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Dehydration and physicochemical changes in myopia control contact lenses: influence of material and maintenance solutions

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ABSTRACT

Purpose: To assess the dehydration rate in different myopia control contact lenses (CLs) and the physicochemical changes that occur after exposure to different maintenance solutions.
Methods: First, the dehydration rate of CLs and its impact on refractive index and diameter were evaluated in three myopia control CLs models (MiSight 1 Day, Bloom Day, and MYLO). Measurements were taken immediately after the CL was removed from the blister and at 5-min intervals over a 30-min period. Second, the effect of different maintenance solutions on the physicochemical properties of monthly replacement myopia control CLs (MYLO) with different diameters were assessed. Refractive index, water content, diameter, lens surface hydrophobicity, and dynamic mechanical properties were measured immediately after the CL was removed from the blister and again after 12 h of immersion in each of the three maintenance solutions studied (Hidro Health HA, OPTI-Free PureMoist and Biotrue).
Results: The dehydration rate exhibited significant disparities among the CLs examined, with daily replacement CLs (MiSight 1 Day and Bloom Day) demonstrating the fastest dehydration and, consequently, the most significant change in refractive index. In contrast, MYLO CLs exhibited the greatest reduction in diameter. When assessing the impact of maintenance solutions on MYLO properties, changes were observed in all evaluated parameters, except for mechanical properties. These changes varied depending on the maintenance solution used and the diameter of CL.
Conclusion: Myopia control CLs can undergo dehydration and changes due to the solutions used for their care, which may significantly affect their physicochemical properties, lens performance, comfort, and stability. Therefore, careful consideration should be given to the properties of the CL material and the maintenance solutions properties to optimize the user experience and ensure consistent lens behavior over time.

1. Introduction

Myopia is a refractive defect characterized by blurred distance vision due to the rays originating from these objects focus before the retina. This condition is primarily attributed to excessive eyeball elongation, with axial length thus being a fundamental parameter in the monitoring of myopic progression, although alternative underlying causes can also contribute [1]. On a quantitative level, it is defined as a condition in which the spherical equivalent refractive error is ≤−0.50 D in either eye [2]. Myopia develops during childhood and early adulthood, influenced by genetic and environmental factors [1,3]. The global prevalence of myopia among adults is estimated at 30 % [4], although in certain regions of East and Southeast Asia, 80 % of young adults are already myopic [5,6]. This high prevalence and its marked increase have led to its labelling as an 'epidemic' [6]. Furthermore, the well-established link between myopia, particularly high myopia, and an elevated risk of various ocular complications that can lead to visual impairment or blindness, underscores the critical need to investigate myopia control

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methods [7]. In the absence of treatments that can reverse myopia once established, recent decades have been marked by efforts to develop preventive interventions to slow its progression during childhood, the period when it usually manifests [8]. These interventions can be categorized into two major classifications: pharmacological and optical. Among optical interventions, contact lenses (CL) have emerged as the predominant approach, with technological advances leading to the commercialization of numerous CL types designed to slow myopia progression [9].

Similar to all CL, the visual quality and comfort of myopia control CL are determined by the physicochemical characteristics of each lens' material. These characteristics include factors such as the refractive index, water content, lens dimension, lens surface hydrophobicity or mechanical properties, all of which play a crucial role in how the lens interacts with the ocular surface health and the user's experience. For instance, the refractive index affects optical performance, water content influences comfort, CL dimensions affect optimal fit and clarity, surface hydrophobicity prevents lipid buildup and mechanical properties may determine durability of the lens [10–12]. However, these properties are not static and can be affected by multiple factors, including CL wear, dehydration [13,14], and external factors such as the use of different maintenance solutions for the care in non-daily replacement CL [15]. Understanding how these interactions influence CL performance is relevant to guide eye care professionals in prescribing the most appropriate CL and maintenance solution for each individual case, improving patient outcomes, and enhancing the effectiveness of myopia control strategies. Moreover, this is of particular importance given that these CLs require to be worn for multiple hours each day by the pediatric population [16]. Despite their growing clinical adoption, detailed studies examining how these properties vary in the absence of proper maintenance or under the use of different maintenance solutions for these lenses are scarce, probably due to their relative novelty in the market. To address this gap, the aim of the present study was to assess the physicochemical properties of various myopia control CLs and to evaluate how these properties are altered under two factors: dehydration and the use of different maintenance solutions. By identifying these changes, this study provides valuable insights into the stability and performance of myopia control CLs, helping to optimize their clinical use and enhance the user experience.

2. Methods

The present study consisted of two parts, each evaluating alterations in different physicochemical properties of myopia control CLs. Part A assessed changes due to dehydration, while Part B investigates the impact of different maintenance solutions. Specific methodologies for each section are described below.

2.1. Part A: in vitro dehydration rate and its impact on myopia control CL properties

2.1.1. Contact lenses

Three CLs designed for myopia control were evaluated. Two of these were daily disposable CL with a single fixed parameter: MiSight 1 Day (CooperVision Inc., United States of America) and Bloom Day (Menicon Co. Ltd., Japan) [17,18]. The third was a monthly disposable CL available in multiple parameters: MYLO (Mark'Ennovy Personalized Care, Spain), and the combination of 8.6 mm radius and 14.5 mm diameter was selected as midpoint between the parameters of the other two CL included in the study [19]. Three samples of each CL were analyzed, all with an optical power of −3.00 D. The characteristics of each CL are detailed in Table 1.

Table 1
Parameters of the CL studied. FDA: Food and Drug Administration, USAN: United States Adopted Names. EDOF: Extended Depth of Focus.

	MiSight 1 Day	Bloom Day	MYLO
Manufacturer	CooperVision	Menicon	Mark'ennovy
USAN	Omafilcon A	Etafilcon A	Filcon 5B
Material	Hydrogel	Hydrogel	Silicone-hydrogel
Replacement	Daily	Daily	Monthly
Oxygen Permeability (Dk/t) @ −3.00 D	28	25	50
Water content	60 %	58 %	75 %
Design	Dual-Focus	EDOF	EDOF
Add power (D)	+2.00	+3.00	+1.50
Base curves (mm)	8.7	8.3	7.1 to 9.8 (0.3 increments)
Diameters (mm)	14.2	14.5	13.5 to 15.5 (0.5 increments)
Sphere power (D)	−0.25 to −10.00	−0.25 to −10.00	−0.25 to −15.00

2.1.2. Experimental procedure

Prior to conducting the experimental tests, a preliminary analysis was conducted to determine reference values (baseline) for the subsequent assessments. In this preliminary analysis, one CL of each model was fully dehydrated by placing it in a specially designed plastic net holder to prevent liquid accumulation and ensure uniform air distribution around the CL. The refractive index of each CL was measured during this process until a final stable value was obtained, corresponding to the fully dehydrated state. The measured values corresponded to the average of three consecutive measurements. From this preliminary analysis, the refractive indices of the dehydrated CLs were 1.4893, 1.4903 and 1.4987 for MiSight 1 Day, Bloom Day and Mylo, respectively. Additionally, the refractive indices of the blister packs solutions containing these CLs were also measured, with a value of 1.3345, 1.3342 and 1.3341 for MiSight 1 Day, Bloom Day and Mylo, respectively. As the preliminary analysis showed that MiSight 1 Day and Bloom Day reached full dehydration after a period of 35 min, experimental evaluations were taken at 5-min intervals of 30 min. These evaluations included the assessment of the refractive index, the water content, and diameter measurement.

The refractive index and water content of the CL were measured using the CLR 12–70CL (Index Instruments, United Kingdom) digital automated refractometer in "continuous scan" mode, with values recorded immediately upon achieving stability [20,21]. The refractometer applied Eq. (1) to obtain the water content [14].

$$Watercontent(\%) = \frac{(n1 - n2)}{(n1 - nS)} \times 100 \quad (1)$$

The variables required for programming the device included the refractive index of the immersion solutions in the blister of each CL (denoted as *nS*), and the refractive index of each model of CL after total dehydration (denoted as *n1*), both measured in the preliminary analysis. The remaining variable, *n2*, corresponds to the refractive index value obtained at the time of measurement.

For diameter measurement, each CL was photographed alongside a millimeter ruler, and the images were analyzed with ImageJ software (National Institutes of Health, Bethesda, United States of America; https://imagej.net/ij/) [22]. The CL measurement was performed with the *oval selection tool* restricted to a circular proportion and a custom macro that automatically calculated the diameter using the geometric ratio between the area and the diameter of a circle (Eq. (2)) [23].

$$Diameter = 2\sqrt{\frac{Area}{\pi}} \quad (2)$$

The pixel-based measurement was then converted into millimeters using a proportional calculation, where the number of pixels corresponding to 1 mm (measured from the millimeter ruler with the *straight, segmented, or freehand lines tool*) served as a reference for each image.

2.2. Part B: impact of maintenance solutions on monthly disposable myopia control CL

2.2.1. Contact lenses

For this part, only the MYLO monthly disposable lens [19] (Table 1) was used to assess the effect of maintenance solutions on various physicochemical properties, as daily lenses are not exposed to this maintenance process during regular use. All CLs used had identical power and base curve characteristics (−3.00 D and 8.3 mm, respectively). Regarding CL diameter, a range of lens diameters (13.5, 14.0, 14.5, 14.5, 15.0, and 15.5 mm) was used for the assessment of the water content, refractive index, and diameter, while for modulus and contact angle analysis measurements, a single diameter (14.5 mm) was employed due to the requirement for CL segmentation in these processes [24]. Three samples of each CL were evaluated for each maintenance solution.

2.2.2. Lens maintenance solutions

Three multipurpose disinfection solutions for CL were evaluated. One solution was the product recommended by the manufacturer the Hidro Health HA (DISOP S.A., Spain). The other two solutions, OPTI-FREE PureMoist (Alcon Inc., United States of America) and Biotrue (Bausch & Lomb, United States of America), had been extensively tested in previous studies [24,25]. In a preliminary analysis, the refractive index measured for each of the maintenance solutions were measured, yielding values of 1.3349 for the blister solution, 1.3343 for Hidro Health HA, 1.3370 for OPTI-Free PureMoist, and 1.3357 for Biotrue. The chemical composition of each solution is detailed in Table 2.

2.2.3. Experimental procedure

The CLs were evaluated for water content, refractive index, diameter, hydrophobicity, and mechanical properties. Initial measurements were performed immediately after removal from the blister pack, and the procedure was repeated after a 12-h soak of the CL in the solution [24]. The measurements of water content, refractive index, and diameter were conducted in accordance with the methodology described in Part A. The measurement of hydrophobicity and mechanical properties required segmentation of the sample [24]. For this purpose, a 5 mm wide slotted metal plate was placed over the CL, ensuring central alignment within a slot. Two incisions were made along both edges of the slot, resulting in a sample with a length equal to the CL diameter and a central width of 5 mm.

Hydrophobicity was assessed by measuring the contact angle of the standard liquid Millipore water on the CL using the OCA 20 device (DataPhysics, Germany) [24]. The dynamic mechanical properties of the CL were evaluated at ambient temperature (21.3 ± 0.37 °C) using a TT-DMA dynamic mechanical analyzer (Triton Technology Ltd., United Kingdom). A frequency sweep was applied twice consecutively in ascending order (1.00–10.00 Hz) simulating a range of human eye movements [26,27]. From the parameters obtained in the analysis, the viscoelastic properties of the CL were evaluated. These properties include: the storage modulus, which measures the reversibly stored deformation energy (the elastic component of the material); the loss modulus, representing the irreversibly dissipated energy during one cycle (the viscous component of the material); and tan delta, the ratio of the loss modulus to the storage modulus (the strength of the material) [28]. The material was categorized as a weak gel if the tan delta ratio has a value close to 1, medium strength between 0.1 and 0.5, and strong for values equal to or less than 0.1 [29].

Table 2
Main components of the lens maintenance solutions tested. Maintenance solutions were classified by the presence and/or combination of the main active and inactive viscosity and lubrication-enhancing ingredients studied. EDTA: Ethylenediaminetetraacetic acid. HA: Hyaluronic acid. MAPD: Myristamidopropyl dimethylamine. PAPB: Polyaminopropyl biguanide. PEG: Polyethylene glycol. PHMB: Polyhexamethylene biguanide.

	Hidro Health HA	Opti-Free Pure Moist	Biotrue
Manufacturer	DISOP	ALCON	B&L
Surfactant/ Wetting agents/ Cleaners	HA, poloxamer 407	HydraGlyde (Polyoxyethylene-polyoxybutylene), Poloxamine (Tetronic 1304)	HA, Poloxamine
Preservative/ Chelating agents	0.0001 % PHMB, 0.02 % EDTA, Citrate	0.001 % Polyquad, 0.0006 % MAPD, EDTA, Citrate	0.00013 % PAPB, 0.0001 % Polyquad, EDTA
Other reported agents (e.g., buffers)	Boric acid, Sodium chloride, sodium tetraborate	Boric acid, Sodium chloride	Sulfobetaine, Boric acid, Sodium borate, Sodium chloride

2.3. Statistical analysis

Data analysis was performed using SPSS statistical software v.23.0 for Windows (SPSS Inc., United States of America). The selected level of statistical significance was $p \leq 0.050$. Prior to analysis, the Shapiro-Wilk test was conducted for all variables to identify any deviations from the normal distribution. Since the variables demonstrated a normal distribution, parametric tests were employed in the data analysis [30].

In Part A, the water loss ratio on air was compared among CLs at each time point using a one-way ANOVA. When significant differences were identified, variance homogeneity was assessed using Levene's test. Since homogeneity was met in all cases, Bonferroni's post-hoc test was applied for pairwise comparisons. Furthermore, intra-CL change in water content and intra-CL differences caused by dehydration in measurements taken at 5-min intervals for the properties studied (refractive index and diameter) of myopia control CLs were evaluated using repeated measures ANOVA for each parameter and lens type, with Mauchly's W-test to test the assumption of sphericity [30,31]. When sphericity was violated, the Greenhouse–Geisser or Huynh–Feldt correction was applied adjusting the degrees of freedom based on the departure from sphericity to control for potential Type I error inflation [30,32]. Once general differences were identified, the Bonferroni post-hoc was applied to detect significant pairwise differences [30,32].

In part B, the impact of maintenance solutions in each studied property (water content, refractive index, diameter, hydrophobicity and dynamic mechanical properties) on the monthly CL was assessed through the analysis of differences by applying a *t*-test for related samples between the baseline values and the values obtained after the 12-h period of immersion in each solution. In addition, to compare the mechanical properties of the CL as a function of the frequency employed (1.00, 3.25, 5.50, 7.75 and 10.00 Hz), an ANOVA test for repeated measurements was performed, with Mauchly's W test to check the sphericity assumption and Bonferroni post-hoc to conduct the pairwise analysis [30].

3. Results

3.1. Part A: in vitro dehydration rate and its impact on myopia control CL properties

The initial measurements for water content, refractive index, and diameter were 60 %, 1.40, and 14.3 mm respectively for the MiSight 1 Day CL, 53 %, 1.41, and 13.9 mm for the Bloom Day CL, and 72 %, 1.38, and 14.3 mm for the MYLO CL. A progressive increase in refractive index and a reduction in diameter were observed for all three CLs throughout the dehydration process. In order to further explore the variations, pairwise analyses were performed.

3.1.1. Water content

For the MiSight 1 Day, Bloom Day and MYLO CLs, the water loss ratio on air at each time point of the measurements was as follows: 7.7, 8.7 and 2.1 % at 5 min; 17.0, 16.2, and 7.5 % at 10 min; 30.4, 29.3 and 15.1 % at 15 min; 43.8, 42.3 and 26.6 % at 20 min; 53.6, 62.3 and 32.6 at 25 min; and 88.2, 85.5 and 41.6 % at 30 min, respectively. The comparison of the water loss ratio among the CLs revealed significant disparities at all time points evaluated from the 15-min measurement (one-way ANOVA, all $p \leq 0.019$). Pairwise analysis indicated that MiSight 1 Day and Bloom Day exhibited higher water loss compared to MYLO (Bonferroni post-hoc, all $p \leq 0.042$).

The water content of each CL at each measurement point was also evaluated (Greenhouse-Geisser, all $p \leq 0.004$). Pairwise analysis revealed that MiSight 1 Day CL maintained stable water content within the first 25 min (Bonferroni post-hoc, all $p \geq 0.059$). However, significant differences were observed at the final measurement, taken after 30 min of dehydration, compared to the initial, 5-min and 10-min measurements (Bonferroni post-hoc, both $p \leq 0.038$). No statistically significant differences were detected between the other measurements (Bonferroni post-hoc, all $p \geq 0.053$). Likewise, Bloom Day CL showed no significant changes in water content during the first 25 min (Bonferroni post-hoc, all $p \geq 0.168$), but significant differences were detected at 30 min, compared to baseline, 5-min and 10-min into the dehydration process (Bonferroni post-hoc, all $p \leq 0.019$). No significant differences were detected between the other measurements (Bonferroni post-hoc, all $p \geq 0.103$). For MYLO CLs, water content remained stable for the first 20 min of exposure to dehydration (Bonferroni post-hoc, all $p \geq 0.167$). However, at 25-min, significant differences were detected compared to baseline, 5-min, 10-min and 15-min measurements (Bonferroni post-hoc, all $p \leq 0.033$). The values obtained at the 20-min measurement did not exhibit any significant disparities when compared to the other values (Bonferroni post-hoc, all $p \geq 0.210$). After 30 min of dehydration, water loss was the most severe in MiSight 1 Day (88 %), followed by Bloom Day (86 %) and MYLO CL (42 %) (Fig. 1).

3.1.2. Refractive index

Dehydration in air, measured at 5-min interval during a 30-min period, resulted in significant variations in refractive index (Greenhouse-Geisser, all $p \leq 0.005$) for the three lenses models analyzed (MiSight 1 Day, Bloom Day, and MYLO). In pairwise analysis, the MiSight 1 Day CL showed no significant change in refractive index within the first 25 min (Bonferroni post-hoc, all $p \geq 0.058$). However, significant differences were observed in the final measurement, taken after 30 min of dehydration, compared to both the initial and the 5-mi measurements (Bonferroni post-hoc, both $p \geq 0.036$). No statistically significant differences were detected between the other measurements (Bonferroni post-hoc, all $p \geq 0.054$). Likewise, no differences were detected for the Bloom Day CL during the initial 25 min (Bonferroni post-hoc, all $p \geq 0.168$), but significant differences were detected when comparing the final value with those obtained at the baseline, at 5 min and 10 min into the dehydration process (Bonferroni post-hoc, all $p \leq 0.028$). No significant differences were found between the other measurements (Bonferroni post-hoc, all $p \geq 0.103$). The MYLO CL showed no significant refractive index variations in the first 20 min (Bonferroni post-hoc, all $p \geq 0.166$). However, at the 25-min, significant differences were found compared to baseline, 5-min, 10-min and 15-min measurements (Bonferroni post-hoc, all $p \leq 0.034$). No significant differences were observed at the 20-min measurement (Bonferroni post-hoc, all $p \geq 0.208$). After 30 min of dehydration, the refractive index of MiSight 1 Day and Bloom Day CLs had increased by 0.08 and 0.07, respectively, while MYLO CL exhibited an increase of 0.05 (Fig. 2).

3.1.3. Diameter

Dehydration in air, measured at 5-min intervals during a 30-min period, resulted in significant variations in their diameter (Greenhouse-Geisser, all $p \leq 0.004$) for all the three lenses (MiSight 1 Day, Bloom Day and MYLO). In pairwise analysis, MiSight 1 Day CL exhibited no significant differences between the baseline and the measurement taken at 5 or 10 min (Bonferroni post-hoc, both $p \geq 0.059$), whereas significant reductions in diameter were observed from the measurement taken at 15 min (Bonferroni post-hoc, $p = 0.021$). For Bloom Day CL, however, significant differences were observed as early as 10 min (Bonferroni post-hoc, $p = 0.007$). For MYLO, significant differences were only observed between the baseline and the final measurement (Bonferroni post-hoc, $p = 0.025$). After 30 min of dehydration, MYLO CL exhibited the largest diameter reduction (4.4 mm), followed by MiSight 1 Day (2.8 mm) and Bloom Day CL (2.4 mm) (Fig. 2).

3.2. Part B: impact of maintenance solutions on monthly disposable myopia control

3.2.1. Water content

Water content exhibited variations according to the maintenance solution employed and the CL diameter (Table 3). The Hidro Health HA solution resulted in a reduction in water content in CL of 14.5, 15.0, and 15.5-mm diameter (paired *t*-test, all $p \leq 0.004$) with no significant differences detected for the remaining diameters (paired *t*-test, both $p \leq 0.155$). The OPTI-Free PureMoist solution led to a significant reduction in water content for all lens diameters tested after the immersion period (paired *t*-test, all $p \leq 0.004$). In contrast, Biotrue affected the water content of the CL for all lens diameters tested (paired *t*-test, $p \leq 0.040$), except for the 14.5 mm diameter lenses (paired *t*-test, $p = 1.000$). Intriguingly, larger diameter lenses (15.0 and 15.5 mm) exhibited a decrease in water content after immersion, while smaller lenses (13.5 and 14.0 mm) demonstrated an increase in water content. Regardless of these changes, the most substantial change observed was a reduction of 1.85 %, relative to the 15.5 mm diameter MYLO CL immersed in the OPTI-Free PureMoist solution.

3.2.2. Refractive index

The refractive index exhibited variations after the immersion period depending on the maintenance solution used and the CL diameter (Table 3). The Hidro Health HA solution resulted in an increase in refractive index for the larger diameter CL (15.0 and 15.5 mm) (paired *t*-

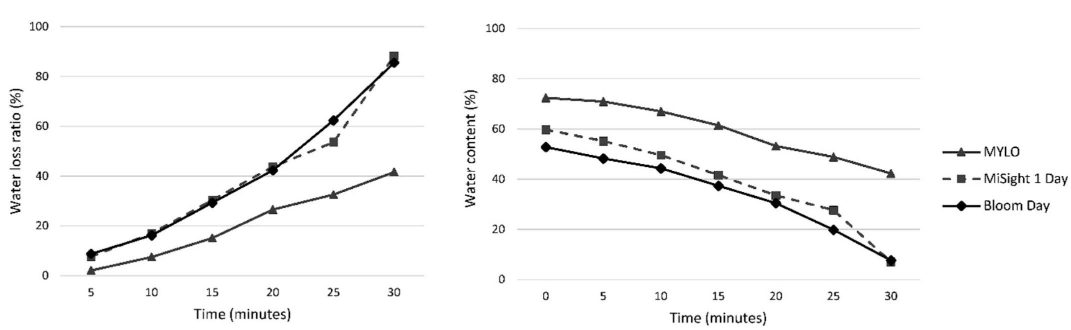

Fig. 1. Water loss rate and total water content of the contact lenses analyzed at each evaluated time point.

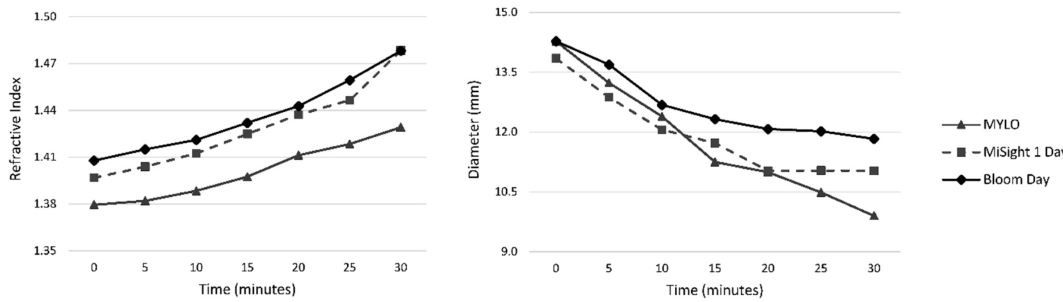

Fig. 2. Alterations in refractive index and diameter of the contact lenses analyzed at each evaluated time point.

Table 3
Mean differences in refractive index and water content for each contact lens diameter and each maintenance solution, relative to the initially measured value. CL: Contact Lens, SD: Standard deviation.

		Hidro Health HA		Opti-Free Pure Moist		Biotrue	
	CL diam. (mm)	Mean dif. ± SD	p	Mean dif. ± SD	p	Mean dif. ± SD	p
Refractive Index	13.5	0.0000 ± 0.0009	0.890	−0.0033 ± 0.0008*	<0.001	0.0004 ± 0.0006	0.119
	14.0	0.0001 ± 0.0007	0.749	−0.0022 ± 0.0005*	<0.001	0.0003 ± 0.0011	0.401
	14.5	−0.0002 ± 0.0005	0.196	−0.0041 ± 0.0005*	<0.001	−0.0006 ± 0.0011	0.136
	15.0	−0.0015 ± 0.0008*	0.001	−0.0043 ± 0.0004*	<0.001	−0.0025 ± 0.0007*	<0.001
	15.5	−0.0019 ± 0.0006*	<0.001	−0.0045 ± 0.0011*	<0.001	−0.0019 ± 0.0014*	0.004
Water content (%)	13.5	0.3 ± 0.6	0.155	1.1 ± 0.5*	<0.001	−0.6 ± 0.4*	0.002
	14.0	0.2 ± 0.4	0.160	0.4 ± 0.3*	0.004	−0.6 ± 0.7*	0.040
	14.5	0.4 ± 0.3*	0.004	1.6 ± 0.3*	<0.001	0.0 ± 0.7	1.000
	15.0	1.2 ± 0.5*	<0.001	1.7 ± 0.2*	<0.001	1.2 ± 0.4*	<0.001
	15.5	1.4 ± 0.4*	<0.001	1.8 ± 0.7*	<0.001	0.8 ± 0.9*	0.024

test, both $p < 0.001$), while no significant changes were observed in lenses with other diameters (paired *t*-test, all $p \geq 0.196$). The OPTI-Free PureMoist solution resulted in a significant increase in refractive index for all lens diameters tested (paired *t*-test, all $p < 0.001$) after the immersion period. Similarly, the Biotrue maintenance solution significantly affected the refractive index of CLs with a diameter of 15.0 and 15.5 mm (paired *t*-test, both $p \leq 0.004$), but not those with a diameter of 14.5 mm or smaller (paired *t*-test, all $p \geq 0.119$). However, despite reaching statistical significance, the magnitude of these changes was minimal, with the largest observed increase being 0.0045 following a 12-h immersion of the 15.5-mm diameter MYLO CL in the OPTI-Free PureMoist solution.

3.2.3. Diameter

The CLs dimensions varied according to the maintenance solution and the CL diameter. After the immersion period in the Hidro Health HA maintenance solution, significant alterations were detected in the 14.0 mm and 14.5 mm diameter CL (paired *t*-test, both $p \leq 0.029$) with an increase of 0.2 mm and a decrease of 0.5 mm, respectively. OPTI-Free PureMoist solution demonstrated a statistically significant reduction of 0.7 mm in the 15.5 mm diameter CL (paired *t*-test, $p = 0.024$), while there were no significant statistical differences in other diameters (paired test, all $p \geq 0.104$). In contrast, the Biotrue solution did not induce any statistically significant alterations in CL dimension across all tested diameters.

3.2.4. Hydrophobicity

The hydrophobicity of the CL surface varied depending on the maintenance solution used. The CL extracted from the blister exhibited a contact angle of 69.3 ± 10.5°. However, immersion in Hydro Health HA and Biotrue solutions resulted in a statistically significant reduction in contact angle (paired *t*-test, both $p \leq 0.030$), with mean difference of −27.0 ± 13.4° and −22.8 ± 8.1°, respectively. This indicates that these solutions interact with the CL surface, thereby reducing its initial hydrophobicity (Fig. 3). In contrast, the OPTI-Free PureMoist solution did not cause a significant change in contact angle (paired *t*-test, $p = 0.062$).

3.2.5. Dynamic mechanical properties

The storage modulus of the CL extracted from the blister pack was found to have a value of 566.0 ± 28.89, 568.0 ± 31.13, 554.1 ± 31.70, 525.9 ± 32.91 and 500.3 ± 27.27 kPa from the lowest to the highest frequency (1–10 Hz). A statistically significant variation across the frequencies was observed (Greenhouse-Geisser, $p < 0.001$), pairwise analyses indicating significant differences (Bonferroni post-hoc, all $p \leq 0.002$), except for the 1.00 Hz vs. 3.25 Hz comparison (Bonferroni post-hoc, $p = 0.897$). It was observed that the value decreased slightly as the frequency increased, suggesting that the CL behaved less rigidly at higher frequencies. No significant differences were observed when comparing the storage modulus of the CL extracted from the blister and after the immersion in any of the maintenance solutions for each of the frequencies studied (paired *t*-test, all $p \geq 0.147$). The loss modulus values obtained were 24.3 ± 2.30, 22.7 ± 2.18, 21.0 ± 2.89, 20.4 ± 3.36 and 42.9 ± 7.08 kPa from the lowest to the highest frequency. A significant inter-frequency variation was detected (Greenhouse-Geisser, $p = 0.002$), with pairwise analysis revealing significant differences between the measurements at 1.00 Hz and all other frequencies (Bonferroni post-hoc, all $p \leq 0.040$), except for 3.25 Hz (Bonferroni post-hoc, $p = 0.051$), as well as between the 10.00 Hz measurement and all others frequencies (Bonferroni post-hoc, all $p \leq 0.040$). Intermediate frequency values did not show significant differences among themselves (Bonferroni post-hoc, $p \geq 0.166$). Similar to the storage modulus, no significant differences were observed when comparing the loss modulus of the CL before and after immersion in any of the maintenance solutions at each frequency studied (paired *t*-test, all $p \geq 0.146$). The tan delta values were measured at 0.043 ± 0.0021, 0.040 ± 0.0022, 0.038 ± 0.032, 0.039 ± 0.0041 and 0.086 ± 0.0173 across the tested frequencies. Thus, under all conditions, the material exhibited the characteristics of a

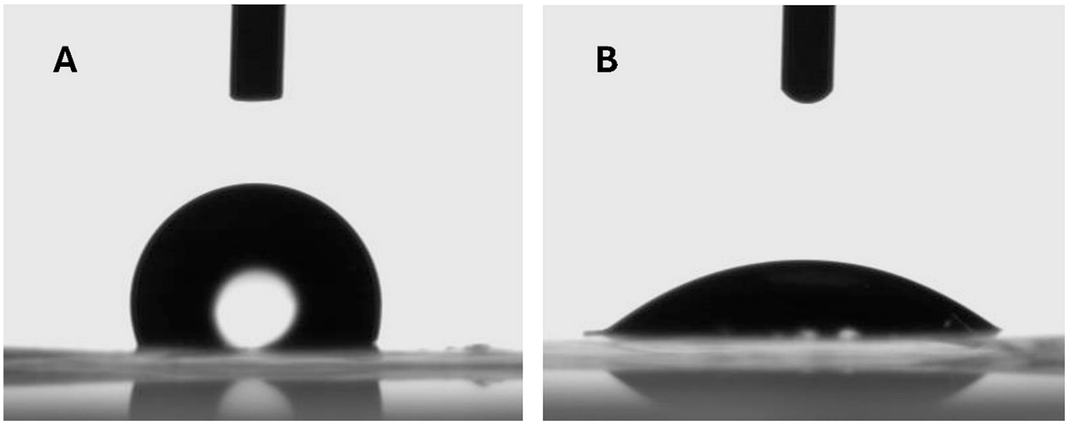

Fig. 3. Image A displays a water drop capture on a contact lens extracted from the blister, while image B presents a water drop capture on a contact lens that was immersed in Biotrue for a duration of 12 h. Both images were obtained with the OCA 20 instrument.

strong gel. A significant inter-frequency variation was noted (Greenhouse-Geisser, $p = 0.002$), with the value obtained at 10 Hz significantly differing from all others (Bonferroni post-hoc, all $p \leq 0.026$). However, immersion in maintenance solutions did not result in significant variations in the tan delta ratio at any measured frequency (paired *t*-test, all $p \geq 0.135$).

4. Discussion

The present study evaluated the differences in dehydration behavior and the effect of different maintenance solutions on the physicochemical properties of different daily and monthly CLs designed for myopia control for pediatric population.

In the first part of the study, during the dehydration process in air, all three CLs studied exhibited an increase in refractive index and a decrease in lens dimensions. The material type used in the CLs plays a crucial role in their dehydration behavior. The monthly replacement CL (MYLO) exhibited the lowest water loss rate, resulting in the smallest change in refractive index, but it showed the greatest reduction in lens diameter. In contrast, the daily disposable CLs (MiSight 1 Day and Bloom Day) showed faster water loss rate and thus a greater refractive index change, reaching almost total dehydration within 30 min. However, the changes in diameter were slightly smaller compared to the MYLO. This suggests that the material properties of MYLO may provide better resistance to dehydration compared to the daily disposables. Daily disposable CLs may offer convenience but could lead to discomfort due to rapid dehydration, while the monthly CLs MYLO may provide better hydration retention, enhancing wearer comfort over time.

These disparities can be attributed to the inherent properties of the lens composition, particularly the distinction between hydrogel and silicone hydrogel. Silicone hydrogel lenses, typically exhibit higher oxygen permeability and better dehydration resistance compared to traditional hydrogel lenses, which may explain their more stable water content and refractive index during dehydration [33]. These results are consistent with previous *in vivo* research, which found that hydrogel materials exhibit greater changes in water content and refractive index compared to silicone hydrogel materials [33]. Specifically, Ramamoorthy et al. [34] observed that hydrogel materials classified as FDA groups II and IV (high water content polymers) exhibited a higher degree of dehydration compared to materials with low water content. Among these, ionic materials (group IV) demonstrated the most significant degree of dehydration. This is due to their inherent ability to absorb and retain water, making them more susceptible to dehydration when exposed to air. Regarding CL dimensions, the results of the present study are consistent with those of Tranoudis et al. [11], who reported a reduction in total lens diameter as water content decrease.

In the second part of the analysis, assessing the impact of maintenance solutions on the monthly replacement CL (MYLO), a slight change in water content was observed, demonstrating a reduction after immersion in Hydro Health HA or OPTI-FREE PureMoist, while Biotrue caused a decrease or an increase depending on the CL diameter. A corresponding change in the refractive index was observed after exposure to each maintenance solution related to the alteration in water content. The greatest change was induced by OPTI-Free PureMoist, due to its refractive index (1.3370), being the most divergent from the original blister solution (1.3349). Most CLs exhibited no significant dimensional variations after immersion in the maintenance solutions. However, a significant reduction in diameter was observed in the 14.5 mm (0.5 mm) and 15.5 mm (0.7 mm) lenses after 12-h immersion in Hydro Health HA and OPTI-Free PureMoist respectively, whereas an increase in the 14.0 mm diameter CL (0.2 mm) after immersion in Hydro Health HA was found.

Wettability is a crucial factor in the performance and comfort of CLs, particularly in the context of myopia control CLs. This study provides valuable insights into how different maintenance solutions affect the wettability of these lenses. In terms of surface hydrophobicity, OPTI-Free PureMoist was the only solution that did not alter the contact angle. In contrast, both Hidro Health HA and Biotrue solutions reduced the contact angle indicating increased hydrophilicity. Since both solutions contain hyaluronic acid as a humectant, this compound may have significantly contributed to the observed changes, potentially improving the interaction between the CL surface and the solution, which in turn affects the overall user experience. Increased hydrophilicity may lead to better moisture retention and reduced dryness, which are critical factors for users of myopia control CLs [35].

In accordance with previous findings, the present study confirms significant alterations in the refractive index and, thus, water content of CL when exposed to different maintenance solutions [20,36]. The solutions evaluated in this study generally increase the refractive index of the CLs following interaction. However, other studies utilizing alternative solutions, such as ReNu Multiplus, have also reported reductions in index values [36].

The impact of maintenance solutions on CL dimensions is particularly relevant considering the tolerance limits established by the International Standards Organization (ISO, Switzerland) which stipulate that CLs should not undergo dimensional changes exceeding 0.2 mm, regardless of their initial diameter [37]. This limit is crucial for ensuring the safety and effectiveness of CLs in clinical practice. In the present study, this tolerance limit was exceeded by various CLs, with variations ranging from 0.2 to 0.7 mm. This indicates that certain maintenance solutions may significantly alter the dimensions of the lenses, potentially impacting their fit and comfort for users. The observed alterations were diameter-dependent, with larger CL exhibiting greater variations. This may be attributed to the increased surface area of larger lenses that are exposed to the liquid, which could enhance their interaction with the solution and its chemical components. These findings align with previous studies on other CLs, which also identified CL diameter as a sensitive parameter. Notably, both the present and previous studies identified OPTI-Free PureMoist as the solution inducing the most significant dimensional change [38]. This could raise concerns about the long-term usability and safety of these CLs in real-world scenarios, as the diameter is a property that is particularly prone to cause dissatisfaction through an inappropriate alteration. A reduction in diameter, while maintaining a constant base curve, will result in a decrease in sagittal height, leading to a flatter CL fit. Consequently, the CLs will exhibit increased mobility within the eye, a phenomenon associated with heightened discomfort and augmented bulbar and limbal hyperemia. On the other hand, an increase in CL diameter will lead to an increase in sagittal height, resulting in a more closed CL, which would interfere with tear exchange and facilitate conjunctival staining.[35] Thus, exceeding the ISO tolerance limits could have clinical implications, as it may affect the lens fit on the eye, leading to discomfort or even complications for the wearer. Moreover, this could also adversely impact the wearer's visual quality or the efficacy of myopia control, as decentration may result in the peripheral defocusing not being conducted on the intended retinal area. Therefore, adherence to these standards is essential for ensuring user safety and satisfaction.

The hydrophobicity of the CL surfaces is a crucial parameter. As a result, numerous studies have focused on developing treatments that improve its hydrophilicity and reduce the accumulation of deposits, with the aim of optimizing CL biocompatibility [39]. However, it has been observed that the interaction between CLs and different lens maintenance solutions can lead to changes in surface hydrophobicity. Consistent with the findings of the present study, previous research has also found alterations in this property following the use of maintenance solutions in other types of CLs [24,40]. In the present study, OPTI-Free PureMoist was the only solution that did not induce variations in CL hydrophobicity. This contrast with the findings of Lira et al. [24], who observed a decrease in the contact angle of some CLs after exposure to this maintenance solution possibly due to differences in material composition. The observed changes are generally considered beneficial for wearer comfort, as they reduce CL hydrophobicity [41].

Finally, none of the solutions affected the viscoelastic properties of the CLs. In the present study, the mechanical properties of the CLs were evaluated under dynamic forces, yielding results that differ from those observed in previous studies conducted under static conditions. The prior research has indicated that certain maintenance solutions [42], as well as CL conditions [43], can influence the material's stiffness (static mechanical properties). In contrast our findings suggest that solution interactions do not affect its viscoelasticity (dynamic mechanical properties). This is crucial, as viscoelasticity is essential for maintaining the functional stability of CL under repetitive deformation, such as that induced by blinking [44].

This suggests that exposure to these maintenance solutions does not compromise the lens's ability to withstand mechanical stress, reducing the risk of tearing during handling or wear. Additionally, since viscoelastic properties influence lens flexibility and adaptation to the ocular surface, the absence of significant changes implies that wearer comfort is unlikely to be negatively impacted. Conversely, it also suggests that the lenses are not more prone to tearing. Given that these are monthly lenses, this could represent a potential concern regarding their durability. If changes had occurred, an increase in stiffness (higher modulus) could have made the lenses less adaptable to the corneal surface, potentially leading to discomfort or mechanical irritation. On the other hand, a reduction in stiffness might have compromised lens handling and structural integrity.

The observed variations in the physicochemical properties of the CLs depending on the maintenance solution used highlight the importance of selecting appropriate care products, especially for CL intended for pediatric use.

A limitation of the present study was the reduced number of CL models, and the limited sample size analyzed. This is partly due to the restricted availability of CLs specifically approved for myopia control, in contrast to the broader range of CLs designed for conditions such as presbyopia. The inclusion of two daily disposable CL models and a single monthly replacement CL is intended to reflect European trends in fitting. Moreover, although other CLs for myopia control are available nationally, the selection of lenses included in this study was based on their wide use in clinical practice in the region [45,46]. Other models with international recognition were not considered due to their lack of availability in the Spanish and Portuguese markets [47]. Additionally, the study was conducted under controlled laboratory conditions, which may not fully reflect real-world usage. Furthermore, the comparison between different solutions was based on a single 12-h immersion period without accounting for the cumulative impact of immersion over days. Overall, the methodology employed in the present study has demonstrated its validity as a tool for the physicochemical evaluation of myopia control CLs. In view of the obtained findings, future research is required to explore the characteristics of other CLs and to consider the effect of alternative maintenance solutions on lens properties, leading to a more comprehensive characterization of the available products.

In conclusion, MiSight 1 Day and Bloom Day dehydrate more rapidly, leading to greater water loss and refractive index shifts, while MYLO retains moisture more effectively, but undergoes the greatest reduction in diameter. Regarding the solutions, alterations in water content and, consequently, the refractive index were observed for all solutions across the various CL diameters tested. Furthermore, Hidro Health HA and OPTI-Free PureMoist altered some CL dimensions, even exceeding ISO limits, while Hidro Health and Biotrue modified the surface contact angle of some CLs. None of the solutions affected the mechanical properties of the CLs. Consequently, careful consideration of both CL material and solution properties is essential to optimizing wearer comfort and CL performance. Ultimately, the right combination of lens and solution can make the difference between optimal performance and discomfort, ensuring the best experience for contact lens users.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors declare that they have no conflict of interest in the present study. This work was supported by the Portuguese Foundation for Science and Technology (FCT) in the framework of the Strategic Funding UID/04650: Physics Center of Minho and Porto Universities (CF-UM-UP).

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