Universidade do Minho
Escola de Ciências

Micael Moreira Alves

Influence of lens care solutions on transmittance and reflectance of contact lenses

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Dissertação de Mestrado
em Optometria Avançada

Trabalho efetuado sob a orientação de
Professora Doutora Maria Madalena da Cunha Faria de Lira
Professora Doutora Elisabete M. S. Castanheira Coutinho

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DECLARAÇÃO

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Título da dissertação: Influência das soluções de manutenção na transmitância e refletância das lentes de contacto

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“Blindness is also: living in a world where there´s no hope left.”

By José Saramago
in Ensaio sobre a cegueira

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A todos o meu sincero **Muito Obrigado!**

ABSTRACT

Influence of Lens Care Solutions on transmittance and reflectance of contact lenses

Relevance: The transmittance is an optical property of contact lenses (CLs) that represents the amount of refracted light. This attribute displays interest in issues related to protection against ultraviolet radiation (UVR) and visual performance of lenses. Currently, epidemiological and experimental evidence exists for the role of UVR phototoxicity in pathological changes to the ocular tissues. When placed in solutions, previous studies have shown that some combinations result in significant changes in the CLs properties, including in the optical domain.

Purpose: To investigate the effects of four lens care solutions on transmittance and reflectance of five contact lenses materials, analyzing the lenses before and after storage.

Methods: From a cohort study, triplicate measurements of tansmittance and reflectance of CLs was evaluated after 8 hours, 1 day and 1 week of storage with three multi-purpose solutions (MPSs: ReNu MultiPlus® MPS, Biotrue™ and Optifree® PureMoist®) and one hydrogen peroxide system (AOSept® Plus). The lenses used in this study were Acuvue Oasys™, Air Optix Aqua™, Purevision® 2, Biofinity™ and one conventional hydrogel material, Proclear™. The outcomes were provided by Shimadzu UV3101-PC UV-vis-NIR spectrophotometer equipped with an integrating sphere, between 200-700 nm. The fluorescence variables of solutions were performed by SPEX-Fluorolog 2 FL3-22 spectrofluorometer to assess the effects of materials in the products.

Results: After immersed in the different solutions, all the materials exhibited a greater or lesser statistically significant differences on study variables over time. The Comfilcon A showed the lowest UVA & UVB attenuation. Balafilcon A and Lotrafilcon B displayed a considerable suppression of UV radiation. Senofilcon A was effective in UVR protection and showed less effect on the fluorescence of liquids. Overall, the reflectance decreased after storage. In the LCSs, the outcomes of AOSept absorbance and fluorescence demonstrated lower affection in relation to MPSs solutions and Lotrafilcon B displayed greater changes in all study variables compared with the other materials.

Conclusion: Significant differences on transmittance were found after storage, probably due to the intractions with the products. AOSept showed greater strength to CLs effect compared with MPSs. The changes exhibited in the visible spectrum have no implications on visual performance.

RESUMO

Influência das soluções de manutenção na transmitância e refletância das lentes de contacto

Relevância: A transmitância é uma propriedade ótica das lentes de contato que representa a quantidade de luz refratada. Este atributo apresenta interesse em questões relacionadas com a proteção contra a radiação ultravioleta (UVR) e com o desempenho visual das lentes. Atualmente, existem evidências epidemiológicas e experimentais para o papel da fototoxicidade da UVR nas alterações patológicas dos tecidos oculares. Quando colocadas em soluções de manuntenção, estudos anteriores mostraram que algumas combinações resultam em mudanças significativas nas propriedades das lentes de contacto, inclusive no domínio óptico.

Objetivo: Investigar os efeitos de quatro soluções de manutenção de lentes na transmitância e refletância de cinco materiais de lentes de contato, analisando as lentes antes e depois de armazenadas.

Métodos: A partir de um estudo coorte, medidas triplicadas de tansmitância e refletância de lentes foram avaliadas depois de 8 horas, 1 dia e 1 semana de armazenamento com três soluções únicas (ReNu MultiPlus® MPS, Biotrue ™ e Optifree® PureMoist®) e um sistema de peróxido de hidrogênio (AOSept® Plus). As lentes usadas neste estudo foram Acuvue Oasys ™, Air Optix Aqua ™, Purevision® 2, Biofinity ™ e um material de hidrogel convencional, Proclear ™. Os resultados foram obtidos pelo espectrofotómetro Shimadzu UV3101-PC UV-vis-NIR equipado com esfera integradora, entre 200 - 700 nm. A variável de fluorescência das soluções foi obtida pelo espectrofluorímetro SPEX-Fluorolog 2 para avaliar os efeitos dos materiais nos produtos.

Resultados: Após imersos nas diferentes soluções, todos os materiais apresentaram diferenças estatisticamente significativas das variáveis de estudo ao longo do tempo. Comfilcon A mostrou a mais baixa atenuação de UVA & UVB. Balafilcon A e Lotrafilcon B exibiram uma considerável supressão da radiação UV. Senofilcon A foi efetivo na proteção da radiação UV e mostrou menor efeito na fluorescência dos produtos. No geral, a refletância diminuiu após armazenamento. Os resultados da absorvância e fluorescência do AOSept demonstraram menor comprometimento em relação às soluções únicas e o Lotrafilcon B mostrou maiores alterações em todas as variáveis de estudo comparado com os outros materiais.

Conclusão: Diferenças significativas na transmitância foram encontradas após o armazenamento, provavelmente devido às interações com os produtos. O AOSept mostrou maior resistência ao efeito das lentes comparado com as soluções únicas. As alterações exibidas no espectro visível não têm implicações no desempenho visual.

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INDEX OF EQUATIONS

$$n = \frac{c}{v} \quad \text{(Equation 1)}$$

$$R_\lambda = \frac{I_r}{I_o} = \frac{(n_t - n_i)^2}{(n_t + n_i)^2} \quad \text{or} \quad \%R_\lambda = \frac{I_r}{I_o} \times 100 \quad \text{(Equation 2)}$$

$$T_\lambda = \frac{I_t}{I_o} = \frac{4n_t n_i}{(n_t + n_i)^2} \quad \text{or} \quad \%T_\lambda = \frac{I_t}{I_o} \times 100 \quad \text{(Equation 3)}$$

$$R_\lambda + T_\lambda + A_\lambda = 1 \quad \text{or} \quad \%R_\lambda + \%T_\lambda + \%A_\lambda = 1 \quad \text{(Equation 4)}$$

$$PF = \frac{1}{T_\lambda} \quad \text{(Equation 5)}$$

$$E = h\nu = \frac{hc}{\lambda} \quad \text{(Equation 6)}$$

$$A_\lambda = -\log_{10} \frac{I_\lambda}{I_0} = \varepsilon_\lambda b C \quad \textit{Law of Lambert-Beer} \text{ – (Equation 7)}$$

$$I_F = I_0 \left(1 - 10^{-\varepsilon(\lambda_{exc}) b C}\right) \phi_F F(\lambda_{em}) d(\lambda_{em}) \quad \text{(Equation 8)}$$

GLOSSARY OF TERMS, ABBREVIATIONS AND ACRONYMS

AM	Acid methacrylic
ANSI	American National Standards Institute
a.u.	arbitrary units
BB	Blue blocking
BC	Base curve radius
CA	Contact angle
CHy	Conventional hydrogel
CLs	Contact lens(es)
CS	Corneal straining
cm	centimeters
D	Diopter(s) of optical power;
d	diffusion coefficient
Dk	Oxigen permeability
Dk/t	Oxigen transmissibility
DW	Daily wear
EDTA	Ethylenediamine tetraacetic acid
EW	Extended wear
FDA	Food and Drug Administration
FI	Fluorescence intensity (a.u.)
GP	Gas permeable
Hy	Hydrogel
HA	Hyaluronic acid
IR	Infrared radiation
LCSs	Lens care solution(s)
m	meters
mm	milimeters
MAPD	myristamidopropyl dimethylamine (or Aldox)

MPSs	Multipurpose solution(s)
nm	nanometers
OS	Oxidative stress
p	p-value: stastistical significance
PF	Protection factor
PHMB	polyhexamethylene biguanide (or PAPB)
PLF	Peripheral light focusing
PQ-1	Polyquatermium-1 (or Polyquad)
P-HEMA	Polyhydroxyethylmethacrylate
SiHy	Silicone hydrogel
SCL	Soft contact lens
R	Refletance, expressed in %; sample correlation coefficient
RGP	Rigid gas permeable
RI	Refractive index
T	Transmitance, expressed in %; thickness of individual CL
UV	Ultraviolet
UVR	Ultraviolet radiation
VA	Visual acuity
WC	Water content
YM	Young´s modulus
α	Cylinder shaft

1. INTRODUCTION

The industry estimates around 140 million of contact lens (CL) wearers world-wide. New and improved materials, designs and modalities have made CLs a practical choice acepted for most of patients. Despite this trend, some eye problems are reported due the properties of CL materials and lens care systems (LCSs) interactions. The spectral transmittance of CLs is particularly important for visual performance and ultraviolet (UV) blocking levels. The transparency characteristics are strongly dependent on the lens material and the protective effect can be correleted with the absorption and stability of the ultraviolet (UV) filter incorporated in the CL matrix. There are no earlier reported studies that evaluate if the transmittance (T) properties remain unchanged during differents CLs storage in differents solutions. In order to contribute to the understanding of the current concern about the transmission of invasive light through a CL and the impact of the products on the optical properties of CL materials, the present experimental research was designed. This study was carried out to measure the mutual effect of storage of soft CLs in lens care solutions in terms of light transmission.

The structure of this dissertation follows the Arezes guideline[1], starting with an introduction and research rationale presented in this 1st chapter. The 2nd chapter support the statement of the problematic issue, the mains goals and hypothesis formulation. From this point, the investigation is divided in two parts. The 1st corresponds to the systematic review of the literature that begins by presenting general concepts about the vision and visual implications of optical radiation, in 3rd chapter. The 4th and 5th chapters provides backgrounds, overviews, trends, clinical implications and main properties of CL and LCS, respectively, with emphasis for the transmittance of the lenses. The 6th disclose the fundamentals of absorbance and fluorescence. The work developed is structured in 2nd part, including the 7th chapter that adopts a methodological perspective with study design, sample characterization, experimental procedure, instrumentation and statistical analysis applied. The presentation of the results is detailed in the 8th chapter with the respective discussions and its potential implications in experimental and clinical research. Finally, the last chapter highlight the main findings of the study, as well as the future lines of work that could be developed.

2. OBJECTIVES AND HYPOTHESIS OF THE STUDY

2.1 Statement of the research problem

Optical properties of CLs are important for wearers, not only in protection context of UVR but also in visual performance.

Experimental observations confirmed that the transmittance values of UV-visible light in Balafilcon A material exhibit statistically significant differences after storage in different multipurpose solutions (MPSs). The deterioration process of CLs affects their intrinsic physical properties and this process can induce a loss of quality of LCSs. The opposite can also be true. There was no evidence about the changes on optical properities of LCSs what could explain this investigation. If there is a relationship between the lens polymer and the contamination of the LCS or vice versa, we can understand problems associated with the use of reusable lenses. Previous in vivo studies have demonstrated the influence of wear on transmittance of soft contact lenses (SCLs) and the authors considered that biofilm formation was associated with the observed changes. The choice of CLs, LCS and the range of spectrum evaluated in this study were chosen to complement and update previous studies about transmittance and reflectance.

Research Question: *"Do the lens care solutions influence the transmittance and refletance of contact lenses?"*

2.2 Objectives

The main aim of this dissertation is to investigate the influence of lens care solutions in UV-visible spectrum transmittance and refletance of SCL over time.

The specific goals of the study are:

1. Understand liquid-lens interactions;
2. Analyse changes in LCS caused by CLs;
3. Find evidence resulting of combinations between the CLs and LCS in the study variables.

2.3 Hypothesis formulation

The hypotheses of this investigation are:

1. The transmittance and reflectance of CLs are not independent of the type of LCS selected;
2. There are not statistically significant differences in the refletance and transmittance of CLs over time after storage in LCSs;
3. The absorbance and fluorescence of LCS are not independent of the material type of CLs selected;
4. There are not statistically significant differences in the absorbance and fluorescence of the LCSs over time after storage with CLs.

1ST PART

LITERATURE REVIEW

This part gives a systematic review of the literature. It starts with general information about the visual system, addressing some visual implications associated with the radiation and then, provides the fundamental background and overviews about contact lenses and lens care solutions, reporting the main properties and also some epidemiologic issues.

Studies about the influence of products on the contact lenses properties are described with greater emphasis, especially for the transmittance and reflectance.

3. VISION OPTICS

3.1 Vision optics - basic concepts about the eye and refractive errors

The visual perception is one of the most complex abilities of the human body that allows the perception of shape, size, colors, movement and position of objects. The eye or eyeball has the ability to focus and transform the electromagnetic radiation in nerve impulses.[2]

This structure is an adjustable lens system consisting of two focusing elements, the cornea and the lens, and a light receptor system, the retina. The cornea is the main focusing element. This transparent layer presents the greatest deflection due to its convexity. The aperture system iris-pupil depends on the intensity of the light and regulate its input. After crossing this "diaphragm", the light ray is subjected to a second deflection by a variable focusing system. The lens or crystalline lens is a flexible and fibrous structure suspended by ciliary muscles. When the eye focuses an object at short distances, the muscles relax and the lens is compressed, increasing its power. This process is known as accommodation.[3] Finally, the rays are focused and received on the retina which has a layer of photosensitive cells. The fovea is the central part of this receptor system responsible for clearer and more detailed information. The eye contains two types of photoreceptor cells: cones and rods. Rods are remarkably sensitive structures; however, they are unable to discriminate colors. In turn, the cones work with higher luminous intensities and there are three types of this cells: S (short wavelength), M (medium wavelength) and L (long wavelength), respectively sensitive to blue, green and red (*figure 3.2*). The focal points are dependent of the wavelength and located within the long axis of the folded membrane in the segment of the retina.[4] The nerve impulses resulting from photoelectric stimuli are transported to the brain along the optic nerve. The most common types of refractive errors are myopia, hyperopia and astigmatism. Refractive errors are measured in diopters (D) and usually can be corrected by lenses in order to correctly focus the light on the retina.

Roughly, myopia is related to a long axial length of the eye and hyperopia with a short length. In myopia, the focuses are formed in front of the retina, resulting in a blurred image (*figure 1.2, I*) and compensation is made by a concave lens.

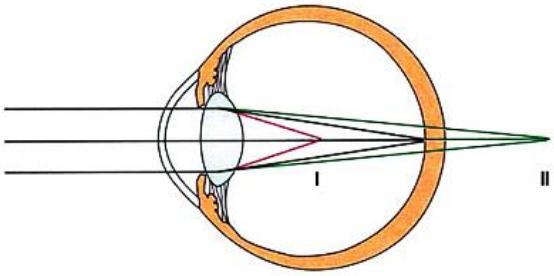

Figure 3.1. Focal points in myopia and hyperopia. (I) In myopia, the image of a point at infinity is projected in front of the retina; (II) In hyperopia, the image is projected behind the retina (Reproduced from Kohnen et al.,2008).[5]

On the other hand, in hyperopia the light is focused behind the retina and the image is likewise blurred (*figure 1.2, II*). In this situation, the error is compensated by a convex lens.[5]

The astigmatism is maybe the most frequent defect of vision result of the curvature difference between two meridians of the cornea-lens system, resulting in a displaced or distorted image.[3] If the planes of curvature are perpendicular, astigmatism is regular and possible to correct; otherwise is irregular and difficult to correct.

In last, presbyopia represents the difficulty in the near vision by normal loss of elasticity of the lens with aging.[3,5]

3.2. Vision optics - optical radiation and ocular implications

The process of color discrimination of an object is promoted by the nature of the light transmitted and reflected by it. Usually, the frequencies absorbed by the object will not contact the visual system. In this sense, light has dual wave-particle character that can be classified from the level of the electromagnetic energy and quantified from radiometric or photometric measurements. Radiation can be considered as ionizing radiation when quantum energy is sufficiently high (E> 10 eV) to promote the release of electrons from an atomic or molecular structure, otherwise it is designated as non-ionizing. The optical radiation is the segment of electromagnetic spectrum that interact with the eye and includes UVR (100-400 nm), visible light (400-760 nm) and infrared radiation (760-10 000 nm) (*figure 3.2*).[6]

The UVR is part of ionizing spectrum and the visible and infrared light are non-ionizing. According to the photobiological effect induced by each UV radiation, the International Commission on Non-Ionising Radiation Protection (ICNIRP) has divided the UV spectrum into

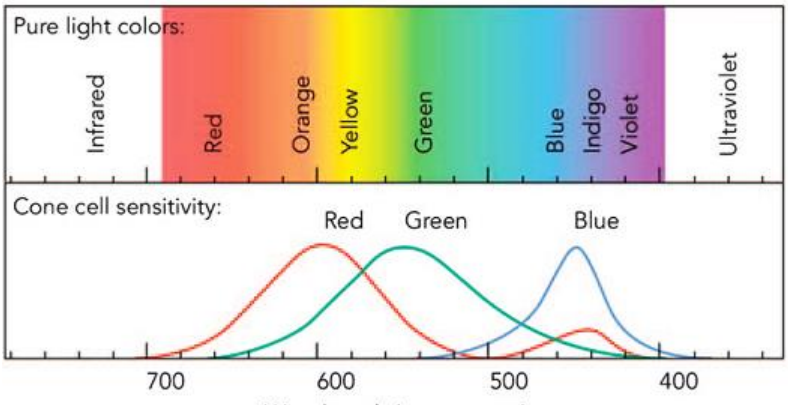

Figure 3.2. Optical radiation of electromagnetic spectrum: UV (100-400 nm), visible (400-760 nm), and infrared (760-10 000 nm) (Reproduced from Bloomfiel, 2005).[6]

three wavebands: UVC between 200 and 280 nm, UVB between 280 and 315 nm and UVA starting in 315 to 400 nm.[7] The International Commission of illumination (CIE) defined the visible light group with short (blue), medium (green) and long wavelength (red) corresponding to the spikes of absorption spectra of the cone cell sensitivity. The infrared radiation has been divided in IRA (700-1400 nm), IRB (1400-3000 nm) and IRC (3000-10 000 nm).

As happens with an object, when radiation is incident on the eye, it may be reflected by the surface or absorbed and scattered by the ocular tissues. The sun is the main source of radiation emission and several studies investigated its effect on ocular tissues. There is evidence that excessive exposure to UVR trough live may seriously contribute to increase in oxidative stress (OS) and causes ocular tissue damage, contributing to the development of pathologies.[2] *Figure 3.3* represents the relative propagation of optical radiation through the ocular tissues. Under normal circumstances, the UVC and UVB radiation are absorbed by the nucleotide bases and aromatic amino acids of the cornea. The IRB and IRC bands are deleted by water molecules into the cornea surface. The lens retains most of UVA, most of short UVB light and 10-20% of blue light.[2,8] The macular pigments in the retina can absorb high energy of blue light in approximately 40%.[4]

In the eye, the toxicity of radiation can be made by three major forms: (1) photothermal, associated with an inflammatory response, (2) photomechanical that shows stress confinement and (3) photochemical by photo-oxidation.[2,9] In the phototherapy, two examples of mechanical and thermal damage are the Yag and photocoagulation lasers respectively.[9] In a first instance, the tissue most affected by higher doses of UVR is the anterior segment of the eye.[10]

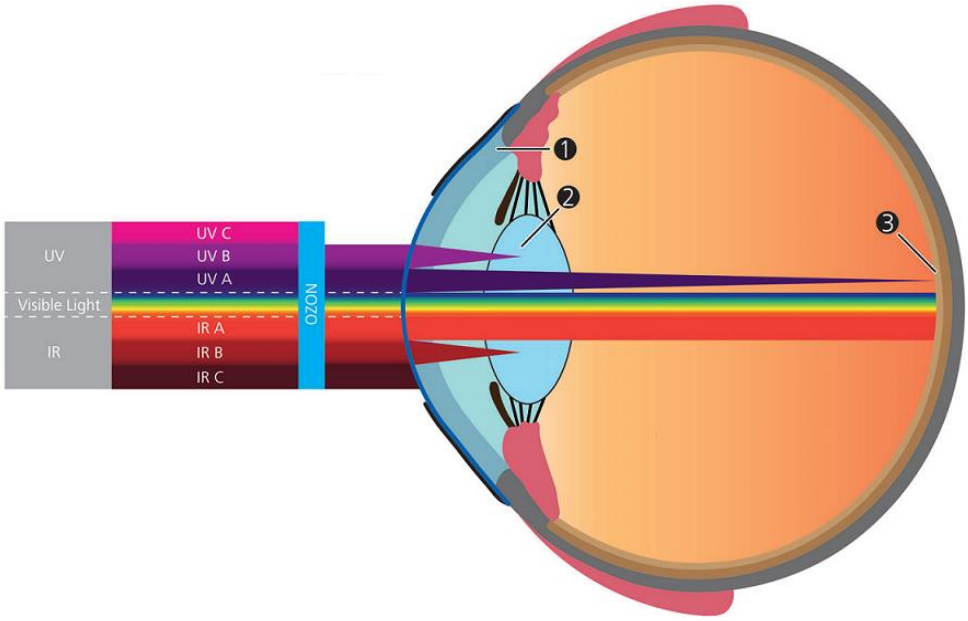

Figure 3.3. Schematic diagram of a cross section eye showing relative propagation of optical radiation through the ocular tissues. UVC and UVB do not propagate past the cornea and the lens, respectively. IRB and IRC are absorbed by the cornea. Respectively, less than 2% and 1% of UVA and UVB radiation reaches the retina. (1) cornea, (2) crystalline lens, (3) retina (Reproduced from Ivanov et al.,2018).[2]

In the literature, the most reported pathologies of this segment are pterygium and photokeratitis or snow blindness, which is strongly associated with UVR chronic exposure.[11,12] In addition, the OS that appears involved in other disorders, such as dry eye syndrome, keratoconus and Fuch´s dystrophy[2], involves photokeratitis by mechanisms of DNA damage and death receptor activation, leading together to cell death.[13,14]

At the same time, the production of proinflammatory cytocines induced by UVR radiation was reported by a few studies in some structures, including at the level of corneal stromal cells in the photokeratitis and into the tears bathing the mucosal surface in the pterygium.[15,16] UVR in the pterygium also exhibited to lead to the formation of abnormal fibroblasts and mutations in the basal epithelial cells.[17] The herpes simplex virus can be reactivated by exposure to sunlight[18] and eyelid malignancies as well as climatic droplet keratopathy are strongly associated with chronic exposure.

Exceeding the threshold levels of radiation, bilateral cataract associated with inflammatory response can occur[18,19] with a strong implication in cortical type.[11] Nuclear and subcapsular cataract, as well as other disorders such as pinguecula, ocular surface squamous neoplasms and ocular melanoma remained limited.[20,21]

Regarding retinal effects, there is insufficient evidence to determine whether age-related macular degeneration (AMD) and uveal melanoma are related to UVR exposure. So, some studies suggest a probable relation with visible radiation, especially with high blue light.[2,8,9,20,21] "Blue light something we are getting exponentially more exposed to because of our transition to a digital lifestyle", says David Friess. In fact, this is a current concern much debated by the scientific community.[22] The position of Optometrists Association is clear: "there is no evidence that visible light causes eye disease in humans. Using screens close to bedtime may contribute to poorer sleep, which can make a person less effective during the day. To avoid eye strain people should adhere to the 20/20/20 rule, every 20 minutes, look away from your screen at something at least 20 feet away for 20 seconds."[23]

As a preventive factor, there is agreement on the importance of eye protection. UV filtering CLs might be a particularly good alternative as they block the light from all angles.[2,10,12,14,21,24-26] A recent study has shown that UV-blocking CLs are a good option to protect limbal niche cells, especially after limbal stem cell transplantation and after pterygia surgery, to prevent recurrences.[27]

4. CONTACT LENSES

4.1 Historical background and overall trends

Contact lenses are a popular and effective medical device supported by the lids, cornea, conjunctiva and tear film and can be worn to correct vision, as well as for cosmetic or therapeutic reasons. The performance of a CL is dependent on several factors, as for example, the manufacturing process, the 3D surface topography and physical-chemical characteristics of materials.[28]

The first conception of a CL, as we know it today, appears with Leonardo da Vinci (1452-1519) in the sixteenth century, by a draft whose idea represents a concave glass structure supported over the eye.[29] After several contributions, including John Hershel, Eugene Kalt and August Muller, appeared the first CL fabricated from ground glass. Although lens designs progressed over the following years from glass to polymers, none reached widespread use until the early 1970s. In 1936, polymethylmethacrylate (PMMA), a resin having greater clarity than glass, was introduced and promoted the development of first commercial CLs. Soft contact lens (SCL) became available to market in 1971 with the approval received by FDA for Bausch and Lomb, based on the discoveries of Witcherle and introduction of Polyhydroxyethylmethacrylate (P-HEMA).[30,31] In later 1990, the first silicone hydrogel (SiHy) lens was marketed and set a stage for a new generation of SCLs. The first generation of SiHy presents a good permeability of oxygen, but slight stiffer and decreased wettability. The next generation appears with improvements in flexibility and wettability. The last and third generation has better water content (WC) and decreased stiffness.[32,33]

Figure 4.1 summarizes the evolution of CL materials, relating the links between materials and clinical success.[34] In 1994, 35 materials were available in USA and 90 materials in the year of 2010.[35]

Many events and trends have been seen in last years that can have an important impact in the CL industry today and in the future.[36] According to industry estimates, there are around 140 millions of wearers in the world. Annual data created by Morgan et al.[37], present the global spectrum of the evolution of the CLs market. Thus, the success of multifocal lenses has brought a greater number of older wearers and at the same time, some evidence also points to younger wearers, with a greater tendency to buy their lenses online.

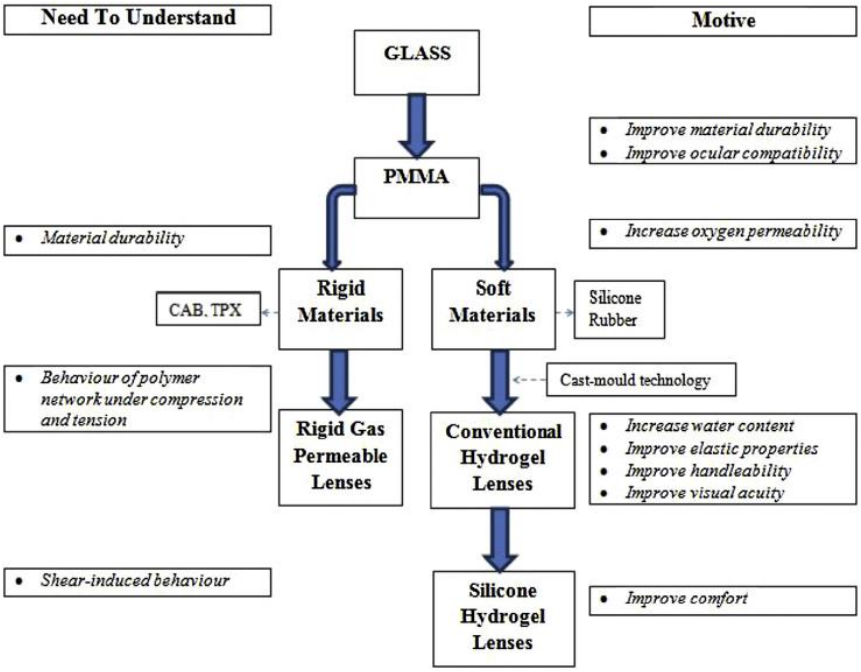

Figure 4.1. Schematic representation of key aspects of contact lens material development (Reproduced from Bhamra TS, 2016).[34]

Two-thirds of the lens fits are to females and the same rate represents “new fits”.

Concerning lens materials, the proportion of gas permeable (GP) lenses fits has changed from 20% of fits in the late 1990s to about 10% to 15% over the past decade (*figure 4.2*). Overall, GP lenses accounted for 11% of all fits and orthokeratology (1%) appears with a small increase compared to 2016, with greater representativeness (4% or more) in France, Hungary and the Netherlands. Soft lenses continue to dominate lens prescribing accounting 89% of new fits and 87% of refits worldwide. With the notable exception of Taiwan (18%), all markets prescribe at least 41% of soft lenses, with emphasis on Bulgaria with more than 90% of fits. The most marked change has been relative to the SiHy lenses, at which represent three-quarters of all reusable soft lenses. Another important change has been the increase in daily disposable lens prescribing, which represent one in four lenses fit today. The SiHy materials for this modality have lagged that of reusable lenses, probably due to its later launch, but 2017 marks the first year in which it is reported more SiHy than traditional hydrogels for daily disposable prescribing.[37]

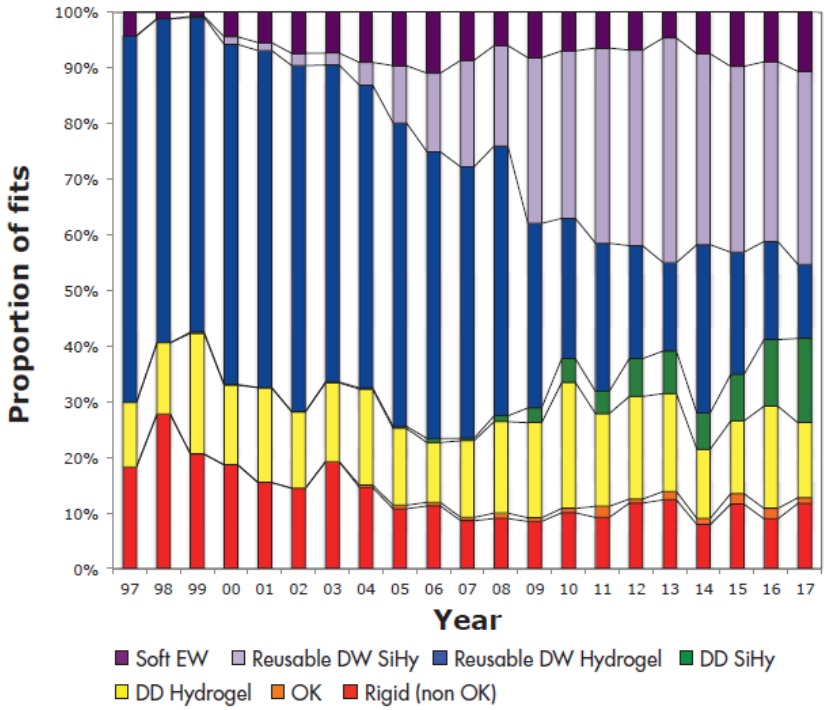

Figure 4.2. Major global trends in contact lens prescribing from 1997 to 2017 (Reproduced from Morgan PB et al, 2018).[37]

According to U.S. Food and Drug Administration (FDA), hydrogel materials were classified into four groups based on water content (WC) and ionicity of the material (*table 4.1*). A subgroup for SiHy is being considered[35] and more grouping systems with a surface criterion is being proposed considering the lens-solution incompatibilities. Green et al.[33] show that preservative uptake in SiHy can be grouped by WC and ionic charge but there are evidences that hydrophobicity of SiHy lenses and the methods used to overcome it may also influence interactions with components of LCS.[38]

The suffix "filcon" was adapted for hydrogel materials and the names of the CLs materials are regulated by United States Adopted Names Council (USAN) criteria. The FDA plays an important role in the development of American National Standards Institute (ANSI) standards. This entity is supported by associations such as the Contact Lens Institute, CL Manufacturers Association, American Optometric Association, American Academy of Optometry, American Academy of Ophthalmology and others. The International Organization for Standardization (ISO) includes approximately 20 countries associated and together with the ANSI development industry standards. Several ISO guidance documents are under current review with significant revisions.[35]

Table 4.1. Some examples of hydrogel materials (Adapted from Weissman BA et al, 2006).[39]

Group 1 Low WC Non-ionic	**Group 2** High WC Non-ionic	**Group 3** Low WC Ionic	**Group 4** High WC Ionic
Senofilcon A	**Omafilcon A**	**Balafilcon A**	Etafilcon A
Lotrafilcon A	Hilafilcon B	Etafilcon A	Methalfilcon A
Comfilcon A	Nelfilcon A	Bufilcon A	Ocufilcon B

The materials in bold were included in this study.

CLs can be worn daily (DW), in which they are cleaned and removed every day and are replaced after a certain time (1 day to 1 year, but the most frequent is monthly replacement). The extended wear intends to use lenses for 7 days and 6 nights, being discarded at the end of this time and continuous wear remain on the ocular surface for 30 days and 30 nights.[40] Extended or continuous CL wear continues to be a delicate topic, which deserves additional discussion.[39] Overnight wear of CLs increases the risk of complications, especially microbial infection. Although new FDA guidelines allow the continuous wear of one month, some researches have shown that this modality maintains the risk for subsequent corneal infection.[41] In 2017, monthly substitution was the most used with 37% of fits, followed by daily disposable with 37%.[37]

The future of CLs walks around myopia control, personalization combined between aberrometers values and prescription, fluid dynamics used in multifocal design to autofocus capability, health monitoring systems (e.g: plan diet, blood sugar level, IOP), visual projection as screens by LCD crystals and improvements like antibacterial coatings.[32]

4.2 Contact lenses – manufacturing techniques and designs

4.2.1 Manufacturing techniques

In the biomaterial's world of CLs, improvements in the manufacturing processes and alternative designs make these an atrractive and effective option for non-invasive vision correction.[42] The typology, chemical structure and manufacturing techniques of the polymer define its behavior, whether in concentrated or diluted solutions.

CLs polymers are a complex and stable structure of macromolecules from the polymerization process that result from the combination of monomers in the presence of crosslinkers and initiators. The polymers can be classified considering the structure, chemical composition and shape. About the chemical composition, it can be used only one type of monomer (homopolymer) as PMMA or can be made more complex (copolymers).

The monomers are usually made of some combination of Carbon (C), hydrogen (H), oxygen (O), nitrogen (N), silicon (Si) and fluorine (F). The most adopted monomers in CLs production are methylmethacrylate (MMA), hydroxyethylmethacrylate (HEMA), methacrylic acid (MA), glyceryl methacrylate (GMA), Ethylene glycol dimethacrylate (EGDMA), N-vinyl pyrrolidone (NVP), methacryloxypropyl tris trimethylsiloxy silane (TRIS), polydimethylsiloxane (silicone) and fluoromethacrylates.

Materials of CLs not only depend of co-monomer compositions but are also influenced by the manufacturing method. The polymerization phase depends on the manufacturing procedure and the most used techniques are lathe cutting, spin casting and cast molding.[43,44] Lathed lenses are obtained from solid buttons of dry material, which are usually bulk polymerized over relatively long time. These buttons are further processed in computerized lathes submitted to low temperatures and low activation energies which may be responsible for the longer chains and, therefore, more chain entanglement.

On the other hand, spin casting is very quick, taking less than an hour to polymerase the final lens. The conditions are usually anaerobic (nitrogen purged) in order to minimize degradation effects. The monomer is placed on a rotating mold that will define the shape of the lens. Different CLs are obtained changing mold´s shape and speed of rotation. Similar, in cast molding, the polymerization also occurs by injecting a small amount of monomer in molds that will define the shape of the finished lens surface. Because it is a fast process and results in high quality lenses, this is the main method used today, particularly for disposable CLs.

The surface treatments enable better biocompatibility with the ocular surface.[35,43] A recent paper has demonstrated how a nanoemulsion polymerization technique can be used to create a transparent nanostructured polymer suitable for use as a UV-blocking photochromic SCL. The material was created by one-pot bicontinuous nanoemulsion and has been tested in both *in vitro* and *in vivo* animal experiments.[45]

4.2.2 Specific designs

The lens design is the key in fitting any CL. The total diameter and base curve radius (BC) of the lens play relevant roles in the relation between the ocular surface and the CL (sagittal height). For instance, keeping diameter and decreasing BC the lens will be tightened and closed on the ocular surface.[46]

Last year, around 45% of CLs users have 0,75 D or more of astigmatism in one or both eyes, so it was expected the same level of toric SCLs fits.[37] This type of design requires stability for consistent visual performance which is obtained by means of stabilized rotation as for example from prism-ballast, peri-ballast and thin-zone designs.[47]

Several studies about myopia progression control present alternatives with different lens designs. There are evidences that spherical SCL design can influence the peripheral defocus profile by myopic eye and several animal studies have demonstrated changes in the shape of posterior chamber by defocus inducement.[48] A recent review by González-Méijome et al.[49] reports a consistent and safe use of CLs in the regulation of myopia in children´s. Orthokeratology is the therapy with more effective outcomes in myopia regulation across different ethnic groups. The designs used are tetracurve and pentacurve reverse geometry for overnight corneal reshaping. At the same time, concentric ring bifocal and peripheral add multifocal SCLs are clinically effective for controlling myopia in school-aged children.[50] Peripheral gradient lenses are another option that compensate central myopic errors and impose peripheral positive defocus.

Regarding presbyopia topic, monovision appears as the first modality and the preferred one for most of the 50-plis years it has been in use. Monovision consists of correcting the dominant eye for distance and the nondominant for near. However, in recent years new improvements in multifocal designs has changed this trend. Designs in common use on the market today are either center-distance or center-near. Today, the available designs are segmented, such as crescent, executive and straight-top and concentric or annular.[51]

On the other hand, there are scleral CLs that are used for corneal irregulatities like keratoconus. These lenses have three zones, scleral (haptic) portion; vault, which is responsable for corneal and limbal clearance of the lens and optical section.[52] The scleral lenses can be air-ventilated (fenestrated) or fluid-ventilated (non-fenestrated), fundamental elements to provide oxygen without compromising the physiology of the ocular surface.[53]

4.3 Contact lenses materials – main properties

Newer lens materials were developed to overcome problems of discomfort and hypoxia. The incorporation of crosslinkers, stabilizers, differing levels of WC and pigments increased lens softness and oxygen permeability.[35,42] In this way, new available materials, designs and modalities make the CLs wear safer and less prone to complications.[32]

CLs materials, which are placed in contact with a biological system (cornea, eyelids and tear film) and causes the minimum perturbation, can be tolerated by the host biological system being considered biocompatible.[54] The way a lens interacts with the tear fluid and the top surface of cornea is the most important factor of lens material. When it satisfies all required bulk characteristics, it can be safely used. Biocompatibility can be better attained by surface treatment to minimize interactions, together with the desired bulk properties, such as high oxygen permeability, mechanical strength, softness, and optical properties. Overall, the CLs industry has achieved significant advances in improving the biocompatibility of SiHy lenses. [30,54]

4.3.1 Optical properties – Refractive Index (RI)

In the group of SCLs, refraction index (RI) is an important physical parameter because of its relationship with EWC, that have optical and physiological implications on lens behavior. [40,43]

In general terms, RI (n) is obtained through the ratio of the propagation speeds between different conditions (*equation 1*), where c represents the velocity of light in vacuum corresponding to the rate of propagation of the photons (c = 3 × 10^8 m/s) and v concerns to the transmitted speed in the material. In addition to the density of the material, the RI also depends on the wavelength of incident light. In most of optical situations, when the light crosses in a dense space, its speed will decrease according to its composition ($v < c$). An important exception is the X-ray, where $v > c$ and $n < 1$. The higher frequency (shorter wavelength) of the incident light wave translates a higher index.[55]

$$n = \frac{c}{v} \qquad \text{Equation 1}$$

Specifically in CL, RI is determinated with a refractometer (Abbe, manual or automatic) [56] that allows objective measures at a low cost.[57] Automatic refractometers can provide higher levels of accuracy.[58] Values of RI are around 1.38 to 1.41 for high WC and hydrogel CLs, and 1.42 to 1.44 for low and medium EWC and SyHi CLs. The WC of lenses and as well the dehydration after wear can be estimated by RI of the polymer.[56,59] So, for conventional hydrophilic lenses, higher hydrated materials have a lower RI and materials with lower water content, have a higher RI.[57] There are evidences that after wear, SiHy CLs have greater capacity to retain or to reach their initial EWC than conventional hydrogel CLs.[60] About lens discontinuations, the dehydration is one of the most important parameters. *In vivo*[61] and *in vitro*[62] studies have demonstrated that this parameter may have ocular repercussions and depends on environmental conditions (relative humidity, air flow, temperature, illumination and atmospheric pressure) as on the lens type (chemical composition and design).

4.3.2 Optical properties – Transmittance (T), Reflectance (R) and Absorbance (A)

As it happens with others optical elements, the transparency is an indispensable property in a CL.

As discussed in the previous section, the cross-process with a dense and flat interface, can cause a decrease of the velocity of a flat wave. In addition, this process is the source of reflection and refraction phenomena, which can be generically explained by the respective law of reflection and Snell´s law respectively.[55,63,64] Roughly speaking, in the CL situation, where RI is larger compared with RI of air ($n_{\text{air}} \approx 1$), so $n_{\text{i}} < n_{\text{t}}$ (a) and the light rays approach to the normal (N) (*figure 4.3*).

On other hand, if multiple reflections were neglected, when the angle of incidence is zero (b), the reflected and transmitted lights follow the normal axis and the fractions are given by: [64]

$$R_\lambda = \frac{I_\text{r}}{I_\text{o}} = \frac{(n_\text{t}-n_\text{i})^2}{(n_\text{t}+n_\text{i})^2} \quad \text{or} \quad \%R_\lambda = \frac{I_\text{r}}{I_\text{o}} \times 100 \qquad \text{Equation 2}$$

$$T_\lambda = \frac{I_\text{t}}{I_\text{o}} = \frac{4n_\text{t}n_\text{i}}{(n_\text{t}+n_\text{i})^2} \quad \text{or} \quad \%T_\lambda = \frac{I_\text{t}}{I_\text{o}} \times 100 \qquad \text{Equation 3}$$

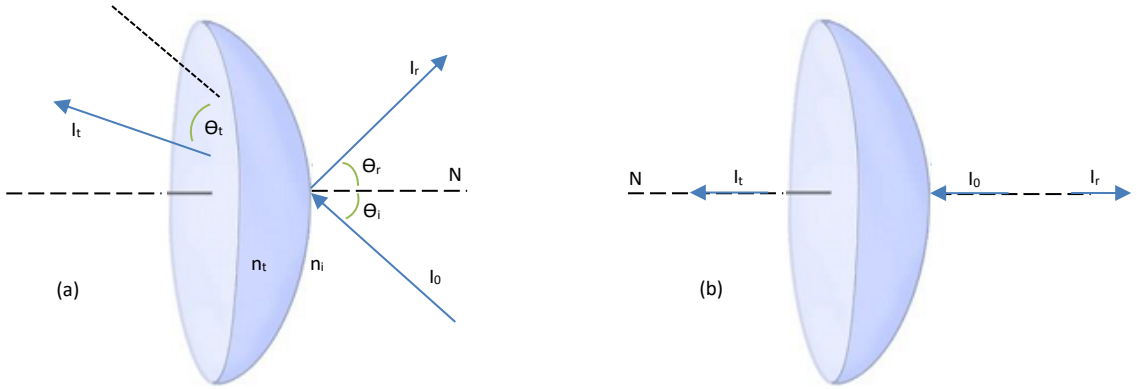

Figure 4.3. Schematic representation of the reflection and transmission light in a contact lens. (a) when a light beam with an initial intensity (I_0), interact an optically denser material ($n_i < n_t$), the transmitted light approaches the normal (N). (b) when the angle of incidence (Θ_i) is zero, the transmitted light follow the normal axis (Adapted from Okuno et al., 1982).[64]

The R_λ represents the reflectance resulting from the reflected light and T_λ the transmittance, whose result is given by refracted light. In an ideal situation, when scattering light can be neglected, the light absorbed or absorbance (A_λ) by the CL can be obtained from these fractions, through the following equation:[64,65]

$$R_\lambda + T_\lambda + A_\lambda = 1 \quad \text{or} \quad \%R_\lambda + \%T_\lambda + \%A_\lambda = 100 \qquad \text{Equation 4}$$

All the processes reported (reflection, absorption, scattering and transmission) can lead to color production.[65]

Transmittance of UV-visible radiation in contact lenses – a hot topic

According to the ANSI Z80.20 standard, there are two classifications of UV-blocking CL approved by FDA:[67]

- Class I: block 90% of UVA and 99% of UVB, recommended for high exposure environments such as mountains or beaches;
- Class II: block 70% of UVA and 95% of UVB, recommended for general environments.

There is an agreement between the recent studies that evaluate the effectiveness of the protective lenses of the UVA and UVB radiation,[67,68] emphasizing the Acuvue CLs with good blocking values,[69,70,71] including during phototherapy treatment.[72] Compared to CLs without UV filters, the UV-blocking lenses dramatically attenuate the UV spectrum of radiation.[73] On the other hand, lenses that do not incorporate UV blocking monomers showed some attenuation of the UV spectrum.[73,74,75] This phenomenon was explained previously by Bruce et al.[76] by the inherent ability of the silicone to absorb some UV radiation.

Table 4.2 includes the results of studies about this subject conducted in the 21st century. The UV-blocking CLs can be especially important for aphakic patients,[77] patients that take drugs with a photosensitive effect and patients who spend a lot of time in outdoors activities.[73] After wear, the UV-blocking lenses kept its filtering characteristics.[78]

The protection factor of CLs (PF) appears in several studies and was defined by Chou et al. as the inverse of transmitted light (*equation 5*). [79]

Regarding to the wear of blue blocking (BB) spectacle lenses to improve visual performance or sleep quality, the results are still inconclusive.[80] In this sense of blue light protection, there are guidelines for the adaptation of BB filters in populations at risk, especially in intraocular lenses (IOLs) [81,82].

$$PF = \frac{1}{T_\lambda} \qquad \text{Equation 5}$$

The wearing of UV-blocking CLs provided eye protection against all angles of incident light.[83,84] The peripheral light focusing (PLF) demonstrated clinical implications in the anterior segment of the eye, especially in the development of pterygia and cortical cataracts. Thus, the peak of light intensity at the nasal limbus is approximately 20 times higher than the intensity of incident light.[17,85]

Figure 4.4 displays the focus of PLF in the anterior segment of eye. From the left side we can see the intense nasal light focus that is a relevant factor in pterygia pathogenesis and on the right side the PLF in the inferior nasal quadrant, having effects on the early onset cortical lens opacity.[11,17,86]

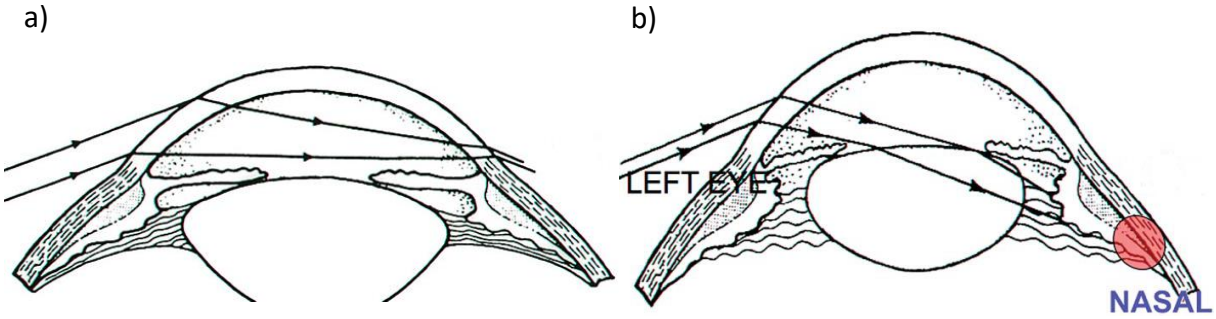

Figure 4.4. Optical representation of peripheral light focusing. a) intense nasal light focus (pterygia implications); b) transcameral and translenticular passage of PLF (implications in early onset cortical lens opacity) (Adapted from Coroneo M., 2011).[11]

4.3.3 Bulk properties - water content (WC)

Hydration properties of SCLs can hold clinical significance (Morgan & Efron, 2003).[87] According to the FDA, WC is considered in lens classification as being low for less than 50% of WC and high for more than 50% (*table 4.1*).

The dehydration of SCLs during wear is a determinant key of their performance in eye. This process of water loss begins immediately after a CL is placed on the eye and is often associated with complaints of dryness and other related symptoms. The equilibrium water content (EWC) in the SCLs materials represents the ability of the hydrogel to bind water in its equilibrium state and depends on the chemical composition and crosslinking density of the polymer.[88] The thickness of the material also affects the degree of dehydration that consequently has an impact on the ocular surface, since it is associated with surface deposit build-up, dryness symptoms and dehydration of the corneal epithelium. Lens dehydration also has the potential to affect ionic and hydraulic permeability, as reduce the lens movement and increasing the chance for microbial colonization. Other changes related with lenses dehydration are less flexibility, decrease of oxygen permeability and the base curve radius become steeper. [89,90] Paradoxically, in SCLs WC is a limiting factor in oxygen permeability, presenting an inverse relationship with Dk. On the contrary, the siloxane molecules in the matrix of SiHy have an extremely high permeability to oxygen, so lowering the WC of a SiHy material allows the silicone to become the main agent responsible for oxygen permeability, resulting in high Dk values.[91]

Table 4.2. Summary of results of studies about UV-blocking CLs in the 21st century.

Author/Year	Instrumentation	Contact Lenses	UVA (%)	UVB (%)
Harris et al. (2000)[74]	Shimadzu UV 160U Dual Beam Spectrophotometer	Surevue	1.5 - 89	1.3 - 3.7
		Acuvue (2 week)	3.2 - 91.3	2.9 - 9.0
		Vistavue	83.2 - 88.4	60.2 - 83.2
Ali et al. (2005)[69]	Shimadzu UV160A Dual Beam Spectrophotometer	Precision UV	8.92	3.0
		Igel Omega	46.51	4.72
		Encore UV	46.61	4.22
		Lunelle UV	53.91	7.55
		Surevue 2	9.01	3.92
		Acuvue 2	11.51	2.83
Moore et al. (2006)[75]	Perkin-Elmer Lambda Dual beam Spectrophotometer	Acuvue Advance	21.07	0.16
		Acuvue Oasys	18.35	0.03
		Night & Day	85.16	68.64
		O_2 Optix	80.71	62.89
		Purevision	69.90	35.97
DePry et al. (2013)[72]	Cary500 UV-vis Dual Beam Spectrophotometer	Acuvue Oasys	-	0.05 - 6.90
		Acuvue 2	-	0.80 - 13.09
		Proclear	-	85.74 - 90.35
Rahmani et al. (2014)[70]	Special Cecil Spectrophotometer	Acuvue Moist	33	1.22
		Zeiss Contact Day 30	43	10.69
		Pretty Eyes AC	32	0.65
		Sauflon 56 UV	48	5.78
Rahmani et al. (2015)[71]	Special Cecil Spectrophotometer	Acuvue Oasys	20.81	0.24
		Acuvue 2	33.49	1.66
		Zeiss Contact Day 30	44.03	10.37
		Sauflon 55 UV	42.53	2.52

In addition, ionic permeability, diffusivity and partition coefficient increases with the WC, associated with a possible dependence on the chemical structure of the polymer.[92] SiHy materials display lower dehydration rates compared with conventional hydrogel and show more capacity to retain or to gain WC.[60]

4.3.4. Bulk properties - oxigen permeability (Dk) and transmissibility (DK/t)

Cornea is an avascular structure and much of the oxygen required to its normal metabolism is obtained directly from the atmosphere. CLs forms a barrier, potentially reducing oxygen flux to the cornea, making this issue one of the most relevant in CL practice.[43,93]

According to Fatt, Dk is the ability of oxygen molecules to move within a polymeric material,[94] and is derived from the product of the diffusion coefficient of oxygen in the CL material "D" and the solubility coefficient of oxygen in the lens "k". On the other hand, oxygen transmissibility (Dk/t) is a more clinically relevant measure, because relates to a specific lens design and can be determined dividing Dk by the thickness (t) section. The units of this property are $\times 10^{11}$ (cm^2/s) mLO_2/ (mL mmHg) also known as 1 barrer.

As was mentioned, siloxane portions have an important contribution in permeation.[91] Nevertheless, Compañ et al. showed that water also supports the gas transport through SyHi lenses.[95] SyHi materials offer higher levels of Dk than conventional contact lens hydrogels.[96] The differences in thicknesses induced by different power of CLs have a significant impact on the Dk/t.[97] Lee et al.[98] showed that Dk of CLs is changed by the pH, osmolality and buffering condition of the tear film. The same author considered that the correlation between tear protein deposition and properties of lens materials affects Dk.[99]

The only two ways whereby oxygen can reach the ocular surface beneath a CL is dissolving in the tears passing around the lens and by diffusing through the material of the lens itself.[100] The first approach to satisfy the needs of cornea oxygenation levels was first provided by the Holden and Mertz criteria.[101] The critical Dk/t value was established in 24 barrer/cm to daily wear and 87 barrer/cm to overnight wear. Subsequently, Harvitt and Bonanno [102] considered a minimum of 35 and 125 barrer/cm for Dk/t, for open and closed eyes respectively. Fonn and Bruce[103] reconsidered through a review of the Holden and Mertz

study[101] a threshold of 125 barrer for Dk. Recently, Morgan et al. have placed values of Dk/t central and peripheral of 19.8 and 32.6 barrer/cm respectively, with open eyes.[104]

In conclusion, to prevent corneal swelling and in agreement with the previous studies, the level of oxygen required with open eyes ranges between 20-24 barrer/cm, while 75-87 barrer/cm is required for closed eyes.[100]

4.3.5 Bulk properties - electrostatic charge (ionicity)

The surface ionicity of the CLs depends on the polymers electrostatic charge and has a significant importance in clinical behavior, having implications in the interaction with surrounding environment, being therefore a parameter considered by FDA for the CLs classification. This property is controversial, since on one hand it improves hydrophilicity and comfort, but increases the adhesion of deposits on the surface of the lenses. [105,106]

In CLs, ionic monomers, such as methacrylic acid, are usually incorporated in synthesis of the hydrogel lens materials. However, these monomers make the lens susceptible to high levels of protein depositions due to electrostatic interactions. Anionic materials (negative charge) attract some of the most abundant tear proteins, such as lysozyme and albumin (positive charge). Carboxylate groups in the hydrogel structure make the materials more reactive, especially in acid solutions, which can cause changes in lens parameters and degradation of the material. [107,108]

On the other hand, ionic lenses demonstrated a loss of WC after wear.[109] In CLs with high WC, the ionicity of materials increases the dehydration of hydrogels. In some studies, the FDA group IV lenses report higher levels of dehydration in relation to group II.[110,111] Moreover, ionic lenses presented values of ionic permeability and diffusivity higher than most non-ionic lenses, but the tortuosity is lower in ionic materials.[92]

4.3.6 Surface properties - wettability

An improvement in the surface wettability appears associated with an increased lubrication of the lens-ocular surface biointerface allowing adequate on-eye movement. Some studies report a correlation between reduction in comfort and surface wettability over time.[112]

Wettability is the ease which a fluid spreads over a solid surface and depends on three forces: solid and liquid surface tension and interfacial tension with air.[113] A solid with a high surface tension acts to pull liquid away from the surface of the dry solid to reduce surface tension. In contactology, the contact angle (CA) is usually integrated into the research methods to evaluate this property. CA is obtained by interfacial interactions between the solid (CL), liquid and vapor. A high CA indicates low wettability or a hydrophobic solid surface and, on the other hand, a low CA reveals a continuous fluid film over the solid surface, meaning a high wettability or a hydrophilic surface. *In vivo*, the wettability can be analyzed by visible inspection of the lens at the slit lamp, measuring the non-invasive tear film break-up time (NIBUT) technique.[35,114]

Developments in the nanoscale phenomena like friction, wear and micro-elastohydrodynamic lubrification of CLs with the corneal surface are being investigated. These parameters can be used by manufacturers in the CLs development to improve surface characteristics.[28] The encapsulated CLs can be worn safely in EW[54] and the use of block copolymer surfactants appears to be a viable mean to improve the surface wettability properties of SCLs.[115]

The inclusion of hyaluronic acid (HA) in the CLs has been tested in order to improve the high level of hydration and lubrification. HA is a natural anionic polyelectrolyte that can be found in many tissues of the human body and has several applications, such as dry eye syndrome.[116,117] A previous study conducted by Korogiannaki reported that the grafting of HA did not showed implications on CL transparency.[118]

4.3.7 Mechanical properties - Young´s modulus (YM) and hardness

Mechanical properties deserve a considered role in the design and quality control of SCLs materials, as its have the ability to maintain their physical dimensions, or return to their original shape after external forces have been applied.[119]

The elasticity modulus or Young´s modulus (YM), named after the 18th century by the scientist Thomas Young, provides the initial description on elastic properties. The SI unit for modulus is Mega Pascal (MPa) and the force can be tensile, compression and shear. The studies of this parameter can provide information about the tensile strength and elongation to break, related to handling and durability.[34] Higher YM indicates a harder material, so it can provide better visual acuity, but may cause some mechanical damage to the eye and ocular discomfort.[120]

In most of the materials, the value of modulus decreases as the amount of WC increases. Increasing the content of hydrophilic monomers in a copolymer will increase lens WC and decrease lens modulus. Cross-linking agents provide mechanical strength and thermal stability.[120] Another consideration was studied by Horst et al., who showed that in general the modulus decrease with higher temperatures.[121]

5. LENS CARE SOLUTIONS

5.1 Lens care solutions - background and overview

In parallel with the CLs evolution, news and continuous efforts appear in LCSs industry over time in order to improve comfort and reduce adverse effects caused by microorganisms and deposits. In general, the goals of LCSs are: (1) clear, (2) prevent/minimize deposits, (3) keep the hydration and wetting, and lastly (4) disinfect and preserve the CL.[122,123]

The first care system used heat and salt tablets added to distilled (not sterile) water. Due to infection and convenience, salt tablets were replaced by ready made sterile saline and heat system by cold disinfection (chemical). In 1970, the chemical care was introduced and considered drugs by the FDA. The first generation of chemical systems contained thimerosal with or without chlorhexidine that was responsible for toxic and hypersensitivity red eye reactions. Initially, chemical regimens required four separate steps: cleaning with surfactant, rinsing with thimerosal or chlorhexidine, soaking in a disinfecting solution and rising again before the LC were reinserted in the eyes. More several steps were required with the introduction of oxidizing systems in 1983, but on the other hand had minimized the number of adverse reactions. The combination of disinfectants with cleaners formed the multipurpose solutions, introduced in 1988, that quickly attracted CL wearers.

Posteriorly, surfactants and lubricants were added to develop all-in-one solutions. Currently, the LCSs were regulated to the CL medical devices.[35,122,123] Although there are already no-rub formulations on the market, it is consensual that the rubbing and rinsing step is recommended.[124]

In 2017, 86% of the LCSs fits are accompanied by the MPS. The use of peroxide had significance in Germany and Austria and was also notable in key markets such as Canada, France, USA and Japan (*Figure 5.1*).[37]

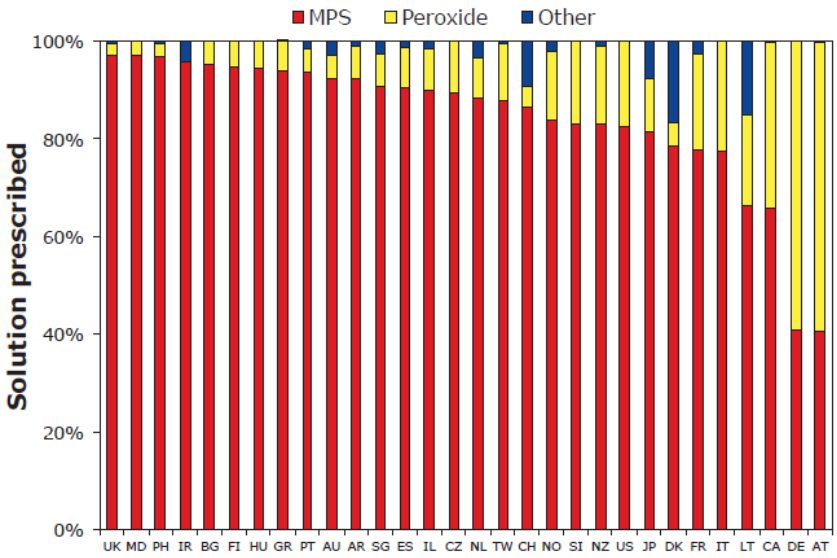

Figure 5.1. Care regimens prescribed in 2017 (Reproduced from Morgan PB et al, 2018).[37]

5.2 Soft lens care solutions – components and functions

The several components of the solutions should to improve comfort, reduce irritation, preventing the risk of infection, keep the CL lifetime and allow a good visual acuity. Currently, in order to ensure its requirements and roles, all the available care systems contain preservatives and active ingredients. In MPS, all the agents work synergistically[122,125]. The components described below are provided from the information contained in the solutions as well as from the studies of the following authors: Rakow (2003)[123], Brennan & Cohen (2000)[126], Fonn (2007)[127] and Levey & Cohen (1996)[122].

5.2.1 Cleaning agents (surfactant)

The surfactant (surface active) or cleaners are detergents with surface action that are used to break and solubilize organic debris on CL surfaces and float it away (e.g. tear film components or cosmetic residues).

They improve the efficacy of the disinfectant by disrupting the normal function of bacterial cell membranes. The viscosity agent can be added to increase contact time while preserving surface action. Some examples of surfactants are poloxamine and sulfobetain.

5.2.2 Preservatives and disinfectants products

Disinfectants and preservative agents are bactericidal and bacteriostatic, respectively, thus having the capacity to preventing and control the proliferation of microorganisms.[128] As previously reported, due to its strong hypersensitivity and toxicity reactions, thimerosal (mercury compound) and chlorhexidine (biguanide) were practically discontinued. The most commonly used products are polyaminopropyl biguanide (PAPB, Dymed®) and polyquaterium-1 (Polyquad®) that have higher molecular weight and were demonstrated to be effective and usually well tolerated. Due to the high molecular weight, they prevent penetration into the lens matrix.

Polyaminopropyl biguanide *(PAPB or PHMB, Dymed®, Bausch & Lomb, Rochester, NY, USA)* has a strong cationic charge separated by a six-carbon chain. PAPB have a similar action to chlorhexidine, with high spectrum and without benzine. It can disintegrate the microorganism by attacking and disrupting the acidic phospholipid groups found in the cell walls of microorganisms, which results in cell death.

Polyquaternium-1 *(Polyquad® or PQ-1, Alcon Laboratories Inc., Fort Worth, TX)* is a quaternary ammonium compound, that prevents absorption into the pores of hydrophilic lenses. This agent is water soluble and contains alcohol. As in PAPB, its long-chain molecular structure prevents it from building up in the lens matrix and minimizes adverse reactions.

Used as an additive with lower molecular weight, miristamidopropyl dimethylamine (MAPD), known as Aldox®, is an amidoamine compound that showed antimicrobial activity and is normally integrated in the Alcon Laboratories. A recent study conducted by Callahan et al.[129] showed that the combination of PHMB + PQ-1 (in the *Biotrue™*) has a significantly greater biocidal efficacy compared with MAPD + PQ-1 (in the *Opti-Free® Pure Moist®*) against gram-negative organisms commonly isolated.

5.2.3 Buffer solution

In order to control tonicity and osmolarity of the tear (approximately 7.45), buffer system needs to be present in the MPS. The most common pH stabilizers are borate, phosphate, citrate and tromethamine. They also help in the removal of proteins, especially in FDA group IV lenses. An increase in pH may cause irritation and corneal damages.

5.2.4 Wetting and lubrification agents

The introduction of wetting agents and lubricants in solutions prevent ocular discomfort. The main goal is to reduce surface tension, similarly to the properties of surfactants, and retain moisture longer. The lubricant hydroxypropyl methyl cellulose (HPMC) binds the lens surface to the MPS solution creating a fluid film of moisture around the lens, and propylene glycol attracts and holds water in the lens matrix. These agents decrease surface friction keeping comfort during wear. In addiction, other agent responsible for improving the wettability is the Tetronic, which converts the hydrophobic surface on the lens surfaces into hydrophilic sites, helping the tear film to spread more easily by water attraction.

5.2.5 Chelating agents

The main role of chelating agents is to decrease the deposits of calcium, magnesium and some proteins from the lens surface (e.g lysozyme). The most used compounds are EDTA (edetate disodium) and citrate (citric acid), that are negatively charged molecules which break the calcium bridges (Ca^{2+}) and consequently unlink the positive protein deposits on the lens surfaces. Hydranate (Hydroxyalkyl phosphonate) is part of the composition of ReNu MultiPLUS®, that contains a multifunctional molecule with four negative charges. The sequestering agents increase the antimicrobial activity of the preservatives.

5.3 Hydrogen peroxide (H_2O_2) – chemical disinfection by oxidation

One of the most effective disinfectants in CL care is the hydrogen peroxide system 3%. It is a compound with a high spectrum of action, which breaks the microbial cell wall through the production of very reactive free radicals (oxidation). This substance has an acid pH (3.0 -

4.0) and can be extremely toxic if placed directly on the eye. So, a neutralization is required which can be done in two ways: (1) one-step system that uses a platinum-coated catalytic disc that gradually decomposes salinized peroxide into isotonic saline and oxygen over 6 hours and (2) two-step system, whose neutralization and disinfection processes are made separately, and uses organic neutralizing tablet combined with saline solution. The first system is the most chosen by wearers due to the easier use.

5.4 Soft contact lenses and products - clinical implications

The combination of some materials with the solutions may result in changes in the properties of the polymers. Several studies were developed on the interaction between SiHy CLs and care systems. Lin et al investigated the impact of surfactants in unworn SCLs and wettability relations and found that most of SiHy CLs exhibited stable and self-sustained surface wettability *in vitro*.[112] Lira et al. have showed changes of surface roughness and RI by solutions.[130]

In addition, systematic research has reported differences between MPS and hydrogen peroxide-based solutions (H_2O_2). Young et al.[131] concluded that MPSs were associated with a decrease in modulus, and hydrogen peroxide resulted in statistically significant increase of modulus in two CLs, probably due the chemical change in the polymer. Recently, differences were also reported from the optical point of view, based on the analysis of transmitted light wavefront pattern.[132] The outcomes of this study showed a change in the morphology of the CL surface and variations of the Zernike coefficients by MPSs effect. The authors emphasized the possibility of absorption of MPSs constituents on the polymeric matrix. According to Dalton et al.[133], there are some differences in physical properties between soft LCSs. The physical properties studied in the Dalton study are shown in *table 5.1* and three of these solutions studied are the same as those used in the current study.

Regarding comfort and tolerance, H_2O_2 solutions have demonstrated a longer reported comfortable wearing time than the MPSs[134] and, at the same time, Opti-Free Express has reported greater comfort and less relative corneal sensitivity than ReNu MultiPlus.[135] In this sense, PHMP contained in ReNu exhibited a statistically significant association of the level of corneal staining (CS) compared with other solutions, but without clinical relevance.[136] About the effects of LCS in the wettability, Fagehi et al. had demonstrated that after 8 hours there

was differences among the performance of the solutions and these presented a significant reduction in CL wettability.[137]

The main form of solutions contamination can occur due to non-compliance by the wearers, such as external/environmental factors. The adhesion and colonization by microorganisms, particularly by bacteria and fungi on CLs continues to be part of many pathological events. This contamination often forms biofilms on lens surfaces and lens storage cases and may be a risk factor for corneal infections.[138,139]

In fact, SCLs tend to accumulate deposits when interact with the ocular flora. Some lipids, such as phospholipids and cholesterol, are absorbed relatively quickly[140] and varies with the lens type, but in general, is found more frequently on nonionic than ionic within the same WC.[126] The tear film has a rich and complex composition, in which lysozyme is the major protein, which has both antibacterial and anti-inflammatory functions. The group IV CLs attract most protein compared with other SCLs materials, due to the ionic affinity between methacrylic acid (MA) in the material and proton functional groups on lysozyme. [111,126] In the same way and despite presenting different patterns, albumin can be minimized if the material exhibits a negative charge.

Soft lens cleaning solutions demonstrated a significant inhibitory effect on deposits and biofilm formation on SCLs and in the lens cases[138] and an appreciable reduction against bacterial and fungal isolates.[141] Accomplish the cleaning steps is essential to remove deposits, debris and metabolic by products, in order to minimize the risk of inflammation.[142]

Table 5.1. Physical properties of three research solutions (Adapted from Dalton et al.,2008).[133]

Physical Properties of Soft LCSs	pH	Osmolarity	Surface Tension	Viscosity (20ºC)
AOSept Plus	6.66 ± 0.04	290.7 ± 2.94	70.3 ± 1.26	0.96 ± 0.00
ReNu® MultiPlus	7.36 ± 0.01	286.2 ± 2.23	36.3 ± 1.52	1.18 ± 1.01
OptiFree® Express	7.82 ± 0.01	225.0 ± 1.79	31.2 ± 1.01	1.04 ± 0.00

Due to its physical and chemical nature, the CL is an invasive material. All CLs have a close interaction with the ocular surface, slowling corneal homeostasis and changing its shape and influencing the physiology of tear film. The hypoxia and palpebral complications can intensify by overnight wear.[143] The LCSs can affect the comfort of SiHy CLs. MPSs induced cell morphology modifications and loss of cell viability.[144] The levels of micropunctate corneal straining may be associated with some combinations of CLs and some lens care product components.[145-147] This corneal implication decreases subjective comfort but on the other hand, peroxide systems have the lowest incidence of corneal infiltrative events[146] and demonstrated to be better tolerated by eyelid tissues than was PHMB-based solution.[148]

In fact, from the notions of inflammation, Efron[149] concluded that CL wear is intrinsically inflammatory. This is a hot and controversial topic for the industry of CLs, but on the other hand, the chronic, subclinical inflammatory shape is a positive phenomenon that reflects an upregulation of the immune system in a non-damaging way. Following this line of thinking, it is inevitable to highlight one of the most common visual disease, the dry eye disease (DED), that have serious effects on physical and psychological health.[150] According to the subcommittee of the International Dry Eye Workshop (DEWS), DED is a multifactorial condition characterized by symptoms of discomfort, visual disturbance and tear film instability.[151] This syndrome can be classified in aqueous-deficient or evaporative.[152]

In general, the efforts to improve comfort associated with CL wear, through the development of new materials, surface modifications and new lens care products, have been evident in the CLS industry. Consequently, these changes are translating into real clinical benefits.[126]

Influence of wear and storage in UV-visible transmittance of silicone-hydrogel contact lenses

In fact, the interaction between the tear film and the lens polymer provide the formation of biofilm and deposits induced by wear.[153] This process may affect the optical properties of the CLs, including the UV-visible light transmittance.[78] Three *in vivo* studies evaluated the influence of wear on lens transmittance. Lira et al. reported a modification on this property after wear especially in the UV spectrum. Five SCLs and SiHy materials used in this study and most of the differences were found in the UVC region for all the lenses with

exception of PureVision and Acuvue Advance in the visible radiation region. The observed variation in the visible range of the spectrum did not show any implications in visual performance of SiHy CLs.[78] At the same time, Fuentes R et al also observed changes in the CL transmittance after wear and the VA did not decrease either in any of the patients. After 30 days of Biofinity™ wear with Hidro Health, similar to ReNu MultiPLUS® composition, a slight decrease in spectral transmittance was found, also without implications in visual performance.[154] The third study conducted by Osuagwu et al. analyzed the UV spectrum of ten materials, after wear and used Opti-Free® Express. Overall, the study indicated safe levels recommended by ANSI for all the UV-blocking CLs (Acuvue CLs). Non-UV blockers, such as in Air Optix for astigmatism, showed UV-attenuation values larger than previously reported. The formation of biofilms on the lens surface appears again as the main factor of changes in the transmittance after lens wear, especially in SiHy CLs.[155]

Another study, with a scheme and objective similar to the one described in this dissertation, is introduced by Ogbuehi KC et al. This investigation used one material (Lotrafilcon B) combinate with six MPS solutions over six days after vials storage. In the last day, significant changes were observed in the transmittance of UVR and visible light. Only one solution combination has demonstrated attenuation in UVR transmittance, in the case of Hippia Multi Plus All-in-one solution and, on the other hand, ReNu MultiPLUS® showed an increase in UVR transmittance, on the order of +6.9% relative to the control lens (day zero). The differences found in T (%) after storage are justified by the author from the different chemical compositions of the solutions.[155]

6. FUNDAMENTALS OF ABSORBANCE AND FLUORESCENCE

General concepts about molecular reactions, spectrophotometry and spectrofluorimetry

In addition to the wave properties discussed earlier, the radiation has corpuscular properties such as energy (equation 6). The energy of a photon (E) in Joule, is inversely related to the wavelength (λ). The frequency is represented by v in seconds, c represents the speed of light in the vacuum and h is the Planck´s constant (= 6.62×10^{-34} J.s).[156]

$$E = hv = \frac{hc}{\lambda} \qquad \text{Equation 6}$$

When a beam of radiation interacts with a material, some frequencies can be selectively absorbed. The energy level of the molecular structures can vary between the ground state and higher states of energy when they are excited. The total energy of a molecule is given by three types of energy: rotational, associated with the rotation about the gravity center; vibrational, related to the vibration of atoms and electronic, which concerns the distribution of the electrons. Each electronic state has a set of vibrational and rotational levels. The electronic transitions are related to the presence of bonding, anti-bonding and non-bonding molecular orbitals.[157]

The intensity of a light beam is attenuated when it interferes with any absorbing solution (Figure 6.1). For a given concentration of the solution (C), the absorbance is provided by Lambert-Beer law (equation 7) in which b represents the length of optical path in the sample and ε_λ corresponds to the molar absorption coefficient, expressed in M^{-1} cm^{-1}.

$$A_\lambda = -\log_{10}\frac{I_\lambda}{I_0} = \varepsilon_\lambda bC \qquad (\textit{Law of Lambert-Beer}) \qquad \text{Equation 7}$$

By means of the difference between the solution that contains the absorbent properties (A) and the one that does not contain the absorbent species (A_{white}), the exact value of the absorbance associated to the studied sample is obtained by log (I_{white}/ I_s). This is the working principle of spectrophotometry.[157]

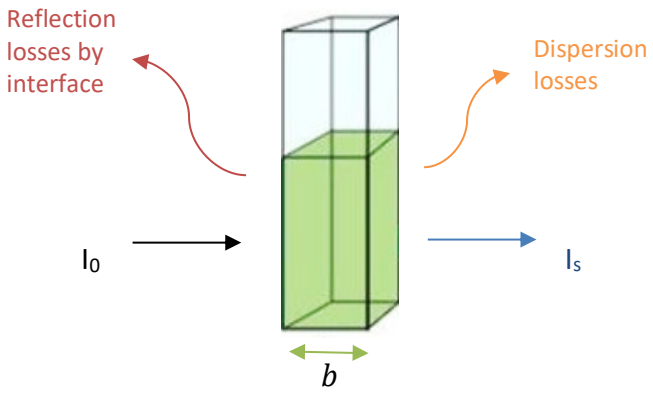

Figure 6.1. Schematic representation of the processes during absorption of radiation beam by a solution. I_0 represent the incident beam, I_s represent the transmitted beam and b is the length of optical path in the sample (Adapted from Martinho, 1994).[157]

After the absorption process, the molecules are in excited electronic states and need to lose the excess of energy. There are essentially two types of de-excitation processes: intramolecular and intermolecular. The intramolecular interactions can happen by radiactive mechanisms, whose process of energy loss occurs by luminescence. Fluorescence is a physical process of luminescence and occurs when a photon is absorbed by a "fluorophore", which may be an atom or a molecule, and then re-emitted as a photon with a longer wavelength.

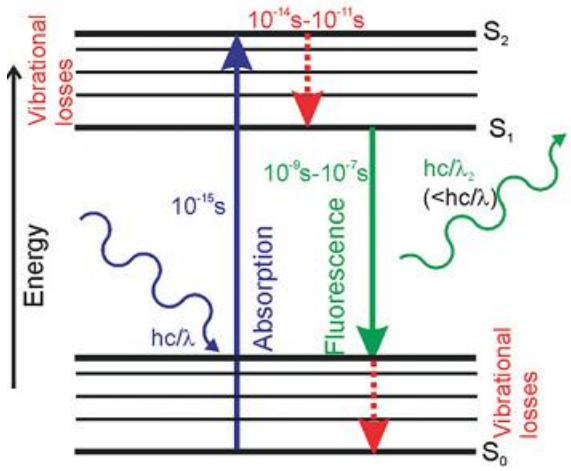

Figure 6.2. Jablonski diagram. An electron of a fluorophore at the ground state (S_0) receives energy from the absorption of a single photon of light which results in excitation transition to a higher energy state (absorption). When the excited electron relaxes to the ground state, following vibrational losses, energy lower than the incident photon and thus with a higher wavelength, is emitted as a single photon causing fluorescence (Reproduced from Shashkova & Leake, 2017).[159]

The oscillations between the atomic/orbitals are the vibrational processes responsible for this loss of energy.[158,159]

Spectrofluorimetric systems have a high sensitivity and excellent resolution time. In this technique, the fluorescence intensity (I_F) obtained depends on many variables:

$$I_F = I_0 \left(1 - 10^{-\varepsilon(\lambda_{exc})bC}\right) \phi_F F(\lambda_{em}) d(\lambda_{em}) \qquad \text{Equation 7}$$

I_0 is the intensity of incident beam; $1 - 10^{-\varepsilon(\lambda_{exc})bC}$ represent the fraction of absorbed radiation; ϕ_F is the fluorescence quantum yield; $F(\lambda_{em})$ is the emitted fraction of light with wavelength equal to λ_{em} and $d(\lambda_{em})$ corresponds to detected fraction of light (related to the detector sensitivity). The Jablonski diagram (Figure 6.2) is a pictorial form to describe the different energy states and transitions between them.[159]

The advantage of fluorescence technique, relative to UV-Visible spectrophotometry, is its high sensitivity and selectivity. However, it is restricted to emissive species and fluorescence intensity is only proportional to fluorophore concentration for very low concentration values.

2ND PART

STUDY DEVELOPMENT

This section provides information about the experimental part of the study. It starts with a methodological perspective, addressing the experimental protocol, sample characterization and statistical analysis used. The outcomes for each research variable are displayed below from a spectral and statistical point of view and then they are discussed, highlighting the main findings, exhibiting general tables with the results of interactions and their potential implications in experimental and clinical research. The time range of 8 hours will be more discussed as it presents higher real meaning. In the end, general conclusions and future works are established.

7. METHODOLOGY

7.1. Study design – ethics in research

This experimental study is observational, prospective and heterogeneous in which five different reusable CLs (cohort group) were analyzed over a week after a common experience (storage with products). This type of study intends to analyses associations to discover cause-effect relations. This research is an "*in vitro*" trial and did not analyses prophylactic or therapeutic measurements, so not bring up ethical issues. Data collection was conducted in the Laboratories of Photophysics I and II of the Centre of Physics, School of Sciences, University of Minho (Braga, Portugal), where instruments used were available.

7.2. Sample size – selection and inclusion criteria

CLs number was done by means of online software provide by Massachusetts General Hospital Biostatistics Center (http://hedwig.mgh.harvard.edu/sample_size/). This was calculated for transmittance/reflectance and the total sample size was 60 CLs. This calculation no includes foreseeable losses to irregularities in the experimental process or unknown results. This project has twenty research groups (5 CLs × 4 LCS). The materials need to have integrity in their characteristics. All the materials were provided by the result of partnerships between the University and CL industry.

7.3. Sample characterization

7.3.1. Contact lenses

Commercial CLs (4 SiHy and 1 CHy lens) with an optical power between -1.00 D and -4.00 D were included in this study. The choice of CLs was based on the representativeness in the market and their selection in later studies. The optical power corresponds to levels that showed no statistically significant effects on transmittance.[160] Their characterization is detailed in *table 7.1*, filled according to the information provided by the respective manufacturers. Almost all the lenses are blue (permanent tint using color additive), monthly disposable with no UV protection, except Senofilcon A (Acuvue®Oasys™) that is colorless, has a UV filter and is prescribed for biweekly wear. Regarding surface properties, Balafilcon A and

Lotrafilcon B are treated using gas plasma techniques. Balafilcon A undergoes plasma oxidation which transforms the silicone components into glassy islands on the surface. Lotrafilcon B lenses are treated with hydrocarbon plasma that reacts with air to create continuous hydrophilic surfaces.

Table 7.1. Properties and parameters of the contact lenses used in this study.

Contact Lenses	Material USAN	EWC (%)	RI	Light T (%)	Dk	FDA Group	Surface Character	Principal Monomers
Silicone Hy								
Acuvue® Oasys™ *By Johnson&Johnson*	Senofilcon A	38	1.42	UVF	103	I	*	HEMA, PDMS, DMA+PVP
Air Optix® Aqua *By Alcon*	Lotrafilcon B	33	1.42	≥96	110	I	*1	DMA, TRIS, SM
PureVision® 2 By Bausch&Lomb	Balaficlon A	36	1.426	>95	99	III	*2	NVP, TPVC, NVA, PBVC, NCVE
Biofinity™ By Coopervision	Comfilcon A	48	1.40	>97	128	I	*	M3U, FMM, TAIC, IBM, NMNVA, NVP, HOB
Conventional Hy								
Proclear™ By Coopervision	Omafilcon A	62	1.387	>90	62	II	*	

USAN: United states adopted name; **EWC**: Equilibrium water content; **RI**: Refractive index; **T**: Transmittance; **UVF**: Ultraviolet filter (class I UV blocker); **DK**: Permeability of oxygen (units: X 10−11cm2/s ml O2/ml.mm Hg); **FDA**: Food and Drug Administration (I: nonionic, low EWC; II: nonionic, high EWC; III: ionic, low EWC); * Hydrophilic; *1: surface treatment with 25 nm of plasm coating; *2: surface treatment with plasma oxidation; **PVP**: polyvinyl pyrrolidone; **MPDMS**: monofunctional polydimethylsiloxane; **DMA**: N,M-dimethylacrylamide; **HEMA**: hydroxyethyl methacrylate; **EGDMA**: ethyleneglycol dimethacrylate; **TEGDMA**: tetraethyleneglycol; **TRIS**: trimethyl siloxysilyl; **NVP**: N-vinyl pyrrolidone; **TPVC**: tris=(trimethyl siloxysilyl) propylvinyl carbamate; **NVA**: N-vinyl amine acide; **PBVC**: poly-(dimethysiloxy) di-(sililbutanol) bis-(vinyl carbamate); **M3U**: αwbis (methacryloyloxyyetil iminocarboxyethyloxypropyl) -poly (dimethylsiloxane) -poly (trifluoropropylmethylsiloxane) -poly (methoxy-poly (ethylene glycol) propylmethyl-siloxane; **FMM**: : α-methacryloyloxyethyl iminocarboxyethyloxypropyl-poly (dimethylsiloxy) -butyldimethylsilane; **TAIC**: 1,3,5-triallyl-1,3,5-triazine-2,4,6 (1H, 3H, 5H) -trione;**IBM**: isobornil methacrylate; **HOB**: 2-hidroxybutylmethacrylate; **NMNVA**: N-methyl-N-vinyl acetamide; **MMA**: metil methacrylate.

7.3.2. Lens care solutions

The reported compositions of the soft contact lens solutions investigated in this study are detailed in *table 7.2*. The peroxide system (AOSept® Plus by Alcon laboratories Inc., Fort Worth, TX) was analyzed after the neutralization process. This process was undertaken according to the manufacturer´s instructions and the "neutralized" values were taken approximately 6 hours after initiated with the platinum disc system. Biotrue™ (Bausch & Lomb, Rochester, NY, USA) and Optifree® Puremoist® (Alcon Laboratories Inc., Fort Worth, TX) are MPS with wetting agents in their composition, Hyaluronate and Hydraglide respectively, and were formulated specifically for SiHy CLs. All solutions of the blisters are buffer saline solutions. As with the CLs, the choice of these solutions corresponds to the most prescribed in international market and which appear in several studies.

Table 7.2. Principal components of soft contact lens solutions investigated.

Solutions	Preservative	Buffer System	Other Agents Surfactants	Chelating Agent
Multipurpose Solutions				
ReNu MultiPLUS® *By Bausch&Lomb*	PHMB 0.0001%	Boric acid; Sodium borate Sodium chloride	Poloxamine 1% (Tetronic 1107)	Hydranate 0.03% EDTA 0.1%
Opti-Free® Pure Moist® *By Alcon*	Polyquad 0.001%; MAPD 0.0005%	Boric acid; Sorbitol;	Poloxamine (Tetronic 1304)	Citrate; EDTA 0.05% *
Biotrue™ By Bausch&Lomb	PHMB 0.00013% Polyquad 0.0001%	Boric acid; Sodium borate; Sodium chloride	Polixamine Sulfobetain	EDTA **
Peroxide System				
AOSept® Plus *By Alcon*	Hydrogen Peroxide (3%)	Sodium Chloride	Phosphates Poloxamer	-

* Hydraglide: polyoxyethylene-polyoxybutylene ** Hyaluronate (wetting agent)
PHMB: polyhexamethylene biguanide (also known as polyhexanid or polyaminoprpyl biguanide, PAPB);
Polyquad: polyquatermium-1; MAPD: myristamidopropyl dimethylamine (Aldox); EDTA: Ethylenediamine tetraacetic acid;
Hydranate: Hydroxyalkylphosphonate; Citrate: citric acid.

7.4. Experimental procedure

The *figure 7.1* display a simplified model of the experiment. Each lens-material combination was analyzed before open and in triplicate for higher robustness of the sample after 8, 24 and 168 hours. The study variables were analyzed by spectroscopy.

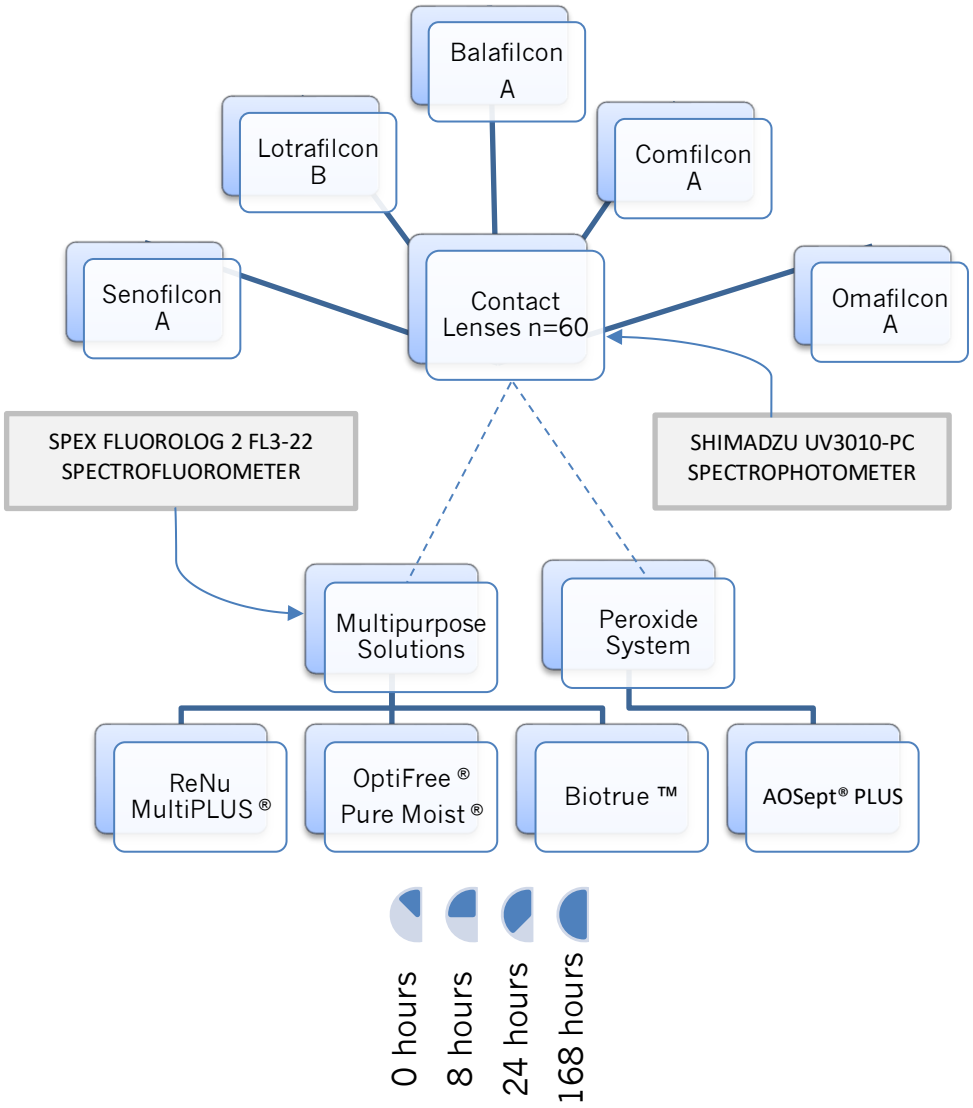

Figure 7.1. Schematic representation of the experimental methodology of this study.

7.5. Transmittance and reflectance measurements

The optical transmittance (T%) and reflectance (R%) were measured with a Shimadzu UV3101-PC UV-vis-NIR spectrophotometer (*figure 7.2*) equipped with an integrating sphere in the detector system, as established by ISO recommendation.[161] The measurements were taken at 0.5 nm intervals, from 250 to 700 nm.

Figure 7.2. Shimadzu UV3101-PC UV-vis-NIR spectrophotometer

After opening the blisters, the lenses were removed with a tweezer with silicone tips and placed perpendicular to the light beam, in the sample holder of the instrument (with the concave surface directed to the light beam). The excess of the solution was gently removed by absorbent paper. The baseline reference was made with white standard plates of barium sulfate, $BaSO_4$ (100% of reflectance) placed in both sample and reference positions. Triplicate measurements were obtained from each CL. The support system is specially designed to sustain the CL and include a foldable black cardboard designed with a limiting hole of 10 mm in diameter (*figure 7.3)*. This opaque black surface absorbs the light not interfering with the sample. The baseline was recorded after a proper stabilization of the optical system (at least, one hour. The radiation beam is incident on the sample and reference positions at the same time (*figure 7.4*).

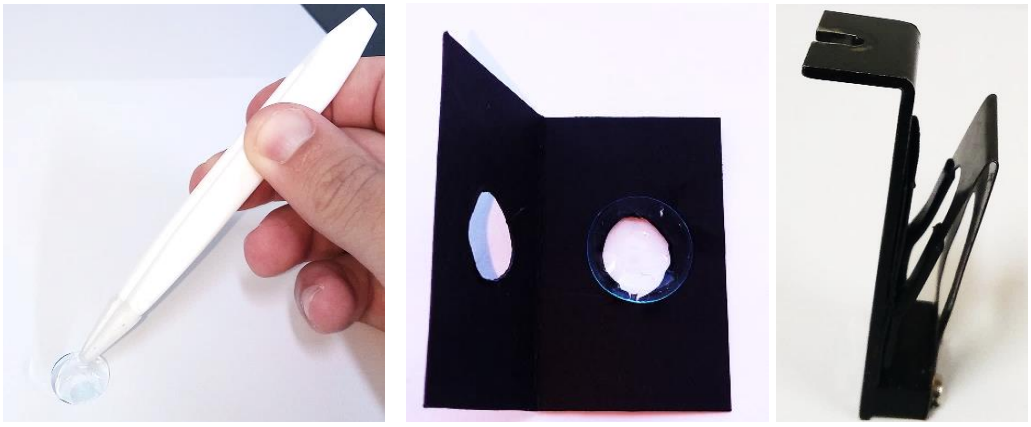

Figure 7.3. Tweezers with silicone tips and support system designed to CLs.

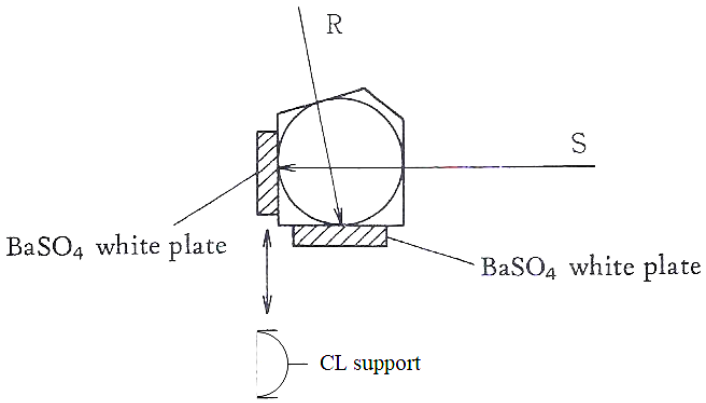

Figure 7.4. Schematic representation of reflectance measurements (Adapted from the user manual of the equipment).

The transmitted light is detected placing the lens in the entrance window of the integrating sphere which corresponds to a thin transmitting sample. For the baseline, only the opaque black cardboard is placed in the sample holder (*figure 7.5*). The result is obtained by comparison of the light transmitted by the sample (S) with the reference light (R) (in this case, the reference is the air).

Each CL was placed in a sterile vial (*figure 7.6*) containing 2 ml of each MPS which corresponds to the usual solution volume used in a CL case. Vials were labeled with a numerical code of each lens-solution combination. The combinations of CLs with hydrogen peroxide were preserved in their cases, due to the need of the neutralization system. Measurements were taken after 8 hours, 24 hours and one week of immersion in each solution. All lenses were compared in the different steps and also with new CLs.

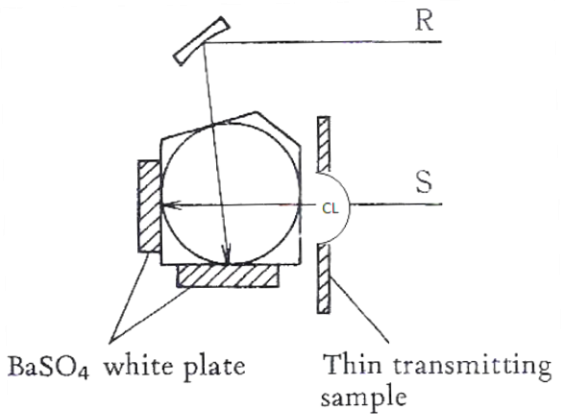

Figure 7.5. Schematic representation of transmittance measurement of CLs (Adapted by instruction manual).

Figure 7.6. Sterile vial with 2 ml of lens care solution and one contact lens.

7.6. Absorbance and fluorescence measurements

For the several LCS used, absorbance (A) was measured with a Shimadzu UV3101-PC UV-vis-NIR spectrophotometer (*figure 7.2*) equipped with a liquid sample cuvette holder. The measurements were taken at 0.5 nm intervals, from 200 to 700 nm.

After taking away the CLs, 1 ml of each LCSs was removed with a syringe and introduced in a high precision cell of quartz SUPRASIL® of 10×10 mm (Hellma Analytics, Germany) (*figure 7.7*). Before that, the baseline correction was made with ultrapure water (Milli-Q grade) in the two rectangular cuvette holders, establishing the reference for 100% of transmission (zero absorbance). The absorbance of each LCS was detected placing the cell in the sample side (*figure 7.8*).

Figure 7.7. High precision quartz glass cell (10×10 mm). Dimensions: 45 × 12,5 × 12,5; volume: 3,5 ml (Hellma Analytics, Germany).

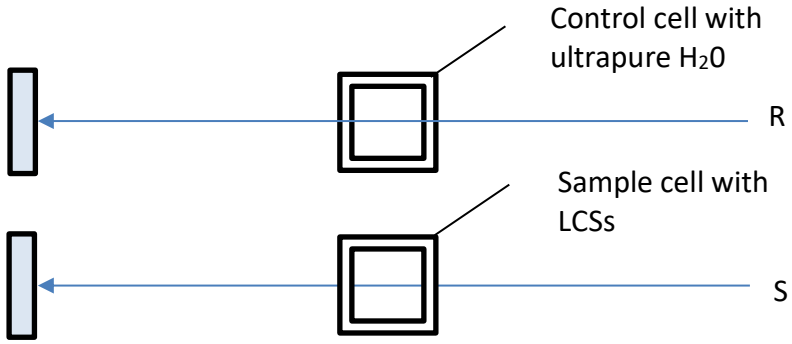

Figure 7.8. Schematic representation of absorbance measurement of liquid samples.

The same quartz cuvette was used for the determination of fluorescence spectra in a SPEX Fluorolog 2 spectrofluorometer – FL3-22 (*figure 7.9*). The integration time was 0.5 seconds and 4 mm slits were used in both excitation and emission. For fluorescence measurements, each solution was placed in the cuvette and the mirror selection was positioned to right angle (RA) for detection at 90 degrees from the incident beam, minimizing the interference with the transmitted light. Two excitation wavelengths were used: 280 nm (with emission scan between 300 and 540 nm) and 350 nm (with emission scan between 370 and 680 nm). All the measurements were performed at room temperature.

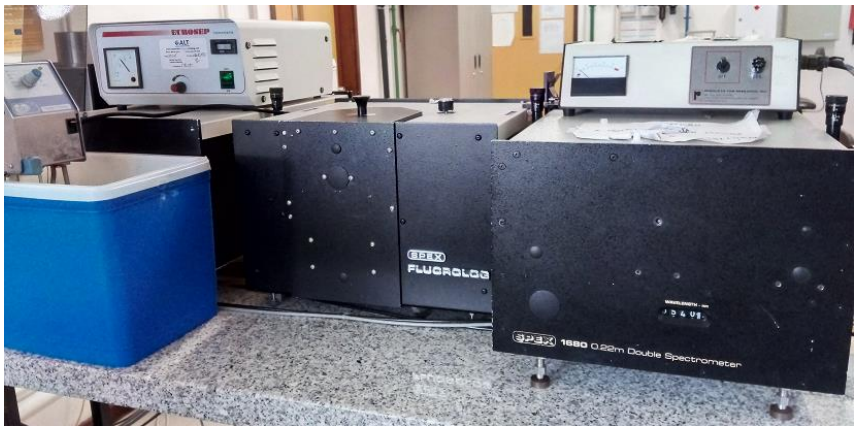

Figure 7.9. SPEX Fluorolog 2 spectrofluorometer.

7.7. Statistical analysis

The statistical analysis was performed with the Statistical Package for Social Sciences (SPSS) version 25.0 (SPSS Inc., Chicago, IL, USA), where the descriptive data are presented in terms of mean ± SD (standard deviation) of transmittance, reflectance, absorbance and fluorescence for each section of the spectrum (UVC, UVB, UVA and visible radiation) per wavelength.

The normality of all variables was evaluated using Kolmogorov-Smirnov, since the sample was larger than 30. In the normality test, if the parameter of statistical significance (p) < 0.05, the null hypothesis was rejected, representing differences in the data distribution compared to a normal distribution sample.

The hypotheses of the study were evaluated with the Friedman ANOVA for repeated measures and Kruskal-Wallis 1-way ANOVA tests to analyses if the variable time interferes in the same sample and for comparisons between solutions/contact lenses, respectively. These tests are an alternative to ANOVA when the sample does not meet the requirements of normality and homogeneity and are based on Chi-square (χ^2) statistics. Multiple comparison tests by post-hoc were applied to extract the pairs of the sample that presented significant differences.

For statistical purposes, the level of significance considered of this study was $\alpha \leq 0.05$.

8. RESULTS AND DISCUSSION

In this part of the thesis it will be presented the results of each lens separately, after being immersed in each of the solutions during the periods of time indicated above. The results will be compared to the values obtained in the new lens after being removed from the blister (control). At the end of each analysis, a common approach was taken to a better understand of the interactions. The outcomes of 8 hours were reported with more emphasis because of their higher clinical proximity with the usual immersion time.

8.1. Effect of lens care solutions on transmittance and reflectance of contact lenses

8.1.1 Analysis of the UV-visible transmittance

The results of transmittance changes for Senofilcon A are shown in *table 8.1* separately for each range of the radiation (UVC, UVB, UVA and visible). The changes can also be analyzed in the several spectra in *figure 8.1*. For all the wavelength groups, Senofilcon A exhibited statistically significant differences ($p<0.01$) of T-(%) within each LCSs group over time. The storage in LCS produced an increase in UVR protection in the mean order of -4.04%, -1.18% and -3.34% for UVC, UVB and UVA, respectively. In all combinations, there was a decrease of T-(%) between 0 and 8 hours. Post-hoc test analysis demonstrated no statistically significant difference between 8h and 24h in UVR spectra. After one week the trend of this CL is to recover the loss of T-(%). There were no statistical significant differences between the LCSs combinations in UVR spectrum, with the exception of AOSept in relation to OptiFree with -2.46% of difference ($p=0.032$) at 8h in UVC. In visible spectrum and after one week of storage, Renu solution contradicted the behavior of the other solutions showing a significant increase of +3.03% ($p=0.00$). All the LCSs represented statistical significant differences, especially between Renu and Optifree after one week (-5.75%).

Similarly, to what happened in other investigations, Senofilcon A exhibited significant protection of UVA and UVB radiation. Some differences were found with other studies, particularly in the UVA region. In the UVB range, Moore and Ferreira[75],

Table 8.1. Mean transmittance values of Acuvue® Oasys before (control) and after storage in the different LCSs, results of Kruskal-Wallis 1-way ANOVA and Friedman ANOVA.

Acuvue® Oasys	**UVC (190–280 nm) (%)**				**p(b)**
LCSs	**Control**	**8h**	**24h**	**168h**	
Renu MP		10.58±2.94	10.95±3.35	11.84±3.29	*<0.01*
OptiFree PM		12.27±4.17	12.68±4.07	13.65±4.38	*<0.01*
BioTrue	14.98±4.71	11.07±3.37	11.13±3.23	12.18±3.54	*<0.01*
AOSept Plus		9.81±2.59	10.66±2.93	11.63±3.30	*<0.01*
p(a)		***0.044***	*0.120*	*0.104*	
UVB (280–315 nm) (%)					
Renu MP		3.84±0.46	3.79±0.48	4.58±0.60	*<0.01*
Opti-Free PM		3.84±0.58	3.97±0.67	4.46±0.67	*<0.01*
BioTrue	4.99±0.78	3.81±0.49	3.97±0.54	4.48±0.58	*<0.01*
AOSept Plus		3.72±0.52	3.81±0.55	4.47±0.63	*<0.01*
p(a)		*0.753*	*0.538*	*0.883*	
UVA (315–400 nm) (%)					
Renu MP		48.57±32.19	50.57±33.12	50.89±33.89	*<0.01*
Opti-Free PM		51.82±31.25	52.05±32.13	50.90±30.55	*<0.01*
BioTrue	53.11±31.74	49.86±32.18	49.36±32.64	49.39±32.19	*<0.01*
AOSept Plus		48.85±32.37	49.66±32.92	47.79±31.57	*<0.01*
p(a)		*0.651*	*0.435*	*0.959*	
Visible (400–700 nm) (%)					
Renu MP		92.24±0.50	94.44±0.44	96.68±0.44	*<0.01*
Opti-Free PM		92.25±0.42	93.50±0.41	90.93±0.41	*<0.01*
BioTrue	93.65±0.36	92.57±0.45	93.49±0.45	93.22±0.39	*<0.01*
AOSept Plus		92.55±0.50	93.98±0.48	91.61±0.50	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold; p(b): Friedman ANOVA, p<0.01 for all comparisons represent strong evidence against Ho. Values are expressed in percentages (%).

and Rahmani et al.[71] showed respectively 0.03% and 0.24% which differs from the 4.99% obtained in this study. For the UVA range, the same studies displayed 18.35% and 20.81% of T-(%), divergent from the results of the present study (53.11%). Nevertheless, Acuvue Oasys CL meets the ANSI standards criteria for UVB class 2, because it blocks more than 95% of UVB radiation. Anyway, and according with the previous studies, Benzotriazole monomer

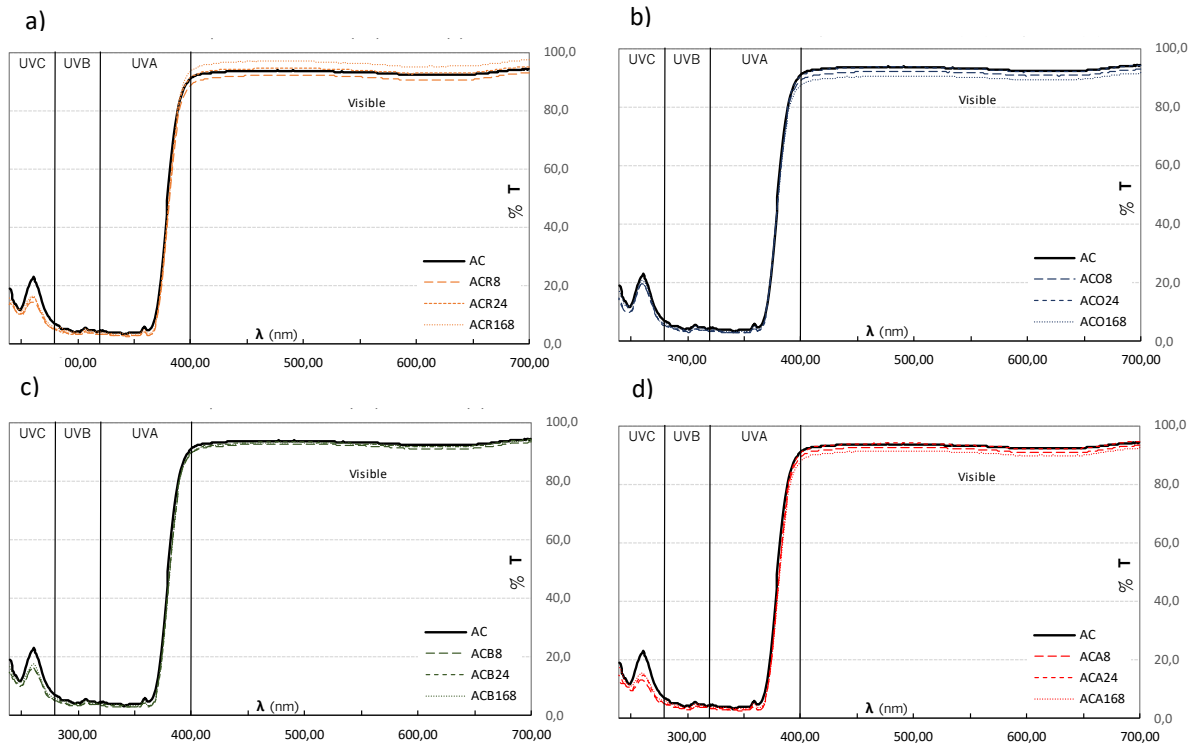

Figure 8.1. Transmittance spectra (UV-visible range) for Acuvue® Oasys after opening (control) and after 8, 24 and 168 hours of storage in the lens care solutions. a) Renu; b) OptiFree; c) Biotrue and d) AOSept.

incorporated in this material provide protection of corneal and limbus structure, including for the laser application in the range of 280 to 320 nm, as reported by Depry et al., 2013.[72] However, this does not invalidate the need to use sunglasses, because UV-block CLs leaves anterior ocular tissues such as the conjunctiva and eyelids exposed to this radiation.

The *figure 8.2* and *table 8.2* display the variance analysis of Lotrafilcon B. This material presents different values of T-(%) in the UVR range due to not incorporating filter. Overall, there was a statistically significant reduction of T-(%) over time with more evidence between control time and after 8 hours. The exception happened in the UVC range of spectrum, in which with Renu increased after 1 week. The K-W test demonstrated $p<0.05$ in visible and UVA spectras. In the similar behavior was evidenced between the effect of Biotrue and AOSept after 8 hours in the visible spectrum ($p = 1.00$).

Table 8.2. Mean transmittance values of AirOptix® Aqua before (control) and after storage in the different LCSs, results of Kruskal-Wallis 1-way ANOVA and Friedman ANOVA.

AirOptix® Aqua LCSs	UVC (190–280 nm) (%)				p(b)
	0h	8h	24h	168h	
Renu MP		41.70±14.64	41.95±14.88	43.90±14.72	*<0.01*
OptiFree PM		37.08±14.12	35.71±14.29	38.73±14.19	*<0.01*
BioTrue	41.26±14.89	34.10±13.80	34.59±14.28	37.85±14.83	*<0.01*
AOSept Plus		34.60±13.87	35.88±14.65	36.80±14.40	*<0.01*
p(a)		*0.089*	*0.133*	*0.151*	
UVB (280–315 nm) (%)					
Renu MP		74.78±5.41	74.23±5.36	73.07±4.49	*<0.01*
Opti-Free PM		72.42±6.55	70.97±6.53	71.48±5.73	*<0.01*
BioTrue	76.14±5.79	70.75±7.09	71.12±7.04	72.42±6.26	*<0.01*
AOSept Plus		71.02±7.25	72.26±7.30	70.05±6.37	*<0.01*
p(a)		***0.030***	*0.098*	*0.164*	
UVA (315–400 nm) (%)					
Renu MP		87.88±1.11	87.86±1.29	84.93±1.11	*<0.01*
Opti-Free PM		87.30±1.26	86.60±1.44	85.46±1.30	*<0.01*
BioTrue	90.43±1.20	86.52±1.32	87.51±1.59	87.39±1.39	*<0.01*
AOSept Plus		87.00±1.29	88.10±1.47	85.43±1.40	*<0.01*
p(a)		***0.022***	***0.003***	***<0.001***	
Visible (400–700 nm) (%)					
Renu MP		91.55±0.19	92.01±0.13	89.28±0.11	*<0.01*
Opti-Free PM		91.05±0.19	91.15±0.15	89.96±0.13	*<0.01*
BioTrue	94.23±0.20	90.92±0.21	91.76±0.17	91.25±0.17	*<0.01*
AOSept Plus		90.92±0.20	92.27±0.16	89.67±0.16	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold; p(b): Friedman ANOVA, p<0.01 for all comparisons represent strong evidence against Ho. Values are expressed in percentages (%).

There was an attenuation of UVR in the mean of 63.13%, 27.76% and 12.82% for UVC, UVB and UVA respectively after 8 hours of product exposure. Regarding the T-(%) of Balafilcon A (*table 8.3*), AOSept demonstrated to have a larger impact on this variable over time than MPSs in the UVR range. In most of wavelength, there was a significant increase of T-(%) after 24 hours by MPSs and a recovery to 1 week. The opposite happened with AOSept effect that

Table 8.3. Mean transmittance values of PureVision®2 before (control) and after storage in the different LCSs, results of Kruskal-Wallis 1-way ANOVA and Friedman ANOVA.

PureVision® 2 LCSs	UVC (190–280 nm) (%)				p(b)
	Control	8h	24h	168h	
Renu MP		35.87±7.56	35.80±7.45	32.15±7.47	*<0.01*
OptiFree PM		36.05±7.74	37.96±7.68	36.61±7.96	*<0.01*
BioTrue	32.17±6.85	32.78±7.25	33.55±6.78	30.83±7.38	*<0.01*
AOSept Plus		26.69±6.61	27.85±6.79	28.24±7.50	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
UVB (280–315 nm) (%)					
Renu MP		56.77±5.11	58.10±4.78	56.64±4.90	*<0.01*
Opti-Free PM		56.76±5.22	55.68±5.28	52.65±5.20	*<0.01*
BioTrue	52.73±5.58	53.73±5.47	53.70±5.29	51.57±5.51	*<0.01*
AOSept Plus		48.15±5.95	49.86±5.99	50.32±5.76	*<0.01*
p(a)		***0.008***	***0.035***	***0.128***	
UVA (315–400 nm) (%)					
Renu MP		87.88±2.34	88.26±2.40	86.33±2.69	*<0.01*
Opti-Free PM		87.92±2.40	87.37±2.42	84.97±2.85	*<0.01*
BioTrue	86.25±2.58	86.73±2.76	85.96±2.61	85.33±3.06	*<0.01*
AOSept Plus		85.63±3.16	86.74±3.10	84.56±3.18	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
Visible (400–700 nm) (%)					
Renu MP		95.95±0.26	96.28±0.27	94.41±0.29	*<0.01*
Opti-Free PM		96.05±0.26	95.47±0.31	94.14±0.35	*<0.01*
BioTrue	95.14±0.34	95.44±0.31	94.73±0.32	94.62±0.37	*<0.01*
AOSept Plus		95.57±0.34	96.41±0.33	94.24±0.35	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold; p(b): Friedman ANOVA, p<0.01 for all comparisons represent strong evidence against Ho. Values are expressed in percentages (%).

decreased T-(%) in all bands after 8 hours. These differences were -8.21% in UVC, -7.60% in UVB and -1.88 in UVA, comparing the means of MPSs with AOSept at 8 hours. The *figure 8.3* supports these outcomes. In the visible spectra, all the solutions resulted in a small increase of T-(%) in the first day and a small decrease after 168 h. In this material, the effect of AOSept displayed stronger attenuation of the UVR-T compared with the MPSs products.

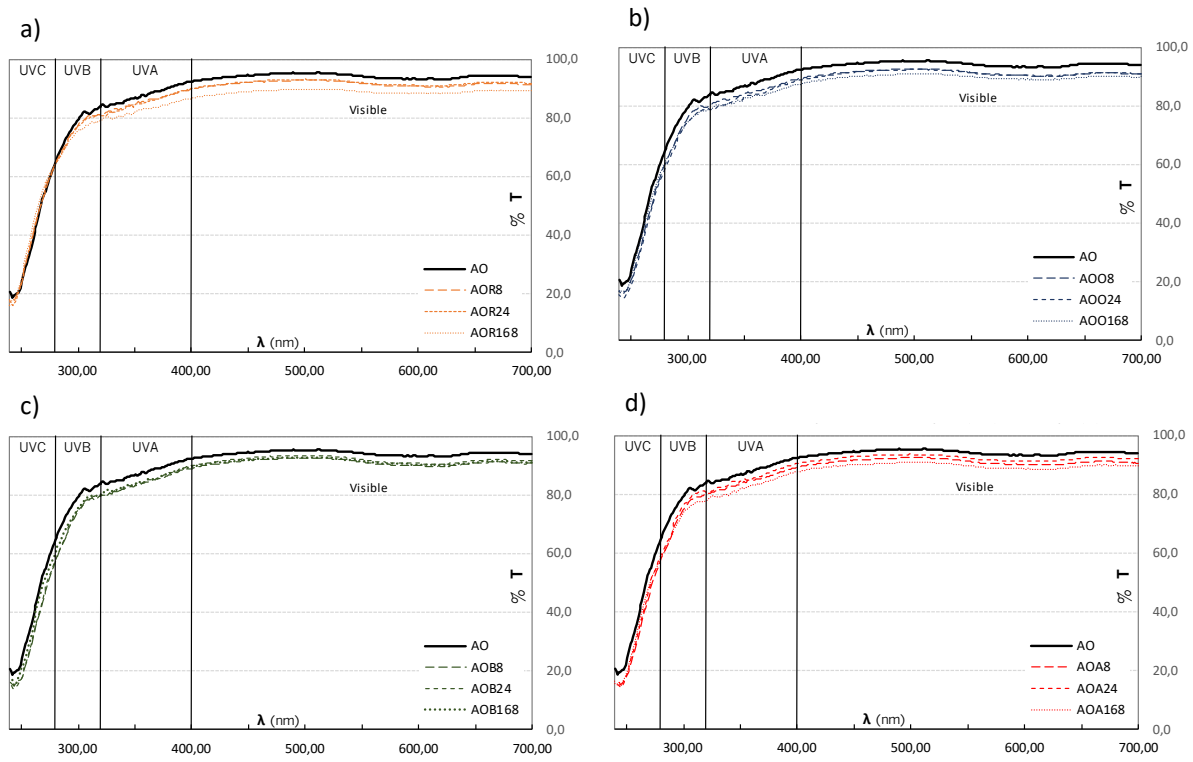

Figure 8.2. Transmittance spectra (UV-visible range) for AirOptix® Aqua after opening (control) and after 8, 24 and 168 hours of storage in the lens care solutions. a) Renu; b) OptiFree; c) Biotrue and d) AOSept.

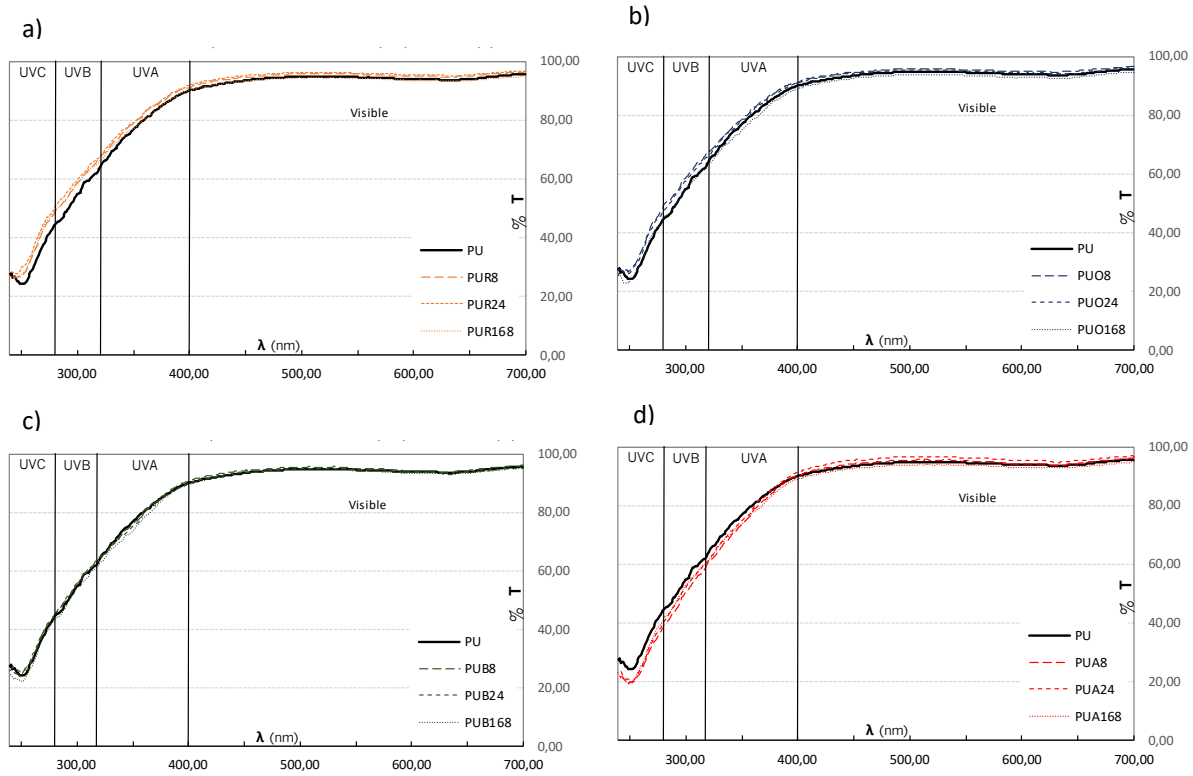

Figure 8.3. Transmittance spectra (UV-visible range) for Purevision® 2 after opening (control) and after 8, 24 and 168 hours of storage in the lens care solutions. a) Renu; b) OptiFree; c) BioTrue and d) AOSept.

In the same way to what happened in the Ogbuehi study, the T-(%) of Balafilcon A increased in the visible spectrum after 8 hours of storage. However, after one week this variable return and drops to lower values. The study conducted by Marín[160] showed lower values of T-(%) for all the SiHy CLs compared with the control lenses of the current study.

Table 8.4. Mean transmittance values of Biofinity™ before (control) and after storage in the different LCSs, results of Kruskal-Wallis 1-way ANOVA and Friedman ANOVA.

Biofinity™ LCSs	**UVC (190–280 nm) (%)**				**p(b)**
	Control	**8h**	**24h**	**168h**	
Renu MP		79.61±5.54	78.04±5.86	81.36±6.03	*<0.01*
OptiFree PM		82.03±5.07	81.83±5.06	83.05±5.34	*<0.01*
BioTrue	84.00±4.75	79.59±5.95	79.65±5.76	80.64±6.27	*<0.01*
AOSept Plus		72.58±7.74	72.52±7.37	75.49±7.20	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
UVB (280–315 nm) (%)					
Renu MP		89.37±1.23	88.15±1.11	91.31±1.30	*<0.01*
Opti-Free PM		90.50±1.13	89.95±0.93	91.29±1.05	*<0.01*
BioTrue	91.81±0.91	89.45±1.18	89.04±1.10	89.97±1.22	*<0.01*
AOSept Plus		89.25±2.17	89.09±1.84	89.14±1.90	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
UVA (315–400 nm) (%)					
Renu MP		93.81±0.61	92.28±0.64	95.71±0.56	*<0.01*
Opti-Free PM		94.23±0.25	93.21±0.54	95.85±0.57	*<0.01*
BioTrue	94.04±0.54	93.92±0.65	93.25±0.70	94.36±0.62	*<0.01*
AOSept Plus		94.01±0.59	92.71±0.63	94.18±0.65	*<0.01*
p(a)		***0.018***	***<0.001***	***<0.001***	
Visible (400–700 nm) (%)					
Renu MP		95.01±0.78	93.51±0.65	95.75±0.12	*<0.01*
Opti-Free PM		95.59±0.80	93.59±0.80	96.68±0.11	*<0.01*
BioTrue	93.83±0.11	95.24±0.80	94.21±0.09	94.95±0.09	*<0.01*
AOSept Plus		95.19±0.08	93.36±0.11	94.79±0.09	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold; p(b): Friedman ANOVA, $p<0.01$ for all comparisons represent strong evidence against Ho. Values are expressed in percentages (%).

About the behavior of T-(%) of Comfilcon A represented in *figure 8.4* and *table 8.4*, all the LCS showed the same effect in the UVA and UVB range with a reduction until 24 hours and a recovery after 1 week. There were significant differences over time ($p<0.01$). Like what happened with the latter material, Comfilcon A showed differences between MPSs and AOSept, especially in the UVC spectra. In the context of the visible spectra, the OptiFree solution exhibited a more significant increase at 8 hours and 168 hours in relation with the other products. Thus, peroxide presented the highest capacity of attenuation in the UVR spectra for the early hours.

The Omafilcon A (Proclear), which is produced by the same manufacturer, manifested a decrease of T-(%) after 8 hours and a subsequent increase to 1 week in overall of the combination. The exception happened with OptiFree that, in addition to presenting differences statistically significant between pairs ($p<0.05$) after 8 hours, its behavior was progressive over time. After opening and until 1 day of storage, the Renu solution presented a larger suppression of radiation; however, and compared with the other solutions, Renu showed a significant leap between 24 hours and 1 week. *Table 8.5 and figure 8.5* display these findings.

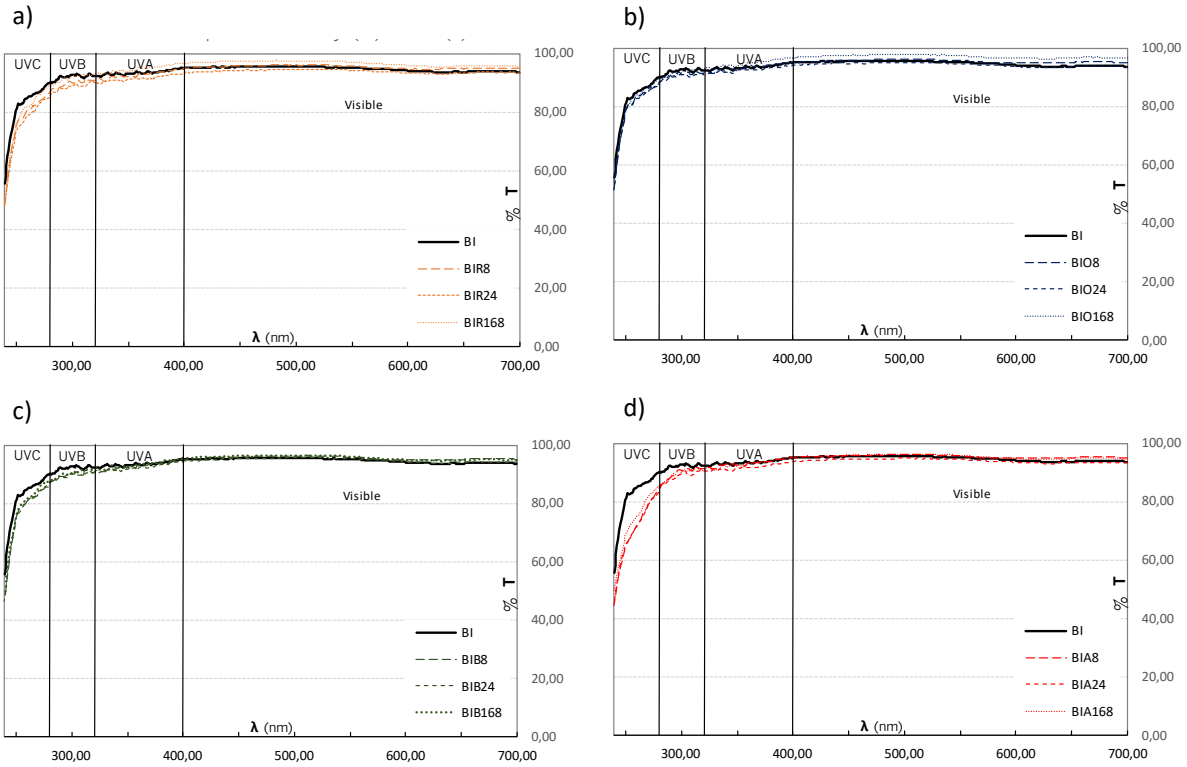

Figure 8.2. Transmittance spectra (UV-visible range) for Biofinity™ after opening (control) and after 8, 24 and 168 hours of storage in the lens care solutions a) Renu; b) OptiFree; c) BioTrue and d) AOSept.

Table 8.5. Mean transmittance values of Proclear™ before (control) and after storage in the different LCSs, results of Kruskal-Wallis 1-way ANOVA and Friedman ANOVA.

Proclear™ LCSs	UVC (190–280 nm) (%)				p(b)
	Control	8h	24h	168h	
Renu MP	80.00±11.01	77.59±11.37	77.37±9.65	82.00±11.60	*<0.01*
OptiFree PM		80.30±11.65	81.00±9.72	82.01±10.86	*<0.01*
BioTrue		76.86±11.96	78.73±10.96	80.01±12.09	*<0.01*
AOSept Plus		77.77±11.03	79.17±10.36	80.69±10.58	*<0.01*
p(a)		***<0.001***	***<0.001***	***0.001***	
UVB (280–315 nm) (%)					
Renu MP	86.50±1.08	84.44±0.86	83.95±0.73	88.46±1.11	*<0.01*
Opti-Free PM		86.59±0.83	86.96±0.88	87.52±1.17	*<0.01*
BioTrue		83.96±1.10	85.83±1.05	87.20±1.20	*<0.01*
AOSept Plus		85.72±1.17	86.51±0.85	87.23±1.17	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
UVA (315–400 nm) (%)					
Renu MP	91.20±1.23	88.73±1.17	89.05±1.66	92.84±1.40	*<0.01*
Opti-Free PM		91.19±1.38	91.82±1.48	91.37±1.05	*<0.01*
BioTrue		89.54±1.62	91.65±1.78	91.29±1.17	*<0.01*
AOSept Plus		90.41±1.21	91.13±1.25	91.62±1.42	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
Visible (400–700 nm) (%)					
Renu MP	92.92±0.59	90.34±0.61	91.60±0.58	94.41±0.69	*<0.01*
Opti-Free PM		92.95±0.61	93.96±0.56	92.54±0.62	*<0.01*
BioTrue		91.99±0.60	94.00±0.63	92.69±0.69	*<0.01*
AOSept Plus		91.92±0.63	92.62±0.63	93.46±0.60	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold; p(b): Friedman ANOVA, p<0.01 for all comparisons represent strong evidence against Ho. Values are expressed in percentages (%).

The *figures 8.6* and *figure 8.7* display the UV-visible spectra between the different lenses without influence of the products and after 8 hours and 1 week of storage with LCSs, respectively. Although 4 of the 5 CLs studied do not posses on UVR filter, overall, the Comfilcon A showed the poorest protection of UVR followed by Omafilcon A. When comparing the two graphs, there was a larger difference in the visible range after one week (-7.4%) than after 8 hours (-5.13%) of storage, which may represent a higher variation of this variable over time.

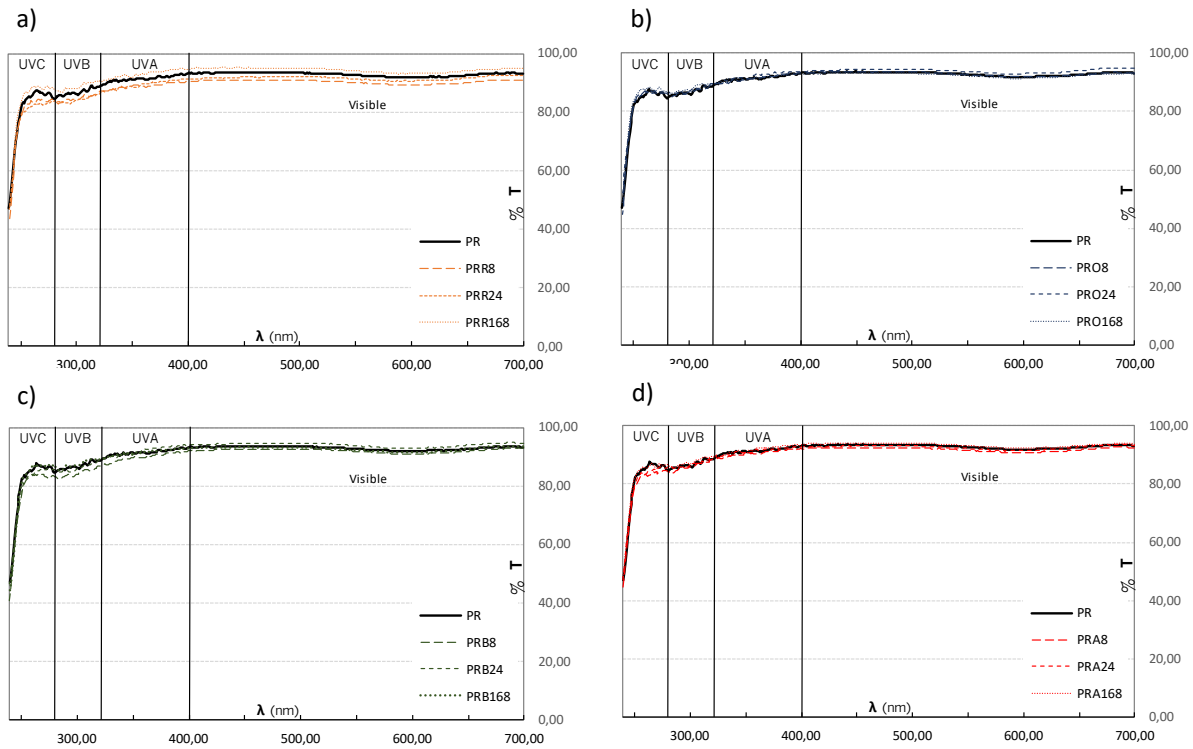

Figure 8.3. Transmittance spectra (UV-visible range) for Proclear™ after opening (control) and after 8, 24 and 168 hours of storage in the lens care solutions. a) Renu; b) OptiFree; c) BioTrue and d) AOSept.

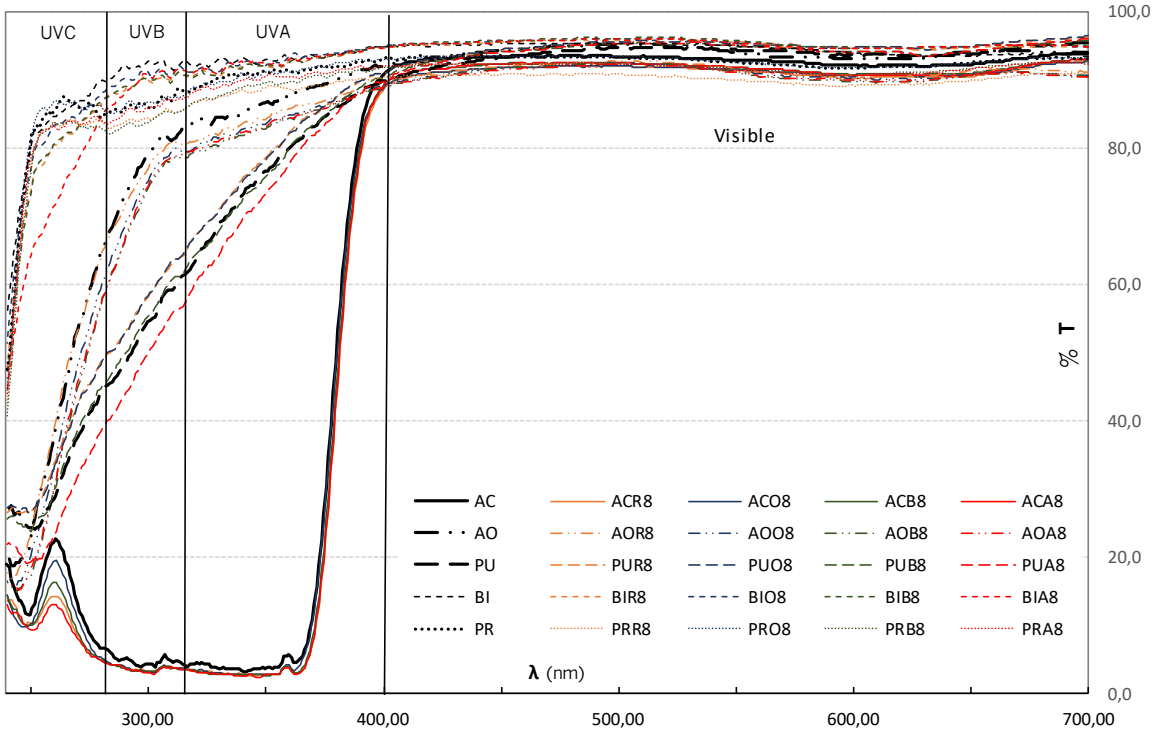

Figure 8.4. Transmittance spectra (UV-visible range) for Acuvue®Oasys (AC), AirOptix® (AO), Purevision® 2 (PU), Biofinity™ (BI) and Proclear™ (PR) after opening (black) and after **8 hours** of storage in Renu (orange), OptiFree (blue), BioTrue (green) and AOSept (red).

As previously described, the UV radiation can cause damage in the ocular tissues from acute or chronic exposure. In order to understand the effect of the solutions on the UVR protection, the *table 8.6.* was created, displaying the combinations of lens-solution that had significant attenuation of transmission of UVA and UVB radiation (higher PF), corresponding to the range that cross the stratospheric ozone. A presentation by Quesnel et al. [162] and the Marín study[160] reported that the thickness of CLs together with the power had effect in UVR transmittance of CLs.

Regarding to *figure 8.6* and *table 8.6*, it can be concluded that Renu induced more suppression in Acuvue Oasys and Biofinity lenses, Biotrue in the Air Optix and Proclear lenses and AOSept in the Purevision lens. For the latter lens, MPSs produced an increase of transmittance. Compared with the study conducted by Ogbuehi,[155] Renu demonstrated the same trend to increase the transmittance of Balafilcon A after storage. Acuvue Oasys and Air Optix showed a considerable decline ($p<0.01$) after 8 hours.

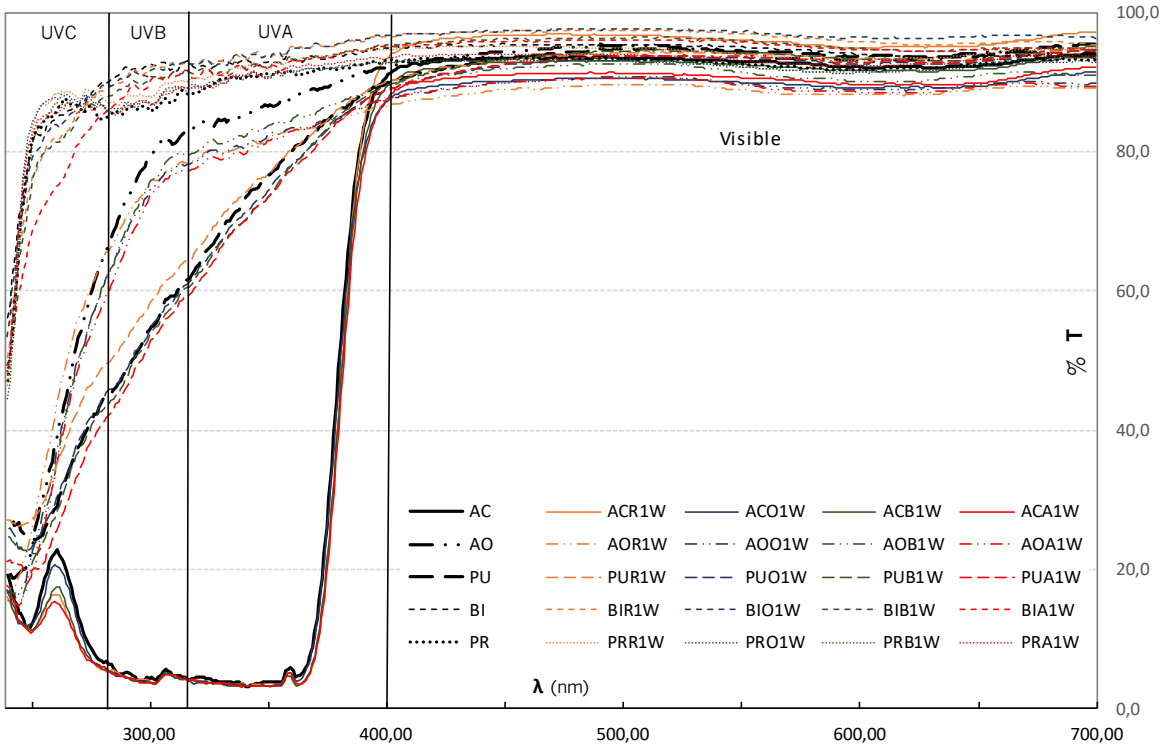

Figure 8.5. Transmittance spectra (UV-visible range) for Acuvue Oasys® (AC), AirOptix® (AO), Purevision® 2 (PU), Biofinity™ (BI) and Proclear™ (PR) after opening (control) and after **1 week** of storage in Renu (orange), OptiFree (blue), BioTrue (green) and AOSept (red).

Table 8.6. Mean transmittance values (%) and protection factor between parentheses for UVA&UVB spectrum after 8 hours for all the combinations.

Solutions / **Contact Lenses**	ReNu MP®	Opti-Free®	Biotrue™	AOSept® Plus	**Control**
Acuvue® Oasys™	26.21 (3.82)	27.83 (3.59)	26.84 (3.73)	26.29 (3.80)	29.05 (3.44)
Air Optix® Aqua	81.33 (1.23)	79.86 (1.25)	78.64 (1.27)	79.01 (1.27)	83.29 (1.20)
PureVision® 2	72.33 (1.38)	72.34 (1.38)	70.83 (1.41)	66.89 (1.49)	69.49 (1.44)
Biofinity™	91.59 (1.09)	92.37 (1.08)	91.69 (1.09)	91.63 (1.09)	92.93 (1.07)
Proclear™	88.73 (1.12)	88.89 (1.12)	86.75 (1.15)	88.07 (1.14)	88.85 (1.13)

Green and pink background represents respectively the lower and higher value of mean transmittance (%).

In general, the LCS promote a decrease in transmittance and AOSept generated a larger change in the transmittance. These findings agree with the study presented by Young et al.,[131] who reported a statistically significant increase in modulus by AOSept. On the other hand, OptiFree demonstrated slight changes of transmittance in this range after 8 hours. This behavior may be related to the MAPD integrated in this solution. So, this difference between MPSs and peroxide solutions are probably caused by their different composition. It can be deduced that while in the MPSs there were a process of chemical absorption, in the peroxide there was an effect on the polymer network.

In clinical practice, the differences found were not significant and in most of the combinations there is a positive effect of the solutions on this optical property as they increase the protection of this radiation. The effects of UV radiation continue to be a relevant concern for most of individuals. In this sense and as alternative of UV-protective eyewear, CLs with UV filters continue to be a good recommendation for all individuals, particularly for outdoor activities. In some situations, the use of lenses displays limitations from the adaptive point of view, however UV blocker CLs can prevent all angles of incident light, having an important role against PLF.

Approach of the visible radiation (400-700 nm)

In the context of the visible spectrum, although the study reports statistically significant differences ($p<0.05$), this no represents clinical significance from transparency of lenses. This premise may be considered because the vision is only degraded when considerable deposition occurs or when the denaturation of the adsorbed proteins was significant [126] or when the material undergoes physical-chemical alteration in its transparency. Ogbuehi et al. [155] admitted clinical relevance when the difference is greater than 50%.

Overall, there was ideal transparency of the materials (>90%) and for all the combinations with products after 8 hours. There is good agreement between the limits of transmittance published by the manufactures for soft CL and the results of this study. For Air Optix and Biofinity materials, the mean transparency of the control lens was slightly lower than the >96% and >97% proposed by the manufacturers, respectively. The lenses Purevision and Proclear performed within the limits of T-(%) proposed by the respective manufacturers. Previous studies reported lower values of transmittance when compared with the results of this study for unworn lenses.[74,75,78] Regarding the outcomes of CL-LCS combinations for the transparency of materials after 8 hours of storage, in *table 8.7*, it is possible to verify that OptiFree increased the transparency of the lenses Purevision, Biofinity and Proclear. Without much clinical relevance, the combinations that presented the lowest value of T-(%) were Proclear-Renu and AirOptix-AOSept.

Table 8.7. Mean transmittance values (%) for visible spectrum after 8 hours for all the combinations.

Solutions / **Contact Lenses**	ReNu MP®	Opti-Free®	Biotrue™	AOSept® Plus	**Control**
Acuvue® Oasys™	92.24	92.25	92.57	92.55	93.65
Air Optix® Aqua	91.55	91.05	90.92	90.92	94.23
PureVision® 2	95.95	96.05	95.44	95.57	95.14
Biofinity™	95.01	95.59	95.24	95.19	93.83
Proclear™	90.34	92.95	91.99	91.92	92.92

Green and pink background represents respectively the lower and higher value of mean transmittance (%).

Considering that people are growing into a digital age, it is important to investigate the implications of blue radiation on the eye and the ways to prevent problems associated to the use of electronic devices. Thus, new mechanisms of digital light protection would be interesting points to be included in the contact lenses industry.

In addition, a recent study showed positive applications for pigmented CLs, such as managing color deficient vision, amblyopia therapy and treatment of photophobia. These lenses have ensured transparency in the visible region and have blocked more than 95% of UVA radiation and provided an additional benefit of filtering more than 90% of the visible energy of the radiation whose chronic exposure is harmful to the retina.[163]

8.1.2 Analysis of the UV-visible reflectance

In this type of applications when a high transparency of the materials is desired, the reflectance is expected to be quite reduced, as shown in this study for all materials.

The outcomes of Senofilcon A reflectance are represented in *figure 8.8* and *table 8.8*. Although the differences are small and of limited clinical significance, all the products showed a statistically significant difference in reflectance over time ($p<0.01$). Overall, the R-(%) of Senofilcon A experienced a reduction after 8 hours with mean differences of -2.56%, -1.16%, -0.82% and -0.03% for UVC, UVB, UVA and visible respectively. In the UVR range the pos-hoc test showed no statistically significant difference between OptiFree-BioTrue and Renu-AOSept pairs, especially after 8 hours. The K-W test showed similarity between pairs after 1 day in the UVR spectrum with $p=0.88$ for UVC, $p=0.34$ for UVB and $p=0.10$ for UVA. AOSept displayed the highest effect in R of Senofilcon A in most of the periods.

The reflectance of Lotrafilcon B is represented in *figure 8.9*. The outcomes of R-(%) exihibited in the *table 8.9* reported no statistically significant difference in the UVC spectrum between LCS, with $p=0.14$ at 8 hours, ($p=0.60$) after 1 day ($p=0.67$) after 1 week of storage. The AOSept preserved a similar R-(%) after 1 week ($p=0.11$) compared with the control value. Marín study[160], that used the same instrumentation reported different values of reflectance of SiHy lenses compared with current control values, especially in the UVC range. This may be due to to the lower sensitivity of the integrating sphere detector for wavelengths below 280 nm, implying less accuracy of R values in this range.

Table 8.8. Mean reflectance values of Acuvue® Oasys before (control) and after storage in the different LCSs, results of Kruskal-Wallis 1-way ANOVA and Friedman ANOVA.

Acuvue® Oasys™ LCSs	**UVC (190–280 nm) (%)**				**p(b)**
	Control	**8h**	**24h**	**168h**	
Renu MP		11.53±2.42	11.40±2.65	12.53±3.09	*<0.01*
OptiFree PM		10.33±2.21	11.15±2.67	11.63±2.72	*<0.01*
BioTrue	13.55±3.28	10.34±2.09	11.13±2.56	11.17±2.64	*<0.01*
AOSept Plus		11.75±2.53	11.46±2.69	12.66±2.95	*<0.01*
p(a)		***0.002***	*0.878*	***0.012***	
UVB (280–315 nm) (%)					
Renu MP		7.56±0.42	7.44±0.54	*7.89*±0.53	*<0.01*
Opti-Free PM		6.80±0.46	7.20±0.57	7.48±0.56	*<0.01*
BioTrue	8.40±0.63	6.82±0.36	7.31±0.43	7.21±0.50	*<0.01*
AOSept Plus		7.80±0.43	7.33±0.45	8.24±0.59	*<0.01*
p(a)		***<0.001***	*0.342*	***<0.001***	
UVA (315–400 nm) (%)					
Renu MP		5.86±0.88	5.69±0.89	5.96±1.10	*<0.01*
Opti-Free PM		5.29±0.73	5.53±0.90	5.60±0.92	*<0.01*
BioTrue	6.49±1.11	5.41±0.70	5.68±0.87	5.58±0.84	*<0.01*
AOSept Plus		6.13±0.87	5.58±0.99	6.24±1.10	*<0.01*
p(a)		***<0.001***	*0.103*	***<0.001***	
Visible (400–700 nm) (%)					
Renu MP		4.03±0.42	3.81±0.37	3.43±0.40	*<0.01*
Opti-Free PM		3.85±0.34	3.58±0.40	3.61±0.38	*<0.01*
BioTrue	4.10±0.45	4.08±0.33	3.73±0.38	3.80±0.37	*<0.01*
AOSept Plus		4.34±0.42	3.43±0.37	3.75±0.41	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold; p(b): Friedman ANOVA, p<0.01 for all comparisons represent strong evidence against Ho. Values are expressed in percentages (%).

Table 8.9. Mean reflectance values of Air Optix® Aqua before (control) and after storage in the different LCSs, results of Kruskal-Wallis 1-way ANOVA and Friedman ANOVA.

Air Optix® Aqua	**UVC (190–280 nm) (%)**				**p(b)**
LCSs	**Control**	**8h**	**24h**	**168h**	
Renu MP		13.81±2.67	11.71±2.36	12.41±2.27	*<0.01*
OptiFree PM		13.31±3.08	12.10±2.54	12.75±2.46	*<0.01*
BioTrue	13.70±3.05	12.70±2.73	11.63±2.40	12.98±2.67	*<0.01*
AOSept Plus		13.10±2.92	12.04±2.60	12.94±2.36	*<0.01*
p(a)		*0.137*	*0.603*	*0.671*	
UVB (280–315 nm) (%)					
Renu MP		9.54±0.58	8.31±0.46	8.84±0.39	*<0.01*
Opti-Free PM		8.95±0.43	8.51±0.41	8.89±0.42	*<0.01*
BioTrue	9.47±0.51	8.52±0.51	8.15±0.55	9.16±0.50	*<0.01*
AOSept Plus		9.07±0.48	8.30±0.42	9.38±0.45	*<0.01*
p(a)		***<0.001***	***0.040***	***<0.001***	
UVA (315–400 nm) (%)					
Renu MP		7.43±1.47	6.47±1.13	7.10±1.21	*<0.01*
Opti-Free PM		6.91±1.38	6.73±1.13	6.94±1.31	*<0.01*
BioTrue	7.56±1.38	6.59±1.29	6.20±1.15	7.13±1.32	*<0.01*
AOSept Plus		7.03±1.34	6.47±1.20	7.41±1.28	*<0.01*
p(a)		***<0.001***	***0.001***	***0.006***	
Visible (400–700 nm) (%)					
Renu MP		4.03±0.39	3.63±0.41	4.07±0.35	*<0.01*
Opti-Free PM		3.58±0.43	3.88±0.39	3.79±0.36	*<0.01*
BioTrue	4.28±0.43	3.42±0.42	3.27±0.39	3.95±0.37	*<0.01*
AOSept Plus		3.75±0.44	3.42±0.43	4.20±0.39	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold; p(b): Friedman ANOVA, p<0.01 for all comparisons represent strong evidence against Ho. Values are expressed in percentages (%).

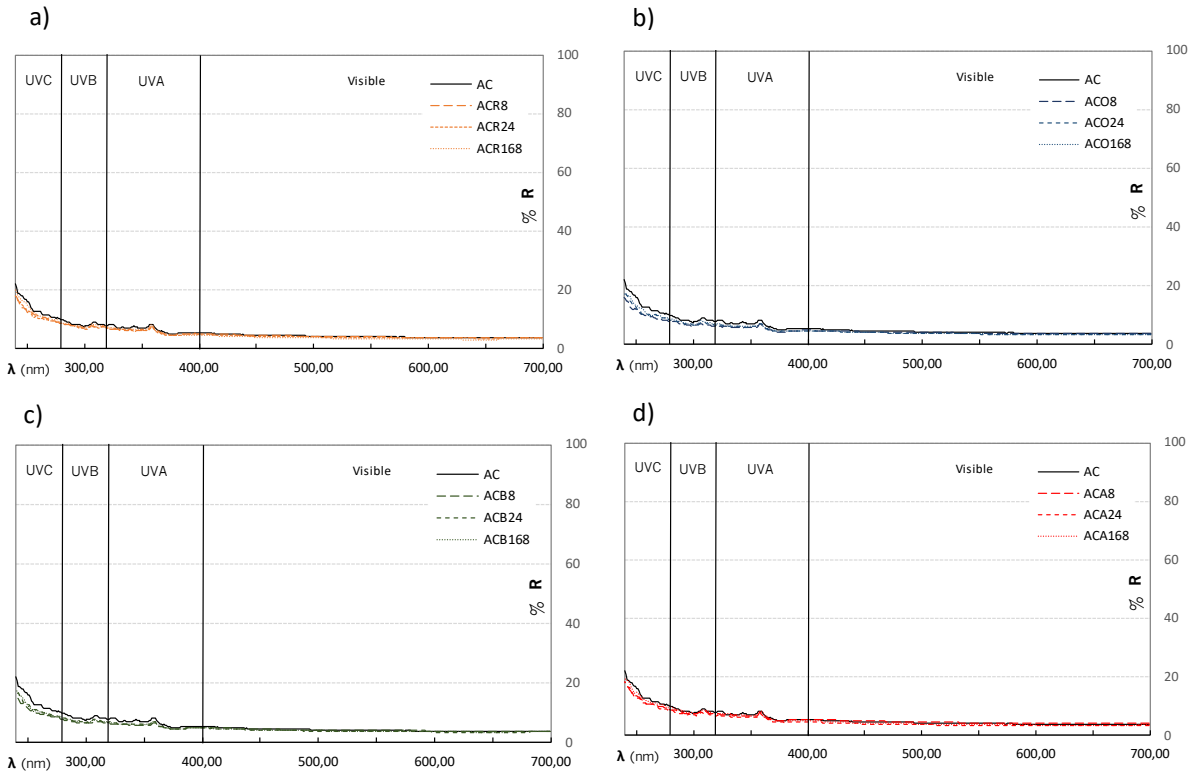

Figure 8.6. Reflectance spectra (UV-visible range) for Acuvue® Oasys after opening (control) and after 8, 24 and 168 hours of storage in the LCS. a) Renu; b) OptiFree; c) Biotrue and d) AoSept.

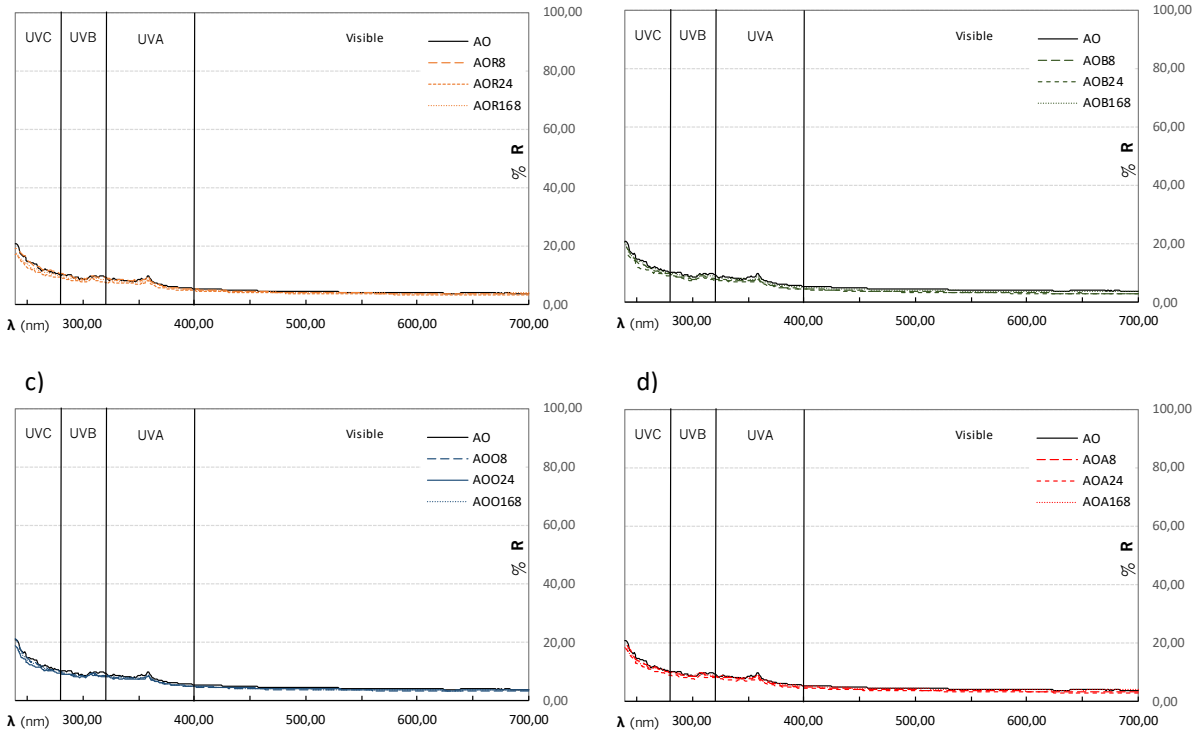

Figure 8.7. Reflectance spectra (UV-visible range) for AirOptix® Aqua after opening (control) and after 8, 24 and 168 hours of storage in the LCSs. a) Renu; b) OptiFree; c) BioTrue and d) AOSept.

Table 8.10. Mean reflectance values of PureVision®2 before (control) and after storage in the different LCSs, results of Kruskal-Wallis 1-way ANOVA and Friedman ANOVA.

PureVision® 2 LCSs	UVC (190–280 nm) (%)				p(b)
	Control	8h	24h	168h	
Renu MP		12.56±2.70	12.38±2.92	11.78±2.70	*<0.01*
OptiFree PM		12.79±2.97	12.52±2.90	11.39±2.50	*<0.01*
BioTrue	13.67±3.06	13.13±3.04	12.05±2.68	12.06±2.60	*<0.01*
AOSept Plus		12.41±2.66	12.22±2.77	11.09±2.56	*<0.01*
p(a)		*0.688*	*0.770*	*0.118*	
UVB (280–315 nm) (%)					
Renu MP		8.49±0.42	8.42±0.52	7.96±0.39	*<0.01*
Opti-Free PM		8.59±0.52	8.42±0.51	7.80±0.45	*<0.01*
BioTrue	9.06±0.63	8.74±0.55	8.13±0.38	8.32±0.52	*<0.01*
AOSept Plus		8.43±0.45	8.16±0.54	7.61±0.41	*<0.01*
p(a)		*0.089*	***0.027***	***<0.001***	
UVA (315–400 nm) (%)					
Renu MP		6.90±1.26	6.62±1.20	6.60±1.07	*<0.01*
Opti-Free PM		6.86±1.25	6.68±1.19	6.28±1.06	*<0.01*
BioTrue	7.29±1.35	6.97±1.32	6.57±1.20	6.68±1.17	*<0.01*
AOSept Plus		6.87±1.10	6.68±1.09	6.07±1.03	*<0.01*
p(a)		*0.746*	*0.744*	***<0.001***	
Visible (400–700 nm) (%)					
Renu MP		3.97±0.31	3.78±0.30	4.07±0.29	*<0.01*
Opti-Free PM		3.84±0.36	3.90±0.32	3.77±1.06	*<0.01*
BioTrue	4.24±0.30	3.88±0.32	3.78±0.29	3.91±0.31	*<0.01*
AOSept Plus		4.20±0.32	4.05±0.33	3.57±0.29	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold; p(b): Friedman ANOVA, p<0.01 for all comparisons represent strong evidence against Ho. Values are expressed in percentages (%).

Regarding *table 8.10* and *figure 8.10* that corresponds to changes in the reflectance spectrum of Purevision CL after storage, there was no spectral divergence over time, except in the UVC range, which mean difference was -0.95% after 8 hours. According to the K-W test, in general of UVR spectra, no differences were found between the solutions. AOSept exhibited a larger decrease of R-(%) compared to the other solutions, after 8 and 168 hours.

Table 8.11. Mean reflectance values of Biofinity™ before (control) and after storage in the different LCSs, results of Kruskal-Wallis 1-way ANOVA and Friedman ANOVA.

Biofinity™ LCSs	**UVC (190–280 nm) (%)**				**p(b)**
	Control	**8h**	**24h**	**168h**	
Renu MP		12.05±2.24	12.84±2.58	13.64±2.87	*<0.01*
OptiFree PM		13.64±2.87	12.46±2.49	12.83±2.82	*<0.01*
BioTrue	14.06±2.79	11.70±2.29	12.12±2.39	13.10±2.51	*<0.01*
AOSept Plus		10.71±2.08	11.84±2.44	12.17±2.45	*<0.01*
p(a)		***0.006***	*0.148*	***0.020***	
UVB (280–315 nm) (%)					
Renu MP		8.50±0.43	9.00±0.55	9.45±0.45	*<0.01*
Opti-Free PM		8.16±0.37	8.66±0.50	8.72±0.41	*<0.01*
BioTrue	9.59±0.75	8.23±0.43	8.32±0.54	8.96±0.47	*<0.01*
AOSept Plus		7.76±0.42	8.34±0.43	8.50±0.46	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
UVA (315–400 nm) (%)					
Renu MP		6.58±1.13	6.81±1.36	7.17±1.45	*<0.01*
Opti-Free PM		6.39±1.10	6.66±1.21	6.71±1.33	*<0.01*
BioTrue	7.26±1.40	6.29±1.12	6.38±1.20	6.83±1.33	*<0.01*
AOSept Plus		6.09±1.01	6.51±1.20	6.46±1.32	*<0.01*
p(a)		***0.001***	***0.008***	***<0.001***	
Visible (400–700 nm) (%)					
Renu MP		3.83±0.30	3.65±0.33	3.79±0.37	*<0.01*
Opti-Free PM		3.76±0.29	3.76±0.33	3.67±0.31	*<0.01*
BioTrue	4.08±0.29	3.52±0.28	3.52±0.28	3.68±0.34	*<0.01*
AOSept Plus		3.56±0.32	3.68±0.28	3.47±0.28	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold; p(b): Friedman ANOVA, p<0.01 for all comparisons represent strong evidence against Ho. Values are expressed in percentages (%).

The R-(%) of Balafilcon A represented in *table 8.11* trend to decrease during the first week in the UVR spectrum except when was exposed to BioTrue, in which increased +0.61 between 24h and 168h. In the visible range, AOSept demonstrated less effect in the R-(%) of Balafilcon A compared with MPSs, but, after one week, it presents a lower value of R-(%) than the other solutions. The MPS kept a constant behavior in this region of the spectrum.

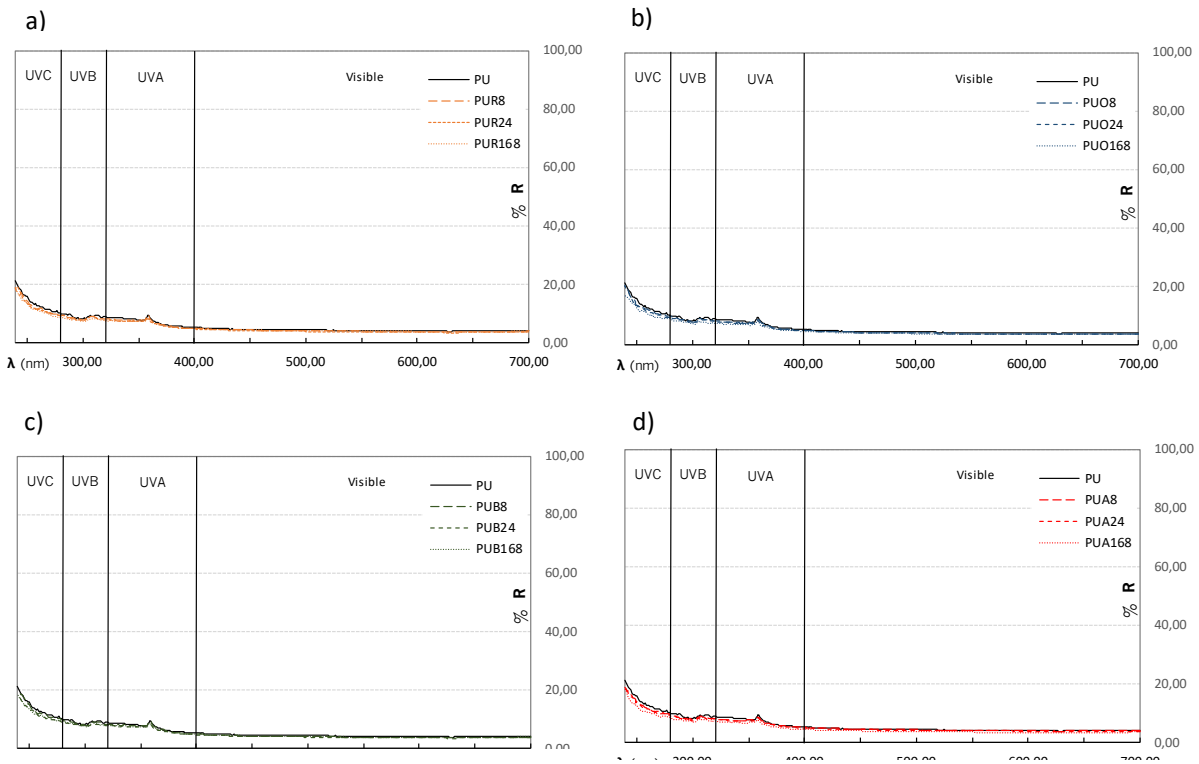

Figure 8.8. Reflectance spectra (UV-visible range) for Purevision® 2 after opening (control) and after 8, 24 and 168 hours of storage in the LCS. a) Renu; b) OptiFree; c) Biotrue and d) AOSept.

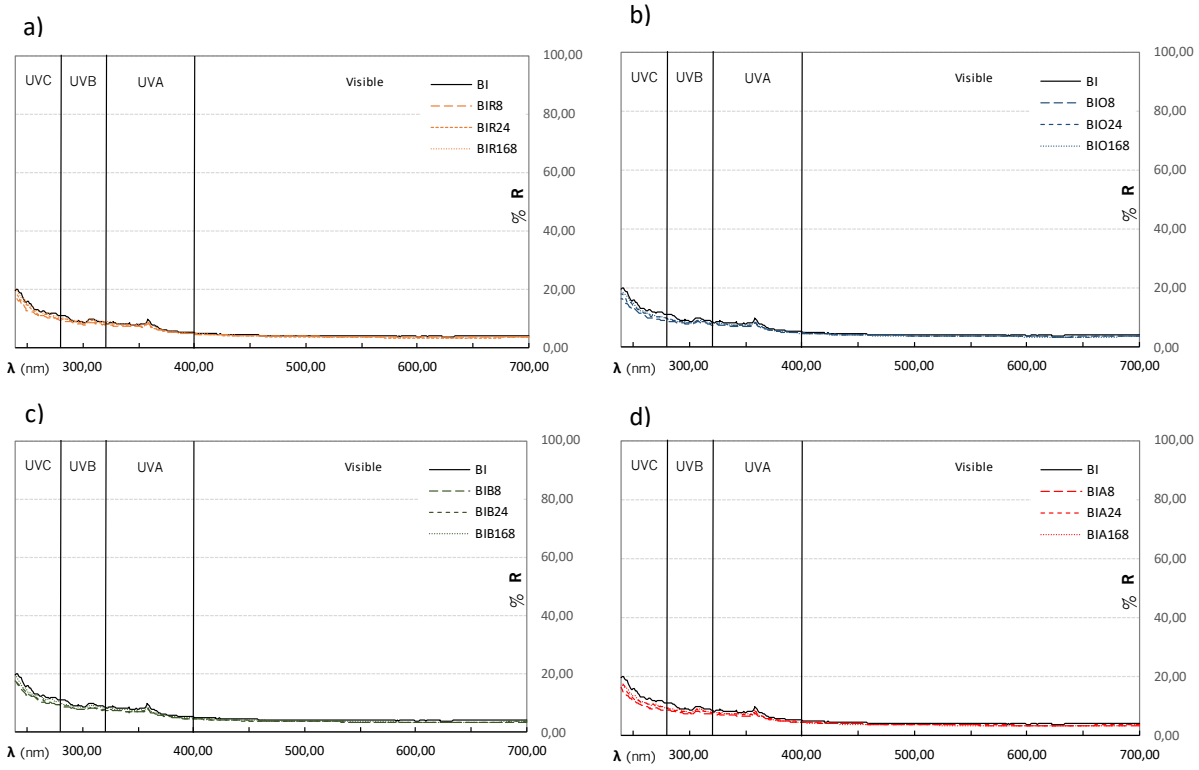

Figure 8.9. Reflectance spectra (UV-visible range) for Biofinity™ after opening (control) and after 8, 24 and 168 hours of storage in the LCS. a) Renu; b) OptiFree; c) Biotrue and d) AoSept.

Table 8.12. Mean reflectance values of Proclear™ before (control) and after storage in the different LCSs, results of Kruskal-Wallis 1-way ANOVA and Friedman ANOVA.

Proclear™ LCSs	UVC (190–280 nm) (%)				p(b)
	Control	8h	24h	168h	
Renu MP		11.50±2.13	12.72±2.42	13.20±2.44	*<0.01*
OptiFree PM		11.02±2.05	12.45±2.47	13.20±2.76	*<0.01*
BioTrue	14.57±3.08	10.96±1.78	12.97±2.46	12.24±2.31	*<0.01*
AOSept Plus		11.64±2.43	12.36±2.42	12.69±2.48	*<0.01*
p(a)		*0.386*	*0.529*	*0.183*	
UVB (280–315 nm) (%)					
Renu MP		8.29±0.40	8.89±0.40	9.13±0.43	*<0.01*
Opti-Free PM		7.89±0.34	8.80±0.54	9.09±0.40	*<0.01*
BioTrue	10.01±0.66	7.81±0.42	8.86±0.41	8.52±0.43	*<0.01*
AOSept Plus		8.12±0.39	8.52±0.42	8.75±0.48	*<0.01*
p(a)		***<0.001***	***0.002***	***<0.001***	
UVA (315–400 nm) (%)					
Renu MP		6.53±1.11	7.04±1.27	7.39±1.28	*<0.01*
Opti-Free PM		6.34±1.05	6.82±1.25	7.06±1.25	*<0.01*
BioTrue	7.72±1.50	6.20±1.05	6.94±1.29	6.70±1.18	*<0.01*
AOSept Plus		6.35±1.13	6.81±1.26	6.97±1.22	*<0.01*
p(a)		***0.029***	*0.274*	***<0.001***	
Visible (400–700 nm) (%)					
Renu MP		3.71±0.37	3.84±0.43	4.20±0.38	*<0.01*
Opti-Free PM		3.67±0.34	3.79±0.35	3.96±0.37	*<0.01*
BioTrue	4.05±0.43	3.61±0.33	3.87±0.33	3.77±0.35	*<0.01*
AOSept Plus		3.51±0.35	3.86±0.34	3.99±0.36	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold; p(b): Friedman ANOVA, p<0.01 for all comparisons represent strong evidence against Ho. Values are expressed in percentages (%).

In UVR spectra, the relectance of Comfilcon A followed an overall trend to decrease after 8 hours and a consecutive increase after this stage (*table 8.11*). Just like happened with Balafilcon A, AOSept produced a higher effect in R-(%) of -1.75 for UVC, -0.54 for UVB and -0.33 for UVA after 8 hours compared with MPSs. Overall, the Renu was the solution that showed less impact in this material (*figure 8.11*). In UVR, the result of statistical analysis

showed a significant difference for the influence of LCS on Biofinity reflectance (%), except after 24 hours in UVC range. The time factor also showed statistically significant differences, however some pairs of time presented similar values, such as between 8 hours and 24 hours in the OptiFree and BioTrue with p-value of 0.85 and 0.57, respectively.

There was a decrease of R-(%) of Omafilcon A with most of the LCS after 8 hours and a consequent increase until one week (*table 8.12*). *Figure 8.12* represents the R-(%) of Proclear without and with the solutions. About LCSs effect, Renu showed a better preservation of R (%) values over time compared with the other products. The K-W test established similarity between the LCSs in the UVC range and after 24 hours in the UVA range.

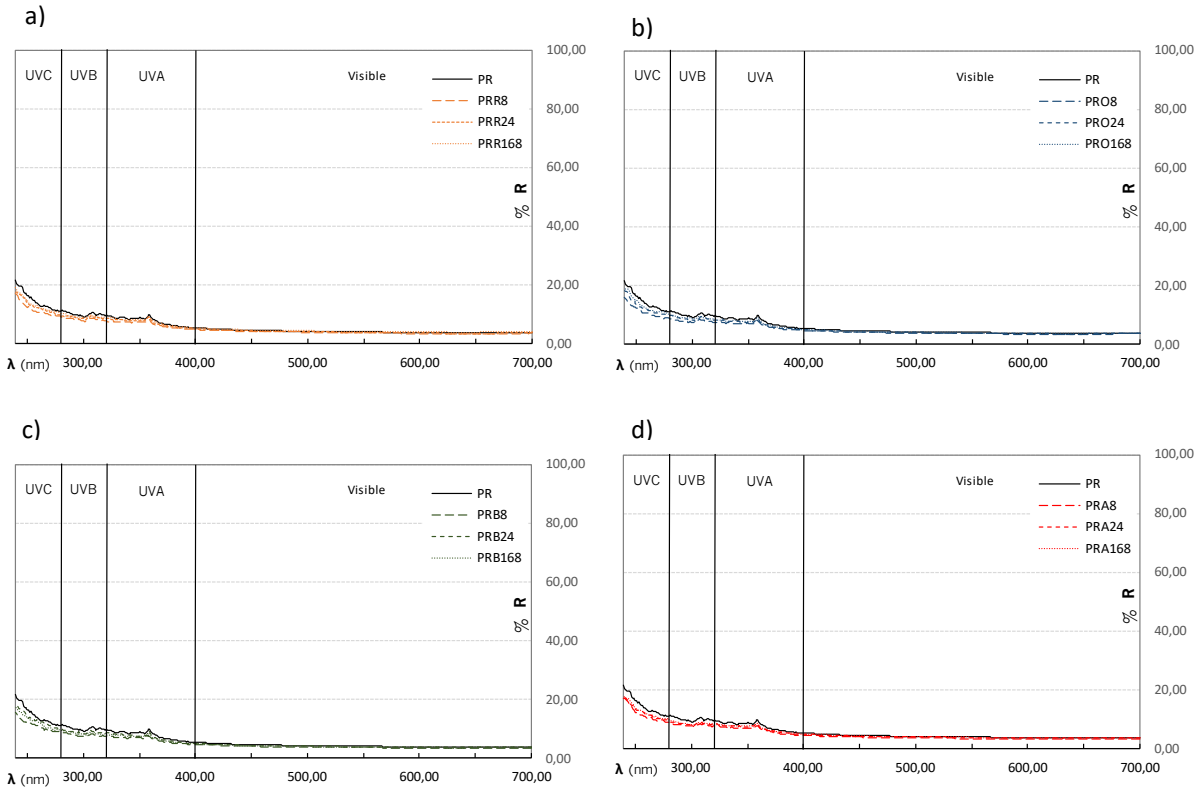

Figure 8.10. Reflectance spectra (UV-visible range) for Proclear™ after opening (control) and after 8, 24 and 168 hours of storage in the LCS. a) Renu; b) OptiFree; c) Biotrue and d) AoSept.

Analyzing the global spectra showing the reflectance of CLs materials with the LCSs after 8 hours (*figure 8.13*), it can be considered that there is a global trend to a decrease in R-(%) after storage in the UVR spectrum. As it happened with transmittance, in some materials there were differences in behavior when comparing MPS with H_2O_2 care system.

Considering the spectrum in the visible region, although the statistical analysis showed significant differences over time and between the products, graphically it can be verified that the R-(%) values did not present divergence after storage. These variations were not considerable from the clinical point of view.

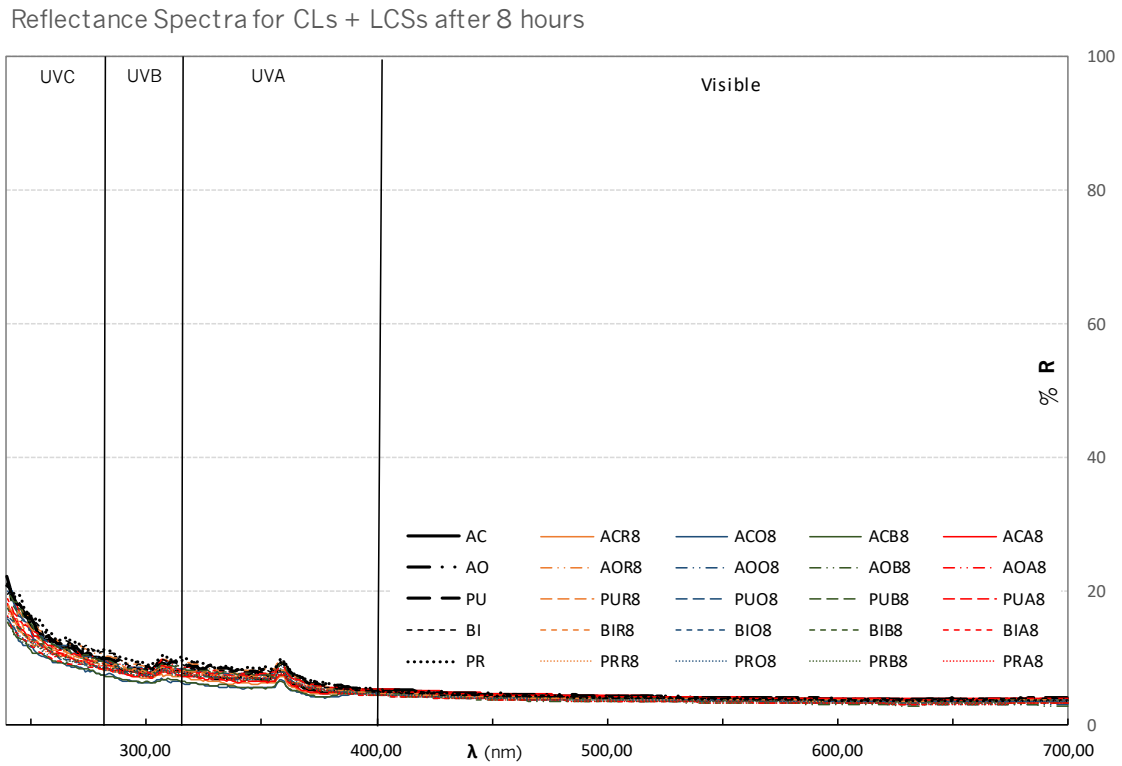

Figure 8.11. Reflectance spectra (UV-visible range) for Acuvue® Oasys (AC), AirOptix® (AO), Purevision® 2 (PU), Biofinity™ (BI) and Proclear™ (PR) after opening (black) and **after 8 hours** of storage in the Renu (orange), OptiFree (blue), BioTrue (green) and AOSept (red).

8.1.3 Overall analysis of Transmittance and Reflectance

The results found in the present study suggest that transmittance and reflectance of CLs reveal different behaviors when exposed to LCSs after storage. The outcomes of T and R showed statistically significant differences after 7 days of storage ($p<0.01$) for the four wavebands (UVC, UVB, UVA and visible). In general, there was also statistically significant differences between the lens care solutions over time. In this sense, it is possible to say that the observed changes in T and R of CLs were due to different interactions manifested with the various chemical compositions of lens care solutions.

The study of these variables allows to analyze the absorbing behavior of the CL materials, considering equation 4 ($R_\lambda + T_\lambda + A_\lambda = 1$). From these data integrated in the *table 8.13* that presents the mean of CLs variables of all wavelengths, it is possible to assess that, after exposed in the storage with the LCSs, the CL materials tend to absorb more light after 8 hours, with a recovery or slight variation after one week. This phenomenon may indicate a potential initial interaction with LCS components.

Table 8.13. Mean of CLs variables (%) after 8 hours under the mean influence of products in UV-visible spectrum. The fraction of absorbed radiation (A) was obtained according to equation 4 ($R_\lambda + T_\lambda + A_\lambda = 1$).

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Variables	CLs	Control	8h	24h	168h
T (%)	Acuvue® Oasys™	66.8	65.1	66.1	65.8
	Air Optix® Aqua	86.6	83.5	83.9	82.5
	Purevision® 2	82.4	83.1	83.3	81.7
	Biofinity™	93.0	92.7	91.7	93.6
	Proclear™	91.0	89.8	90.9	95.5
R (%)	Acuvue® Oasys	5.7	5.2	5.0	5.1
	Air Optix® Aqua	6.1	5.5	5.2	5.7
	Purevision® 2	6.0	5.6	5.5	5.3
	Biofinity™	6.0	5.2	5.3	5.4
	Proclear™	6.1	5.1	5.6	5.7
A (%)	Acuvue® Oasys™	27.5	29.7	28.9	29.1
	Air Optix® Aqua	7.3	11.0	10.9	11.8
	Purevision® 2	11.6	11.3	11.2	13.0
	Biofinity™	1.0	2.1	3.0	1.0
	Proclear™	2.9	5.1	3.5	-1.2

CL materials have been shown to absorb components of the care liquids which may cause a consequent decrease in transmittance and reflectance.

The Balafilcon A displayed an initial decrease and showed a lower variation of the absorption fraction over time, which could mean a higher resistance to the products effects. These differences can be due to its low WC. The lens Comfilcon A (Biofinity) showed the lowest modification after 8 hours. Comfilcon A lens is a SiHy material using “Aquaform” technology. This fabrication method uses a longer silicon chain, which converts into a lower silicon content, making the lens more flexible and causing better wetting. It also keeps water in its interior, minimizing dehydration.

The AirOptix lens should be highlighted because it had reported larger changes of the variables after storage, as it can be observed in *figure 8.14* that represents the transmittance variations. This behavior can be explained by the interaction between the polymers of the lens and the components of liquids, which may be facilitated by the plasma surface treatment of this lens. Lotrafilcon B has an ultrathin (25 nm) continuous, hydrophilic plasma coating with high refractive index which forms a thin hydrophilic surface. In this way, it can be deduced that this surface treatment influences the absorption ability of the lens material.

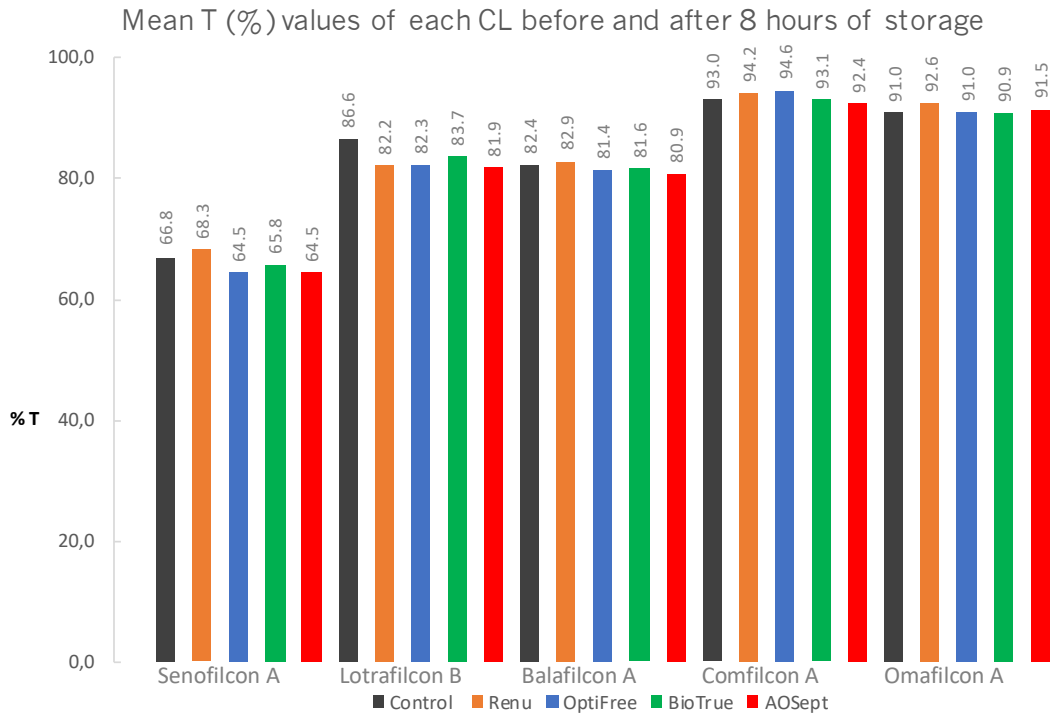

Figure 8.12. Mean transmittance of each CL material before (control in gray) and after 8 hours of storage in the Renu (orange), OptiFree (blue), BioTrue (green) and AOSept (red).

Regarding the effect of LCS in the CL wettability, the study conducted by Silva[164] reported a general trend to a decrease of the contact angle after storage. Like what happened in the Silva´s study, Lotrafilcon B exhibited more differences, while Comfilcon A presented smaller variations. The positive effect shown in this study, which reported a decrease in hydrophobicity, agrees with the slight positive attenuation of UV radiation displayed in this study. On the other hand, Fagehi et al. [137] detected a significant reduction in CL wettability by solutions after 8 hours.

In this field, the integration of hyaluronic acid in CLs showed favorable points against discomfort and ocular dryness.[165] Considering that HA not affect the optical transparency[118], it is a good topic to be developed.[166] Another advance has been verified in the liposomal CLs, which in the same way, in addition to exhibit biocompatibility, does not affect the visible light range.[167]

There is experimental evidence which emphasizes the presence of relaxation and swelling of the polymeric network close to the CL surface when the materials were exposed to LCSs.[132] This study detected changes caused by MPSs in the morphology of the CL surface which was more wrinkled, together with changes in the CL optical properties with variations of the Zernike coefficients. As in the current study, Lotrafilcon B material demonstrated the largest changes. This rationale allows to underline that an adsorption process of constituents of MPS can be the precursor to this change in the optical context of the lens. Another study conducted by Lira et al.[130] showed statistically significant differences in the surface roughness of Comfilcon A, Senofilcon A and Lotrafilcon B with high impact caused by Renu. The increased roughness caused by MPSs can lead to a larger diffusion of light, translating in a slight variation in transmittance which was projected in this study, especially in Lotrafilcon B. Although the plasma oxidation treatment improved the wettability, the higher roughness associated with the use of lens care products could have implications in the clinical step, especially in the adhesion of deposits.[40] Contrary to what happened in the latter two studies, H_2O_2 care solution showed considerable changes in the study variables that could be explained by the higher oxidative effect in the polymer chemical structure.

Considering the water content, the polymer network of CLs has a free water composition that moves easily within and out the polymer.[43] Thus, the hydrogel materials are good solvents for some hydrophilic or amphiphilic solutes included in cleaning systems, such as PHMB, EDTA, MAPD or surfactant molecules. This fact may enhance the adsorption of care

solution components which consequently disturb the optical properties of materials. Looking at the study reported by Lira et al.[130], the RI of Comfilcon A, Senofilcon A and Lotrafilcon B decreased after immersed on Renu and AOSept solutions over 24 hours. These observations are common to the outcomes of this study, being possible to consider that, after exposure to the solutions, the WC of the materials increases, translating the consequent variations of the absorption of light by diffuse particles. In the context of ionicity, as analyzed in other studies, in general terms, the AOSept displayed a higher effect in ionic groups. In the current study, there was a larger reduction in T-(%) by AOSept in the Balafilcon A lenses (group 3) compared with group 1 and 2, in the UVR range. These results agree with the considerations done by Guillon et al. and Maissa et al. that consider a higher reactivity between acid products and ionic materials, which may cause changes in CL properties, as well as in their degradation.[107,148]

Depending on the type of material selected, its behavior will be different after exposed to the lens care products and the ocular flora. Regarding for the study conducted by Dalton et al., the different physical properties analyzed can justify the changes observed in this study. In this sense, for example, the changes in WC may be explained by the differences in osmolality of the LCS products. A solution with higher osmolarity may have more impact on the properties of the lenses due to its higher concentration of solute per volume unit. On the other hand, the higher surface tension, as well as a lower pH of AOSept, compared with the MPSs, can explain its effects.[133] From Gavara and Compañ "the increase of the ionic permeability of SiHy materialls may be due to the confinment of ions in nanoscale water channels involving possible decreased degrees of freedom for diffusion of both water and ions."[92]

According to Brennan and Coles[126], in a real situation, there is a complex distribution of variables that can influence the deterioration of the CL material. As can be seen from the findings of this study, as well as from previous studies, the LC material should not be selected based only in the Dk value (as it was earlier). This study of the spectral analysis of UV-visible radiation revealed different behaviors after the CLs are exposed to LCSs, depending on the type of CL material and the composition of the lens care soutions. Thus, the interactions between the two systems, when deeply investigated, could provide a specific option for decision making in the clinical setting.

8.2. Influence of contact lenses on absorbance and fluorescence properties of lens care solutions

Not only the LCSs have influence on CLs properties, but the opposite may also occur, considering that the lenses can adsorb components of the lens care products or even release some components to the liquid. Taking this in mind, optical properties (absorbance and fluorescence emission) of the lens care solutions were also investigated, before and after the CLs were immersed in them, for the same time intervals as before.

8.2.1 Analysis of the UV-visible absorbance of lens care solutions

In general, the absorption spectra (*figure 8.15-8.19*) of the lens care liquids exhibit a strong absorption for wavelengths below 250 nm, with an exponential-like increase with decreasing wavelength. This behavior is typical of small structures that cause significant light scattering, like the surfactant micelles, which exhibit typical sizes of a few nanometers (e.g. 15 – 30 Å). In fact, Rayleigh scattering of light is proportional to the inverse of λ^4, causing a notable increase in light scattering at short wavelengths. The scattered radiation (I_D) does not reach the instrument detector, implying a lower transmittance (T) and a higher absorbance (*equation 7, figure 8.15*), where I is the intensity of transmitted radiation and I_0 is the intensity of incident radiation.

$$A_\lambda = -log\,\mathrm{T} = -log\frac{I_\lambda}{I_0} \qquad \text{Equation 7}$$

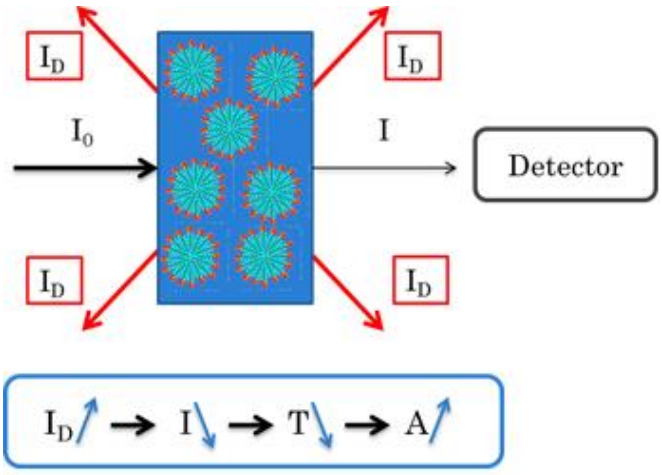

Figure 8.13. Schematic representation of light scattering by micelles in solution.

Nevertheless, other LCS components can absorb in this region, like the pH buffer components (e.g. boric acid, citric acid), disinfectants and isolated surfactant molecules. The presence of surfactant micelles is inferred from the much lower surface tension (*vd* table 5.1) of these LCS when compared to the value for pure water (72.5 mN/m at room temperature), except for AOSept. The poloxamines (Tetronic) are amphiphilic block copolymers forming non-ionic micelles at low concentrations.[168] Nevertheless, hydrogen peroxide-based cleaning solutions also contain surfactants, such as Pluronic® 17R4 (BASF Corporation) and the block copolymer of ethyleneoxide-butyleneoxide.

From the absorbance spectra of ReNu MP displayed in *figure 8.16* and the corresponding statistical analysis in *table 8.14*, the values of Biofinity combination had more expression compared with the other CLs, especially after 8 hours of storage with +0.07 in UVC spectra, +0.06 in UVB, +0.02 in UVA and +0.03 in visible spectra. In this time, Acuvue Oasys produced a decrease of -0.02%. There were no statistically significant differences between the groups of CLs in UVC level, but in this field is necessary to clarify that this test is not sensitive for sample with a high coefficient of variation, consequence of the heterogeneous outcomes. After 8 hours, the pairs Purevision-Proclear exhibited a similar behavior with p-value of 0.44 and 0.06 in the UVA and visile range respectively. About the effect of storage time, in all the combinations, the absorbance had a trend to increase in the first 8 hours and to slightly increase or maintain after this time. The same does not happen with Biofinity CL that reported a regression after 8 hours. Over time, the absorbance of ReNu showed statistically significant differences ($p<0.01$).

These results point to some release of CL components to the LCS during immersion time, causing an increase in absorbance of the liquids in the UV region. For Biofinity, the opposite may occur at 8h, with some adsorption of liquid components into the lenses, especially surfactant micelles.

Regarding to the *figure 8.17* and *table 8.15* corresponding to spectrum and statistical analysis of OptiFree, there was a similar variation of absorbance compared to the previous solution. In fact, there was an increase after 8h in general of the situations and a subsequent increase or maintenance until one week. The highest value of absorbance corresponded to Acuvue Oasys after 1 week with +0.10 for UVC, +0.05 for UVB, +0.03 for UVA and +0.02 for

Table 8.14. Mean absorbance values of ReNu MP® before (control) and after storage with the different CLs, results of Kruskal-Wallis 1-way ANOVA and Friedman ANOVA.

ReNu MP®	UVC (190–280 nm)				p(b)
CLs	Control	8h	24h	168h	
Acuvue Oasys	0.78±0.94	0.76±0.91	0.78±0.92	0.83±0.97	*<0.01*
AirOptix Aqua		0.79±0.91	0.81±0.92	0.82±0.93	*<0.01*
PureVision 2		0.78±0.90	0.80±0.92	0.81±0.94	*<0.01*
Biofinity		0.85±0.92	0.82±0.91	0.79±0.90	*<0.01*
Proclear		0.79±0.88	0.82±0.90	0.79±0.89	*<0.01*
p(a)		*0.285*	*0.602*	*0.913*	
UVB (280–315 nm)					
Acuvue Oasys	0.01±0.00	0.02±0.00	0.03±0.01	0.04±0.01	*<0.01*
AirOptix Aqua		0.03±0.01	0.04±0.01	0.04±0.01	*<0.01*
PureVision 2		0.04±0.01	0.04±0.01	0.03±0.01	*<0.01*
Biofinity		0.07±0.11	0.05±0.01	0.04±0.11	*<0.01*
Proclear		0.04±0.11	0.04±0.01	0.04±0.10	*<0.01*
p(a)		***<0.001***	***<0.001***	***0.001***	
UVA (315–400 nm)					
Acuvue Oasys	0.00±0.00	0.01±0.00	0.01±0.00	0.02±0.00	*<0.01*
AirOptix Aqua		0.01±0.00	0.02±0.00	0.02±0.00	*<0.01*
PureVision 2		0.02±0.00	0.02±0.00	0.02±0.00	*<0.01*
Biofinity		0.02±0.00	0.02±0.00	0.02±0.00	*<0.01*
Proclear		0.02±0.01	0.02±0.00	0.02±0.00	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
Visible (400–700 nm)					
Acuvue Oasys	0.00±0.00	0.00±0.00	0.01±0.00	0.01±0.00	*<0.01*
AirOptix Aqua		0.01±0.00	0.01±0.00	0.01±0.00	*<0.01*
PureVision 2		0.01±0.00	0.01±0.00	0.02±0.00	*<0.01*
Biofinity		0.03±0.00	0.01±0.00	0.01±0.00	*<0.01*
Proclear		0.01±0.00	0.01±0.00	0.01±0.00	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold;
p(b): Friedman ANOVA, p<0,01 for all comparisons represent strong evidence against Ho.

visible. However, after 8 hours, Comfilcon A exhibited higher influence, except in the UVC spectra, where the AirOptix had a larger effect of +0.09. The post-hoc test provided no statistically significant differences between some products in some parts of the spectrum,

Table 8.15. Mean absorbance values of Opti-Free® PM® before (control) and after storage with the different CLs, results of Kruskal-Wallis 1-way ANOVA and Friedman ANOVA.

Opti-Free® PM®	UVC (190–280 nm)				p(b)
CLs	Control	8h	24h	168h	
Acuvue Oasys	0.52±0.75	*0.54*±0.75	0.58±0.76	0.62±0.79	*<0.01*
AirOptix Aqua		0.61±0.77	0.60±0.76	0.61±0.78	*<0.01*
PureVision 2		0.58±0.76	0.59±0.77	0.59±0.78	*<0.01*
Biofinity		0.59±0.74	0.58±0.76	0.59±0.77	*<0.01*
Proclear		0.55±0.74	0.60±0.77	0.60±0.79	*<0.01*
p(a)		*0.091*	*0.597*	*0.397*	
UVB (280–315 nm)					
Acuvue Oasys	0.01±0.00	0.02±0.00	0.04±0.01	0.06±0.01	*<0.01*
AirOptix Aqua		0.04±0.01	0.04±0.01	0.06±0.01	*<0.01*
PureVision 2		0.04±0.01	0.04±0.01	0.04±0.01	*<0.01*
Biofinity		0.06±0.01	0.04±0.01	0.04±0.01	*<0.01*
Proclear		0.03±0.01	0.05±0.01	0.04±0.01	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
UVA (315–400 nm)					
Acuvue Oasys	0.00±0.00	0.01±0.00	0.02±0.01	0.03±0.01	*<0.01*
AirOptix Aqua		0.02±0.01	0.02±0.01	0.03±0.01	*<0.01*
PureVision 2		0.02±0.01	0.02±0.00	0.03±0.00	*<0.01*
Biofinity		0.03±0.01	0.02±0.00	0.02±0.00	*<0.01*
Proclear		0.01±0.01	0.03±0.01	0.02±0.01	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
Visible (400–700 nm)					
Acuvue Oasys	0.00±0.00	0.01±0.00	0.01±0.00	0.02±0.00	*<0.01*
AirOptix Aqua		0.01±0.00	0.01±0.00	0.02±0.00	*<0.01*
PureVision 2		0.01±0.00	0.01±0.00	0.02±0.00	*<0.01*
Biofinity		0.02±0.00	0.01±0.00	0.01±0.00	*<0.01*
Proclear		0.01±0.00	0.02±0.00	0.01±0.00	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold;
p(b): Friedman ANOVA, p<0,01 for all comparisons represent strong evidence against Ho.

such as the pairs Acuvue-Proclear and Purevision-AirOptix after 8 hours in the UVB and UVA ranges.

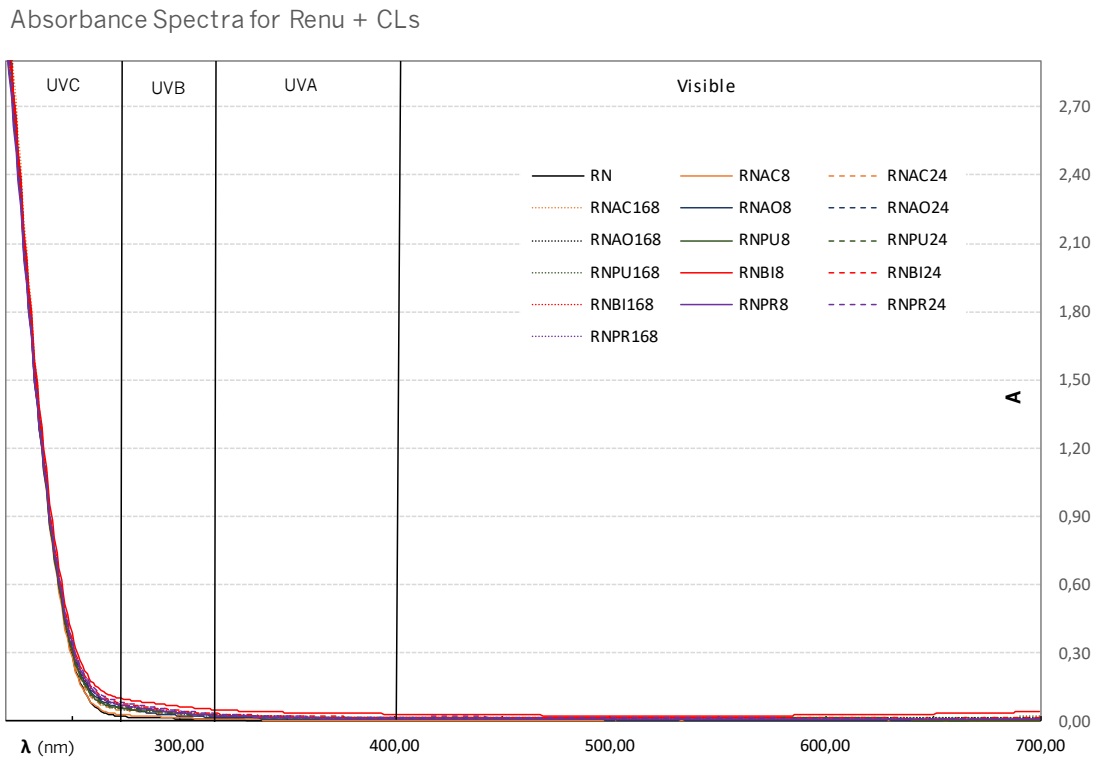

Figure 8.14. Absorbance spectra (UV-visible range) for ReNu MP® before (black) and after 8, 24 and 168 hours of storage with Acuvue Oasys (AC - orange), AirOptix (AO - blue), Purevision (PU - green), Biofinity (BI - red) and Proclear (PR - purple).

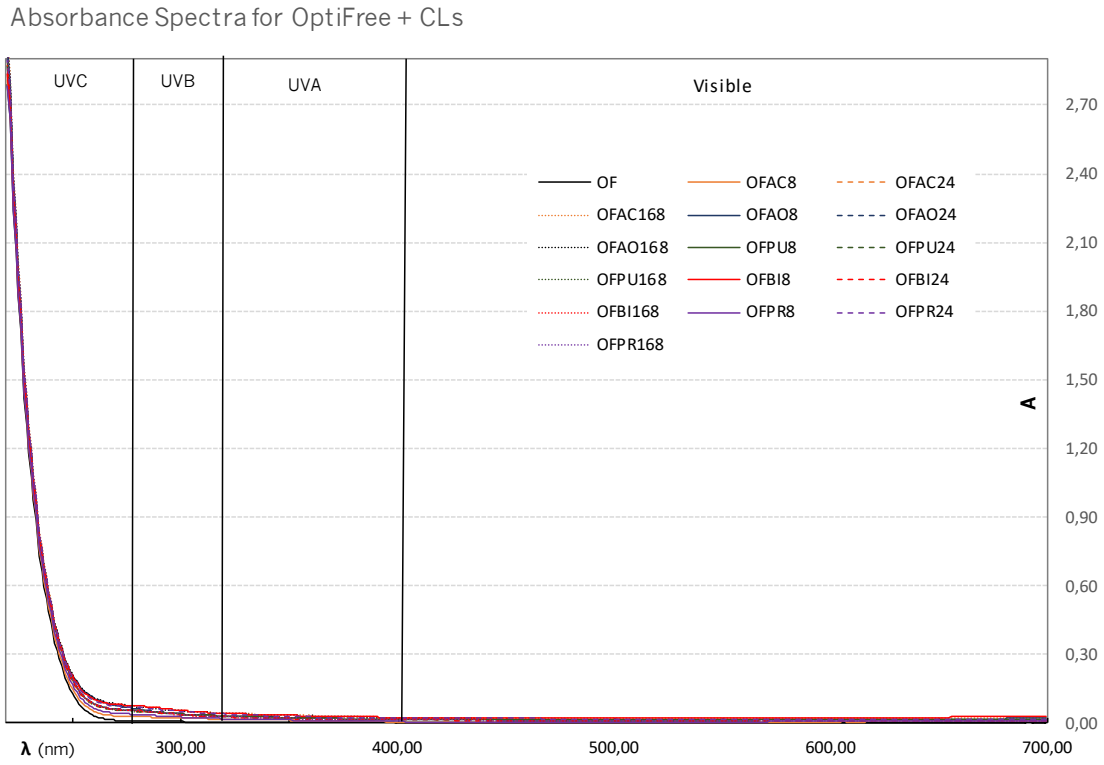

Figure 8.15. Absorbance spectra (UV-visible range) for Opti-Free® PM® before (black) and after 8, 24 and 168 hours of storage with Acuvue Oasys (AC - orange), AirOptix (AO - blue), Purevision (PU - green), Biofinity (BI - red) and Proclear (PR - purple).

The study of BioTrue solution is represented in *table 8.16*. On more time, the absorbance tended to increase after storage with the CLs. There was no general divergence between the values over time, except in the UVB range. The analysis of pairs for Friedman test demonstrated that there were no differences without lens and after 8 hours of storage in the Acuvue Oasys, Purevision and Proclear materials, with p=1.00. At the end of 8 hours of storage, the Acuvue and AirOptix CLs had a less and more effect in the absorbance of BioTrue, respectively. Comparing with the others LCSs and after 1 week, Omafilcon A exhibited the least impact on this product. The analysis between pairs showed similar behavior of AirOptix-Purevision pair. Overall, the absorbance representation (*figure 8.18*) did not differ from the other MPSs representations.

The absorption spectra of AOSept are presented in *figure 8.19.* These spectra exhibit notable differences in the UVC and UVB ranges compared to the other MPSs. This shows that AOSept also contains compounds that absorb strongly in the UV region, which may be surfactants and/or buffer components. Looking for the spectral variance, the most discrepant values were produced by Omafilcon A after one day of storage with a peak of A=0.197 at 262 nm, showing a strong rise in absorption relatively to the control, which may be due to some CL components released to the clean solution. Moreover, for Lotrafilcon B, Balafilcon A and Comfilcon A after 1 week one new peak at λ_{max}=247 nm, with values of A=0.193, A=0.224 and A=0.218, respectively, arises evidencing the release of CL compounds to the liquid at long times of immersion. The same, but in a less extent, happens for Omafilcon A.

These results could be mainly justified by the release of tint additives to the care solution at long times, as these CLs are blue-tinted. For the non-tinted CL (Acuvue Oasys), this effect of rising absorption at 247 nm is much lower. In general, the post-hoc analysis exhibited similar performance of absorbance before and after 8 hours of storage, compared with the other time intervals in the UVC and UVA ranges. Overall, the K-W test displayed significant differences between all groups (*table 8.17*).

In summary, the UVC and UVB parts of the spectrum exhibited most of changes between the different LCSs. The immersion of CLs in the cleaning products showed a global trend to increase and change the absorbance of the care liquids over time, that although statistically significant, may not represent a clinical relevance. This aspect justifies further investigation.

Table 8.16. Mean absorbance values of BioTrue™ before (control) and after storage with the different CLs, results of Kruskal-Wallis 1-way ANOVA and Friedman ANOVA.

BioTrue™	**UVC (190–280 nm)**				**p(b)**
CLs	**Control**	**8h**	**24h**	**168h**	
Acuvue Oasys	0.29±0.32	0.29±0.31	0.34±0.33	0.37±0.34	*<0.01*
AirOptix Aqua		0.35±0.33	0.36±0.34	0.37±0.34	*<0.01*
PureVision 2		0.31±0.30	0.33±0.32	0.35±0.34	*<0.01*
Biofinity		0.32±0.34	0.34±0.33	0.33±0.33	*<0.01*
Proclear		0.31±0.33	0.32±0.33	0.32±0.34	*<0.01*
p(a)		*0.062*	*0.523*	*0.052*	
UVB (280–315 nm)					
Acuvue Oasys	0.02±0.00	0.03±0.01	0.06±0.01	0.07±0.01	*<0.01*
AirOptix Aqua		0.05±0.01	0.05±0.01	0.05±0.01	*<0.01*
PureVision 2		0.05±0.01	0.06±0.01	0.06±0.01	*<0.01*
Biofinity		0.04±0.01	0.05±0.01	0.05±0.01	*<0.01*
Proclear		0.04±0.01	0.05±0.01	0.04±0.01	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
UVA (315–400 nm)					
Acuvue Oasys	0.01±0.00	0.01±0.00	0.03±0.01	0.04±0.01	*<0.01*
AirOptix Aqua		0.02±0.00	0.02±0.00	0.03±0.01	*<0.01*
PureVision 2		0.02±0.00	0.03±0.00	0.03±0.00	*<0.01*
Biofinity		0.02±0.00	0.03±0.01	0.03±0.01	*<0.01*
Proclear		0.02±0.01	0.02±0.00	0.02±0.00	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
Visible (400–700 nm)					
Acuvue Oasys	0.00±0.01	0.00±0.00	0.02±0.00	0.02±0.00	*<0.01*
AirOptix Aqua		0.01±0.00	0.01±0.00	0.02±0.00	*<0.01*
PureVision 2		0.01±0.00	0.02±0.00	0.03±0.00	*<0.01*
Biofinity		0.01±0.00	0.01±0.00	0.01±0.00	*<0.01*
Proclear		0.01±0.00	0.02±0.00	0.01±0.00	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold;
p(b): Friedman ANOVA, p<0,01 for all comparisons represent strong evidence against Ho.

Table 8.17. Mean absorbance values of AoSept® Plus before (control) and after storage with the different CLs, results of Kruskal-Wallis 1-way ANOVA and Friedman ANOVA.

AoSept® Plus CLs	UVC (190–280 nm)				p(b)
	Control	8h	24h	168h	
Acuvue Oasys	0.10±0.04	0.09±0.04	0.09±0.04	0.11±0.05	*<0.01*
AirOptix Aqua		0.11±0.06	0.11±0.05	0.16±0.06	*<0.01*
PureVision 2		0.11±0.05	0.12±0.05	0.18±0.06	*<0.01*
Biofinity		0.10±0.06	0.09±0.04	0.17±0.06	*<0.01*
Proclear		0.11±0.04	0.18±0.03	0.12±0.04	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
UVB (280–315 nm)					
Acuvue Oasys	0.03±0.01	0.01±0.01	0.02±0.01	0.03±0.01	*<0.01*
AirOptix Aqua		0.03±0.11	0.03±0.01	0.03±0.01	*<0.01*
PureVision 2		0.03±0.01	0.03±0.01	0.03±0.01	*<0.01*
Biofinity		0.02±0.01	0.02±0.01	0.03±0.01	*<0.01*
Proclear		0.03±0.01	0.06±0.03	0.02±0.01	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
UVA (315–400 nm)					
Acuvue Oasys	0.01±0.00	0.00±0.00	0.01±0.00	0.01±0.00	*<0.01*
AirOptix Aqua		0.01±0.00	0.01±0.00	0.01±0.00	*<0.01*
PureVision 2		0.01±0.00	0.02±0.00	0.01±0.00	*<0.01*
Biofinity		0.01±0.00	0.00±0.00	0.00±0.00	*<0.01*
Proclear		0.01±0.00	0.01±0.00	0.01±0.00	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
Visible (400–700 nm)					
Acuvue Oasys	0.01±0.00	0.00±0.00	0.01±0.00	0.01±0.00	*<0.01*
AirOptix Aqua		0.01±0.00	0.01±0.00	0.01±0.00	*<0.01*
PureVision 2		0.01±0.00	0.01±0.00	0.01±0.00	*<0.01*
Biofinity		0.00±0.00	0.00±0.00	0.00±0.00	*<0.01*
Proclear		0.00±0.00	0.01±0.00	0.00±0.00	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold;
p(b): Friedman ANOVA, p<0,01 for all comparisons represent strong evidence against Ho.

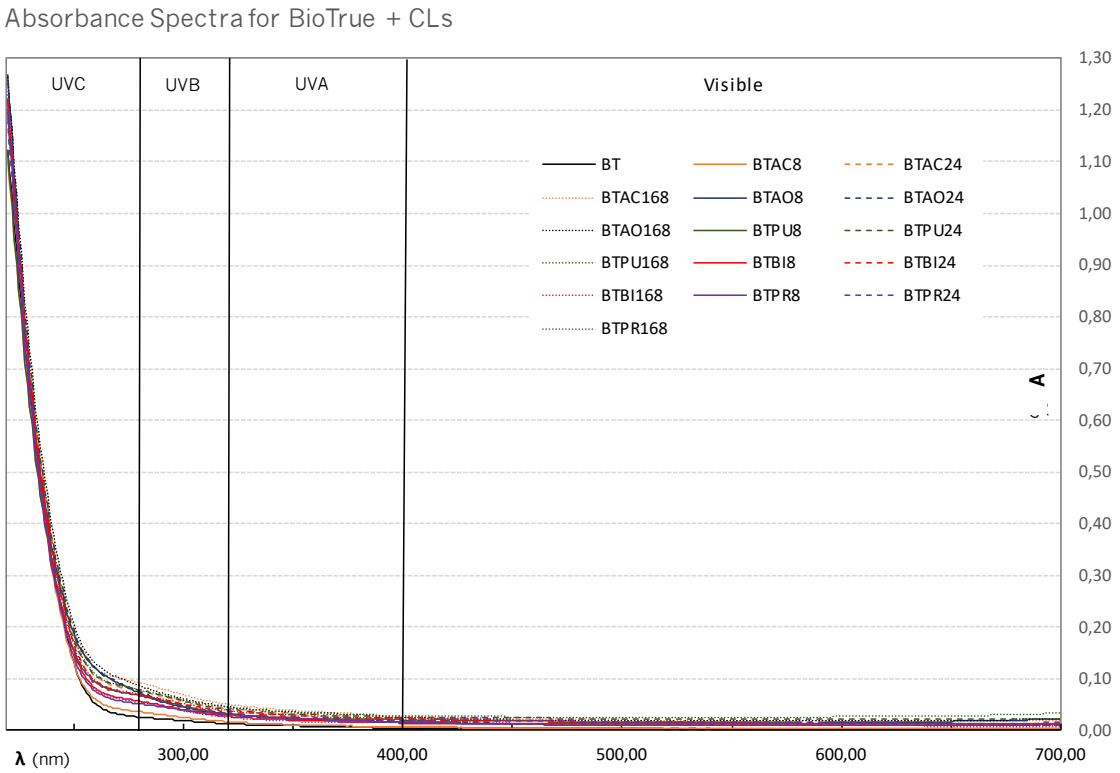

Figure 8.16. Absorbance spectra (UV-visible range) for BioTrue™ before (black) and after 8, 24 and 168 hours of storage with Acuvue (AC - orange), AirOptix (AO - blue), Purevision (PU - green), Biofinity (BI - red) and Proclear (PR - purple).

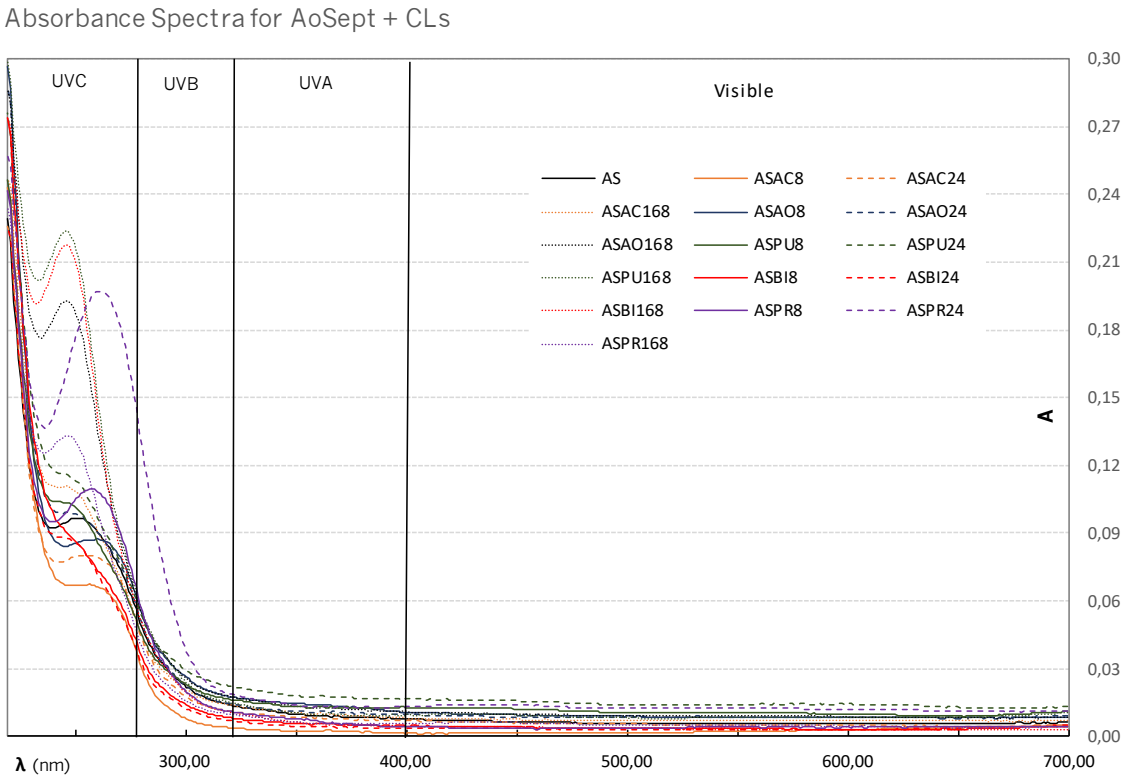

Figure 8.17. Absorbance spectra (UV-visible range) for AOSept® before (black) and after 8, 24 and 168 hours of storage with Acuvue (AC - orange), AirOptix (AO - blue), Purevision (PU - green), Biofinity (BI - red) and Proclear (PR - purple).

8.2.2 Analysis of the UV-visible fluorescence of lens care solutions

In order to complement the results obtained with the UV-Visible absorption technique, fluorescence emission measurements were performed. Fluorescence emission spectroscopy has the advantage of its selectivity and extremely high sensitivity. However, its application is restricted to fluorescent compounds.

Two excitation wavelengths were used for the determination of fluorescence emission spectra, 280 nm and 350 nm. At 280 nm, it is possible to excite compounds such as surfactants (e.g. benzalkonium chloride, BAK) or other compounds with aromatic groups (e.g. antimicrobial compounds with indole derivatives). At 350 nm, other compounds like CL components can be detected. One major fluorescent CL component, exhibiting strong fluorescence emission with maximum near 380 nm, is poly (N-vinylpyrrolidone, PVP) corresponding to polymerized NVP.[169]

The effect of CLs materials on fluorescence of ReNu MP is included in *table 8.18* and can be seen in *figure 8.20*. In all the combinations, the intensity of fluorescence (IF) expressed in arbitrary units (a.u.) increased after 8 hours in contact with the CLs. As it can be observed, for excitation at 280 nm, the Acuvue Oasys induced lower changes in Renu solution when compared with the other materials. In most of the other lenses, the FI increased to the double or more. It must be emphasized that the first sharp peak in the fluorescence spectra is due to Raman scattering and should not be considered as due to CL or LCS components. In general, it can be observed an increase in fluorescence emission with immersion time of CL in the liquid, for excitation at both 280 nm and 350 nm, evidencing the release of CL components as PVP and tint additives, among others. One notable feature is that, for Purevision 2, the components release occurs in the first hours of immersion, being constant thereafter.

The outcomes of statistical analysis showed strong differences between the materials in the time intervals and reported significant changes over time. The post-hoc test exhibited a similar behavior between Proclear and Biofinity lenses. For excitation at 350 nm in the Renu solution, it can be deduced that, as happened for 280 nm excitation, Coopervision CLs displayed a higher increase of the fluorescence intensity, when compared with the other materials. In the UVA region, the Senofilcon A showed an average of +0.08E6 a.u. after 8 h when compared with the baseline outcome. In the visible range, the fluorescence emission is mainly observed in the lower wavelength region (blue).

Table 8.18. Mean fluorescence intensity values for the excitation at 280 nm and 350 nm for ReNu® before (control) and after storage with the different CLs, results of K-W and Friedman.

ReNu®	**UVB (300–315 nm) – Exc 280**				**p(b)**
CLs	**Control**	**8h**	**24h**	**168h**	
Acuvue Oasys	0.68E6±1.20E5	0.92E6±0.99E5	1.11E6±0.85E5	1.24E6±0.79E5	*<0.01*
AirOptix Aqua		1.89E6±0.92E5	1.70E6±0.84E5	1.58E6±0.68E5	*<0.01*
PureVision 2		1.40E6±0.71E5	1.39E6±0.62E5	1.47E6±0.97E5	*<0.01*
Biofinity		1.37E6±0.95E5	1.37E6±0.59E5	1.27E6±1.55E5	*<0.01*
Proclear		1.46E6±1.08E5	1.47E6±0.64E5	1.34E6±0.17E5	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
UVA (315–400 nm) – Exc 280					
Acuvue Oasys	0.24E6±0.90E6	0.39E6±0.14E6	0.51E6±0.17E6	0.59E6±0.19E6	*<0.01*
AirOptix Aqua		0.69E6±0.40E6	0.70E6±0.35E6	0.93E6±0.45E6	*<0.01*
PureVision 2		0.70E6±0.34E6	0.72E6±0.34E6	0.67E6±0.32E6	*<0.01*
Biofinity		0.63E6±0.22E6	0.86E6±0.35E6	0.46E6±0.19E6	*<0.01*
Proclear		0.61E6±0.13E6	1.00E6±0.39E6	0.47E6±0.19E6	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
Visible (400–540 nm) – Exc 280					
Acuvue Oasys	0.08E6±0.38E5	0.10E6±0.45E5	0.13E6±0.54E5	0.15E6±0.66E5	*<0.01*
AirOptix Aqua		0.13E6±0.67E5	0.14E6±0.74E5	0.16E6±0.83E5	*<0.01*
PureVision 2		0.11E6±0.55E5	0.11E6±0.58E5	0.10E6±0.54E5	*<0.01*
Biofinity		0.18E6±0.92E5	0.20E6±0.10E6	0.14E6±0.63E5	*<0.01*
Proclear		0.22E6±0.13E6	0.25E6±0.14E5	0.14E6±0.75E5	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
UVA (370–400 nm) – Exc 350					
Acuvue Oasys	0.11E6±0.98E5	0.19E6±0.62E5	0.11E6±0.68E5	0.13E6±0.73E5	*<0.01*
AirOptix Aqua		0.12E6±0.80E5	0.13E6±0.82E5	0.13E6±0.81E5	*<0.01*
PureVision 2		0.11E6±0.65E50.	0.10E6±0.63E5	0.11E6±0.64E5	*<0.01*
Biofinity		17E6±0.89E5	0.18E6±0.92E5	0.18E6±0.85E5	*<0.01*
Proclear		0.15E6±0.88E5	0.18E6±0.93E5	0.16E6±0.80E5	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
Visible (400–680 nm) – Exc 350					
Acuvue Oasys	0.44E5±0.47E5	0.49E5±0.48E5	0.73E5±0.70E5	0.77E5±0.73E5	*<0.01*
AirOptix Aqua		0.81E5±0.86E5	0.85E5±0.90E5	0.86E5±0.88E5	*<0.01*
PureVision 2		0.60E5±0.62E5	0.58E5±0.57E5	0.52E5±0.51E5	*<0.01*
Biofinity		0.99E5±0.10E6	1.05E5±0.11E6	0.89E5±0.92E5	*<0.01*
Proclear		1.05E5±0.11E6	1.16E5±0.11E6	0.79E5±0.82E5	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold; p(b): Friedman ANOVA, p<0.01 for all comparisions represent strong evidence against Ho. Values are expressed in arbitrary units (a.u

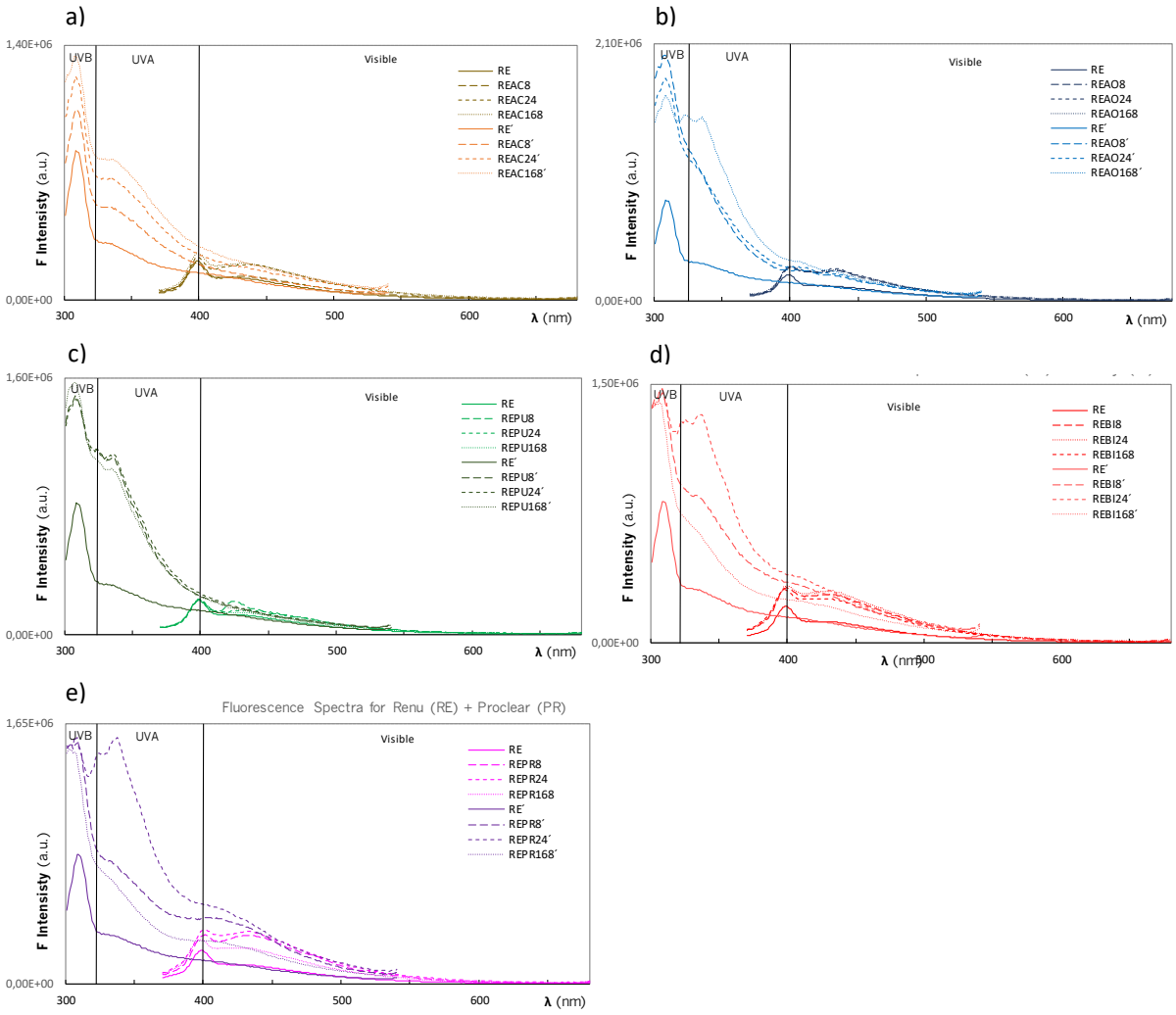

Figure 8.18. Fluorescence spectra (UV-visible range) for ReNu MP® before (control) and after 8, 24 and 168 hours of storage with the CLs. a) Acuvue; b) Air Optix; c) Purevision; d) Biofinity and e) Proclear. The above spectra (´) represent excitation at 280 nm and below spectra represent the excitation at 350 nm.

The OptiFree solution, which contains PQ-1, showed changes very similar to Renu, which has PHMB, especially in the differences of the FI over time (*figure 8.21*). Here, the positive charge of the ammonium groups of PQ-1 (while PHMB has neutral NH groups) seems not to influence the release of CL compounds.

As previously, the Lotrafilcon B had a higher impact on fluorescence in the UVB range; in this situation, an increase of +0.99E6 a.u. was detected after 8h compared with the control product. Senofilcon A produced the least effect in the first 8 hours but increased over time, getting the highest value after 1 week, when compared to the other materials. After 8h and until 1 week, the CHy lens exhibited no significant differences in UVC range, but in the UVA-visible spectrum, the FI increased to 24 hours. The K-W test showed statistically significant

Table 8.19. Mean fluorescence intensity values for the excitation at 280 nm and 350 nm for Opti-Free® before and after storage with the different CLs, results of K-W and Friedman.

Opti-Free® PM® CLs	UVB (300–315 nm) – Exc 280				p(b)
	Control	8h	24h	168h	
Acuvue Oasys	0.72E6±0.10E6	0.84E6±1.00E5	1.12E6±0.83E5	1.53E6±0.76E5	*<0.01*
AirOptix Aqua		1.71E6±0.87E5	1.52E6±0.78E5	1.35E6±0.68E5	*<0.01*
PureVision 2		1.02E6±0.60E5	1.03E6±0.58E5	1.05E6±0.75E5	*<0.01*
Biofinity		1.12E6±0.90E5	1.10E6±0.70E5	1.00E6±0.14E5	*<0.01*
Proclear		1.23E6±1.10E5	1.26E6±0.54E5	1.27E6±1.81E5	*<0.01*
p(a)		**<0.001**	**<0.001**	**<0.001**	
UVA (315–400 nm) – Exc 280					
Acuvue Oasys	0.15E6±0.00E6	0.29E6±0.10E6	0.51E6±0.16E6	0.90E6±0.31E6	*<0.01*
AirOptix Aqua		0.69E6±0.35E6	0.69E6±0.31E6	0.81E6±0.38E6	*<0.01*
PureVision 2		0.59E6±0.19E6	0.61E6±0.26E6	0.50E6±0.22E6	*<0.01*
Biofinity		0.53E6±0.19E6	0.63E6±0.26E6	0.28E6±0.15E6	*<0.01*
Proclear		0.41E6±0.17E6	0.85E6±0.39E6	0.37E6±0.20E6	*<0.01*
p(a)		**<0.001**	**<0.001**	**<0.001**	
Visible (400–700 nm) – Exc 280					
Acuvue Oasys	0.06E6±0.02E6	0.12E6±0.36E5	0.17E6±0.55E5	0.20E6±0.93E5	*<0.01*
AirOptix Aqua		0.17E6±0.81E5	0.16E6±0.80E5	0.17E6±0.80E5	*<0.01*
PureVision 2		0.13E6±0.64E5	0.12E6±0.58E5	0.17E6±0.44E5	*<0.01*
Biofinity		0.13E6±0.64E5	0.13E6±0.64E5	0.65E6±0.24E5	*<0.01*
Proclear		0.11E6±0.54E5	0.15E6±0.71E5	0.08E6±0.33E5	*<0.01*
p(a)		**<0.001**	**<0.001**	**<0.001**	
UVA (370–400 nm) – Exc 350					
Acuvue Oasys	0.10E6±0.59E5	0.12E6±0.70E5	0.15E6±0.80E5	0.15E6±0.78E5	*<0.01*
AirOptix Aqua		0.15E6±0.92E5	0.15E6±0.88E5	0.15E6±0.86E5	*<0.01*
PureVision 2		0.13E6±0.74E5	0.12E6±0.75E5	0.12E6v0.67E5	*<0.01*
Biofinity		0.12E6±0.78E5	0.12E6±0.75E5	0.10E6±0.60E5	*<0.01*
Proclear		0.11E6±0.69E5	0.14E6±0.78E5	0.11E6±0.64E5	*<0.01*
p(a)		*0.155*	*0.496*	*0.267*	
Visible (400–700 nm) – Exc 350					
Acuvue Oasys	0.39E5±0.38E5	0.64E5±0.59E5	0.94E5±0.82E5	1.01E5±0.92E5	*<0.01*
AirOptix Aqua		1.05E5±1.10E5	0.97E5±1.00E5	0.91E5±0.91E5	*<0.01*
PureVision 2		0.73E5±0.72E5	0.77E5±0.81E5	0.60E5±0.60E5	*<0.01*
Biofinity		0.82E5±0.86E5	0.77E5±0.80E5	0.40E5±0.38E5	*<0.01*
Proclear		0.64E5±0.65E5	0.86E5±0.87E5	0.52E5±0.53E5	*<0.01*
p(a)		**<0.001**	**<0.001**	**<0.001**	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold; p(b): Friedman ANOVA, p<0.01 for all comparisons represent strong evidence against Ho. Values are expressed in arbitrary units (a.u.).

differences (p=0.00) for excitation at 280 nm. *Table 8.19* corresponds to mean FI values of OptiFree solution. There were no statistical differences reported by K-W analysis for the UVA part of the spectrum at excitation 350 nm. Overall of the combinations, the OptiFree displayed high values of FI (a.u.) in the high energy part of the visible spectra, evidencing release of CL components with blue fluorescence. Again, for Purevision 2, the CL components release occurs in the first hours of immersion, as happened in ReNu solution. Air Optix shows a similar behavior to Purevision (as in ReNu), except for 168 h, where an increase in fluorescence is observed around 340-350 nm (for excitation at 280 nm).

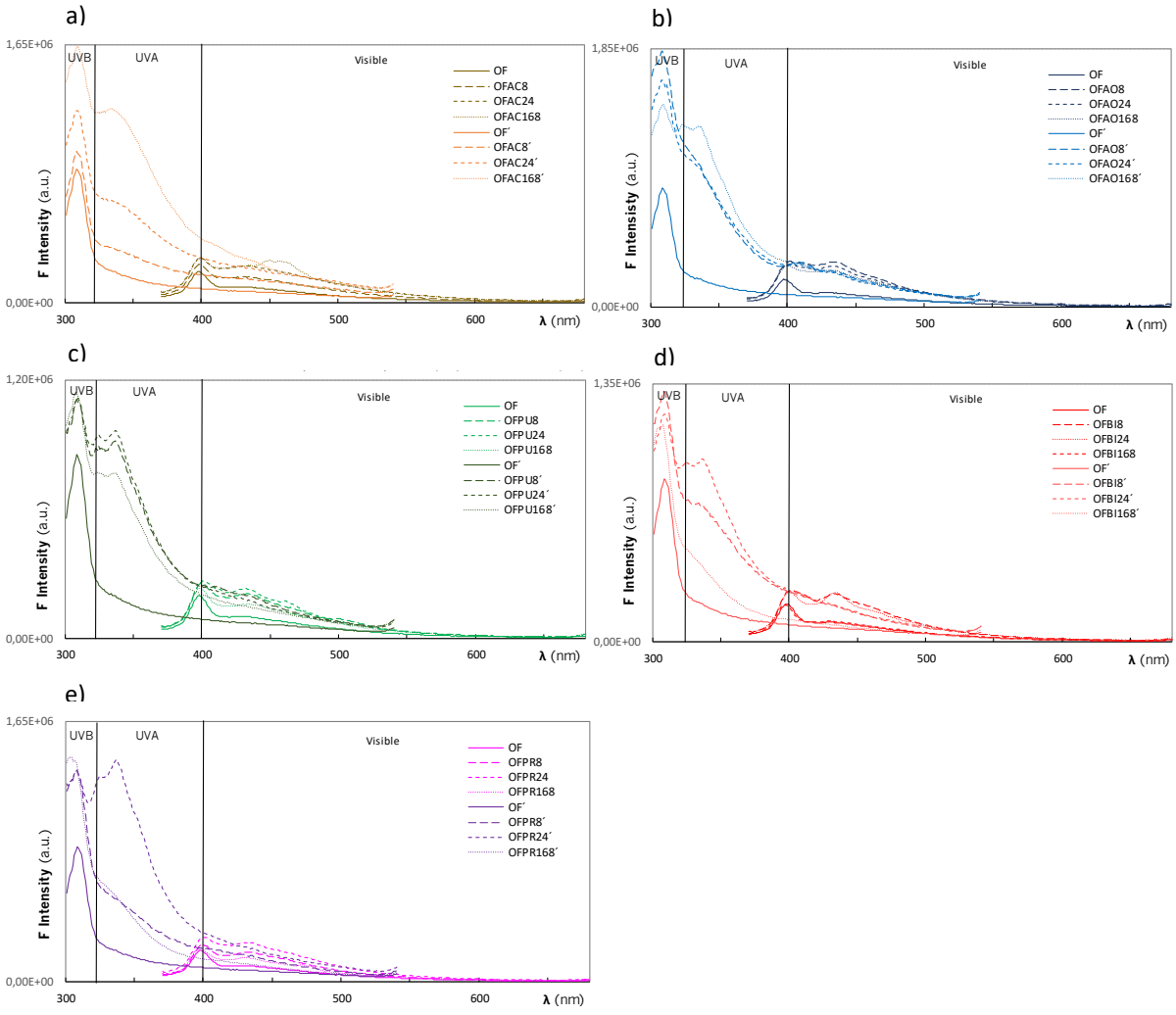

Figure 8.19. Fluorescence spectra (UV-visible range) for Opti-Free® PM® before (full lines) and after 8, 24 and 168 hours of storage with the CLs. a) Acuvue; b) Air Optix; c) Purevision; d) Biofinity and e) Proclear. The above spectra (´) represent excitation of 280 nm and below spectra represent the excitation of 350 nm.

One more time and not too different from what happened with previous products, after 8 hours, Lotrafilcon B induced more effect on the fluorescence of BioTrue solution (*figure 8.22*), with +1.35E6, +0.54E6 and +0.09E6 for UVB, UVA and visible spectrum compared with the control value without lens at excitation 280 nm. Senofilcon A exhibited the same behavior, increasing the FI (a.u.) over time and Proclear, such as the Purevision lens, showed a high effect after one day of storage, with respectively +0.59E6 and +0.60E6 in the UVA range compared with the baseline outcome (control). The K-W test reported significant differences for all the excitations between the CLs (*table 8.20*). For excitation at 350 nm, the post-hoc analysis showed similar changes between 1 day and 7 days for Balafilcon A and Comfilcon A and between 8 hours and 168 hours from Lotrafilcon B and Omafilcon A.

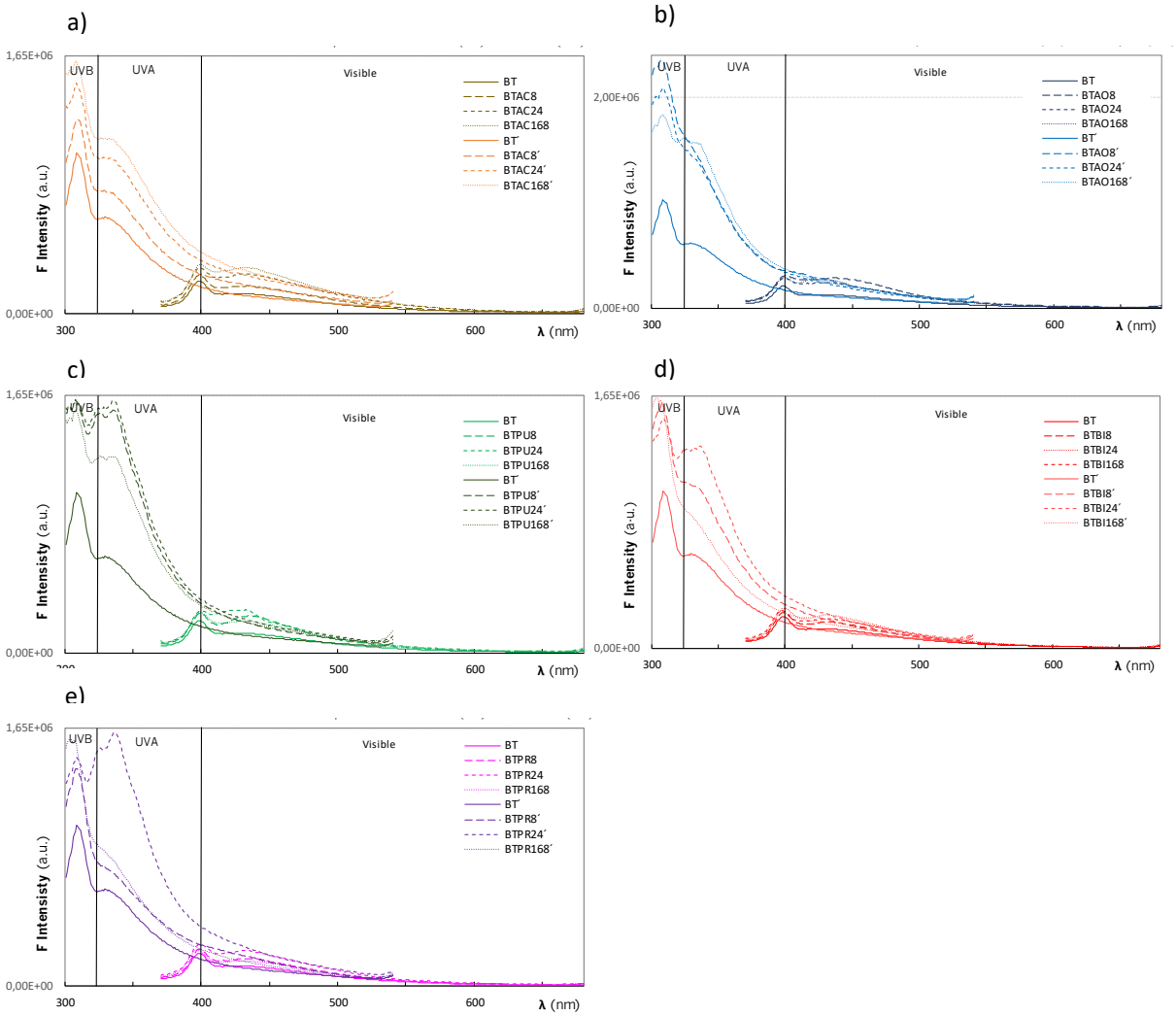

Figure 8.20. Fluorescence spectra (UV-visible range) for BioTrue™ before (full lines) and after 8, 24 and 168 hours of storage with the tested CLs. a) Acuvue; b) Air Optix; c) Purevision; d) Biofinity and e) Proclear. The above spectra (´) represent excitation of 280 nm and below spectra represent the excitation of 350 nm.

Table 8.20. Mean fluorescence intensity values for the excitation at 280 nm and 350 nm for BioTrue™ before and after storage with the different CLs, results of K-W and Friedman.

BioTrue™ CLs	UVB (300–315 nm) – Exc 280				p(b)
	Control	8h	24h	168h	
Acuvue Oasys	0.89E6±1.06E5	1.13E6±0.94E5	1.37E6±0.68E5	1.53E6±0.73E5	*<0.01*
AirOptix Aqua		2.24E6±1.03E5	2.00E6±0.77E5	1.75E6±0.62E5	*<0.01*
PureVision 2		1.54E6±0.57E5	1.56E6±0.40E5	1.47E6±0.73E5	*<0.01*
Biofinity		1.49E6±0.95E5	1.41E6±0.61E5	1.49E6±1.63E5	*<0.01*
Proclear		1.27E6±0.88E5	1.38E6±0.54E5	1.45E6±1.56E5	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
UVA (315–400 nm) – Exc 280					
Acuvue Oasys	0.41E6±0.17E6	0.54E6±0.21E6	0.71E6±0.25E6	0.82E6±0.28E6	*<0.01*
AirOptix Aqua		0.95E6±0.49E6	0.92E6±0.44E6	1.00E6±0.46E6	*<0.01*
PureVision 2		0.96E6±0.45E6	1.00E6±0.46E6	0.82E6±0.36E6	*<0.01*
Biofinity		0.71E6±0.30E6	0.87E6±0.36E6	0.56E6±0.26E6	*<0.01*
Proclear		0.54E6±0.21E6	1.01E6±0.44E6	0.56E6±0.25E6	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
Visible (400–700 nm) – Exc 280					
Acuvue Oasys	0.09E6±0.34E5	0.13E6±0.53E5	0.18E6±0.68E5	0.20E6±0.83E5	*<0.01*
AirOptix Aqua		0.18E6±0.86E5	0.16E6±0.76E5	0.18E6±0.81E5	*<0.01*
PureVision 2		0.14E6±0.68E5	0.15E6±0.72E5	0.15E6±0.62E5	*<0.01*
Biofinity		0.13E6±0.66E5	0.15E6±0.78E5	0.12E6±0.48E5	*<0.01*
Proclear		0.13E6±0.64E5	0.17E6±0.87E5	0.11E6±0.51E5	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
UVA (370–400 nm) – Exc 350					
Acuvue Oasys	0.10E6±0.61E5	0.13E6±0.70E5	0.16E6±0.81E5	0.16E6±0.86E5	*<0.01*
AirOptix Aqua		0.16E6±0.86E5	0.15E6±0.81E5	0.15E6±0.81E5	*<0.01*
PureVision 2		0.13E6±0.71E5	0.14E6±0.73E5	0.14E6±0.72E5	*<0.01*
Biofinity		0.12E6±0.69E5	0.13E6±0.74E5	0.14E6±0.69E5	*<0.01*
Proclear		0.12E6±0.66E5	0.14E6±0.73E5	0.13E6±0.65E5	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	
Visible (400–700 nm) – Exc 350					
Acuvue Oasys	0.05E6±0.46E5	0.07E6±0.63E5	0.10E6±0.88E5	0.11E6±0.10E5	*<0.01*
AirOptix Aqua		0.11E6±0.10E5	0.09E6±0.85E5	0.09E6±0.91E5	*<0.01*
PureVision 2		0.08E6±0.79E5	0.09E6±0.90E5	0.08E6±0.72E5	*<0.01*
Biofinity		0.06E6±0.61E5	0.08E6±0.76E5	0.07E6±0.65E5	*<0.01*
Proclear		0.06E6±0.63E5	0.08E6±0.79E5	0.06E6±0.58E5	*<0.01*
p(a)		***<0.001***	***0.009***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold; p(b): Friedman ANOVA, p<0.01 for all comparisons represent strong evidence against Ho. Values are expressed in arbitrary units (a.u.).

In all the other situations, there were significant differences by Friedman test ($p<0.05$).

According to the findings presented in the previous spectra and statistical analyses, it can be considered that all the CL materials caused an increase in fluorescence of MPSs at all wavelengths, especially by Lotrafilcon B lenses that have a specific surface treatment by 25 nm of plasma polymerization.

As can be observed in *figure 8.23*, the fluorescence of AOSept solution for all interaction conditions with the lenses exhibited spectra roughly different from the previous MPSs solutions. These spectra exhibit light scattering effects in the lower wavelength region, indicating the presence of particles/aggregates of nanometric size.

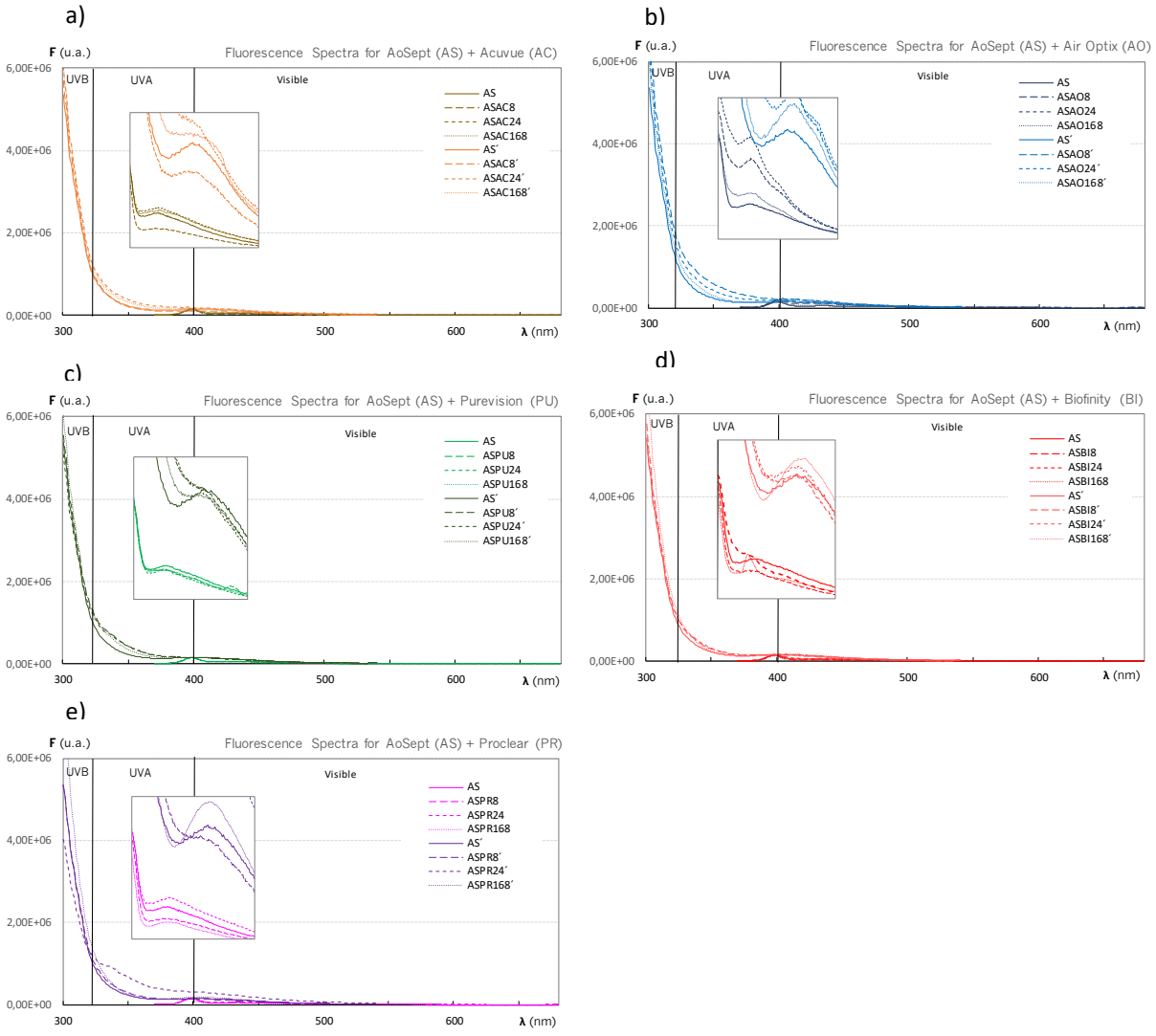

Figure 8.21. Fluorescence spectra (UV-visible range) for AoSept® Plus before (full lines) and after 8, 24 and 168 hours of storage with the tested CLs. a) Acuvue; b) Air Optix; c) Purevision; d) Biofinity and e) Proclear. The above spectra (´) represent excitation of 280 nm and below spectra represent the excitation of 350 nm. Zoom window shows 400 nm level.

Table 8.21. Mean fluorescence intensity values for the excitation at 280 nm and 350 nm AOSept® before(control) and after storage with the different CLs, results of K-W and Friedman.

AOSept® Plus CLs	UVB (300–315 nm) – Exc 280				p(b)
	Control	8h	24h	168h	
Acuvue Oasys	3.35E6±1.00E6	3.67E6±1.11E6	3.91E6±1.19±6	3.88E6±1.21E6	*<0.01*
AirOptix Aqua		4.37E6±1.26E6	4.05E6±1.19E6	3.82E6±1.20E6	*<0.01*
PureVision 2		3.63E6±1.08E6	3.34E6±0.97E6	3.86E6±1.22E6	*<0.01*
Biofinity		3.70E6±1.16E6	3.56E6±1.07E6	4.28E6±1.46E6	*<0.01*
Proclear		3.51E6±1.04E6	2.74E6±0.74E6	4.63E6±1.60E6	*<0.01*
p(a)		*0.348*	***0.011***	*0.536*	
UVA (315–400 nm) – Exc 280					
Acuvue Oasys	0.38E6±0.40E6	0.38E6±0.44E6	0.51E6±0.47E6	0.47E6±0.46E6	*<0.01*
AirOptix Aqua		0.69E6±0.56E6	0.55E6±0.51E6	0.45E6±0.56E6	*<0.01*
PureVision 2		0.53E6±0.47E6	0.51E6±0.43E6	0.48E6±0.47E6	*<0.01*
Biofinity		0.44E6±0.44E6	0.45E6±0.44E6	0.44E6±0.50E6	*<0.01*
Proclear		0.42E6±0.42E6	0.66E6±0.35E6	0.47E6±0.54E6	*<0.01*
p(a)		***<0.001***	***<0.001***	***0.022***	
Visible (400–700 nm) – Exc 280					
Acuvue Oasys	0.72E5±0.48E5	0.52E5±0.34E5	0.85E5±0.53E5	0.81E5±0.53E5	*<0.01*
AirOptix Aqua		0.96E5±0.66E5	0.97E5±0.65E5	0.84E5±0.62E5	*<0.01*
PureVision 2		0.67E5±0.46E5	0.63E5±0.43E5	0.66E5±0.44E5	*<0.01*
Biofinity		0.64E5±0.47E5	0.69E5±0.52E5	0.78E5±0.57E5	*<0.01*
Proclear		0.61E5±0.41E5	0.14E5±0.89E5	0.79E5±0.59E5	*<0.01*
p(a)		***<0.001***	***<0.001***	*0.095*	
UVA (370–400 nm) – 350 nm					
Acuvue Oasys	0.57E5±0.51E5	0.53E5±0.51E5	0.63E5±0.54E5	0.62E5±0.53E5	*<0.01*
AirOptix Aqua		0.71E5±0.63E5	0.77E5±0.70E5	0.61E5±0.55E5	*<0.01*
PureVision 2		0.58E5±0.52E5	0.56E5±0.50E5	0.62E5±0.52E5	*<0.01*
Biofinity		0.57E5±0.52E5	0.58E5±0.55E5	0.58E5±0.50E5	*<0.01*
Proclear		0.55E5±0.51E5	0.65E5±0.52E5	0.57E5±0.47E5	*<0.01*
p(a)		*0.077*	*0.116*	*0.583*	
Visible (400–700 nm) – 350 nm					
Acuvue Oasys	0.22E5±0.24E5	0.15E5±0.18E5	0.26E5±0.26E5	0.25E5±0.25E5	*<0.01*
AirOptix Aqua		0.38E5±0.43E5	0.44E5±0.54E5	0.25E5±0.28E5	*<0.01*
PureVision 2		0.21E5±0.23E5	0.20E5±0.23E5	0.21E5±0.22E5	*<0.01*
Biofinity		0.15E5±0.20E5	0.21E5±0.27E5	0.17E5±0.18E5	*<0.01*
Proclear		0.18E5±0.19E5	0.25E5±0.26E5	0.14E5±0.16E5	*<0.01*
p(a)		***<0.001***	***<0.001***	***<0.001***	

p(a): Kruskal-Wallis 1-way ANOVA, statistically significant differences between the groups are presented in bold; p(b): Friedman ANOVA, p<0.01 for all comparisons represent strong evidence against Ho. Values are expressed in arbitrary units (a.u.)

This difficults the interpretation of the fluorescence changes, but an expansion of the spectra shows a general increase of intensity with immersion time. However, this is not a monotonic behavior for all cases. Although there is a reported difference by Friedman test ($p<0.01$), in general terms, the FI (a.u.) of AOSept does not suffer significant changes after lens immersion. The hydrogen peroxide-based solution was no exception for the Lotrafilcon B effect, that showed a higher influence on the increase after 8h, compared with the baseline solution, especially in the UVA range with +0.31E6 a.u. On the other hand, Balafilcon A was the material that demonstrated the lowest effect in the FI values, especially in the visible range for 280 nm excitation (*table 8.21*). In overall of the combinations, with AOSept, the materials did not display such significant effects compared to MPSs, being possible to infer that the AOSept system show higher resistance to the influence of CL materials. Regarding the analysis of differences between the solutions over time, there were no statistically significant differences in fluorescence intensity in the UVA region (for excitation at 350 nm) and after one week of storage in UVB and visible ranges (for excitation at 280 nm). The post-hoc test showed strong divergence in the visible range for 350 nm excitation and in the UVA range for 280 nm excitation, for example, between the behavior of Proclear and the SiHy CLs after one day ($p<0.01$).

The Lotrafilcon B CL showed the most increase effect in fluorescence compared with the other materials. The fluorescence of the AOSept liquid exhibited lower affectation after storage with CLs (in relation to MPSs solutions) and showed a different behavior especially in the UVR spectra for excitation at 280 nm (*figure 8.24 and 8.25*). As previously reported, the fluorescence emission technique is more sensitive than UV-visible absorption measurements. In the two variables, the general of the care solutions were more affected by Lotrafilcon B and Comfilcon A. Senofilcon A was the material that showed the least effect in the solutions.

Regarding to *tables 8.22* and *8.23,* presenting the mean of fluorescence of solutions for 280 nm and 350 nm excitations for all the combinations, it is possible to highlight the previously reported findings. In fact, Lotrafilcon B has taken the strongest effect on all products, except for Renu at 350 nm excitation, which was more susceptible to Omafilcon A material. Considering the two excitation wavelengths, the AOSept showed higher resistance to the release of CL materials, when compared to the MPS solutions. These general findings coincide with the findings reported by the results obtained with the lenses. The Lotrafilcon B

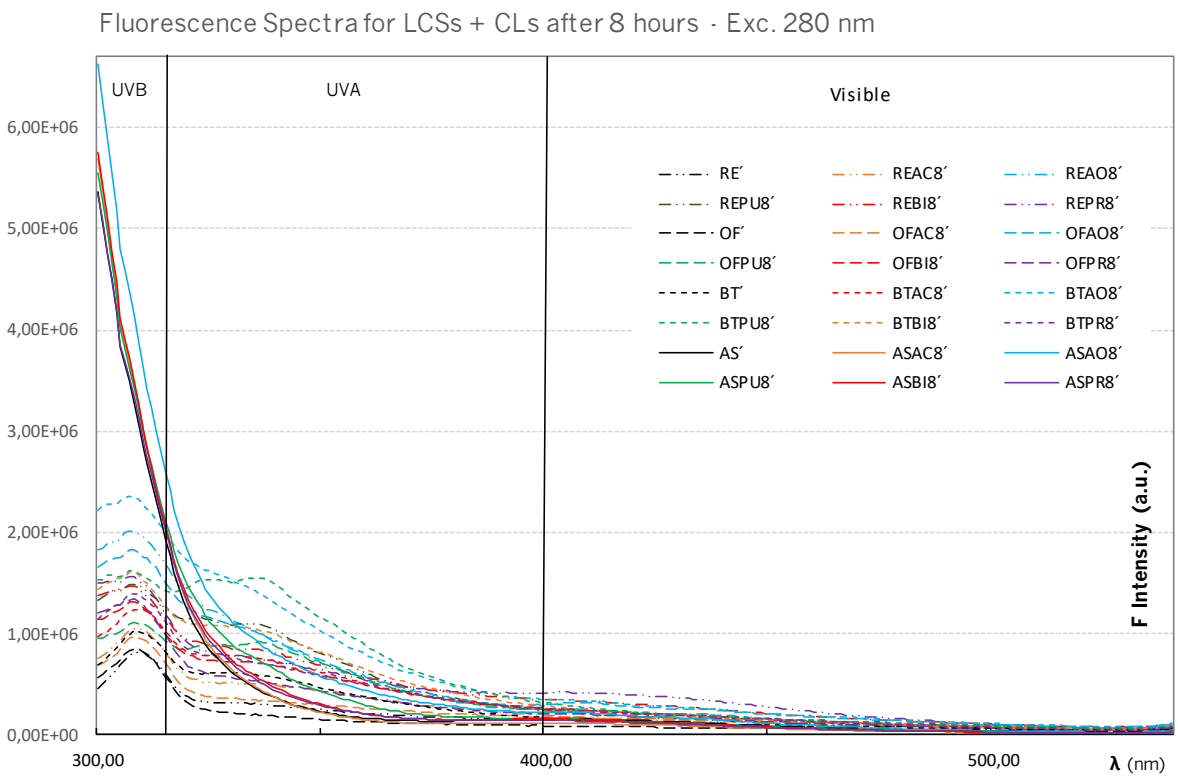

Figure 8.24. Fluorescence spectra (UV-visible range) for the excitation at 280 nm for Renu® (RE), OptiFree® (OF), BioTrue™ (BI) and AOSept® (AO) after opening (black) and **after 8 hours** of storage with Acuvue (orange), Air Optix (blue), Purevision (green), Biofinity (red) and Proclear (purple).

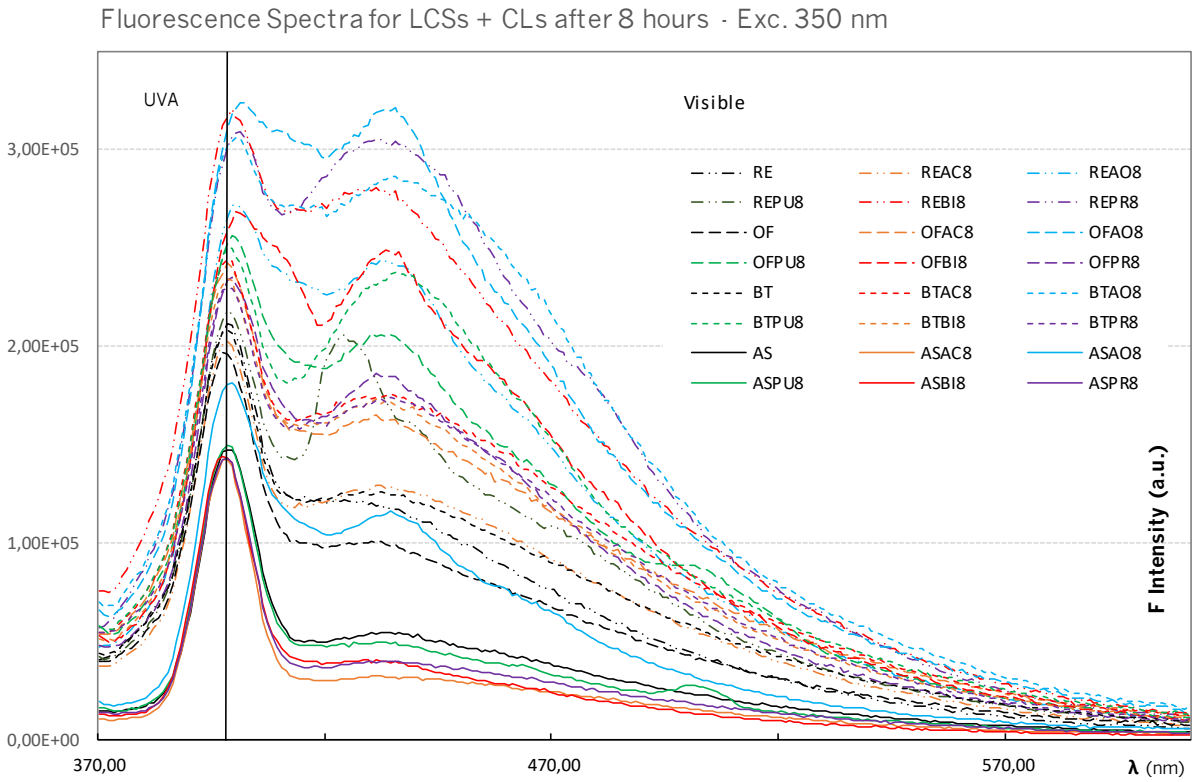

Figure 8.25. Fluorescence spectra (UV-visible range) for the excitation at 350 nm for Renu® (RE), OptiFree® (OF), BioTrue™ (BT) and AOSept® (AO) after opening (black) and **after 8 hours** of storage with Acuvue (orange), Air Optix (blue), Purevision (green), Biofinity (red) and Proclear (purple).

was the lens material that was most affected by the care liquids and was the material that, in turn, affected more study variables of products.

Table 8.22. Mean fluorescence intensity values (a.u.) for all the combinations of excitation at 280 nm after 8 hours.

Solutions / **Contact Lenses**	ReNu MP®	Opti-Free® PM®	Biotrue™	AOSpet® Plus
Acuvue® Oasys™	2.53E5	2.22E5	3.43E5	3.99E5
Air Optix® Aqua	4.43E5	4.52E5	5.83E5	5.80E5
PureVision® 2	3.98E5	3.50E5	5.21E5	4.59E5
Biofinity™	4.14E5	3.36E5	4.21E5	4.13E5
Proclear™	4.32E5	2.87E5	3.46E5	4.10E5
Control	1.73E5	1.36E5	2.52E5	3.99E5

Green and pink background represents respectively the lower and greater value of mean FI (a.u.).

Table 8.23. Mean fluorescence intensity values (a.u.) for all the combinations of excitation at 350 nm after 8 hours.

Solutions / **Contact Lenses**	ReNu MP®	Opti-Free® PM®	Biotrue™	AOSpet® Plus
Acuvue® Oasys™	5.38E4	7.02E4	7.44E4	1.83E4
Air Optix® Aqua	8.49E4	1.10E5	1.11E5	4.05E4
PureVision® 2	6.43E4	7.79E4	8.49E4	2.40E4
Biofinity™	1.06E5	8.62E4	6.93E4	1.92E4
Proclear™	1.09E5	6.85E4	6.97E4	2.09E4
Control	4.92E4	4.49E4	5.54E4	2.53E4

Green and pink background represents respectively the lower and greater value of mean FI (a.u.).

8.3 Overall analysis with clinical associations

With all this understanding, it was possible to infer that, when the LCSs are in contact with a CL material, multiple interactions occur, including affectation of CL optical properties and release of CL components to the care solutions.

The results of this study showed that, after storage in the LCSs, there were significant differences in the variables when Lotrafilcon B lens was immersed within the products.

Senofilcon A showed protection against UVR and reported less effect on fluorescence and absorbance of liquids, possibly due to the absence of tint. All angles of incidence of direct and indirect UVR light contribute to eye damage.[170] In this sense, the most suitable option is to combine UV-blocking CLs with sunglasses.

Overall, the current study reported grater effect of PQ-1 compared with PHMB in the transmittance of materials. However, the same was not verified in the fluorescence measurements. The study developed by Horner et al.[171] reported two different types of interaction for these two antimicrobial agents used in LCS in models of corneal epitelial surface: by intercalation in PQ-1 and by absorption in PHMB. Thus, it would be interesting to study more specifically if these two compounds that may present different ways of interaction with the polymer network of the materials. This is expected since, as already referred, PQ-1 is a tetra-ammonium compound, with four positive charges, and PHMB is a neutral polyamine (with a sequence of NH groups). The interaction by intercalation may also justify the reported cytotoxicity of PQ-1 in human corneal epithelial cells.[172]

The MPSs may cause sensitivity and toxicity reactions. The sensitivity responses are more serious because they involve the immune system. The corneal staining is usually reported as a toxic response to the products and is characterized by the involvement of a large part of the corneal surface with more than 50%.[173,174] The Andrasko staining grid displayed the percentage of average corneal staining area at 2 hours between some combinations of CLs with LCSs. [175] Thus, this effect was larger in LCS with PHMB, especially when combined with group 2 of CHy lenses and some SiHy materials, like Purevision material. Some studies indicate that this process occurs in a short duration.[176]

Regarding the Andrasko's staining grid, it is not feasible to compare these combinations with those reported in the present work, because they are different studies. However, it can be verified that, contrarily to what happened in this context, PQ-1 has shown

lower UVR attenuation (*figure 8.6*). In addition to having less ocular effect as presented in the study of Andrasko, the H_2O_2-based systems showed to be a good option in context of the optical properties of the lenses.

According to Kuc and Lebow[177], it is recommended to use peroxide-based care systems for patients with poor lens hygiene or ocular allergies. In this work, it was shown that, the hydrogen peroxide care system presented a strongest resistance to the release of CL material components.

9. CONCLUSION AND FUTURE WORK

This investigation highlights the following general conclusion:

- Lens care solutions induced changes on transmittance and reflectance of contact lenses after storage. These differences are more evident in the UVR regions of the spectrum;
- There were interactions between the CL materials and the solutions showing statistically significant differences over time. These interactions may be important in clinical practice, after further investigation, especially in the selection of the pair CL/LCS;
- The effect of LCSs in Senofilcon A improved its blocking ability of UVA and UVB radiation, being a good option for blocking these spectral ranges and for PLF effect. This CL displayed a lower effect on fluorescence and absorbance of LCS (possibly due to the absence of tint);
- The changes reported in the visible region do not seem to have implications in the lens transparency and, therefore, do not compromise visual performance of CLs;
- Within the group of no UVR-blockers CLs, the lenses with surface treated showed greater UVR attenuation compared to lenses without surface treatment.
- Lotrafilcon B presented a larger interaction with the lens care products. In this sense, and after exposed to LCS, the CL constituents (including tint additives and those used in the surface treatment) may induce a higher adsorption of LCS components. On the other hand, the release of CL components into the liquids seems also to be higher, having more effect on the fluorescence and absorbance of the care solutions;
- The peroxide disinfection system had a larger effect on the transmittance of the lenses, but, contrarily, exhibited more resistance to the influence of CL materials.

The suggestions for future works are:

- Investigation of the type of physical-chemical interactions between each CL material and LCS components;
- I*n vivo* studies to verify if the wear of these CL/LCS combinations is statistical and clinically relevant. In this field, it would be important to analyze associations with physiological and symptomatic responses.
- Further studies using other UV-block CLs to understand if the lens care solutions have a similar influence on CL optical properties
- To include further studies in the field of blue light inherent in electronic devices.

10. BIBLIOGRAPHY

(1) Arezes, PM. Notas sobre a escrita e formatação das dissertações de metrado. Universidade do Minho. (2011). Available at: https://alunos.uminho.pt/pt/estudantes/paginas/infouteisformatacao.aspx

(2) Ivanov IV, Mappes T, Schaupp P, Lappe C, Wahl S. Ultraviolet radiation oxidative stress affects eye health. *Journal of Biophotonics* 2018;*11*(7):1–13.

(3) Hecht E. Optics Systems. In: *Optics* 3rd ed. F. Gulbenkian Calouste. 2002; 241–250.

(4) Almsherqi Z, Margadant F, Deng Y. A look through "lens" cubic mitochondria. *Interface Focus* 2012;*2*(5):539–545.

(5) Kohnen T, Strenger A, Klaproth OK. Basic knowledge of refractive surgery: correction of refractive errors using modern surgical procedures. *Deutsches Arzteblatt International* 2008;*105*(9):163–170.

(6) Bloomfiel LA. In: *How Things Work: The physics of everyday life* 3rd ed. Wiley. University of Michigan; 2005.

(7) ICNIRP. Guidelines on limits of exposure to ultraviolet radiation of wavelengths between 180 and 400 nm (incoherent optical radiation). *Health Phys* 2004;*87*(2):171–186.

(8) Logan P, Bernabeu M, Ferreira A, Burnier MN. Evidence for the role of blue light in the development of uveal melanoma. *Journal of Ophthalmology 2015*;2015:1-7.

(9) Youssef PN, Sheibani N, Albert D M. Retinal light toxicity. *Eye* 2011;*25*(1):1–14.

(10) Chandler, H. Ultraviolet absorption by contact lenses and the significance on the ocular anterior segment. *Eye and Contact Lens* 2011;*37*(4):259–266.

(11) Coroneo, M. Ultraviolet radiation and the anterior eye. *Eye and Contact Lens* 2011;*37*(4): 214–224.

(12) Moore LA, Hussey M, Ferreira JT, Wu B. Review of photokeratitis: corneal response to ultraviolet radiation (UVR) exposure. *S Afr Optom* 2010;*69*(3):123–131

(13) Pauloin T, Dutot M, Joly F, Warnet JM, Rat P. High molecular weight hyaluronan decreases UVB-induced apoptosis and inflammation in human epithelial corneal cells. *Molecular Vision* 2009;*15*:577–583.

(14) Willmann, G. Ultraviolet Keratitis: From the Pathophysiological Basis to Prevention and Clinical Management. *High Altitude Medicine & Biology* 2015;*16*(4):277–282.

(15) Kennedy M, Kim KH, Harten B, Brown J, Planck S, Meshul C, Anselj J C. Ultraviolet Irradiation Induces the Production of Multiple Cytokines by Human Corneal Cells. *Investigative Ophthalmology & Visual Science* 1997; *38*(12):2483–91.

(16) Tahara T, Shibata T, Nakamura M, Yamashita H, Yoshioka D, Okubo M, Maruyama N, Kamano T, Kamiya Y, Nakagawa Y, Fujita H, Nagasaka M, Iwata M, Takahama K, Watanabe M, Hirata I, Arisawa T. Effect of MDR1 gene promoter methylation in patients with ulcerative colitis. *International Journal of Molecular Medicine* 2009;*23*(4):521-27.

(17) Coroneo MT. Pterygium hypothesis. *British Journal of Ophtalmology* 1993;*77(11)*:734-39.

(18) Meyer L M, Löfgren S, Holz FG, Wegener A, Söderberg P. Bilateral cataract induced by unilateral UVR-B exposure - Evidence for an inflammatory response. *Acta Ophthalmologica* 2013;*91*(3):236-42.

(19) Söderberg PG, Talebizadeh N, Yu Z, Galichanin K. Does infrared or ultraviolet light damage the lens? *Eye* 2016;*30*(2):241–46.

(20) Johnson GJ. The environment and the eye. *Eye* 2004;*18*(12):1235-50.

(21) Yam JCS, Kwok AKH. Ultraviolet light and ocular diseases. *International Ophthalmology* 2014;*34*(2):383–400.

(22) American Optometric Association. Battling Blue Light. *AOA Website* 2016. Available at: https://www.aoa.org/news/clinical-eye-care/battling-blue-light. Accessed: 28 Sept 2018.

(23) Join A. Visible blue light. *AOP Website* 2018:10-12. Available at: https://www.aop.org.uk/advice-and-support/policy/position. statements/visible-blue-light. Accessed: 28 Sept 2018.

(24) Bergmanson JP, Soderberg PG. The significance of ultraviolet radiation for the eye diseases. *Ophtalm Physiol Opt* 1995;*15*(2):83-91.

(25) Norval M. The mechanisms and consequences of ultraviolet-induced immunosuppression in the skin and eye. *Eye and Contact Lens* 2011;*37*(4):176-84.

(26) Walsh JE, Bergmanson JPG. Does the eye benefit from wearing ultraviolet-blocking contact lenses? *Eye and Contact Lens* 2011;*37*(4):267-72.

(27) Notara M, Behboudifard S, Kluth MA, Maßlo C, Ganss C, Frank MH, Cursiefen C. UV light-blocking contact lenses protect against short-term UVB-induced limbal stem cell niche damage and inflammation. *Scientific Reports* 2018;*8*(1):12564.

(28) Stach S, Ţălu Ş, Trabattoni S, Tavazzi S, Siek P, Zając J, Zaj J. Morphological Properties of Siloxane-Hydrogel Contact Lens Surfaces Morphological Properties of Siloxane-Hydrogel Contact Lens Surfaces. *Current Eye Research* 2017;42(4):498-505.

(29) Gonzalez-Meijome JM. Origens e evolução das lentes de contacto. In Gonzalez-Meijome JM, ed. *Contactologia*. Santiago de Compostela. Unidixital 2005;13-27.

(30) Jacob JT. Biocompatibility in the development of silicone-hydrogel lenses. *Eye and Contact Lens* 2013;*39*(1):13-19.

(31) Pearson RM. A review of the limitations of the first hydrogel contact lenses. *Clinical and Experimental Optometry* 2010;*93*(1):15-25.

(32) Athreya PK, Bhardwaj GK. Contact Lens Materials and Modalities. *Trend in Opfthalomology* 2018;*1*(1):1-5.

(33) Green JA, Phillips KS, Hitchins VM, Lucas AD, Shoff ME, Hutter JC, Eydelman, MB. Material properties that predict preservative uptake for silicone hydrogel contact lenses. *Eye and Contact Lens* 2012;*38*(6),350-357.

(34) Bhamra TS, Tighe BJ. Mechanical properties of contact lenses: the contribution of measurement techniques and clinical feedback to 50 years of materials development. *Contact Lens and Anterior Eye* 2017;*40*(2):70-81.

(35) Szczotka-flynn ML, Ahearn PDG, Barr J, Benjamin WJ, Kiang T, Nichols JJ, Winterton L. History, evolution and evolving standards of contact lens care. *Contact Lens and Atnterior Eye* 2013;*36*:S4-S8.

(36) Nichols JJ. Contact Lens 2017. *Contact Lens Spectrum* Jan,2018;20–25.

(37) Morgan PB et al. International contact lens prescribing in 2017. *Contact Lens Spectrum* Jan,2018;28-33.

(38) Hutter JC, Green JA, Eydelman MB. Proposed silicone hydrogel contact lens grouping system for lens care product compatibility testing. *Eye and Contact Lens* 2012;*38*(6):358-62.

(39) Weissman BA. et al. *Care of the Contact Lens Patient*. *Optometric Clinical Practice Guideline by AOA*; 2006.
Available at: https://www.aoa.org/documents/optometrists/CPG-19.pdf.
Accessed: 12 Sept 2018

(40) Lira M. Uso de Lentes de Contacto: Deterioração das suas Propriedades e Alterações Fisiológicas Associadas.Tese de doutoramento, Universidade do Minho. 2007.

(41) Schein OD, McNally JJ, Katz J, Chalmers RL, Tielsch JM, Alfonso E, Shovlin J. The incidence of microbial keratitis among wearers of a 30-day silicone hydrogel extended-wear contact lens. *Ophthalmology* 2005;*112*(12):2172-79.

(42) Nicolson PC, Vogt J. Soft contact lens polymers: an evolution. *Biomaterials* 2001;*22*(24): 3273-83.

(43) Gonzalez-Meijome JM. Objective analysis of properties an material degradation in contact lens polymers using different techniques. Tese de Doutoramento, Universidade do Minho 2007.

(44) Maldonado-Codina C, Efron N. Impact of manufacturing technology and material composition on the surface characteristics of hydrogel contact lenses. *Clinical & Experimental Optometry* 2005;*88*(6),396–404.

(45) Pek YS, Wu H, Chow EPY, Ying JY. Transparent nanostructured photochromic UV-blocking soft contact lenses. *Nanomedicine* 2016;*11*(12):1599–1610.

(46) Young G, Hall L, Sulley A, Osborn-Lorenz K, Wolffsohn J. Inter-relationship of soft contact lens diameter, base curve radius, and fit. *Optometry and Vision Science* 2017;*94*(4):458-65.

(47) Edrington, TB. A literature review: the impact of rotational stabilization methods on toric soft contact lens performance. *Contact Lens and Anterior Eye* 2011;*34*(3):104–10.

(48) Moore KE, Benoit JS, Berntsen DA. Spherical Soft Contact Lens Designs and Peripheral Defocus in Myopic Eyes. *Optom Vis Sci* 2017;*94*(3):370-79.

(49) González-Méijome JM, Matos SC, Ribeiro MF, Ferreira DP, Jorge J, Legerton J, Queiros A. Strategies to regulate myopia progression with contact lenses: A review. *Eye and Contact Lens* 2016;*42*(1),24-34.

(50) Li SM, Kang MT, Wu SS, Meng B, Sun YY, Wei SF, Wang N. Studies using concentric ring bifocal and peripheral add multifocal contact lenses to slow myopia progression in school-aged children: a meta-analysis. *Ophthalmic and Physiological Optics* 2017;*37*(1): 51–59.

(51) Bennett ES. Contact lens correction of presbyopia. *Contact Lens and Anterior Eye*, 2009;*32*(4):191-192.

(52) Rathi VM, Mandathara PS, Taneja M, Dumpati S, Sangwan VS. Scleral lens for keratoconus: Technology update. *Clinical Ophthalmology* 2015;*9*:2013-2015.

(53) Pullum KW, Whiting MA, Buckley RJ. The Expanding Role. *Cornea* 2005;*24*(3);269-277.

(54) Yasuda H. Biocompatibility of nanofilm-encapsulated silicone and silicone-hydrogel contact lenses. *Macromolecular Bioscience* 2006;*6*(2):121-138.

(55) Hecht, E. Transmition and Refractive Index. In: *Optics* 3rd ed. F. Gulbenkian Calouste. 2002; 123-136.

(56) Fatt I. Comparative study of some physiologically important properties of six brands of disposable hydrogel contact lenses. *CLAO Journal* 1997;*23*:49-54.

(57) Brennan, NA. A simple instrument for measuring the water content of hydrogel lenses. *Int Contact Lens Clin*, 1983;*10*:357-361.

(58) Nichols JJ, Berntsen DA. The assessment of automated measures of hydrogel contact lens refractive index. *Ophthalmic and Physiological Optics* 2003;*23*(6):517-25.

(59) Morgan PB, Efron N. Hydrogel contact lens ageing. *CLAO Journal* 2000;*26*:85-90.

(60) Lira M, Santos L, Azeredo J, Yebra-Pimentel E, Oliveira ECD. The effect of lens wear on refractive index of conventional hydrogel and silicone-hydrogel contact lenses: A comparative study. *Contact Lens and Anterior Eye* 2008;*31*(2):89-94.

(61) Rosa AL, Martín-Montañez V, López-Miguel A, Fernández I, Calonge M, González-Méijome JM, González-García MJ. Ocular response to environmental variations in contact lens wearers. *Ophthalmic and Physiological Optics* 2017;*37*(1):60–70.

(62) Martín-Montañez, V., Lõpez-Miguel, A., Arroyo, C., Mateo, M. E., González-Méijome, J. M., Calonge, M., & González-García, M. J. (2014). Influence of environmental factors in the in vitro dehydration of hydrogel and silicone hydrogel contact lenses. *Journal of Biomedical Materials Research - Part B Applied Biomaterials*, *102*(4), 764–771.

(63) Alonso M, Finn JE. Reflection and refraction of flats waves. In: *Physics* 1st ed. 2012;695–697.

(64) Okuno E, Caldas I, Chow C. Reflection and Refraction of the light. In: Harbra Ed. *Fisics for biological and biomedical sciences*. São Paulo. 1982;252-54.

(65) Tilley R. The interaction of light with a transparent material. In BL Wiley Ed. *Colour and the optical properties of materials.* Cardiff University. 1999;16-17

(66) American Optometric Association. *UV Protection with Contact Lenses. AOA Website* Available at: https://www.aoa.org/patients-and-public/caring-for-your-vision/uv-protection/uv-protection-with-contact-lenses
Accessed: 28 Sept 2018.

(67) Quesnel NM, Simonet P. Spectral Transmittance of UV-Absorbing Soft and Rigid Gas Permeable Contact Lenses. *Optometry & Vision Science* 1994;*72*(1):2-10.

(68) Walsh JE. Can UV radiation-blocking soft contact lenses attenuate UV radiation to safe levels during summer months in the southern United States? *Eye and Contact Lens*, *29*(2): 135.

(69) Ali BM, Goh EH. Light Transmission through UV Coated Contact Lenses. *Jurnal Sains Kesihatan Malaysia* 2005;*3*(2):1-8.

(70) Rahmani S, Mohammadi M, Akbarzadeh A. Spectral transmittance of UV-blocking soft contact lenses: A comparative study. *Contact Lens and Anterior Eye* 2014;*37*(6):451-54.

(71) Rahmani S, Nia MM, Baghban AA, Nazari M, Ghassemi-Broumand M. Do UV-blocking soft contact lenses meet ANSI Z80.20 criteria for UV transmittance? *Journal of Ophthalmic and Vision Research*, 2015;*10*(4):441-44.

(72) Depry J, Golding R, Szczotka-Flynn L, Dao H, Baron E, Cooper K. UVB-protective properties of contact lenses with intended use in photoresponsive eyelid dermatoses. *Photodermatology Photoimmunology and Photomedicine* 2013;*29*(5):253-260.

(73) Harris M, Minnh D, Garrod S, Walter W. Ultraviolet Transmittance of Contact Lenses. *Optometry and Vision Science*, 1994;*71*(1):1-5.

(74) Harris MG, Chin RS, Lee DS, Tam MH, Dobkins CE. Ultraviolet transmittance of the Vistakon disposable contact lenses. *Contact Lens and Anterior Eye* 2000;*23*(1):10-15.

(75) Moore L, Ferreira JT. Ultraviolet (UV) transmittance characteristics of daily disposable and silicone hydrogel contact lenses. *Contact Lens and Anterior Eye*, 2006;*29*(3):115-122.

(76) Bruce AS, Dain SJ, Holden BA. Spectral transmittance of tinted hydrogel contact lenses. *Optometry and Vision Science*, 1986;*63*(12):941-47.

(77) Lin KK, Lin YC, Lee JS, Chao AN, Chen HSL. Spectral transmission characteristics of spectacle, contact, and intraocular lenses. *Annals of Ophthalmology* 2002;*34*(3):206–15.

(78) Lira M, Coutinho EM, Santos L, Azeredo J, Yebra-Pimentel E, Oliveira MECDR. Changes in UV-visible transmittance of silicone-hydrogel contact lenses induced by wear. *Optometry and Vision Science* 2009;*86*(4):332-39.

(79) Chou B, Cullen A, Dumbleton K. Protection factors of Ultraviolet-blocking contact lenses. *Int Contact Lens Clin* 1988;*11*:106–114.

(80) Lawrenson JG, Hull CC, Downie LE. The effect of blue-light blocking spectacle lenses on visual performance, macular health and the sleep-wake cycle: a systematic review of the literature. *Ophthalmic and Physiological Optics*, 2017;*37*(6):644–654.

(81) Downie LE. Blue-light filtering ophthalmic lenses: to prescribe, or not to prescribe? *Ophthalmic and Physiological Optics* 2017;*37*(6):640-43.

(82) Downie LE, Busija L, Keller PR. Blue-light filtering intraocular lenses (IOLs) for protecting macular health. *Cochrane Database of Systematic Reviews*, *2018*(5):1-173.

(83) Chandler H, Nichols J. UV Protection with Contact Lenses. *Tvci*. *2011;22*(24):3257-60.

(84) Kwok LS, Kuznetsov VA, Ho A, Coroneo MT. Prevention of the adverse photic effects of peripheral light-focusing using UV-blocking contact lenses. *Investigative Ophthalmology and Visual Science* 2003;*44*(4):1501-07.

(85) Kwok LS, Daszynski DC, Kuznetsov VA, Pham T, Ho A, Coroneo MT. Peripheral light focusing as a potential mechanism for phakic dysphotopsia and lens phototoxicity. *Ophthalmic and Physiological Optics* 2004;*24*(2):119-129.

(86) Cruickshanks KJ. Sunlight and Age-Related Macular Degeneration. *Archives of Ophthalmology*, 1993;*111*(4):514.

(87) Morgan PB, Efron N. In Vivo Dehydration of Silicone Hydrogel Contact Lenses 2003;*29*(3): 173-76.

(88) Pereira EI, Lira M. Comfort, Ocular Dryness, and Equilibrium Water Content Changes of Daily Disposable Contact Lenses. *Eye & Contact Lens: Science & Clinical Practice* 2017;*44*:233-240.

(89) González-Méijome JM, López-Alemany A, Almeida JB, Parafita MA, Refojo MF. Qualitative and Quantitative Characterization of the In Vitro Dehydration Process of Hydrogel Contact Lenses. *Journal of Biomedical Materials Research - Part B, Applied Biomaterials* 2007;*83*(2):340-44.

(90) BrennanM NA, Efron N, Truong VT, Watkins RD. Definitions for Hydration Changes of Hydrogel Lenses. *Ophthalmic and Physiological Optics* 1986;*6*(3):333-38.

(91) Efron N, Morgan PB, Cameron IAND, Brennan NA, Goodwin M. Oxygen Permeability and Water Content of Silicone Hydrogel Contact Lens Materials. *Optometry and Vision Science* 2007;*84*(4):328-337.

(92) Gavara, R, Compañ V. Oxygen, water, and sodium chloride transport in soft contact lenses materials. *Journal of Biomedical Materials Research - Part B Applied Biomaterials* 2017;*105*(8):2218-31.

(93) Copper LL. Oxygen permeability of the pigmented material used in cosmetic daily disposable contact lenses. *Clinical Ophthalmology* 2016;*10*:2469-74.

(94) Fatt I. New physiological paradigms to assess the effect of lens oxygen transmissibility on corneal health. *CLAO J*ournal 1996;*22*(1):25-29.

(95) Compañ V, Andrio A, López-Alemany A, Riande E, Refojo MF. Oxygen permeability of hydrogel contact lenses with organosilicon moieties. *Biomaterials* 2002;*23*(13):2767-72.

(96) Brennan NA. Beyond flux: total corneal oxygen consumption as an index of corneal oxygenation during contact lens wear. *Optom Vis Sci.* 2005;*82*(6):467-72.

(97) Lira M, Pereira C, Oliveira MECDR, Coutinho EMSC. Importance of contact lens power and thickness in oxygen transmissibility. *Contact Lens and Anterior Eye* 2015;*38*(2):120-126.

(98) Lee SE, Kim SR, Park M. Oxygen permeability of soft contact lenses in different pH, osmolality and buffering solution. *International Journal of Ophthalmology* 2015;*8*(5): 1037-42.

(99) Lee SE, Kim SR, Park M. Influence of Tear Protein Deposition on the Oxygen Permeability of Soft Contact Lenses. *Journal of Ophthalmology*, *2017*;2017:5131764.

(100)Papas, EB. The significance of oxygen during contact lens wear. *Contact Lens and Anterior Eye* 2014;*37*(6):394-404.

(101)Holden BA, Mertz GW. Critical oxygen levels to avoid corneal edema for daily and extended wear contact lenses. *Investigative Ophthalmology and Visual Science* 1984;*25*(10):1161-67.

(102)Harvitt D, Bonanno J. Re-evaluation of the oxygen diffusion model for predicting minimum contact lens Dk/t values needed to avoid corneal anoxia. *Optometry and Vision Science* 1999;*76*(10):712-19.

(104)Morgan PB, Brennan NA, Maldonado-Codina C, Quhill W, Rashid K, Efron N. Central and peripheral oxygen transmissibility thresholds to avoid corneal swelling during open eye soft contact lens wear. *Journal of Biomedical Materials Research - Part B Applied Biomaterials*, 2010;*92*(2):361-65.

(105)Garrett Q, Chatelier RC, Griesser HJ, Milthorpe BK. Effect of charged groups on the adsorption and penetration of proteins onto and into carboxymethylated poly(HEMA) hydrogels. *Biomaterials*, 1998;*19*(23):2175-86.

(106)Soltys-Robitaille CE, Ammon DM, Valint PL, Grobe GL. The relationship between contact lens surface charge and in-vitro protein deposition levels. *Biomaterials* 2001;22(24):3257-60

(107)Maïssa C, Franklin V, Guillon M. Influence of contact lens material surface characteristics and replacement frequency on protein and lipid deposition. *Optom Vis Sci* 1998;*75*(9): 697-705.

(108)Guillon M, McGrogan L, Guillon JP, Styles E, Maissa C. Effect of material ionicity on the performance of daily disposable contact lenses. *Contact Lens and Anterior Eye* 1997;*20*(1):3-8.

(109)Cabrera JV, Velasco MJG. Recovery of the water content of hydrogel contact lenses after use. *Ophthalmic and Physiological Optics*, 2005:*25*(5):452-57.

(110)Ramamoorthy P, Sinnott LT, Nichols, JJ. Contact lens material characteristics associated with hydrogel lens dehydration. *Ophthalmic and Physiological Optics* 2010;*30*(2):160-66.

(111)Omali NB, Subbaraman LN, Coles-Brennan C, Fadli Z, Jones LW. Biological and Clinical Implications of Lysozyme Deposition on Soft Contact Lenses. *Optometry and Vision Science* 2015:92(7):750-57.

(112)Lin MC, Svitova TF. Contact Lenses Wettability In Vitro : Effect of Surface Active Ingredients. *Optometry and Vision Science* 2010;*87*(6):440-47.

(113)Khang G, Rhee JM, Lee JH, Lee I, Lee HB. Interaction of different types of cells on poly(L-lactide-co-glycolide) surface with wettability chemogradient. *Korea Polymer Journal* 2000;*8*:276-84.

(114)Menzies KL, Jones L. The impact of contact angle on the biocompatibility of biomaterials. *Optometry and Vision Science* 2010;*87*(6):387-99.

(115)Ketelson HA, Meadows DL, Stone RP. Dynamic wettability properties of a soft contact lens hydrogel. *Colloids and Surfaces B: Biointerfaces* 2005;*40*(1):1-9.

(116)Talu S. Characterization of Surface Rouhness of Unworn Hydrogel Contact Lenses at a Nanometric Scale Using Methods of Modern Metrology. *Polymer Engineering and Science* 2014;*54*:1066-80.

(117)Aragona P. Long term treatment with sodium hyaluronate-containing artificial tears reduces ocular surface damage in patients with dry eye. *British Journal of Ophthalmology* 2002;*86*(2):181-84.

(118)Korogiannaki M, Zhang J, Sheardown H. Surface modification of model hydrogel contact lenses with hyaluronic acid via thiol-ene “click” chemistry for enhancing surface characteristics. *Journal of Biomaterials Applications* 2017;*32*(4):446-462.

(119)Tranoudis I, Efron N. Tensile properties of soft contact lens materials. *Contact Lens and Anterior Eye* 2004;*27*(4):177-91.

(120)Boyraz S, Güngör I. The effects of the modulus of the lens material on intraocular pressure measurement through soft contact lenses. *Irish Journal of Medical Science* 2013;*182*(3): 331-35.

(121)Horst CR, Brodland B, Jones LW, Brodland GW. Measuring the modulus of silicone hydrogel contact lenses. *Optometry and Vision Science* 2012;*89*(10):1468-76.

(122)Levey SB, Cohen EJ. Methods of disinfecting contact lenses to avoid corneal disorders. *Survey of Ophthalmology*, 1996;*41*(3):245-51.

(123)Rakow PL. Current contact lens care systems. *Ophthalmology Clinics of North America* 2003;*16*(3):415-32.

(124)Kilvington S, Lonnen J. A comparison of regimen methods for the removal and inactivation of bacteria, fungi and Acanthamoeba from two types of silicone hydrogel lenses. *Contact Lens and Anterior Eye* 2009;*32*(2):73-77.

(125)Lipener C, Ray CBM. Sistemas atuais de cuidados e manutenção de lentes de contato. *Arquivos Brasileiros de Oftalmologia*, 2009;*71*:9-13.

(126)Brennan NA, Coles MLC. Deposits and symptomatology with soft contact lens wear. *International Contact Lens Clinic* 2000;*27*(3):75-99.

(127)Fonn D. Targeting contact lens induced dryness and discomfort: what properties will make lenses more comfortable. *Optometry and Vision Science* 2008;84(4):279-85.

(128)Borazjani RN, Kilvington S. Efficacy of multipurpose solutions against Acanthamoeba species. *Contact Lens and Anterior Eye* 2005;*28*(4):169-75.

(129)Callahan D, Kovacs C, Lynch S, Rah M. Biocidal efficacy of multipurpose solutions against Gram-negative organisms associated with corneal infiltrative events. *Clinical and Experimental Optometry* 2017;*100*(4):357-64.

(130)Lira M, Franco S, Vazquez-Dorrio JB, Oliveira MECDR, Costa MFM. Surface roughness and refractive index changes in contact lens induced by lens care systems. *Eye and Contact Lens* 2014;*40*(3):140-47.

(131)Young G, Garofalo R, Harmer O, Peters S. The effect of soft contact lens care products on lens modulus. *Contact Lens and Anterior Eye* 2010;*33*(5):210-14.

(132)Chiericati S, Borghesi A, Cozza F, Ferraro L, Acciarri M, Farris S, Tavazzi S. Care system versus transmitted light wavefront pattern of contact lenses. *Eye and Contact Lens*, 2017;*43*(3):181-85.

(133)Dalton K, Subbaraman L, Rogers R, Jones L. Physical Properties of Soft Contact Lens Solutions. *Optometry and Vision Science* 2008;*85*(2):122-28.

(134)Keir N, Woods CA, Dumbleton K, Jones. Clinical performance of different care systems with silicone hydrogel contact lenses. *Contact Lens and Anterior Eye* 2010;*33*(4):189-95.

(135)Epstein AB. Contact lens care products effect on corneal sensitivity and patient comfort. *Eye and Contact Lens* 2006;*32*(3):128-32.

(136)Sorbara L, Peterson R, Woods C, Fonn D. Multipurpose disinfecting solutions and their interactions with a silicone hydrogel lens. *Eye and Contact Lens* 2009;*35*(2):92-97.

(137)Fagehi R, Pearce EI, Oliver K, Abusharha AA, Tomlinson A. Care solution effects on contact lens in vivo wettability. *Clinical and Experimental Optometry* 2017;*100*(6):623-32.

(138)Kackar S, Suman E, Katian S. Bacterial and Fungal Biofilm formation on Contact Lenses and their Susceptibility to Lens Care Solutions. *Indian Journal Med Microbiol* 2017;*35*: 80-84.

(139)McLaughlin-Borlace L, Stapleton F, Matheson M, Dart JKG. Bacterial biofilm on contact lenses and lens storage cases in wearers with microbial keratitis. *Journal of Applied Microbiology* 1998;*84*(5):827-38.

(140)Pucker AD, Thangavelu M, Nichols JJ. In vitro lipid deposition on hydrogel and silicone hydrogel contact lenses. *Investigative Ophthalmology and Visual Science* 2010;*51*(12): 6334-40.

(141)Boost M, Lai S, Ma C, Cho. Do multipurpose contact lens disinfecting solutions work effectively against non-FDA/ISO recommended strains of bacteria and fungi? *Ophthalmic and Physiological Optics* 2010;*30*(1):12-19.

(142)Muntz A, Subbaraman LN, Sorbara L, Jones. Tear exchange and contact lenses: A review. *Journal of Optometry* 2015;*8*(1):2-11.

(143)Stapleton F, Stretton S, Papas E, Skotnitsky C, Sweeney DF. Silicone hydrogel contact lenses and the ocular surface. *Ocular Surface* 2006;*4*(1):24-43.

(144)Dutot M, Reveneau E, Pauloin T, Fagon R, Tanter C, Warnet JM, Rat P. Multipurpose solutions and contact lens: Modulation of cytotoxicity and apoptosis on the ocular surface. *Cornea* 2010;*29*(5):541-49.

(145)Andrasko G, Ryen. Corneal staining and comfort observed with traditional and silicone hydrogel lenses and multipurpose solution combinations. *Optometry* 2008;*79*(8):444-54.

(146)Carnt NA. Contact Lens–Related Adverse Events and the Silicone Hydrogel Lenses and Daily Wear Care System Used. *Archives of Ophthalmology* 2009;*127*(12):1616.

(147)Willcox MDP, Phillips B, Ozkan J, Jalbert I, Meagher L, Gengenbach T, Papas E. Interactions of lens care with silicone hydrogel lenses and effect on comfort. *Optometry and Vision Science* 2010;*87*(11):839-46.

(148)Guillon M, Maissa C, Wong S, Patel T, Garofalo R. The influence of lens care systems on eyelid tissue changes during silicone hydrogel contact lens wear. *Contact Lens and Anterior Eye* 2018;*41*(4):362-68.

(149)Efron N. Current and Future Controversies in Contact Lenses. *Contact Lens Spectrum Jun 2018*;28-34.

(150)Clayton JA. Dry eye. *The New England Journal of Medicine*, 2018;378:2212-23.

(151)Craig JP, Nelson JD, Azar DT, Belmonte C, Bron AJ, Chauhan SK, Sullivan DA. TFOS DEWS II Report Executive Summary. *Ocular Surface* 2007;*15*(4):802-12.

(152)Lemp MA, Baudouin C, Baum J, Dogru M, Foulks GN, Kinoshita S, Toda I. The Definition and Classification of Dry Eye Disease: Report of the Definition and Classification Subcommittee of the International Dry Eye WorkShop. *The Ocular Surface* 2007;*5*(2):75-92.

(153)Zhao Z, Wei X, Aliwarga Y, Carnt NA. Garrett Q, Willcox MDP. Proteomic analysis of protein deposits on worn daily wear silicone hydrogel contact lenses. *Molecular Vision* 2008;*14*:2016-24.

(154)Fuentes R, Fernández E, Pascual I, García C. UV-visible transmittance of silicone-hydrogel contact lenses measured with a fiber optic spectrometer. 8th Iberoamerican Optics Meeting and 11th Latin American Meeting on Optics, Lasers, and Applications 2013; *8785*.

(155)Ogbuehi KC, Khan FMJ, Alanazi SA, Almubrad TM, Osuagwu UL. Transmittance Properties of Contact Lens Multipurpose Solutions and Their Effects on a Hydrogel Lens. *Annual Research & Reviee in Biology* 2014;*4*(15): 2484-2500.

(156)Owen T. In: A. Technologies Ed., *Fundamentals of Modern UV-visible Spectroscpy*. 2000.

(157)Martinho JMG. Absorption spectroscopy in the ultraviolet and visible. In *Chemistry* 1994(52):44-48.

(158)Shanker N, Bane SL. Basic aspects of absorption and fluorescence spectroscopy and resonance energy transfer methods. In *Methods in Cell Biology* 2008(84):213-42.

(159)Shashkova S, Leake MC. Single-molecule fluorescence microscopy review: shedding new light on old problems. *Bioscience Reports* 2017;*37*:1-19.

(160)Marín G. Variação da transmitância, refletância e índice de refração das lentes: influência da potência e material das lentes. Universidade do Minho, *Uminho repository* 2017.

(161)ISO. ISO 10640 Plastics-Methodology for assessing polymer photoageing by FTIR and UV/visible spectroscopy. 2011.

(162)Quesnel N et al. Effect of back vertex power on transmittance of contact lenses with UV protection. *Poster: AAO meeting* 2005. San Diego.

(163)Sekar P, Dixon PJ, Chauhan A. Pigmented contact lenses for managing ocular disorders. *International Journal of Pharmaceutics* 2019;555:184-97.

(164)Silva AR. Lentes de Contacto e Líquidos de Manutenção: alterações na humectabilidade. Universidade do Minho, *Uminho repository* 2015.

(165)Singh A, Li P, Beachley V, McDonnell P, Elisseeff JH. A hyaluronic acid-binding contact lens with enhanced water retention. *Contact Lens and Anterior Eye* 2015;*38*(2):79-84.

(166)Rah MJ. A review of hyaluronan and its ophthalmic applications. *Optometry* 2011;*82*(1): 38-43.

(167)Giasson CJ, Djouahra S, Sauvageau P, Bioinge LD. Biocompatibility and Light Transmission of Lipossomal Lenses. *Optometry and Vision Science* 2007;*84*(10):954-61.

(168)Alvarez-Lorenzo C, Rey-Rico A, Sosnik A, Taboada P, Concheiro A. Poloxamine-based nanomaterials for drug delivery. *Frontiers in Bioscience* 2010;*2*(2):424-40.

(169)Song G, Lin Y, Zhu Z, Zheng H, Qiao J, He C, Wang H. Strong fluorescence of poly (N-vinylpyrrolidone) and its oxidized hydrolyzate. *Macromolecular Rapid Communications* 2015;*36*(3):278-85.

(170)Birt B, Cowling I, Coyne S. UVR reflections at the surface of the eye. *Journal of Photochemistry and Photobiology B: Biology* 2005;*77*:71-77.

(171)Horner IJ, Kraut ND, Hurst JJ, Rook AM, Collado CM, Atilla-Gokcumen GE, Bright FV. Effects of Polyhexamethylene Biguanide and Polyquaternium-1 on Phospholipid Bilayer Structure and Dynamics. *Journal of Physical Chemistry B* 2015;*119*(33):10531-42.

(172)Paimela, T., Ryhanen, T., Kauppinen, A., Marttila, L., Salminen, A., & Kaarniranta, K. (2012). The preservative polyquaternium-1 increases cytoxicity and NF-kappaB linked inflammation in human corneal epithelial cells. *Mol Vis*, *18*(March), 1189–1196.

(173)Lievens CW, Hakim N, Chinn. The effect of multipurpose solutions on the ocular surface. *Eye and Contact Lens* 2006;*32*(1):8-11.

(174)Pritchard N, Young G, Coleman S, Hunt C. Subjective and objective measures of corneal staining related to multipurpose care systems. *Contact Lens and Anterior Eye* 2003:*26*(1): 3-9.

(175)Andrasko GJ, Ryen KA, Garofalo RJ, Lemp JM. Ocular Response Observed with Silicone Hydrogel Lenses and Multi-Purpose Solution Combinations, *AOA* 2006;*1*.

(176)Garofalo RJ, Dassanayake N, Carey C, Stein J, Stone R, David R. Corneal staining and subjective symptoms with multipurpose solutions as a function of time. *Eye and Contact Lens* 2005;*31*(4):166-74.

(177)Kuc CJ, Lebow KA. Contact Lens Solutions and Contact Lens Discomfort. *Eye & Contact Lens: Science & Clinical Practice* 2018;*44(6):355-66.*