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Low-cost method for manufacturing self-adherent PDMS lenses for presbyopia

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A R T I C L E I N F O

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A B S T R A C T

We present an easy method for manufacturing elastomeric self-adherent lenses with optical quality. The lenses were manufactured in polydimethylsiloxane using ophthalmic and trial lenses of different base curve as master molds to generate different refractive powers. The diameter of the manufactured lenses ranged between 30 mm and 60 mm. We characterized the lenses alone and after being self-adhered to different spherocylindrical ophthalmic lenses, by measuring the refractive power and the Zernike aberrations. Besides, an artificial myopic eye was used to quantify the image quality provided by the lenses self-adhered to several ophthalmic lens. The manufactured lenses showed good optical quality with no aberrations. Low order refractive errors were found in one case after self-adhesion. The results confirm the suitability and simplicity of the proposed method to manufacture high quality elastomeric lenses that can be self-adhered to ophthalmic lenses to add power and help with presbyopia.

1. Introduction

Eventually, presbyopia will arrive at our lives, affecting well-being at different levels. The reduction of the magnitude of accommodation is a progressive process that starts in the childhood and continues silently up to the middle forties, near fifties, were accommodation demand is higher than the one offered by our eyes. At that moment we need help, we need an "add", a plus lens to compensate the lack of accommodation. Nowadays we have different alternatives: reading spectacles; bifocals; progressive lenses; multifocal contact lenses; and even refractive surgery [1].

However, these solutions cost money, so developing presbyopes look for temporary cost-effective solutions that helps them in near visual tasks without the nuisance of being changing spectacles from far to near vision, or changing corrections faster than desired. One solution that fulfills these requirements are lenses that can be adhered to ophthalmic lenses to compensate the lack of accommodation at near visual tasks.

In the market it can be found an example of these lenses, Hydrotac stick on bifocals, manufactured by the company Optx 20/20. These lenses are made of a transparent rubber that adhere to the lens due to slight pressure and a few drops of water. So, the lenses can be sticked on or peeled off easily without damaging the ophthalmic lens.

During the revision of the current state of the art, we found few works in relation with the development and use of self-adherent lenses with ophthalmic purposes. In fact, they were mainly patents describing different applications and methods. Thus, in patent US3904281A [2] the author describes the use and fabrication of Jampolsky prisms (which are not lenses but optical elements used to deviate the apparent position of an object). This prism is used for correcting strabismus or phorias. They consist of Fresnel prisms manufactured in flexible membranes that adhere to the ophthalmic lens by applying pressure. The second document is patent US5478824A [3]. In this document, Burns and Bernheiser describe the use of an adherent thermoplastic rubber for changing the refractive power of ophthalmic lenses. In patent US2511329A [4], Edward proposes the use of tinted adhesive films to reduce glare. Finally, in Patent US 2018/0259794A1 [5], Arieli, Engler and Erlichman propose the use of an optical film adherend to an ophthalmic lens to get a progressive ophthalmic correction.

So, there are few documents on self-adherent lenses for ophthalmic applications. Furthermore, we could not find any work analyzing the

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Table 1
Anterior and posterior surface power of the potential molds, and expected power of the PDMS lenses.

	Anterior Surface Power (D)	Posterior Surface Power (D)	Expected Power PDMS (D)
Ophthalmic Lenses			
L1	4.50	−3.50	2.83
L2	4.75	−5.00	4.05
L3	8.00	−2.75	2.23
L4	−3.00	−10.00	8.10
L5	−3.00	−10.00	8.10
L6	1.25	−14.75	11.94
L7	1.50	−14.75	11.94
L8	−3.00	−10.00	8.10
L9	8.50	−3.00	2.43
L10	−2.00	−7.50	6.07
L11	−2.00	−7.75	6.28
L12	−2.25	−7.25	5.87
L13	8.00	−2.75	2.23
L14	3.50	−6.75	5.47
L15	2.25	−8.25	6.68
L16	1.50	−10.25	8.30
L17	3.00	−6.00	4.86
L18	−0.25	−9.00	7.29
L19	4.00	−5.00	4.05
L20	4.75	−5.00	4.05
L21	0.00	0.00	
L22	3.75	3.75	
Trial Lenses			
TL1	−1.00	−1.00	0.81
TL2	−2.00	−2.00	1.62
TL3	−3.00	−3.00	2.43
TL4	−4.00	−4.00	3.25
Hydrotac*	3.00	−2.00	

Table 2
Refractive power of the ophthalmic lenses used as molds; refractive power of the posterior surface; expected and measured power of the manufactured lenses. All the values are in D. TL = Trial Lens; L = ophthalmic Lens.

Lens	Power (D)	Posterior Surface Power (D)	Expected Power PDMS (D)	Measured Power PDMS (D)
L1	1.75	−3.50	2.84	2.75
L2	0.25	−5.00	4.06	4
L3	6.00	−2.75	2.23	2
TL1	−1.00	−1.00	0.81	0.75
TL2	−2.00	−2.00	1.62	1.5
TL3	−3.00	−3.00	2.43	2.25
TL4	−4.00	−4.00	3.25	3

optical performance of this kind of lenses, their aberrations before and after being adhered to the ophthalmic lenses and examples of the image quality provided by them.

One of the materials of choice used in optical application and for the manufacture of components for biomedical purposes is Polydimethylsiloxane (PDMS). PDMS is a silicone elastomer chemically inert, non-toxic, thermally stable, durable, optically transparent, gas permeable and impermeable to water, and easy to handle and manipulate [6,7]. PDMS presents good optical and mechanical properties that depends highly on the mixture ratio (proportion of curing agent vs polymer), and curing temperature and time [8,9]. For example, PDMS refractive index can be changed in the range between 1.408 and 1.445 by changing the catalyser concentration between 1 and 2 and the curing temperature 100 °C to 200 °C. This range of parameters provide a change in the tensile and compressive modulus of 0.94–1.83 MPa and 2.50–3.78 Mpa respectively [9]. PDMS maintains their properties in the range of temperatures of −45 °C to 200 °C [10]. For the most commonly used mixture proportion (base:catalyst) of 10:1, the Abbe number is 44.54 (curing temperature and time of 60 °C and 4 h, respectively) [11].

Regarding the process used to manufacture PDMS lenses, we have found few works that describe diverse methods. However, they are centered on manufacturing small lenses for microscopy or arrays of microlenses. The work of Karunakaran et al. in 2018 proposed a method for fabricating miniature lenses for smartphones or handheld microscopes based on the generation of a plano-convex lens by releasing PDMS over glycerol, so the curvature of the meniscus can be adjusted by playing with the hydrostatic pressure in the glycerol [12]. In 2014, Lee

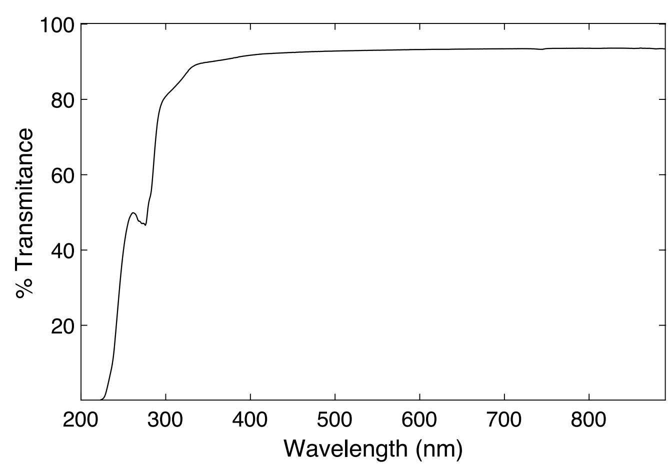

Fig. 2. Optical transmission spectra of the thermally treated PDMS sheet.

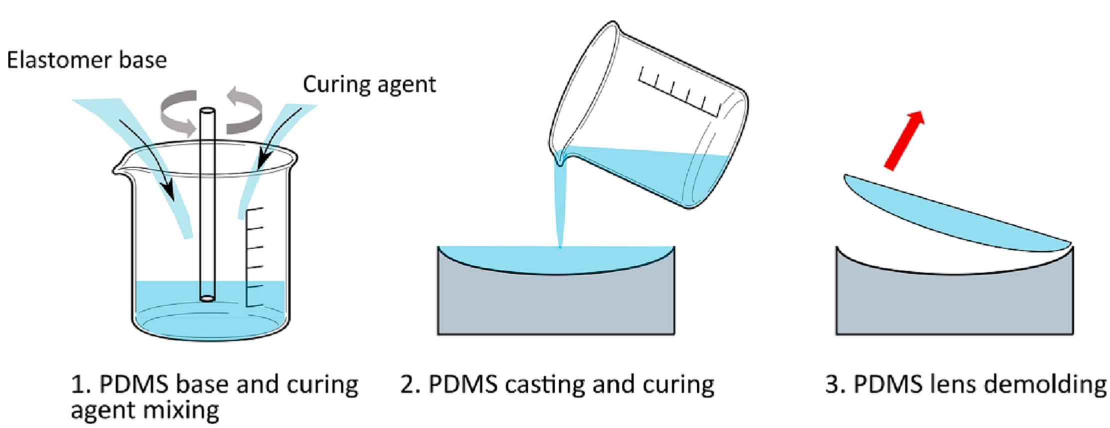

Fig. 1. Fabrication procedure of PDMS lenses. (a) Mixing of the PDMS and the curing agent (10:1); (b) the PDMS precursor is casted on the mold lens; (c) demolding of the resulting PDMS lens.

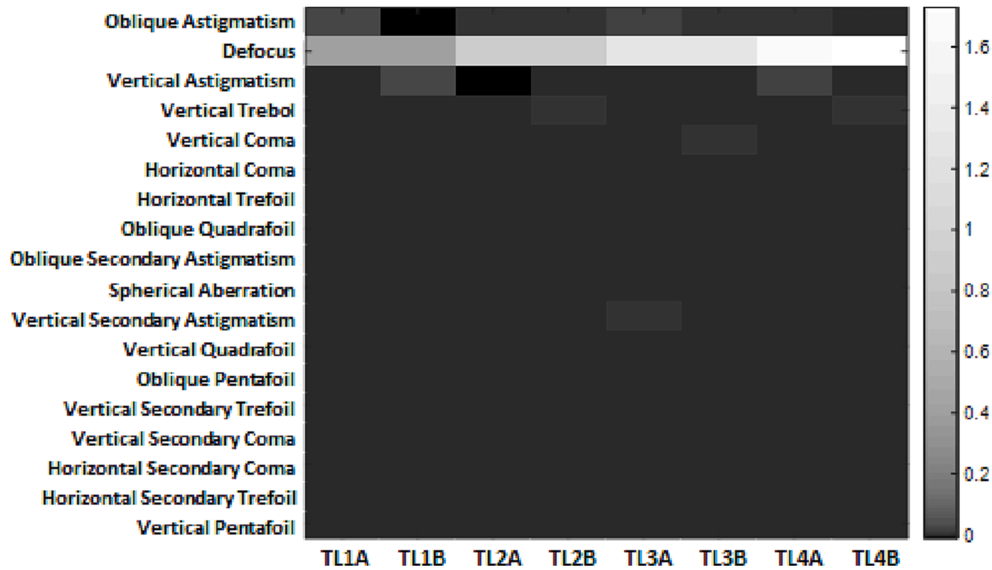

Fig. 3. Aberrometric data of the lenses manufactured with trial lenses as molds. Measurements performed at 4 mm pupil size.

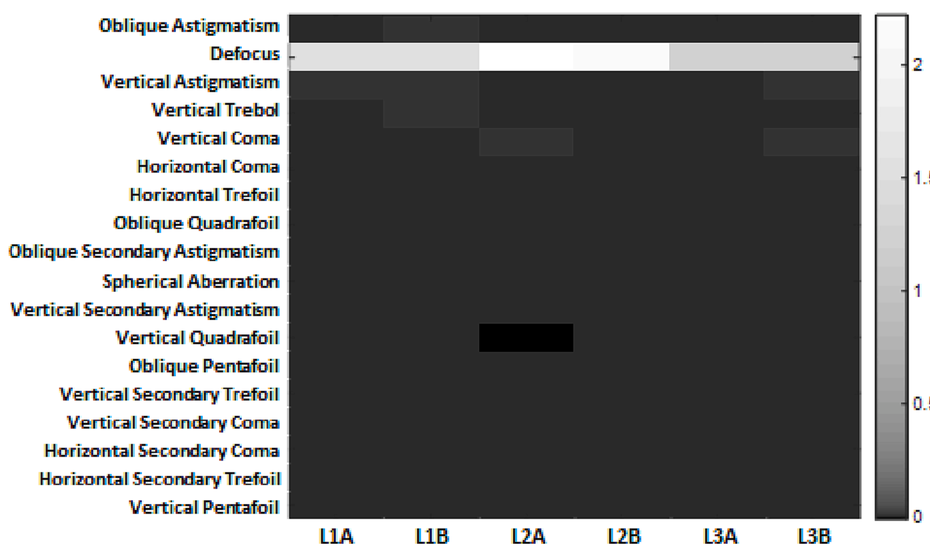

Fig. 4. Aberrometric data of the lenses manufactured with ophthalmic lenses as molds. Measurements performed at 4 mm pupil size.

Table 3
Power vector and spherocylindrical data of the lenses manufactured with trial lenses as molds.

Pupil = 4 mm	Units: mm								
Power Vectors	**M**	0.70	0.72	1.50	1.52	2.25	2.21	2.95	3.00
	J0	−0.02	0.02	−0.01	0.00	−0.03	0.01	0.02	0.00
	J45	0.04	−0.03	0.01	0.01	0.04	0.01	0.01	0.00
Spherocylindrical notation	**Sphere**	0,75	0.75	1.52	1.54	2.30	2.22	2.97	2.99
	Cylinder	−0,09	−0.07	−0.03	−0.03	−0.10	−0.02	−0.04	−0.01
	Axis	–	–	–	–	–	–	–	–

et al. proposed the deposition of droplets over a transparent substrate [13]. The curvature of the lens is adjusted by adding droplets and inversion of the slide. In 2013, Liebetraut et al. showed how to obtain an elastomeric lens with tunable astigmatism [14]. They use as mold a planoconcave optical lens of one inch of diameter. Then they put the lens in a holder with a six stretching arms in a hexagonal arrangement to introduce the different magnitudes and orientation of astigmatism. However, none of these works are dedicated to obtaining self-adherent lenses for changing the refractive power of ophthalmic lenses.

In our work we present a new alternative to correct presbyopia by taking advantage of the optical and mechanical characteristics of PDMS to manufacture positive power self-adherent lenses using the back side of ophthalmic lenses and trial lenses as master molds. The manufactured lenses will have a convex front face and a flat back face that will self-adhere thanks to Van der Waals force and little pressure made by hand, to the front face of the lens worn by the subject. We will show a

Table 4
Power vector and spherocylindrical dataof the lenses manufactured with ophthalmic lenses as molds.

Pupil = 4 mm	Units: D						
		L1A	**L1B**	**L2A**	**L2B**	**L3A**	**L3B**
Power Vectors	**M**	2.63	2.66	3.86	3.82	2.10	2.12
	J0	0.01	0.02	−0.01	−0.01	0.00	0.02
	J45	0.00	0.00	0.00	0.00	0.01	−0.01
Spherocylindrical notation	**Sphere**	2.64	2.68	3.87	3.83	2.11	2.14
	Cylinder	−0.03	−0.05	−0.02	−0.02	−0.01	−0.04
	Axis	–	–	–	–	–	–

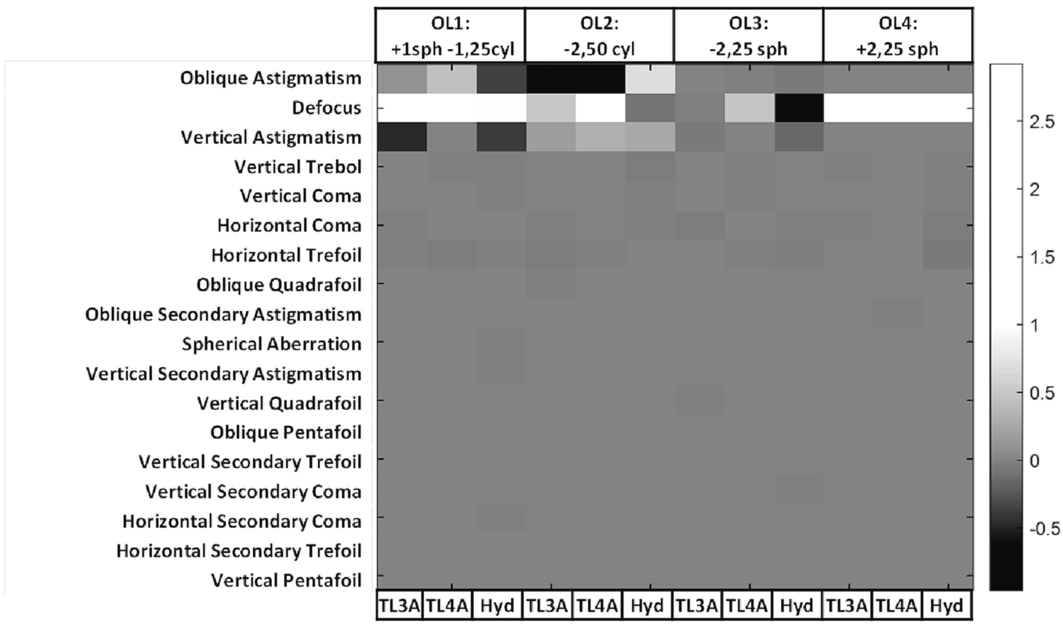

Fig. 5. Wavefront aberrations of the system formed by the PDMS lenses self-adhered to ophthalmic lenses with different spherocylindrical power. Measurements performed at 4 mm pupil size.

simple and reliable manufacturing process in combination with an analysis of the optical performance of the manufactured lenses, and one commercially available adherent lens. The lenses were manufactured for correcting presbyopia, although they can be used just as magnifiers that can be hold at the spectacles of the user. Optical analysis was performed by measuring refractive power and optical aberrations with a focimeter and a Hartmann-Shack aberrometer. In addition, we tested the image quality using an artificial eye. We will show that the manufactured lenses present good optical quality in terms of aberrations and image quality. Moreover, the obtained lenses are easy to stick on the wearer's spectacle, as well as easy to peel off, allowing them to be worn when addition is needed for near vision tasks and easily removed when desired.

2. Materials and method

2.1. Materials

In this work we used the following material for fabricating the PDMS self-adherent lenses:

- Ophthalmic lenses: we used the lenses as master molds to shape the PDMS, and as substrates for adhering the elastomeric lenses. We started with twenty-two ophthalmic lenses (see Table 1 for details) from which we selected 3 to use as molds. Four ophthalmic lenses were selected for self-adhesion of the PDMS lenses: OL1: +1 sph −1.25 cyl; OL2: −2.50 cyl; OL3: −2.25 sph; OL4: +2.25 sph.
- Trial lenses: we used concave trial lenses TL1, TL2, TL3, TL4 for molding the PDMS lenses (see Table 1 for details).
- Spherometer: we used this instrument to measure the refractive power of the anterior and posterior surfaces of the ophthalmic and trial lenses. The measurement is given in diopters (D).
- Polydimethylsiloxane (Sylgard 184, Dow Chemical Company, Midland, Michigan) [10]: we used the PDMS for manufacturing the elastomeric lenses
- Vacuum chamber (Trinos Vacum): this equipment was used for degassing the PDMS after mixing the curing agent and the polymer.
- Furnace (Nannetti S.R.L., Faenza RA, Italia): the furnace was used to heat cure the PDMS.

In Table 1 we present the refractive power of the anterior and posterior surfaces of the potential molds, measured with the spherometer, and the expected power of the PDMS manufactured using the posterior surface. The expected power of the manufactured lenses was calculated by adjusting the refractive power provided by the spherometer (calibrated for a refractive index of 1.53) to the refractive index of the PDMS and considering that the lenses are going to be plano-convex.

2.2. PDMS lenses fabrication

PDMS was prepared from commercial Sylgard 184 elastomer [10]. It is supplied as a two-parts liquid system consisting on a prepolymer base and cross-linking agent that, when mixed, is curable at either room temperature or higher temperatures. For this work, the PDMS precursor

Table 5
Power vector and spherocylindrical power of the PDMS lenses self-adhered to different ophthalmic lenses.

	OL1: +1sph −1.25cyl		
	TL3A (+2.25 D)	TL4A (+3 D)	Hyd (+1.25 D)
M	2.48	3.15	1.83
J0	−0.56	0.04	−0.39
J45	0.11	0.54	−0.41
Sphere	3.05	3.70	2.40
Cylinder	−1.14	−1.09	−1.13
	OL2: −2.50 cyl		
	TL3A (+2.25 D)	TL4A (+3 D)	Hyd (+1.25 D)
M	0.87	1.75	−0.17
J0	0.21	0.37	0.32
J45	−0.96	−1.18	0.85
Sphere	1.85	2.99	1.52
Cylinder	−1.97	−2.48	−1.81
	OL3: −2.25 sph		
	TL3A (+2.25 D)	TL4A (+3 D)	Hyd (+1.25 D)
M	−0.07	0.80	−1.08
J0	−0.06	0.01	−0.17
J45	0.03	−0.02	−0.05
Sphere	−0.01	0.82	−0.91
Cylinder	−0.13	−0.04	−0.35
	OL4: +2.25 sph		
	TL3A (+2.25 D)	TL4A (+3 D)	Hyd (+1.25 D)
M	4.29	5.04	3.55
J0	0.03	0.04	0.01
J45	0.01	0.04	−0.01
Sphere	4.32	5.10	3.56
Cylinder	−0.06	−0.11	−0.03

Fig. 6. Picture of spectacles with: PDMS lens (top); Hydrotac lenses (center). adhered to ophthalmic lenses; and full-frame PDMS lens (bottom).

synthesis was done following supplier's recommendations. Thus, all PDMS samples were obtained by mixing the PDMS base and crosslinking agent at a weight ratio of 10:1 and stirred uniformly.

A set of different lenses were replicated using the commercial lenses described in Table 2 as molds. The PDMS precursor was casted in the posterior surface of the lenses and introduced in a vacuum chamber to remove air bubbles produced during the mixing process. Upon degassing, the PDMS deposited over the mold was cured in the furnace at 60 °C for 12 h. The PDMS lens was then cooled down to room temperature and demolded from the master lens. The production process is illustrated in Fig. 1.

We manufactured two replicas of each of the selected molds to evaluate the reliability of the procedure.

2.3. *Samples characterization*

The optical characterization of the lenses comprised the following measurements: Transmission spectrum; Refractive index and Abbe number; Optical aberrations; Refractive power; and Expected visual quality.

The transmission spectrum was measured with a UV/Vis spectrometer (PerkinElmer Lambda 25 UV/Vis Spectrophotometer, PerkinElmer Inc., Waltham, Massachusetts). The refractive index and the Abbe number were measured with the Abbe refractometer 2WAJ, using a 300 µm thickness film of PDMS manufactured with the same protocol and proportions used to manufacture the self-adherent lenses.

The optical aberrations were measured with a Hartmann-Shack wavefront sensor (Thorlabs WFS30-14AR, Thorlabs GmbH). This wavefront sensor was used to measure the aberrations of the lenses, and the aberrations of the system composed by the ophthalmic lens and the PDMS lens after self-adhesion. The wavefront sensor provides the aberrometric characterization in terms of Zernike polynomials (mm), spherocylindrical power (D), and power vectors [15,16] (mm). The Refractive power (D) was also measured with a focimeter, which provides the spherocylindrical refractive power of the ophthalmic and trial lenses [17].

The expected visual quality was evaluated objectively using an artificial eye consisting of a CCD camera (DCC1645C, Thorlabs GmbH), a plano-convex lens of 25.4 m focal length and a variable iris at 4 mm of diameter, both elements from Thorlabs GmbH. Far and near vision optotypes, comprising different lines of letters of decreasing angular size, in the range of visual acuities (VA) between 0 logMar and 0.4 logMar.

3. Results and discussion

Fig. 2 shows the transmittance spectra of a representative PDMS sheet of 1.7 mm thick. PDMS is highly transparent from the UV to the NIR spectral region with a very flat behavior in the visual region. This property is remarkably interesting from the visual point of view, providing a good light transmission without altering the color of the objects.

The measured refractive index and the Abbe number of the PDMS provided by the Abbe refractometer were $n_D = 1.4226$ (at 589 nm) and $v_D = 43.77$. We want to emphasize that the sample was manufactured with a weight ratio of 10:1, and cured at 60 °C during 12 h. Different proportions, temperature or curing time will produce different refractive index and Abbe number.

Table 2 collects the refractive power of the ophthalmic lenses used as molds, the curvature of the posterior surface, and the expected and measured power of the PDMS lenses. All the values are given in D. We approximated the value to a quarter of D.

In Figs. 3 and 4 we present the aberrometric information (measured over a pupil of 4 mm diameter) of the lenses manufactured using two kind of molds: trial lenses (Fig. 3); and ophthalmic lenses (Fig. 4). Each mold was used to manufacture 2 replicas (for example TL1A and TL1B).

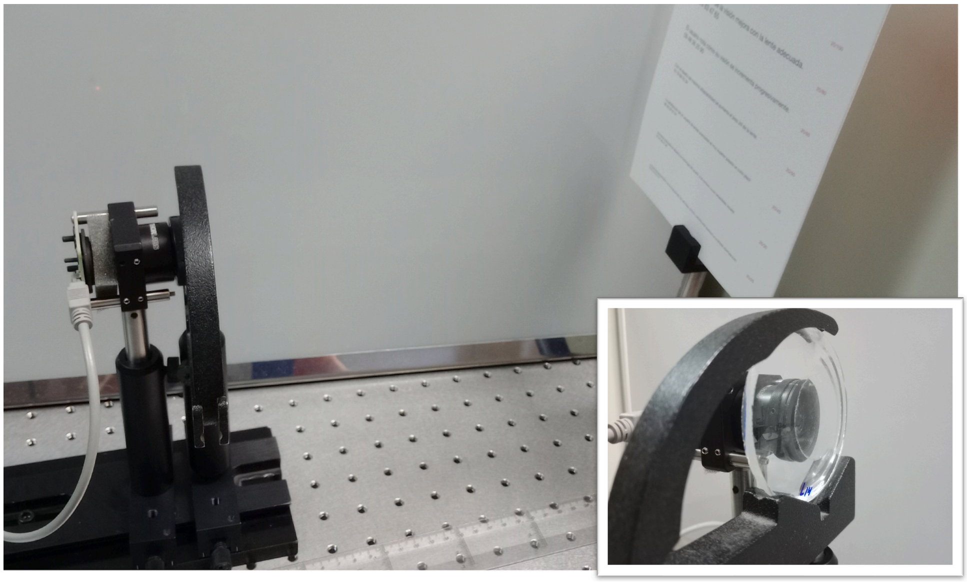

Fig. 7. Experimental setup for assessing the performance of the lenses with an artificial eye with the near vision optotype.

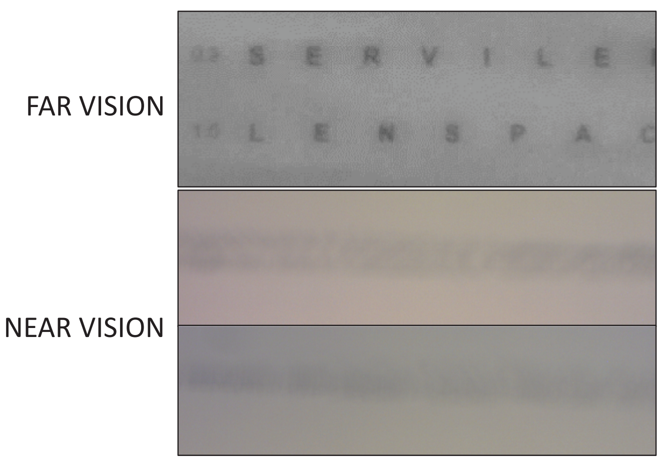

Fig. 8. Images of the letters of 0.00 logMar and 0.1 logMar at far; and 0.17 logMar and 0.10 logMar at near vision. Images obtained after correcting the myopic eye with an ophthalmic lens of −3 D.

The Zernike notation provides information on the low and high order aberrations, reporting (if present) the existence of coma, trefoil, or spherical aberration. The data used to create Fig. 3 and Fig. 4 is included in Appendix I in Tables A1 and A2.

Figs. 3 and 4 show that the manufactured lenses have good optical quality in terms of Zernike aberrations. They present negligible values of astigmatism, coma, trefoil, spherical aberration and quadrafoil or pentafoil. The defocus is the only term that presents meaningful values. The replicas manufactured with each mold show remarkably close aberrometric data, demonstrating the reproducibility of the process independently on the refractive power.

Tables 3 and 4 provide the back vertex power of the lenses, manufactured with the two kinds of molds, in two notations: power vectors (M, J0, J45); and Spherocylindrical notation. Power vector and spherocylindrical notation are calculated from the Zernike expansion, but we consider useful to include this data to have a quick overview of the refractive power of the manufactured elements.

Although the manufacturing process shows such a good result, the lenses are fabricated for being sticked on ophthalmic lenses to provide the addition needed for reading or near work vision. So, we measured the aberrations of the system formed by the PDMS lenses self-adhered to ophthalmic lenses with different spherocylindrical power. Fig. 5 presents the measured aberrations. TL3 and TL4 correspond to the PDMS lenses manufactured with trial lens of −3 D and −4 D, while Hyd corresponds to the commercial lens Hydrotac (+1.25 D). OL1 to OL4 corresponds to 4 different ophthalmic lenses where we self-adhered the PDMS and Hydrotac lenses. The data used to create Fig. 5 is included in Appendix I at Table A3.

In Table 5, the refractive power of the PDMS lens self-adhered to ophthalmic lenses OL1 to OL4 in terms of Power Vectors and spherocylindrical notation is shown. PDMS lenses provide an increase in the spherical refractive power. In the case of OL1, OL3 and OL4, PDMS lenses induce negligible amounts of astigmatism. The error obtained after adhering the PDMS lenses to these lenses is less than 0.12 D which is the maximum power error admitted in the norm that regulates the ophthalmic lens manufacturing [18]. If we compare our PDMS lenses with the performance of commercially available lenses (Hydrotac lenses) we see that although the add power of the commercial lens is + 1.25 D the induced astigmatism is higher than the one induced by our lenses. In the case of OL2 the data shows that Hydrotac lenses induced an astigmatism error of 0.6 D, and PDMS lens TL3A 0.53D of astigmatism. With OL2 the induced error is significantly higher than that allowed by the norm. Considered all the data in Table 5, we think that the astigmatism induced by TL3A in the case of OL2 and the Hydrotac lens with OL3 must be caused by a wrong adhesion of the self-adhered lenses. Lens OL2 presents cylindrical power of −2.50 cyl, so at first sight this condition might direct the explanation to the error induced by the PDMS lens to a wrong adhesion induced by the toric surface of the ophthalmic lens. However, the front surface of ophthalmic lenses is spherical (as in OL2), inducing the astigmatic correction in the back surface of the lens. This question, in addition to the good result obtained with TLA4, points to a wrong adhesion of TLA3 to OL2 as the source of the astigmatic error in this case.

In Fig. 6 we show a picture with three different adherent lenses: one with the PDMS self-adherent lens (top); one with the Hydrotac lenses (center); and one with a full-frame PDMS lens to be cut to cover the ophthalmic lens completely. The picture shows how these lenses are sticked on the ophthalmic lenses, and their optical transparency. The Hydrotac lens, is a commercial lens to by sticked on to create a bifocal spectacle. Our lenses are bigger, providing a wider field of view. However, we can create a segment equal to the Hydrotac just by cutting the PDMS lens with a scissors. The PDMS lens at the bottom covers all the

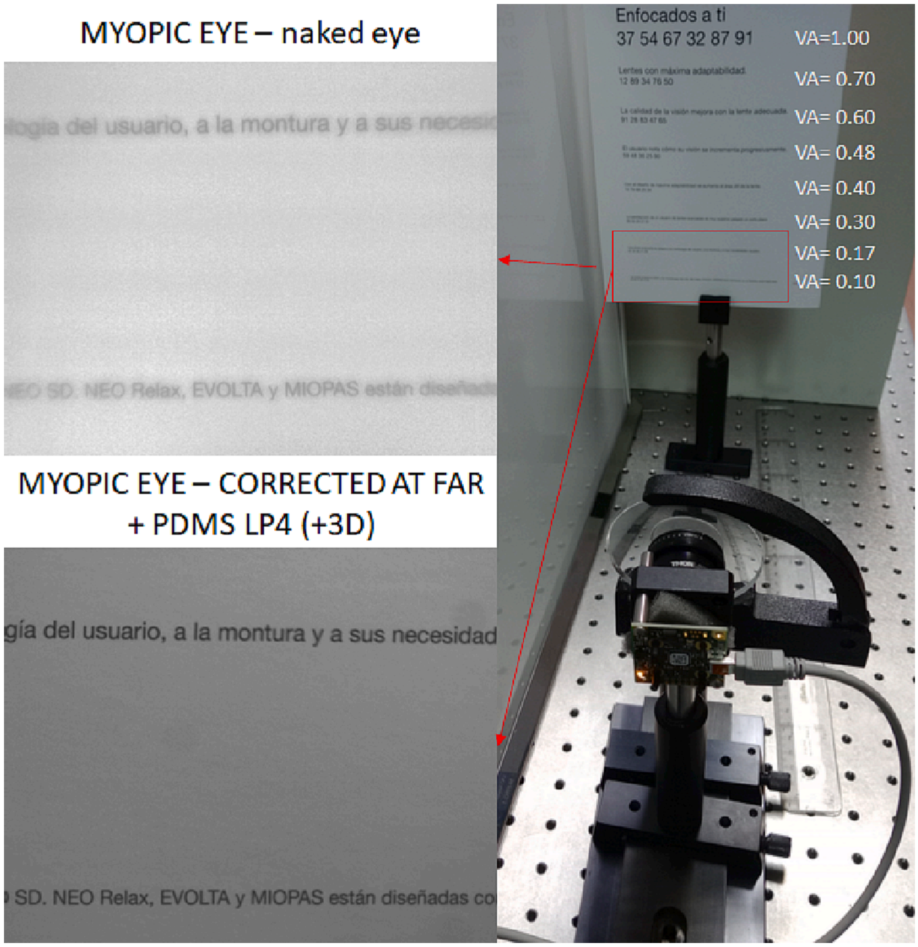

Fig. 9. Images at near (optotype at 0.30 m) with the naked (top-left) and with adherent lens TL4A (+3 D) attached to the myopic correction of −3 D (bottom-left).

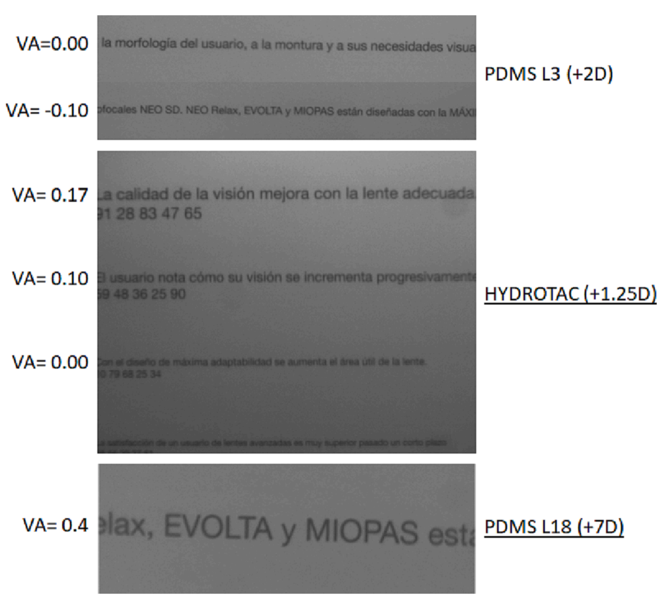

Fig. 10. Images at near with the + 2 D adherent lens L3A. Hydrotac lens and L18 lens with + 7 D, attached to the myopic correction of −3 D (button). The near test was placed at the corresponding distances (0.50 m, 0.75 m and 0.14 m respectively). VA: visual acuity.

ophthalmic spectacle. It can be cut with the shape of the frame providing a good aesthetic aspect and an increased field of view in comparison with the smaller PDMS and Hydrotac lenses.

In addition to the aberrometric characterization of the lenses, we assessed the performance of the self-adherent lenses with an artificial eye. This eye consisted of a CCD color camera (acting as the retina), a plano-convex lens of 25.4 mm focal length and a variable iris at 4 mm size. In Fig. 7 we show the setup with the artificial eye; the ophthalmic lens used for myopic correction; and the near vision test.

We used two optotypes, one for distance (6 m) and other for near work. We built an artificial eye to mimic a myopic eye with refractive error of −3 D, that was corrected at far with an ophthalmic lens of −3 D. In Fig. 8 we show the images of the letters of 0.10 logMar and 0.00 logMar at far, and 0.17 logMar; 0.10 logMar at near (0.30 m), after correcting the myopic eye with the ophthalmic lens of −3 D.

In Fig. 9 we present the images obtained at near (optotype at 0.30 m) with the naked eye (top) and with the adherent lens TL4A (+3 D) self-adhered to the myopic correction of −3 D (bottom). The letters correspond to visual acuities of 0.17 logMar and 0.10 logMar.

We completed the study using two more lenses: L3A (+2 D PDMS lens); and the + 1.25 D Hydrotac lens. The optotype was placed at different distances (at 0.50 m. and 0.75 m) in accordance with the power of the lens. Besides we included the image obtained with a + 7 D PDMS lens to show the possibility of manufacturing high refractive lenses. In this case the optotype was placed at 0.14 m. In Fig. 10 we show the images obtained for these lenses.

Figs. 9 and 10 show the performance of the self-adherent lenses over a −3 D ophthalmic lens used to correct an artificial myopic eye of −3 D. Our PDMS lenses and the Hydrotac lens provide equivalent results with

Table A1
Aberrometric data of the lenses manufactured with trial lenses as molds.

Pupil = 4 mm	**Units: mm**										
	Z	**n**	**m**	**TL1A**	**TL1B**	**TL2A**	**TL2B**	**TL3A**	**TL3B**	**TL4A**	**TL4B**
Oblique Astigmatism	**4**	2	−2	0.03	−0.01	0.01	0.01	0.02	0.01	0.01	0.00
Defocus	**5**	2	0	0.40	0.42	0.87	0.87	1.29	1.30	1.71	1.73
Vertical Astigmatism	**6**	2	2	0.00	0.03	−0.01	0.00	0.00	0.00	0.02	0.00
Vertical Trebol	**7**	3	−3	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01
Vertical Coma	**8**	3	−1	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Horizontal Coma	**9**	3	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Horizontal Trefoil	**10**	3	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oblique Quadrafoil	**11**	4	−4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oblique Secondary Astigmatism	**12**	4	−2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Spherical Aberration	**13**	4	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vertical Secondary Astigmatism	**14**	4	2	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Vertical Quadrafoil	**15**	4	4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Oblique Pentafoil	**16**	5	−5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vertical Secondary Trefoil	**17**	5	−3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vertical Secondary Coma	**18**	5	−1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	000
Horizontal Secondary Coma	**19**	5	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Horizontal Secondary Trefoil	**20**	5	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vertical Pentafoil	**21**	5	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Units: D										
	M			0.70	0.72	1.50	1.52	2.25	2.21	2.95	3.00
Power Vectors	**J0**			−0.02	0.02	−0.01	0.00	−0.03	0.01	0.02	0.00
	J45			0.04	−0.03	0.01	0.01	0.04	0.01	0.01	0.00
	Units: D										
	Sphere			0,75	0.75	1.52	1.54	2.30	2.22	2.97	2.99
Spherocylindrical notation	**Cylinder**			−0,09	−0.07	−0.03	−0.03	−0.10	−0.02	−0.04	−0.01
	Axis			–	–	–	–	–	–	–	–

Table A2
Aberrometric data of the lenses manufactured with ophthalmic lenses as molds.

Pupil = 4 mm	**Units: mm**								
	Z	**n**	**m**	**L1A**	**L1B**	**L2A**	**L2B**	**L3A**	**L3B**
Oblique Astigmatism	**4**	2	−2	0.00	0.01	0.00	0.00	0.00	0.00
Defocus	**5**	2	0	1.52	1.53	2.22	2.21	1.22	1.23
Vertical Astigmatism	**6**	2	2	0.01	0.01	0.00	0.00	0.00	0.01
Vertical Trebol	**7**	3	−3	0.00	0.01	0.00	0.00	0.00	0.00
Vertical Coma	**8**	3	−1	0.00	0.00	0.01	0.00	0.00	0.01
Horizontal Coma	**9**	3	1	0.00	0.00	0.00	0.00	0.00	0.00
Horizontal Trefoil	**10**	3	3	0.00	0.00	0.00	0.00	0.00	0.00
Oblique Quadrafoil	**11**	4	−4	0.00	0.00	0.00	0.00	0.00	0.00
Oblique Secondary Astigmatism	**12**	4	−2	0.00	0.00	0.00	0.00	0.00	0.00
Spherical Aberration	**13**	4	0	0.00	0.00	0.00	0.00	0.00	0.00
Vertical Secondary Astigmatism	**14**	4	2	0.00	0.00	0.00	0.00	0.00	0.00
Vertical Quadrafoil	**15**	4	4	0.00	0.00	−0.01	0.00	0.00	0.00
Oblique Pentafoil	**16**	5	−5	0.00	0.00	0.00	0.00	0.00	0.00
Vertical Secondary Trefoil	**17**	5	−3	0.00	0.00	0.00	0.00	0.00	0.00
Vertical Secondary Coma	**18**	5	−1	0.00	0.00	0.00	0.00	0.00	0.00
Horizontal Secondary Coma	**19**	5	1	0.00	0.00	0.00	0.00	0.00	0.00
Horizontal Secondary Trefoil	**20**	5	3	0.00	0.00	0.00	0.00	0.00	0.00
Vertical Pentafoil	**21**	5	5	0.00	0.00	0.00	0.00	0.00	0.00
	Units: D								
	M			2.63	2.66	3.86	3.82	2.10	2.12
Power Vectors	**J0**			0.01	0.02	−0.01	−0.01	0.00	0.02
	J45			0.00	0.00	0.00	0.00	0.01	−0.01
	Units: D								
	Sphere			2.64	2.68	3.87	3.83	2.11	2.14
Spherocylindrical notation	**Cylinder**			−0.03	−0.05	−0.02	−0.02	−0.01	−0.04
	Axis			–	–	–	–	–	–

good visual quality. We showed the performance of PDMS lens placed in primary gaze position. However, they can be used in secondary gaze positions without loss of visual quality.

4. Conclusions

In this work we present a simple method for manufacturing self-adherent lenses for presbyopia. We manufactured PDMS lenses of different spherical power with no astigmatism and without high order aberrations using trial lenses and ophthalmic lenses as molds. The self-adherent lenses were compared to commercially available lenses (Hydrotac + 1.25 D), providing better results with less induced astigmatism. We verified that the manufacturing process is reliable by fabricating more than one element with each mold. All the replicas were equal to its pair independently on the refractive power of the manufactured lenses. The expected visual quality has been assessed using a myopic artificial eye. We selected the master molds to get PDMS lenses in the power range of the addition found in lenses for presbyopia.

Table A3
Wavefront generated by the PDMS lenses self-adhered to different ophthalmic lenses.

Pupil = 4 mm				OL1: +1sph −1,25cyl			OL2: −2,50 cyl			OL3: −2,25 sph			OL4: +2,25 sph		
	Z	n	m	TL3A	TL4A	Hyd	TL3A	TL4A	Hyd	TL3A	TL4A	Hyd	TL3A	TL4A	Hyd
	Units: mm														
O. Astig.	**4**	2	−2	0.11	0.45	−0.34	−0.80	−0.96	0.71	0.01	−0.01	−0.04	0.01	0.02	0.00
Defocus	**5**	2	0	1.45	1.85	1.02	0.50	1.03	−0.08	−0.02	0.47	−0.62	2.49	2.92	2.06
V. Astig.	**6**	2	2	−0.46	0.02	−0.37	0.18	0.31	0.27	−0.04	0.01	−0.15	0.02	0.02	0.00
V. Trebol	**7**	3	−3	0.00	−0.02	−0.02	0.00	0.00	−0.03	0.00	−0.01	0.01	−0.01	0.01	−0.01
V. Coma	**8**	3	−1	0.00	0.01	−0.01	0.00	0.00	−0.01	0.00	−0.01	0.02	0.00	0.01	−0.01
H.Coma	**9**	3	1	−0.01	0.01	0.02	−0.01	0.00	−0.01	−0.03	0.01	−0.01	−0.01	0.01	−0.03
H. Trefoil	**10**	3	3	−0.01	−0.03	−0.01	−0.03	−0.01	0.00	0.02	−0.02	−0.03	0.01	0.00	−0.04
O. Quadrafoil	**11**	4	−4	0.00	0.00	0.00	−0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
O. Secondary Astigm.	**12**	4	−2	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	−0.01	0.00
Spherical Aberration	**13**	4	0	0.00	0.01	−0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
V. Secondary Astigm.	**14**	4	2	0.00	0.00	−0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V. Quadrafoil	**15**	4	4	0.01	0.00	0.00	0.01	0.00	0.00	−0.01	0.01	0.01	0.01	0.00	0.01
O.Pentafoil	**16**	5	−5	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V. Secondary Trefoil	**17**	5	−3	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V. Secondary Coma	**18**	5	−1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	−0.01	0.00	0.00	0.00
H. Secondary Coma	**19**	5	1	0.00	0.00	−0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
H. Secondary Trefoil	**20**	5	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V. Pentafoil	**21**	5	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Although we have also shown that the method can be used to manufacture lenses up to + 7D. We think that we have demonstrated the possibility of manufacturing self-adherent lenses that can be used for early presbyopes that do not want to start with bifocals or progressive lenses. The self-adhesion is just due to Van der Waals force, so no glue is involved, and the ophthalmic lens is not damaged. The lenses can be used several times keeping their optical properties and without damaging the ophthalmic lenses where they self-adhere. Moreover, they can be easily cleaned with water and soap, without damaging the lens (cleaning is important for the correct self-adherence of the PDMS lens and clear vision). We think that the proposed solution is easy to use, cost-effective and can be an alternative to other solutions to presbyopia or as an additional help for developing very near tasks. Besides, we consider that they can specially help presbyopes of developing countries where having spectacles is nearly a luxury, and people might have to choose between far or near vision. Self-adherent lenses will help significantly, but mostly those with astigmatism that cannot get cost-effective, pre-assembled near vision spectacles. Although we focused our experiments on proving that the proposed lenses are good for presbyopia, our lenses are even better candidates for those users that present a temporary refractive error, such as those subjects that were implanted with an intraocular lens after refractive surgery that suffer one or two months of fluctuating refractive error and do not have the right spectacle correction. Or for example subjects that are starting with orthokeratology, a vision correction procedure involving the overnight use of gas-permeable contact lenses, that experience none permanent correction during all day at the early stage of the treatment.

CRediT authorship contribution statement

Ana Isabel Gómez-Varela: Conceptualization, Methodology, Investigation, Validation, Supervision, Writing – original draft. **Alejandro Fernández-Rodríguez:** Methodology, Investigation, Visualization. **Carmen Bao-Varela:** Resources, Methodology, Writing – review & editing. **Justo Arines:** Conceptualization, Methodology, Formal analysis, Resources, Supervision, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

See Tables A1, A2 and Table A3.

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