorded every second. Due to the substantial amount of data obtained, our analysis included the results from every third measurement only (i.e. every 3 s). This typically resulted in approximately 500 data points per experimental run being recorded.

To investigate the impact of changes in ambient conditions on lens dehydration it was necessary to control the relative humidity (RH) and airflow into the sample chamber, which had an internal volume of 100 cm³ (6.1 in³). Two different relative humidities (20 and 60%) and airflow rates (9 and 30 ml/min) were chosen, to reflect typical differences in humidity and “draughty” conditions experienced.
Humidity was reduced to 20% and experiment (a) repeated. These results provided information on water content behaviour under low humidity conditions.

The airflow surrounding the materials was increased to 30 ml/min and experiment (a) repeated. This condition simulated the dehydration response rate of the materials in a “draughty” environment at room temperature. This was considered relevant as increased air flow has been shown to impact on tear film break-up time [36] and lens dehydration [37] and may help to explain the “dryness” reported by subjects when wearing lenses, for example, in a car with the air conditioning or heater on.

Each lens under each condition was measured in the TGA three times, so that a mean and standard deviation could be determined. Due to the size of the sample pan inside the TGA’s heating chamber a whole lens would not fit into the pan. Initial experiments in which whole lenses were suspended from the balance arm indicated that the results obtained became highly variable, particularly in high-speed wind conditions. To overcome this, three circular lens discs with approximate diameters of 5.0 mm were cut from the mid-peripheral portion of the whole lenses, using a metal hole-punch. After the lens discs were cut out of the lens they were placed back into the shipping solution within the lens foil for 15 min, allowing them to equilibrate with the solution in which they were originally transported.

Lenses samples were introduced into the analysis chamber of the TGA apparatus in a moist-state, directly from the lens vial, after removing excess water by blotting on slightly dampened Whatman #1 filter paper (as described previously). The total time the lens portion was exposed to air prior to measurements being taken was between 15 and 20 s for all lenses.

The dehydration exhibited by the lens materials was expressed as the relative percentage dehydration (RPD) and determined using the following equation [38]:

\[ \text{Relative percentage dehydration} = \frac{\text{initial EWC} - \text{final EWC}}{\text{initial EWC}} \times 100 \]  

### Table 1

<table>
<thead>
<tr>
<th>Proprietary name</th>
<th>Manufacturer</th>
<th>FDA</th>
<th>USAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focus Night&amp;Day</td>
<td>CIBA-Vision</td>
<td>B&amp;L</td>
<td>B&amp;L</td>
</tr>
<tr>
<td>PureVision</td>
<td>B&amp;L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optima FW</td>
<td>B&amp;L</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acuvue</td>
<td>Vistakon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proclear</td>
<td>Biocompatibles</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Stated Ct: manufacturers stated center thickness in millimeters (at −3.00 D lens (mean ± S.D.), determined using a Rehder ET-1 gauge. Measured Ct: center thickness of −3.00 D lens (mean ± S.D.), determined using a Rehder ET-1 gauge. EWC: manufacturers stated equilibrium water content. Dk: non-edge corrected oxygen permeability. For the silicone hydrogel lenses these are manufacturers stated values. For the conventional hydrogel materials Dk has been calculated using the formula of Fatt (Dk = stated values). For the conventional hydrogel materials Dk has been calculated using the formula of Fatt (Dk = stated values). Dk: non-edge corrected oxygen permeability. For the silicone hydrogel lenses these are manufacturers stated values.
Table 2
Microwave gravimetric results

<table>
<thead>
<tr>
<th>Lens type</th>
<th>N</th>
<th>Reported water content (%)</th>
<th>Measured water content (mean ± S.D.) (%)</th>
<th>Difference (reported – measured) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lotrafilcon</td>
<td>4</td>
<td>23.5 ± 1.5</td>
<td>23.5 ± 1.5</td>
<td>-0.5</td>
</tr>
<tr>
<td>Balafilcon</td>
<td>4</td>
<td>37.2 ± 0.9</td>
<td>37.1 ± 1.0</td>
<td>+1.2</td>
</tr>
<tr>
<td>Polymacon</td>
<td>4</td>
<td>38.1 ± 0.9</td>
<td>38.1 ± 0.9</td>
<td>+0.1</td>
</tr>
<tr>
<td>Etafilcon</td>
<td>4</td>
<td>57.9 ± 1.3</td>
<td>57.9 ± 1.3</td>
<td>-0.1</td>
</tr>
<tr>
<td>Omafilcon</td>
<td>4</td>
<td>60.4 ± 1.2</td>
<td>60.8 ± 1.2</td>
<td>-1.6</td>
</tr>
</tbody>
</table>

Initial water content was that determined from the microwave dehydration experiment described previously. Final water content was determined for each experimental condition by obtaining the change in lens water mass after 25 min, as measured by the TGA equipment.

2.4. Statistical analysis

All data (for all three lenses for each material) were plotted and analysed by fitting a non-linear regression model to each graph. The results were best fitted with a double exponential, non-linear regression model, which accounted for at least 99% of the variance. Materials were compared and contrasted by comparing the time (\(T\)) for each sample to dehydrate to 1/e (which was approximately one-third of the original hydration) and the rate (\(R\)) of dehydration (or slope of the dehydration curve). These two factors provided data on the total mass of water lost and the rate of that water loss from each sample. Using this model, materials that dehydrate rapidly have a low \(R\) value (indicating a rapid rate of dehydration) and materials that lose a substantial amount of water have a large \(T\) value. The values for the time \(T\) and dehydration rates \(R\) which were used in the statistical comparisons were the mean value of the triplicate experiments for each factor. These values were compared using a one-way ANOVA, with statistical significance being taken at \(P < 0.05\). Post hoc analysis for differences between factors that proved significant was undertaken using the Tukey test.

3. Results

3.1. Initial water content measurement

Table 2 summarises the results of the microwave gravimetric experiment to determine the actual water content of the lenses investigated, as compared with the manufacturers reported water content. These values were calculated using Eq. (1) and were used in the subsequent calculation of the RPD of the lenses under investigation (Eq. (2)).

![Dehydration data for triplicate runs of the Optima FW material, being heated from 22 to 100°C under 60% relative humidity and 9 ml/min airflow. This representative data indicates that the triplicates were similar in terms of their dehydration profile and validates the use of the mean dehydration time (T) and rate (R) values in subsequent calculations of the rates of dehydration and relative percentage dehydration.](image-url)
Table 3

<table>
<thead>
<tr>
<th>Lens type</th>
<th>60% RH at the rate 9ml/min</th>
<th>20% RH at the rate 9ml/min</th>
<th>60% RH at the rate 30ml/min</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (min)</td>
<td>R (ml/min)</td>
<td>T (min)</td>
</tr>
<tr>
<td>Lotrafilcon</td>
<td>11.3 ± 0.2</td>
<td>6.7 ± 0.7</td>
<td>6.7 ± 0.2</td>
</tr>
<tr>
<td>Balafilcon</td>
<td>11.5 ± 0.3</td>
<td>7.4 ± 1.3</td>
<td>8.4 ± 0.3</td>
</tr>
<tr>
<td>Polymacon</td>
<td>12.0 ± 0.6</td>
<td>8.6 ± 0.9</td>
<td>8.0 ± 0.2</td>
</tr>
<tr>
<td>Etafilcon</td>
<td>18.4 ± 0.9</td>
<td>9.0 ± 0.9</td>
<td>3.3 ± 0.4</td>
</tr>
<tr>
<td>Omafilcon</td>
<td>18.2 ± 0.6</td>
<td>8.8 ± 0.4</td>
<td>13.9 ± 1.6</td>
</tr>
</tbody>
</table>

Values for T (time to dehydrate to 1/e) and rate of dehydration (R) were obtained by fitting the data from the TGA with a double exponential non-linear regression model. The values given reflect the mean ± S.D. for three runs with each material under each environmental condition. For comparative purposes, materials that dehydrate rapidly have a small R and materials which lose a substantial amount of water have a large T.

3.2. Rate of dehydration

Dehydration data for all lens types for all conditions demonstrated a typical ogival form, as shown in Fig. 1. This figure indicates the results for the Optima FW material under 60% RH and 9 ml/min airflow and indicates the typical level of repeatability obtained with three samples for any given lens type under each condition tested. This result indicates that a high level of repeatability for the three samples tested was obtained and validates our decision to use the mean T and R values for the comparisons between materials and test conditions.

Table 3 provides the T and R values for all lens materials and test conditions. Statistical analysis reveals that there was a significant difference between materials for all three testing conditions (P < 0.01). Post hoc analysis reveals that these differences were significant (P < 0.05) for etafilcon and omafilcon in comparison with the other materials for the initial condition and between omafilcon and the other four materials for the reduced humidity and increased airflow conditions. Examination of the data reveals that the T values are closely linked to the initial water content of the materials for each differing testing condition, as shown in Fig. 2, which compares the initial water content with the T values for the high humidity, low airflow condition. This figure demonstrates the close association between these two parameters for this test condition. Analysis of the remaining two testing conditions provided R² values of 0.7 (P < 0.001) for both the low humidity and high airflow conditions.

Fig. 3 graphically summarises the R (rate of dehydration) data and shows that the differing environmental conditions have vastly differing impacts on the rate of dehydration, with reduced humidity increasing the rate of dehydration.
and increased air velocity dramatically increasing the speed of dehydration. Figs. 4 and 5 provide the actual dehydration data for the three testing conditions for the balafilcon and omafilcon materials, respectively. This further demonstrates the obvious differences obtained with the three varying environmental conditions, with wind velocity providing a greater stimulus to enhanced dehydration than reduced humidity. Statistical analysis demonstrated that, regardless of
lens material, environmental condition had a significant effect on the rate of dehydration \( (P < 0.001) \), with increased airflow having a greater effect than reduced humidity \( (P < 0.05) \). With respect to differences between materials, for the initial and reduced humidity condition the etafilcon material proved to dehydrate at a greater rate than the other lens materials \( (P < 0.05) \), which were not significantly different to each other \( (P = \text{NS}) \). For the increased airflow condition there was no statistically significant difference between any of the materials \( (P = \text{NS}) \).

### 3.3. Relative Percentage Dehydration (RPD)

The RPD of the materials under test provides comparative data between materials. The RPD of the lens materials examined is detailed in Table 4 and Fig. 6 reveals the relationship of the water content of the materials with their RPD under the three testing conditions. Analysis reveals that there was a statistically significant difference between the three testing conditions \( (P < 0.03) \) and that the three low water content materials (polymacon, lotrafilcon and balafilcon) were significantly different from the two high water content materials (omafilcon and etafilcon) \( (P < 0.01) \). Within the two groupings, materials were not statistically different from each other with regards to their RPD \( (P = \text{NS}) \).

### 4. Discussion

Lens dehydration results in alterations in soft lens fitting characteristics [39,40] and reduced oxygen transmission [41]. In addition, dehydration plays a role in corneal epithelial staining [15,42] and may play a role in contact lens comfort. This latter point is controversial, with some studies finding that increased dehydration results in reductions in lens comfort [3,38,43,44] and others finding that no such correlation exists [4,45]. The recent release of silicone hydrogel lenses has provided clinicians with a new alternative to fit patients with hydrogel lenses. The purpose of this study was to determine the level of dehydration which occurs with these novel materials and to investigate if varying environmental influences impacted on this level of dehydration. The study used an in vitro model to determine dehydration, as used by several researchers previously [25,26,28,46–48].

Whilst the value of conducting in vitro studies to predict in vivo behaviour has been questioned [47,48] it was felt that an in vitro analysis of the dehydration levels obtained with silicone hydrogel materials was worthy of study, in order to rank them with respect to conventional hydrogel lens materials.

Previous in vivo studies that investigated the impact of the environment on soft lens dehydration have differed in their conclusions. Whilst Andrasko [5,12] showed that low
humidity environments resulted in increased dehydration compared with high humidity environments, Brennan et al. [6] were not able to demonstrate this, finding that humidity had a minimal influence on dehydration. Our in vitro data are consistent with Andrasko’s in vivo findings, with reduced humidity resulting in increased dehydration. It is possible that differences in the technique used to determine the degree of dehydration may explain the results, as Brennan et al. [6] used a refractive index technique, as compared with the gravimetric method used in this study and that of Andrasko [5,12]. Further differences may exist due to the fact that Brennan et al.’s study [6] was conducted over a longer time in the “normal” living environment of the subjects, compared with the laboratory-based data from this work and Andrasko [5,12]. The only previous study to investigate the impact of airflow on lens hydration [12] found that increasing the air velocity across the face of a soft lens wearer resulted in reduced lens dehydration being measured. This appears counter intuitive, in that lens wearers frequently complain that the impact of direct air flow onto their lenses (such as that produced by air conditioning units or fans blowing in their car) results in a marked increase in the sensation of dryness. Additionally, increased airflow on non-lens wearing eyes results in reduced tear film break-up times [36]. Andrasko [12] explained his unexpected result by surmising that the airflow acted as a stimulant to make the patient tear, resulting in reduced dehydration. Our results do not concur with Andrasko’s data [12] and suggest that increased airflow acts as a significant factor to dehydrate lenses, having a much greater dehydrating impact than reducing the local humidity. Clearly methodological differences exist in our experiment compared with that of Andrasko, in that our experiment used an in vitro model as compared with Andrasko’s in-eye clinical study and we used a controlled airflow, as compared with the previous study, which used a room fan at a distance of 5 ft. It is possible that such differences explain the disparity in our results, but we feel confident that environmental factors do play a significant role in lens-related dehydration and symptoms of dryness, based on patient symptoms reported during routine clinical questioning at after-care appointments, along with our in vitro findings reported in this study.

Increasing evidence from fundamental studies of water transport across hydrogel membranes has shown that the rate of evaporative water loss at the anterior surface of the hydrogel is closely related to the hydraulic transport within the contact lens [28,49,50]. The diffusion rate for water molecules in hydrogels is a strong function of water content; the potential for water to diffuse through a hydrogel and be lost from the surface is related to the proportion of relatively mobile or “loosely bound” water, which is fundamentally greater in a higher water content lens [27,28]. In other words, evaporation is primarily diffusion controlled and is closely related to the bulk equilibrium water content, with only subtle differences in water loss occurring in materials with identical water contents, as shown by Fig. 2. These subtle differences occur due to minor differences in bound water levels and occur due to differences in polymer...
composition and the polymer’s ability to bind water to the bulk material [51]. Our rate of dehydration data is similar to that previously reported [26,28] with a relatively linear loss for the first 15–20 min of the experiment, followed by a plateau. Consideration of the dehydration time (T) and rate (R) values (in Table 3 and Fig. 3) provide similar data to that recently reported [28] in which higher water content lenses typically take longer to equilibrate and dehydrate at a faster rate. These results disagree with previous in vitro work, in which the rate of dehydration was lower with high water content lenses [11,47].

The degree of in vivo material dehydration measured following a period of lens wear varies depending upon the technique used to determine water loss. Polymacon and omafilcon lenses lose approximately 2% absolute water content [4,7,9,41,45,52] which equates to approximately 5% RPD. Etafilcon reportedly loses 6–10% of its absolute water content [4,38,41,53] which equates to 10–16% RPD. Clearly our RPD results (Fig. 6 and Table 4) are far greater than the published in vivo RPD data, with, in some cases, amounts almost an order of magnitude greater than published in vivo values. However, our results are similar to other published in vitro studies using gravimetric techniques [26,28]. This disparity between in vivo and in vitro data is not entirely surprising, for a number of reasons. Firstly, during in vivo studies only one side of the lens is exposed to the atmosphere, inevitably resulting in a reduction in the rate of evaporation from the material surface. Secondly, the eye blinks numerous times during the day when the lens is worn, acting to reｗet the lens material after each blink and limiting evaporation. Finally, the lipid layer of the tear film may act to limit the dehydration rate from the lens surface [46]. In light of these factors, in vitro modelling will inevitably result in dehydration data that is markedly greater than that experienced on-eye.

In conclusion, in vitro dehydration studies of conventional and novel silicone-containing hydrogel materials indicates that evaporation rates from materials are predominantly water content related, with only subtle differences between materials of similar water contents being seen. Environmental conditions have a significant impact on in vitro dehydration, with increased airflow having a greater impact than reduced humidity on increasing dehydration rates. In vitro dehydration is closely related to bulk water diffusion rates and, as a result of their low water content, silicone-containing hydrogel materials exhibit low levels of dehydration compared with high water content hydrogel contact lens materials. Further in vivo studies are necessary to determine if the in vitro behaviour of silicone hydrogel materials is predictive of in-eye performance.

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