New-generation of PDMS-based Lenses for Color Blindness Correction

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ABSTRACT— Being a color blind or having color vision deficiency (CVD) problems is a type of ocular disorder that prevents the recognition of particular spectrum of colors. Until now, no type of treatment has for CVD have been provided. But recently, glasses and contact lenses based on chemical dyes have been investigated as promising tools for color vision deficiency management. In this paper, we propose a plasmonic PDMS-based lenses to improve the red-green color vision deficiency. We utilized polydimethylsiloxane (PDMS) for fabricating the lens which is a biocompatible, nontoxic, stretchable, and transparent material with applicability of being used in the production of contact lenses. Finally, the suggested material for contact lens based on PDMS was immersed in a $HAuCl_4 \cdot 3H_2O$ gold solution. Our suggested plasmonic lens based on localized surface plasmon resonance (LSPR) effect and plasmonic gold nanoparticles dispersed in the production contact lens suggest a suitable color filteration for CVD improvement. The fabricated contact lens has good features including having biocompatibility, durability, and stretchability property, that may be used for solving color vision deficiency problems.

KEYWORDS: color blindness, contact lens, color vision deficiency, gold nanoparticles, plasmonic.

I. INTRODUCTION

Color eyesight arises from three different groups of cone cells: short (S), medium (M), and long cones (L), which play a key role in sensing blue, green, and red colors, respectively. The S, M, and L cone-shaped photoreceptors have spectral sensitivity peak at the wavelengths of 430, 530, and 560 nm, respectively. Considering natural eyesight coloring, all three photoreceptors are active, with performances corresponding to their sensitivity peaks.

Color blindness or color vision deficiency (CVD) is a type of visual defect that prohibits the recognition of distinct colors. In general, the deficiency congenital or not [1], color blindness is related to the missing or deficiency of the cone cells.

There are three different types of color vision deficiences: anomalous trichromacy, dichromacy, and monochromacy [2]. Anomalous trichromacy appears when one of the cone cells was deficient. Depending on which photoreceptors is faulty, anomalous trichromacy is classified into three groups: protanomaly (deficient red photoreceptors), deuteranomaly (deficient green photoreceptors), and tritanomaly (deficient blue photoreceptors). Dichromacy occurs when one of the cone-shaped photoreceptors is entirely missing. Dichromacy is also classified into three categories: protanopia (lacking red photoreceptors), deuteranopia (lacking green photoreceptors), and tritanopia (lacking blue photoreceptors). Monochromacy is the rarest type of color vision deficiency in which at least two cone cells are lacking. Monochromat persons are fully colorblind (achromatopsia) or have only blue cone cells.

The most prevalent groups of color vision deficiency are protans (protanopia and protanomaly) and deutans (deuteranopia and

deuteranomaly) which are called deuteranomaly color vision deficiencies. The sensitivity peak of the red photoreceptors has blue-shifted in protanomaly, whereas the spectral peak of the green photoreceptors has red-shifted in deuteranomaly. So, people who cannot make distinction between colors, they have the problem of overlapping in the spectral range of green and red photoreceptors.

Until now, the certain treatment for color vision deficiency was not discovered. However, several methods including the gene therapy [3]-[6], tinted glasses [7]-[9], contact lenses [10]-[11], optoelectronic glasses, and sofort and so on [12]-[13] were studied to improve the color perception in the color-blind people. Upon these methods, glasses have received more attention from colorblind users. Of course, the idea of using color filters was first introduced by Seebeck in 1837 [14]. By application of red and green filters, Seebeck noted that color-blind people can distinguish between different shades of green and red colors.

Today, many glasses based on the color filteration is extensively studied and even commercially is used [7]-[9] for correction of the color vision deficiency. Whereas these glasses are efficient to correct the color sensing characterstics of the CVD persons, but they have restrictions as costly, bulky and incongruity with other vision correction glasses.

Lately, contact lenses were studied for correction of color vision deficiency. Badawy et al. developed dye-based contact lenses for color blindness correction [15]. Furthermore, nanostructures such as plasmonic metasurfaces [16] and plasmonic nanoparticles [17]-[18] were also studied for CVD correction.

In this paper, we particularly consider deuteranomaly color blindness, which is the most prevalent group of CVD classes. In the study, we proposed the plasmonic PDMS-based lenses for CVD correction. The proposed plasmonic contact lenses consist of gold nanoparticles embedded in the PDMS matrix. PDMS is a biocompatible, stretchable, and transparent material which will be a suitable option for producing the contact lenses. This non-toxic and biocompatible substance is applied in biology, medicine, and chemistry as well[19]-[23]. Furthermore, plasmonic gold nanoparticles are biocompatible and have been utilized in many applications such as biology [24]-[26], drug delivery [27]-[29], biosensing [30]-[32], and biomedical imaging [33]-[35]. Therefore, the proposed plasmonic contact lenses are biocompatible and nontoxic which suggest great stability and effectiveness for correction of color vision deficiency.

II. EXPERIMENTAL METHOD

A. *Fabrication process*

In this paper, the plasmonic PDMS-based lenses have been proposed for correction of color vision deficiency. A graphic layout of the preparation procedure for the fabricated contact lens based on PDMS is demonstrated in Fig. 1(a). As a first step, PDMS composite was prepared by mixing the PDMS base (SYLGARD 184 DOW CORNING) with curing agent at a weight ratio of 10:1. These two materials were mixed by a DC stirrer for five minutes to reach a homogenous composite material. Afterward, it was poured into the lens mold. For removing the air bubbles, sample was placed in the vacuum chamber for 15 min. Next, the sample is placed on the heater and cured with a gradually increasing the temperature from 50 ^{0}C to 100 ^{0}C for 1 h. After 24 h, the PDMS-based lens was peeled off the mold and thus a biocompatible lens based on PDMS was successfully fabricated.

Next, the produced lenses based on PDMS were immersed into a 0.01 M gold solution ($HAuCl_4 \cdot 3H_2O$ gold chloride trihydrate) with different immersion times of 12, 18, 24, 36, during 72 hours. A real picture of the obtained plasmonic lenses based on PDMS with different incubation times and $HAuCl_4.3H_2O$ gold solution is shown in Fig. 1(b). By doing this , the plasmonic and biocompatible PDMS-based lenses were fabricated and evaluated for correction of the color vision deficiency.

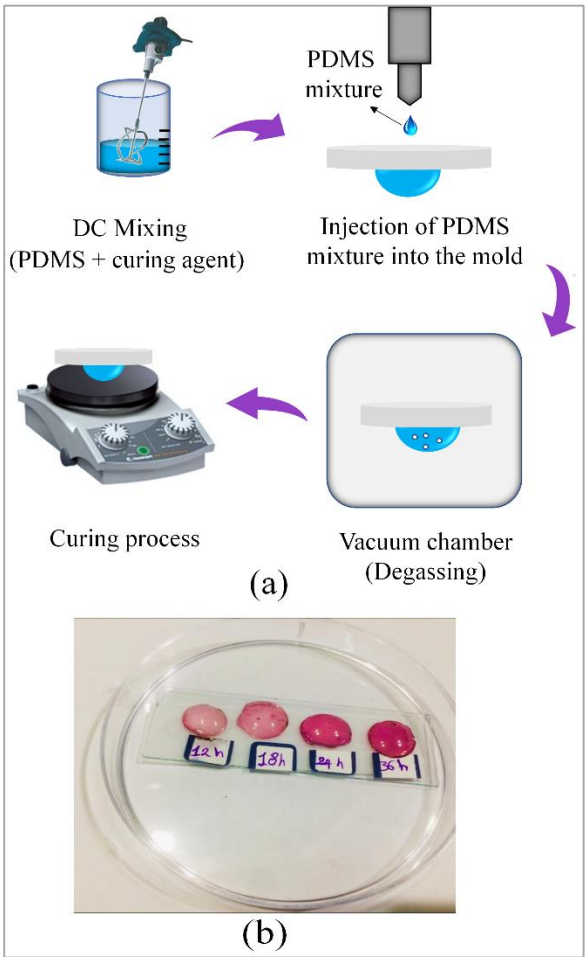

Fig. **1** (a) A schematic array of the fabrication procedure of the proposed PDMS-based lenses, and (b) the real image of the fabricated plasmonic PDMS-based lenses.

B. *Results and discussion*

The absorption spectra of the suggested plasmonic PDMS-based lenses with various incubation times were recorded by a UV-Vis spectrum analyzer shown in Fig. 2(a). According to the results, the absorption intensity was increased with increasing the incubation time, which is due to increase in the content of gold nanoparticles in PDMS matrix. Furthermore, plasmonic resonance peaks were observed at the wavelengths of λ=532, 533, 535, 542, 543 nm for lenses with incubation times of 12, 18, 24, 36, and 72 h, respectively. Consequently, the absorption peak is red-shifted up 11 nm with increasing the incubation time from 12 h to 72 h.

Also, observation of the absorption peak with a red spectrum shifting of 1 nm and immersion time from 36 to 72 h, showed no shift in the spectrum position of the absorption peak. This phenomenon confirms the stabilization of the gold nanoparticles embedded into the PDMS matrix after an immersion time of 36 h; so, the optimum incubation time is 36 hours.

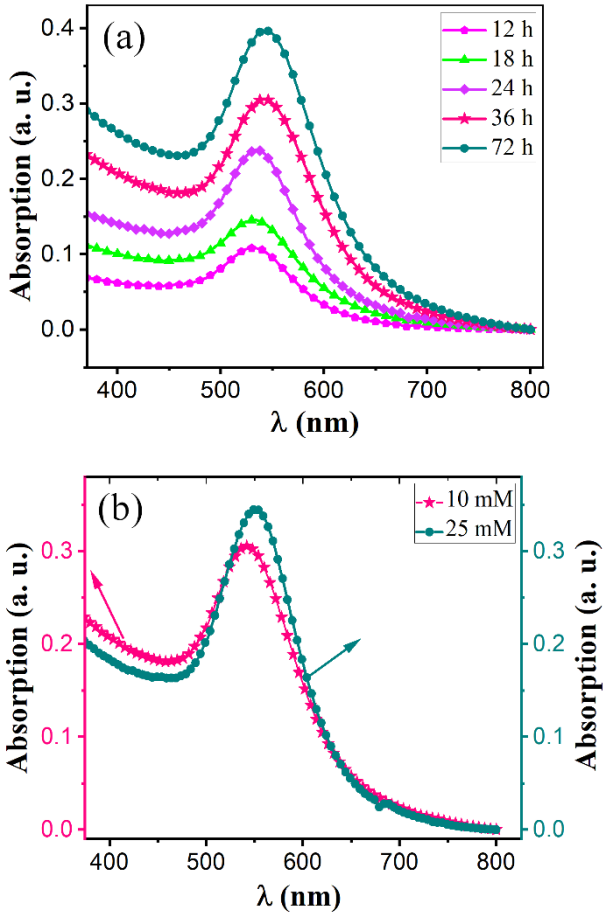

Fig. **2** (a) Measured absorption spectra of the fabricated plasmonic PDMS-based lenses which immersed into $HAuCl_4$ solution at different incubation times of 12, 18, 24, 36, and 72 h, and (b) absorption spectra of the PDMS-based lenses which immersed into the $HAuCl_4.3H_2O$ gold solutions with concentration of 0.01 and 0.025 M for 36 h.

In addition, the concentration of the $HAuCl_4.3H_2O$ gold solution has been increased from 0.01 to 0.025 M, with fabricated lens being immersed into the 0.025 M gold solution for 36 hours. For a closer look, the absorption spectra of the lenses that were immersed into the 0.010- and 0.025-M gold solutions are shown in Fig. 2(b)). The plasmonic resonance peak is red-shifted about 11 nm with increasing the concentration of the gold solution from 0.010 to 0.025 M, with absorption peak being observed at λ=553 nm. Indeed, the size of the

gold nanoparticles increased with increasing the concentration, so the peak wavelength was red-shifted. In addition, the absorption intensity was enhanced with increasing the concentration of the gold solution.

Our suggested plasmonic lens is based on tunable LSPR effect and can be utilized for improvement of deuteranomaly color blindness. Localized surface plasmon resonance (LSPR) is generated by metallic nanoparticles, such as gold or silver NPs, which is related to the collective oscillation of electrons on the metallic NPs excited by the incident light at the resonant wavelength [36]-[38]. The excitation of LSPR modes enables a strong resonance absorption peak in the visible range.

Plasmonic gold nanoparticles incorporated within the contact lens exhibit narrow absorption in the visible region due to their plasmonic resonance properties (Fig. 2). In addition, a strong coupling was occurred between the localized surface plasmon resonances caused by Au NPs with different diameters, causing the strong plasmonic resonance and, thus, the absorption peak at the resonance wavelength for the proposed plasmonic contact lenses (Fig. 2).

The wavelength range of 540-580 nm (problematic wavelength range) should be filtered to improve the red-green color vision deficiency, so the resonance peak must occur at the wavelength of about 560 nm. Since, plasmonic resonance of gold nanoparticles occurs at the wavelength range of 540-580 nm, plasmonic gold NPs were incorporated into the PDMS-based contact lens and plasmonic contact lens based on gold NPs was proposed for improvement of deuteranomaly (red-green) color blindness. Consequently, plasmonic gold nanoparticles trapped in proposed lens based on PDMS suggest a suitable color filter for correction of deuteranomaly color vision deficiency.

Furthermore, the resonance plasmonic features of the Au nanoparticles can be tuned by change their morphology such as size, shape, and solvent. In this work, the size of plasmonic NPs can be controlled by optimizing the immersion time and concentration.

In this research, we have considered deuteranomaly (red-green) color blindness cases, which is the most prevalent group of CVD classes. Also, plasmonic contact lens based on gold NPs. was proposed for improvement of deuteranomaly (red-green) color blindness. For other types of color vision deficiency, such as blue-yellow color blindness, the overlapping wavelength range of 450-500 nm should be blocked to improve the color vision efficiency. In this case, it is better the plasmonic silver nanoparticles to be utilized, where their plasmonic resonance response is in our considered wavelength range. In the future, we will investigate plasmonic contact lenses and eyeglasses based on silver nanoparticles to correct the blue-yellow color blindness deficiency problem.

III. Conclusion

In this paper, the plasmonic and biocompatiblity PDMS-based lens has been proposed and evaluated for correction of deuteranomaly color blindness. Polydimethylsiloxane was utilized for fabricating the lens which is a biocompatible, nontoxic, stretchable, with being a transparent substance and will be a suitable option for producing the contact lenses. The produced lenses based on PDMS were immersed into a $HAuCl_4 \cdot 3H_2O$ gold solution. The plasmonic lens based on tunable LSPR effect and gold nanoparticles suggest a siutable color filteration property for improvement of red-green color vision deficiency. Furthermore, the plasmonic resonance features of the Au nanoparticles can be tuned by changing their morphology such as size, shape, and solvent properties. The proposed lens may provide good features including biocompatibility, durability, and stretchability, that will be helpful for CVD management.

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