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A TUNABLE MORPHING POLYELECTROLYTE SYSTEM FOR SMART OCULAR APPLICATIONS

ABSTRACT

For the first time, a focal-length tunable intra-ocular lens (IOL) device has been realized by a standard-shaped, homogeneous "one material" system. Different to existing technologies, this poly(N-isopropylacrylamide) gel (PNIPAM) based polyelectrolyte system doesn't require any additional materials (e.g. metal electrodes, movable mechanical structures) to achieve a controllable lens shape transformation for the focal-length shifting actuation. The designed morphological deformation mechanism employs ionic-strength responsive mechanical buckling via controlled swelling of PNIPAM in phosphate buffered saline (PBS) with similar concentration to human eye liquid. This unique approach will unlock great potential in a wide range of smart ocular applications.

KEYWORDS

PNIPAM, PNIPAAm, responsive polymer, intra-ocular lens, focal length, swelling;

INTRODUCTION

The crystalline lens (CL) is the main functional part for the focusing control mechanism of human eyes, directing the light coming through the cornea towards the retina. Cataract is a common eye disease that affects the human eye via CL opacification. It comprises around half of the world blindness, while the number of patients will continue to increase with the aging population [1-3]. Since the invention of modern cataract surgery with artificial Intra Ocular Lenses (IOLs), it has been developed significantly into an effective way to cure this problem [4, 5]. One desirable property is the switchable focal length, where adaptive vision correction is needed when eye conditions change [6, 7]. While existing multifocal IOL designs provide a benefit for near and intermediate vision for some cases, they do not allow dynamic focus length shifting in a continuous fashion. Technical innovations towards new generation of eye implants are therefore desired in terms of improving patient experiences as well as driving efficiencies in public healthcare expenditure.

Meanwhile, latest manufacturing technologies have enabled advanced materials for smart ocular system applications, such as 3D printed artificial cornea [8], customized ocular prosthesis [9], 3D printed iris [10], smart contact lenses with ocular pressure sensing [11,12]. Looking beyond human ocular applications, tunable bio-optical configurations in other advanced devices have been achieved in recent developments, which no longer require complicated mechanical units [13 – 15]. Some of the recently developed smart polymer achieve tunable optical focal length, responding to and controlled by external stimulation such as pH-responsive [16], electric field [17], and ion concentration [18] with mechanical confinement structures or electrical interconnects. However, limited efforts have been found on developing easy-to-implant artificial ocular device with responsive focal shifting, since the above devices may require non-compatible materials (e.g. metal electrodes), liquid/solid interactions and stimuli for actuation are hard to fulfil in in-vivo, as in the human eyes.

With these regards, we proposed and demonstrated a new polyelectrolyte system based on PNIPAM (also named PIPAAM or PNIPAAm), to advance the robust optical implant technology with focal shifting. For the first time, tunable morphological deformation has been realized by a homogeneous "one-material" polyelectrolyte system with either freestanding (this abstract's focus), or edge-confined configurations.

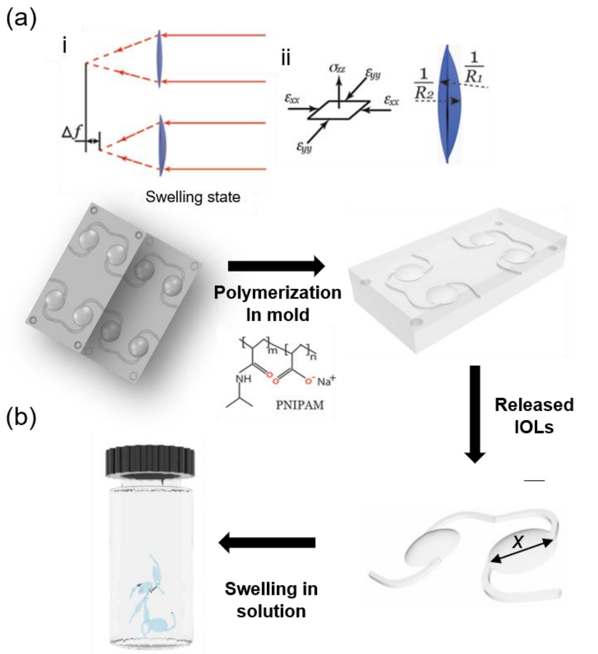

Figure 1: (a) Proposed focal length shifting mechanism: mechanical buckling of the dual-curved IOL shape change; (b) Low cost and facile fabrication process of the PNIPAM tunable IOLs

The designed morphological deformation mechanism is to be achieved by responsive mechanical buckling, which is a common phenomenon in thin, soft structures that may yield rapid out-of-plane deformation (**Fig. 1a**). Such out-of-plane deformation results in dynamic changes in designed IOL morphology parameters therefore achieving the desired tunable optical properties. Taking advantage of the "one-material" design, this standard-shaped, dual-curved, mono-focal IOL structure employs a "one-step-molding" facile fabrication process. The IOLs were fabricated through a cast-molding/polymerization process of polyelectrolyte hydrogels (**Fig. 1b**) inside 3D printed molds.

It should be noted that the targeted focal length f (reciprocal of the lens diopter $D = \frac{1}{f}$) shifting is relatively small, at around 10% increment of the original value, as required for the ocular application we are interested in. IOL calcification tests were also conducted at the end to demonstrate the suitability for potential human eye implantation.

RESULTS AND DISCUSSION

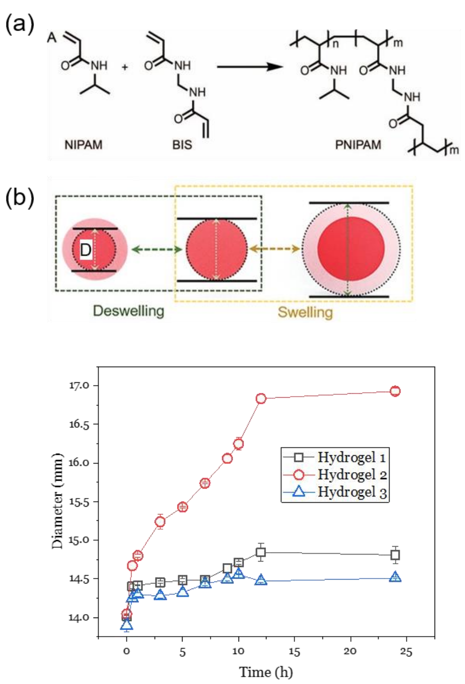

Figure 2: (a) Synthesizing process of the PNIPAM poly-electrolyte system; (b) Swelling ratio characterization using PNIPAM spheres with results from three different composites: Hydrogel 1, 2 and 3 (Table 1) respectively.

Figure 2a shows the synthesizing process of the proposed PNIPAM responsive IOL hydrogel structure. The ionic-strength responsive swelling behavior was characterized by immersing spherical shaped PNIPAM hydrogel balls in phosphate buffered saline (PBS) solutions, while studying the relationship between their diameters D vs. swelling time. Three different PNIPAM composites were used, labelled "Hydrogel 1, 2 and 3" respectively (**Table 1**). **Figure 2b** shows the hydrogel ball diameters D increased rapidly in the first hour after being immersed in the 0.01 M PBS solution. The swelling velocity gradually reduced, with the swelling ratio "saturated" at around 24 hours mark. As expected, due to its addition of Sodium Acrylate (SA) in the polyelectrolyte system Hydrogel 2 has the largest swelling ratio change (up to 125% at 24th hour). On the other hand, due to the higher crosslinker N,N'-methylenebisacrylamide (BisAA) content in Hydrogel 3, it has the smallest overall swelling ratio (up to 105%).

Table 1: PNIPAM composition of Hydrogels 1, 2 and 3.

	Hydrogel 1 (wt%)	Hydrogel 2 (wt%)	Hydrogel 3 (wt%)
Acrylamid	8.34	8.34	8.34
Sodium Acrylate (SA)	0	1.59	0
BisAA	0.416	0.416	0.832
TEMED	0.0015	0.0015	0.0015
APS	0.1	0.1	0.1
H_2O	91.14	89.56	90.72

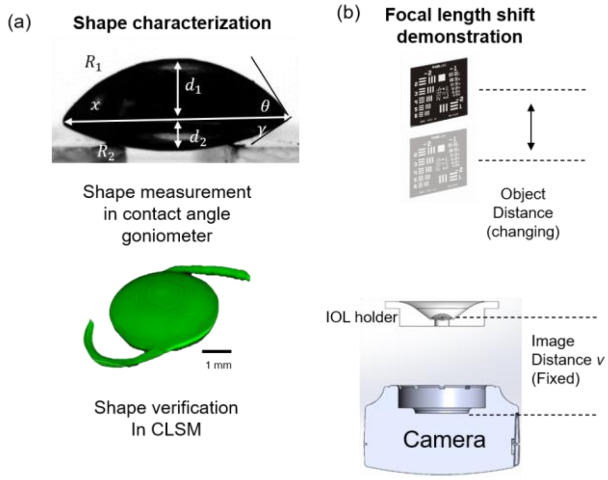

Figure 3: (a) IOL shape characterization using contact angle goniometer and CLSM systems; (b) Schematic of the focal length shifting demonstration imaging set-up.

Next, we analyzed the tunable morphological deformation mechanism of the designed IOL structures, by measuring key shape parameters using a contact angle goniometer (**Figure 3a**). The IOL shape was also verified in a Confocal Laser Scanning Microscopy (CLSM) system. The relationship between optical properties and dual-curved IOL lens designs can be described by equation (1):

$$\varphi = \frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)d}{nR_1R_2}\right) \qquad (1)$$

where φ is the diopter of the optical power, f is the focal length, d is the lens thickness in the air, R_1 and R_2 are the surfaces with radii of curvature, and n is the refractive index (n=1.349) by Byron et al. [19]

At the end, a simple focal length shifting optical demonstration experiment was also conducted by fixing the image distance with photos taken at different object distance as illustrated in **Figure 3b**. As our targeted focal length shift is around 10% of the original value, Hydrogel 1 was chosen for the shape characterization study.

To understand the ionic strength effect on morphological deformation, dual-curved IOL test structures were immersed in PBS solutions with different concentrations (0.001 - 0.1M), and for different length of time periods (up to 24 hours). **Fig. 4** shows that the IOL swells rapidly during the first hour, before slowing down and saturated after that. This largely agrees with the swelling behavior shown in figure 2. It was also observed that the IOL expanded more along the X-direction (**Fig. 4a**), resulting a reduction in both curvatures (reciprocal of the radius, $\frac{1}{R_1}$ and $\frac{1}{R_2}$), and thus an increased focal length over time (**Figure 4b, 4c** and **4d**). Numerical simulations were also conducted to help verify this relationship. The initial result (**Fig. 4d**) shows quicker swelling at the X-direction than the d-direction.

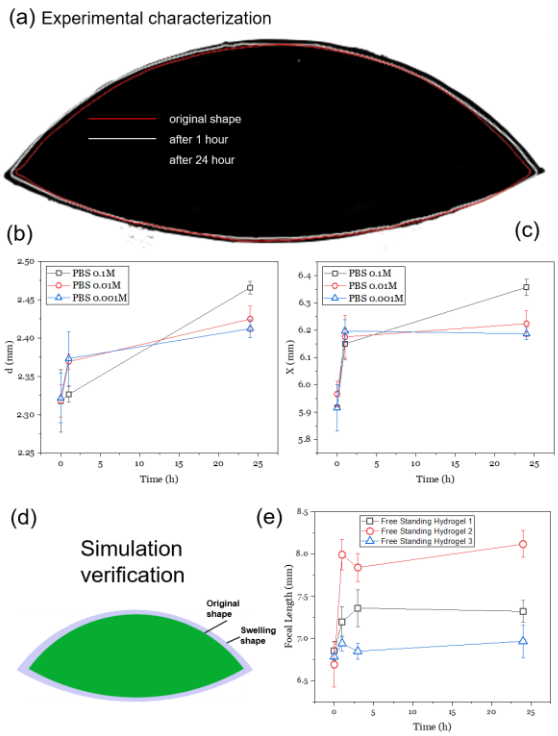

Figure 4: Free-standing, dual-curved IOL shape characterization. (a) Direct shape comparison of the IOL at different swelling stages (profile outline comparison); (b) relationship between swelling time and the IOL shape parameter d (d=d_1+d_2); (c) relationship between swelling time and the IOL shape parameter X; (d) initial simulation results verified the experimental observation; (e) resulted focal length change (free standing) of hydrogel composites 1, 2 and 3, at PBS concentration of 0.01M

Optical bench system for focal length shifting demonstration and verification have been designed and constructed as illustrated in **Figure 3b**. With the image distance fixed to v = *10.9 mm*, and object (1951 USAF test chart, **Fig. 5a**) distances u were calculated based on focal length f values following equation 2 below:

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f} \qquad (2)$$

This object distances *vs.* IOL swelling time and resulted images were then evaluated by the optical bench system to demonstrate the configurable focal length shifting for the fabricated gel structure, with initial results shown in **Figure 5b**. A clear shifting of object distance in focus from around 25-30 to 40 mm can be observed.

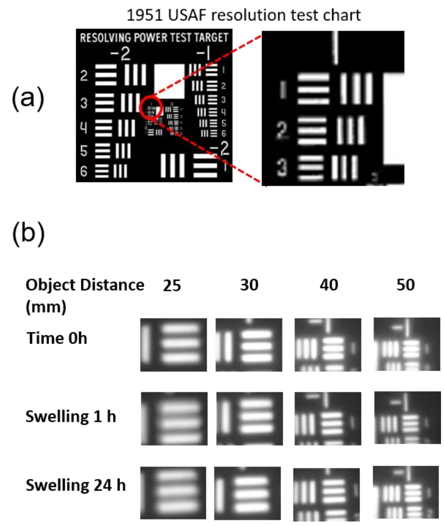

Figure 5: Focal length shifting optical demonstration with (a) 1951 USAF test chart as testing object, with (b) shifting of the object distance in focus observed with IOL lenses at different swelling stages.

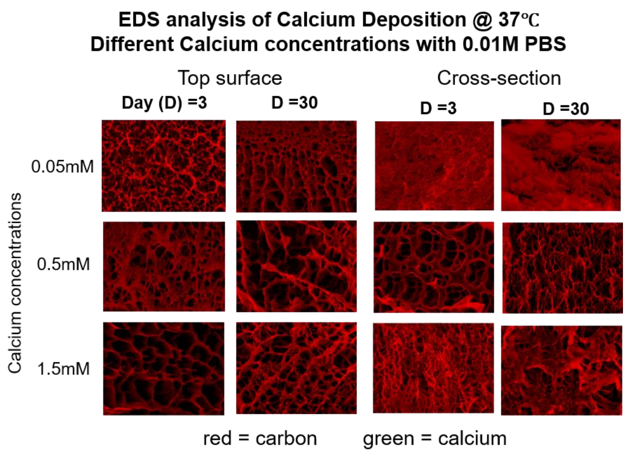

Figure 6: Anti-calcification demonstration experiment: EDS image showing little calcium deposition after 30 days of sample immersion in calcium solutions.

For IOL applications, it is important to conduct a standard calcification evaluation experiment, typically performed by immersing the PNIPAM gels in a solution of 0.05 - 5 mM of calcium nitrate solutions for up to 30 days as reported by Yokoi et al. [20].

Both the surface and cross-section of the PNIPAM IOLs were examined. **Figure 6** shows the EDS surface view, where carbon and calcium elements were represented by red and green colors, respectively. From observation, the gel surface remains “calcium-free” even after 30 days’ immersion in the 1.5mM calcium solution. As the normal range of calcium in human tear is around 0.5mM [21], and majority groups studied in a previous work 50 were below 1.5mM, it can be argued this PNIPAM gel has a low calcification risk in ocular applications.

CONCLUSIONS

Tunable focal length shifting has been characterized and demonstrated by the proposed PNIPAM-based responsive morphing polyelectrolyte IOL devices. This concept benefits from a homogeneous "one material" approach, with great potential to be adapted in scalable, low cost, facile manufacturing process.

The development of this responsive buckling induced configurable optical technology is also a primary step to translate fundamental scientific knowledge into modern manufacturing technologies for future ocular implant product developments.

ACKNOWLEDGEMENTS

This work was supported by EPSRC UK Fluid Network (grant no. EP/N032861, https://fluids.ac.uk/). The authors would also like to acknowledge other support from the EPSRC (grant Nos. EP/N007921 and EP/L026899). Data associated with this article are available via Northumbria Research Data Management scheme.

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