Modifying the Soft Contact Lens for Color Vision Deficiency Correction by Plasmonic Gold Nanoparticles

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ABSTRACT— Color vision deficiency (CVD) is a disorder in which patients cannot distinguish specific colors. In the last few decades, the researchers have attempted to find a solution to cure this deficiency, despite valuable attempts by scientists, a promising and effective remedy has not been attained yet. As curing of CVD with the tinted or dyed glasses and lenses in colorblind patients is not satisfying, in this work, we have studied a novel and simple method using plasmonic gold nanoparticles in the contact lenses to improve CVD based on surface plasmon resonance of gold nanoparticles in the visible spectral range. In this technique, the dispersion of gold particles into the contact lens and transforming them to plasmonic gold nanoparticles provides a color filter that can be applied in the correction of the red-green type of colorblindness. The modified lens blocks a narrow band centered at 560nm, the wavelength that vision spectra of CVD patients overlap at those ones.

KEYWORDS: CVD, Colorblindness, plasmonic, gold nanoparticles, SPR, contact lens.

I. INTRODUCTION

Color vision deficiency (CVD) is a condition that patients cannot distinguish specific colors or differentiate between the shades of certain colors, and it is known as color blindness. Roughly, 8-15 percent of men and 0.5 percent of women are suffered from these conditions [1-4]. Until now, there was no known remedy to cure this deficiency, but several methods are suggested to help patients in color distinction such as gene therapy, tinted glasses, and lenses, smart glasses, etc. Although these methods cannot correct CVD, they improve patients' color vision by increasing the contrast of the colors and show promising results; however, more works is needed in this field.

There are three different receptor cells for color vision known as cone cells; S, M, and L cones (short, medium, and long cones) [5, 6]. They also known as blue, green and red cones which have a spectral peak centered at 440nm, 540nm and 560nm in normal vision, respectively [1, 2. 7-10]. If these three types of photoreceptor cones exist and work properly, incoming light activates the cones (regarding the incoming light wavelength specific cone is activated), eyes receive the combination of the signals from these photoreceptors, and the brain analyzes the signals, so one can see and distinguish the colors [11]. Figure 1 shows the types of these cones and their spectral ranges. In the patients who suffering from CVD, one of these photoreceptors is missing or is not functional. According to this, and the type of the cone, there are different types and levels of CVD.

The most common CVD types are protans (missing or defect of red cones) or deutons (missing or defect of green cones), which are known as red-green color blindness [12]. In the case of defective photoreceptor cones, in the former type, the spectral peak of the red cone is blue-shifted and in the latter one the spectral peak of the green cone is red-shifted. So, the light received at the overlapped wavelengths cannot be distinguished by the patient, as shown in Fig. 2 [11].

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Until now, several methods have been suggested, one of them (the most common) is wearable tinted glasses [12-17]. These devices use Seebeck's idea back in 1837 who applied a red and then green filter to differentiate the colors' brightness [13, 18]. The basic of wearable glasses used today for red-green CVD correction is on blockage the overlap of M cone and L cone of the patient spectral vision wavelengths (540- 580nm) [11, 19]. The most famous wearable tinted glasses for CVD correction are Enchroma glasses that utilize multiple dye filters to block red and green overlap spectrum [12, 14]. In the methods which use Enchroma technology the proper dyes which have the highest absorption in desired wavelengths are applied on glasses to block mentioned wavelengths. Another famous brand in CVD wearable glasses is VINO/O2Amp. In these glasses, same as Enchroma, increasing the contrast leads to improving the color distinction, but cannot correct the CVD [11].

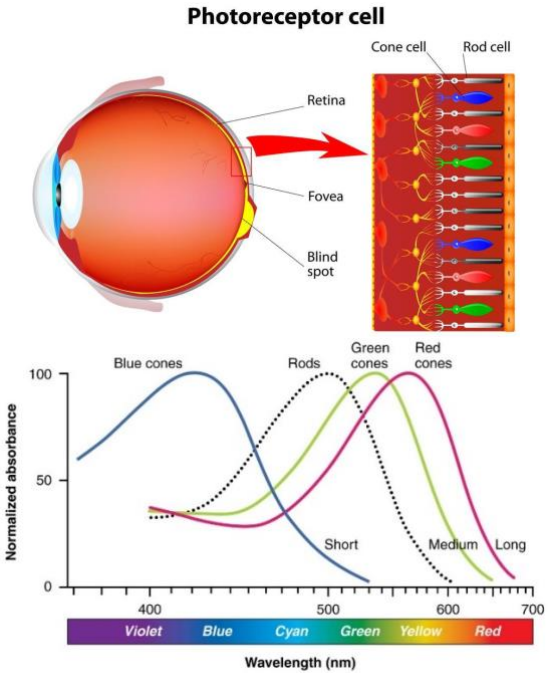

Fig. 1. (top) Photoreceptor cones, (bottom) spectral range of photoreceptor cones [19, 20].

Although these brands are very famous in this field, the percentage of the patients who claimed their color vision improved by wearing these devices is very low; of course, it depends on the type and severity of the deficiency [11, 12, 16].

In addition to the glasses, several companies have introduced their contact lenses like X-Chrom and ChromaGen to aid CVD patients. They have used the tinted lens and applied dyes to block the overlapped wavelengths in the colorblind person vision spectrum [23-29].

In the case of contact lenses, the biocompatibility of the lens and the materials used for color blindness correction should be considered as well.

The same as tinted glasses, dyed lenses increase the contrast to aid patients in the distinction of the color [24].

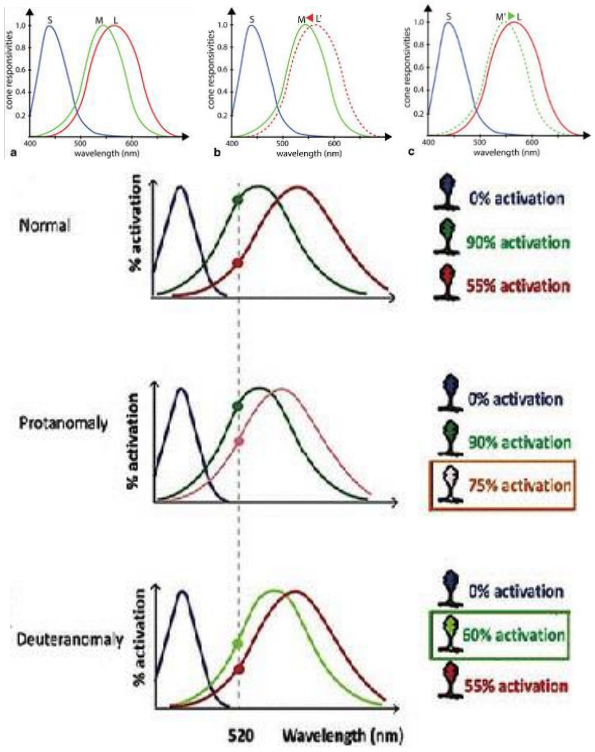

Fig. 2. (top) Comparison of normal vision spectra and overlapped spectra in CVD patients. (bottom) Photoreceptor cells activation percentage at 520nm for normal, protan, and deutan [21, 22].

ChromaGen reported it could improve color vision in some patients [30]. So, in the tinted glasses and lenses, users can distinguish the red color from the green color or different shades of a certain color because of the relative contrast and brightness among these colors and shades, but CVD is not cured [11].

In this study, as gold nanoparticles have extraordinary plasmonic and optical properties,

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we have used a simple and novel method and have utilized plasmonic gold nanoparticles in the soft contact lenses to remove a narrow band in the overlap of red and green spectra in patients' vision spectrum.

In plasmonic materials like gold and silver, plasmon oscillation is induced by interaction between the conduction band electrons and the electromagnetic field of the light [31]. The plasmon resonance happens when the frequency of incident light is resonant with the conduction band electrons oscillation [19, 32-34]. As the resonance often arises on the surface of the plasmonic materials, the phenomenon known as the surface plasmon resonance (SPR) [35]. By transferring from the bulk to the nanoscale, the properties of the plasmonic materials change widely, particularly the optical properties differ significantly [36-38]. In nanoparticles when the particle's size is in the same range of the incident light wavelength, the SPR phenomenon is replaced by localized surface plasmon resonance (LSPR) [39]. The LSPR of plasmonic nanoparticles results in strong light absorption described by Mie solution to Maxwell's equations [33, 40-42]. The characteristics of the LSPR and the properties of absorption depend on several parameters such as morphology, material, concentration, size and shape of the plasmonic nanoparticles [37-38, 43-45]. Particularly, the plasmonic resonance frequency (SPR wavelength) and the absorption band width are associated with the size of the nanoparticles [31, 46]. By changing nanoparticles' sizes, the LSPR wavelength, absorption band and therefore the wavelength of the blocked region can be altered and different applications can be defined [38].

The SPR and therefore the absorption band is much stronger for gold and silver nanoparticles than other metals [47]. For spherical gold and silver nanoparticles, the absorption bands are detected in the visible wavelengths while for other metals happen in UV wavelengths and they are very weak and broad bands making gold and silver nanoparticles appropriate for many applications [38, 48-50].

The size of the nanoparticles plays a crucial role in their application [46]. By reduction the size of the material from bulk to nanoparticles, new properties show up and chemical, structural and optical properties are changed in nanoscale, so plasmonic nanoparticles especially gold nanoparticles which are biocompatible become suitable for variety of biomedical applications in diagnostics, biosensing, bioimaging and drug delivery [51-59]. Many applications of the plasmonic nanoparticles in biological labeling and sensing are based on the SPR effect [60-62]. The LSPR of plasmonic nanoparticles caused these nanoparticles to be considered as powerful label-free biosensors. The characteristics of these sensors and other plasmonic nanoparticles applications depend on the size, shape and chemical properties of the nanoparticles [38, 40, 47, 63]. Recently, in nanomedicine, applying plasmonic gold nanoparticles has become common for diagnosing cancer because of extraordinary optical properties of gold nanoparticles, simple fabrication, feasible surface modification, strong absorption and biocompatibility for medical applications [47].

The UV-Vis absorption spectra of the samples give some information about nanoparticles' sizes according to the LSPR wavelength peaks [46]. J. Cao, *et al*. showed the dependence of the absorption bands to the nanoparticles' size, the bands red shifted by increasing the size of the gold nanoparticles from 520 nm to 580 nm [38]. Reduction the size of the nanoparticles leads to blue shift of the absorption wavelength. T. El-Brolossy, *et al.* explained the strong absorption band for the Au nanoparticles with diameter size around 20 nm occurs at around 522 nm, while very small Au nanoparticles (less than 2 nm) and bulk gold do not show this absorption band [31]. Some other researches showed the absorption band of synthesized spherical Au nanoparticles occurred at approximately 527 nm and 520 nm depending of the size of the nanoparticles [47, 50, 62].

In this study, among plasmonic nanoparticles like gold and silver nanoparticles, we have chosen Au nanoparticles for CVD correction as the wavelengths needed to be blocked for CVD correction are matched to the wavelength of Au

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nanoparticles' absorption band. In addition, Au nanoparticles absorb light in narrower band and much stronger than the organic dye molecules or other material with the same absorption wavelength, so they block the desired light wavelengths completely [47].

II. METHODS AND MATERIALS

To embed gold nanoparticles in the contact lens, we have used soft commercial contact lenses manufactured by Neo vision Co. ltd. made in Korea. The characteristics of the lenses were; material: Methafilcon A, Base curve: 8.6mm, diameter: 14.2mm, water content: 55%, and sphere power 0.00 [64]. Tetrachloroauric (III) acid trihydrate 99% ($HAuCl_4.3H_2O$) was purchased from Sigma-Aldrich. $HAuCl_4$ was diluted by water to make solutions with different concentrations (25mM and 10mM). The contact lenses were immersed in the solution of $HAuCl_4$ to change lens optical properties. Gold particles were dispersed to the contact lens and were transformed to gold nanoparticles to block the wavelengths at which CVD patients have difficulty in distinguishing colors. UV/Vis spectrometry investigated the optical properties and absorption spectra of the lenses with gold nanoparticles embedded in them. The absorption spectra were taken 24h, 48h and 72h after immersion to track the changes in absorbance and optical properties of the samples during the time. Different concentrations were used to study the effect of concentration on optical properties of the lenses content gold nanoparticles. The UV/Vis spectroscopy was performed in the spectral range from 200nm to 800nm (although some parts of spectra were cut in the following figures). Prior to UV/Vis measurements, the immersed lenses were washed with DI water to remove nanoparticles on the surface of the lenses which were not absorbed in the lenses. The absorbance of the lens before immersion in $HAuCl_4$ solution was measured, and it did not show any absorbance. After specific time, one of two lenses deepened in 25mM $HAuCl_4$ solution transferred to lens washing solution and another one transferred to buffer saline solution (the solution that original lenses were kept in it) to investigate the stability of the nanoparticles in lenses in different environments.

The color of the contact lenses changed to gold-brownish in the first 24 hours of immersion in $HAuCl_4$ solution and then became stable. It shows the gold particles entered the lenses. The color of the solution was yellow and did not change during the time the lenses were sunk in it and it shows the nanoparticles were stable during the time lenses were immersed in $HAuCl_4$ solution.

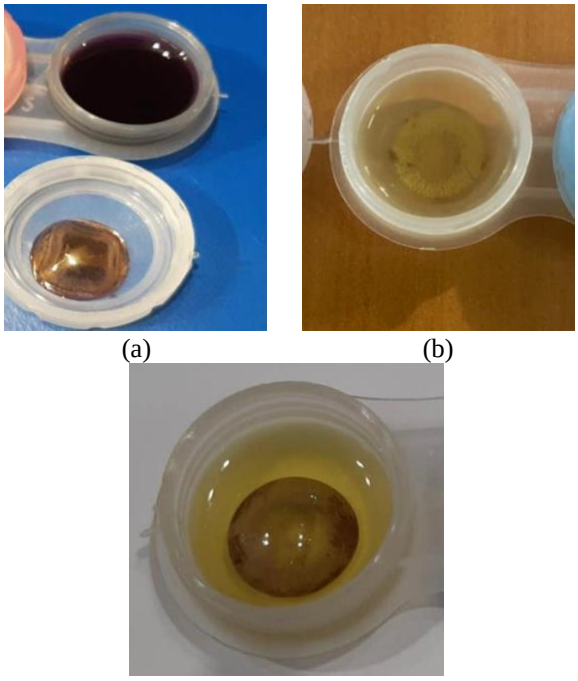

Fig. 3. (a) Sample after transferring to the lens washing solution, and lens washing solution that its color turned to dark pink, (b) sample transferred to the buffer saline solution and (c) lens in $HAuCl_4$ solution.

When the sample was transferred to the lens washing solution, the color of the lens did not change, but the transparent lens washing solution became dark pink that shows some nanoparticles in the lenses interacted with the solution and entered the lens washing solution or Au nanoparticles on the surface of the lens washed off by lens washing solution. The absorption spectrum of lens washing solution involved nanoparticles has been shown in appendix A. It shows a band corresponding to gold nanoparticles. The surface of the lenses should be coated by a proper material to avoid

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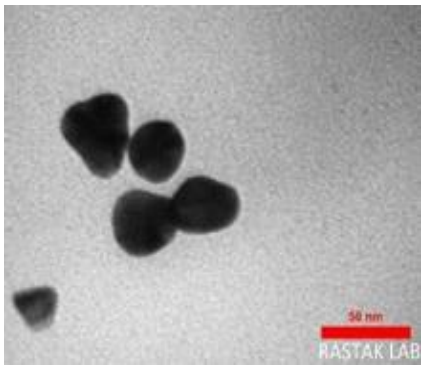
interaction lens washing solution with Au nanoparticles. The dark pink color of the solution showed reduction of $HAuCl_4$, and gold particles entered to the lens were transformed to the gold nanoparticles. However, it did not happen when the sample transferred from $HAuCl_4$ solution to the buffer saline solution, the color of the lens became gold-yellow, and the color of the transparent solution slightly changed to yellow. Fig. 3 is the pictures of the lens during different steps of the experiments.

The morphology and the size of the nanoparticles in the contact lenses were studied by transmission electron spectroscopy (TEM) and scanning electron spectroscopy (SEM). SEM and TEM were recorded for the lens immersed in $HAuCl_4$ solution for 48h and two other lenses that were submerged in $HAuCl_4$ solution for 72h, then transferred and kept in lens washing solution for a week. We used Renu lens washing solution, which contains poloxamine, poloxamer 181, diglycine, sodium citrate, boric acid, sodium borate, edetate disodium, and sodium chloride.

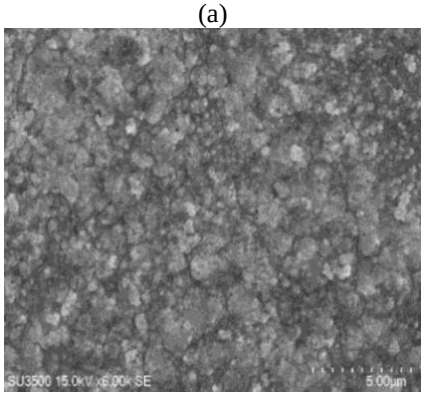
III. Results and Discussion

SEM and TEM results of gold nanoparticles spread in the soft contact lenses have been shown in Fig. 4. These results confirm the reduction of $HAuCl_4$, and gold particles transformed to gold nanoparticles when they entered the contact lens. The material of the lenses used in this study was Methafilcon A [64]. Methafilcon A is a copolymer of hydroxyethylmethacrylate and methacrylic acid. Reduction of $HAuCl_4$ by methacrylic acid leads to formation of gold nanoparticles in the contact lenses. Although $HAuCl_4$ is acidic and cannot be used in the contact with eyes and skin, by its reduction and transforming to Au nanoparticles, it is not harmful any more since Au nanoparticles are biocompatible. Furthermore, for practical applications health safety tests will be considered.

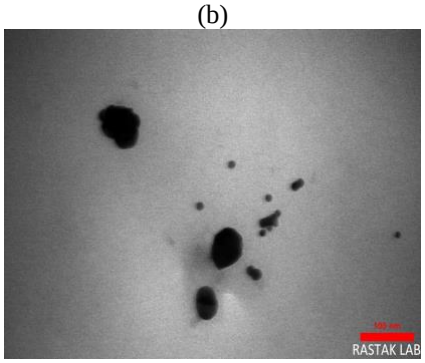
As can be seen in Fig. 4, the nanoparticles are homogeneously dispersed, and the signs of nanoparticles agglomeration cannot be realized in the pictures. The SEM and TEM belong to three different samples synthesized in the same manner to check the repeatability of results. TEM results show the size of the gold nanoparticles in the lens immersed in 25mM $HAuCl_4$ solution for 48h is smaller than 50nm while TEM and SEM recorded the size of the nanoparticles less than 100nm for the samples sunk to 25mM $HAuCl_4$ solution for 72h and transferred to lens washing solution and were kept in it for one week. Increasing the size of the nanoparticles expresses agglomeration of the nanoparticles in new environment and long period of time. Furthermore, it should be considered the agglomeration in the samples is not intense, and it will be discussed in the following sections. According to the pictures, formed Au nanoparticles have spherical shape.



(a)



(b)



(c)

Fig. 4. (a) TEM results of gold nanoparticles in the contact lens immersed in 25mM HAuCl4 solution for 48h. SEM (b) and TEM (c) results of the samples

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submerged to 25mM HAuCl4 solution for 72h and transferred to lens washing solution and were kept in it for one week.

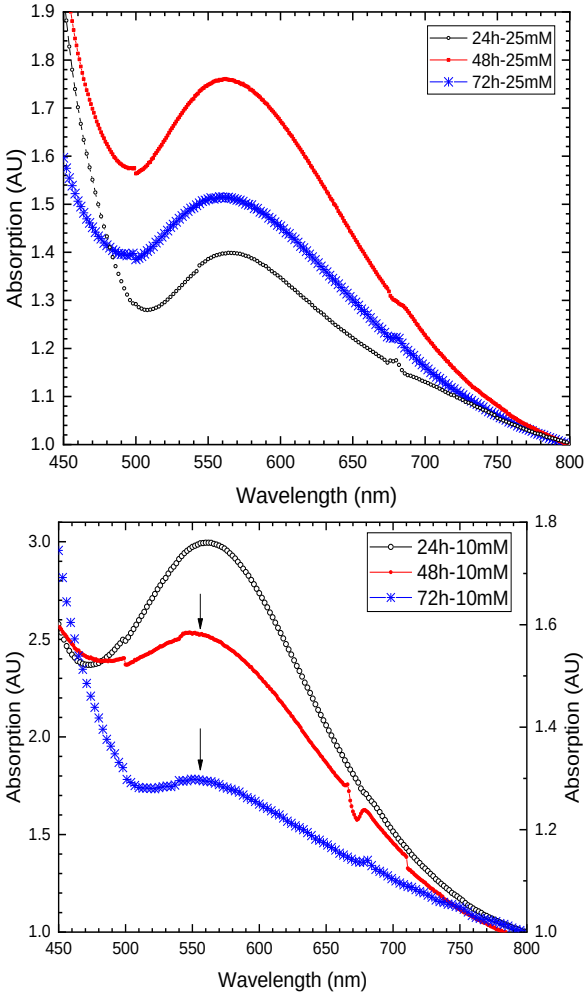

Fig. 5. The absorption spectra of the dispersed gold nanoparticles into the contact lens immersed to 25mM (top) and 10mM (bottom) $HAuCl_4$ solution for 24h, 48h and 72h. The graphs of 48h and 72h of immersion in 10mM of solution have been plotted in new scale (left "y" axis and have been shown by arrows).

The absorption spectra of the dispersed gold nanoparticles into the contact lens have been shown in Fig. 5 -for the contact lens immersed to 25mM and 10mM $HAuCl_4$ solution for 24h, 48h, and 72h- and the effect of the immersion time on absorption band was studied. The absorption spectra of the lenses with embedded gold nanoparticles in them are similar to the gold nanoparticles spectra, which confirms gold particles transformed to the gold nanoparticles in the soft contact lenses.

As it can be seen in Fig. 5, both samples show an absorption peak centered on 560nm. For the lens submerged in 25mM $HAuCl_4$ solution, the maxima happened at 566nm, 563nm, and 560nm, for 24h, 48h and 72h of immersion, respectively. These maxima are at 562nm, 554nm, 552nm for the lens immersed in 10mM $HAuCl_4$ solution, which belongs to spectra taken at 24h, 48h, and 72h of wallowing, respectively. So, in both samples, the peak wavelength slightly blue-shifted (a few nanometers) during the time. Besides, in both samples, by increasing the immersion time, the FWHM is increased. Agglomeration of the nanoparticles can affect the FWHM of absorption band. As aggregation and therefore the size of the particles is increased, the energy which is needed to relocate the electrons is decreased; therefore, the wavelength will be increased. In consequence, surface plasmon wavelength is increased, also FWHM is increased as a result of inhomogeneous nanoparticles dispersion [19]. The results express that increasing the band width of the absorption peak was caused by the agglomeration of bigger particles, and small particles which form a larger number of the particles in the solution and their size is smaller than the average size of the particles in the solution remain unchanged and responsible for absorption peak blue shift. As the increase of FWHM is not large, aggregation is not severe in the samples.

For the lens deepened in 25mM $HAuCl_4$ solution, the absorption intensity was increased after 48h of immersion with respect to the absorption peak recorded at 24h, then the intensity reduced after 72h, although it is still higher than the peak taken at 24h. Therefore, as both parameters of absorption intensity and band width are important, 48h lens immersion in 25mM $HAuCl_4$ solution gave us the optimum results. The trend of the absorption band was slightly different for lens deepened in 10mM $HAuCl_4$ solution. In this sample, by increasing the time, the absorption intensity decreased and the band width increased; hence, the optimum time for the sample sunk in 10mM $HAuCl_4$ solution is 24h to take out the lens from $HAuCl_4$ solution.

Absorption spectra of nanoparticles dispersed into the lenses immersed in different

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concentrations of $HAuCl_4$ solution in 24h and 48h of submergence are compared in Fig. 6. As it can be seen in this figure, a comparison of the absorption spectra of the lenses bathed in the 25mM and 10mM $HAuCl_4$ solution for 24h and 48h illustrates the peaks wavelength for the lens in 10mM solution are slightly smaller than the one in 25mM solution; they are 562nm and 554nm for the lens in 10mM $HAuCl_4$ solution in 24h and 48h of immersion, respectively, which are 566nm in 24h and 563nm in 48h for the lens in 25mM $HAuCl_4$ solution. Hence, it can be concluded that the nanoparticles formed in the lens immersed in the solution with lower concentration are slightly smaller than another sample, since different concentration leads to different rates of nucleation and growth and consequently different nanoparticles sizes [65]. However, it should be mentioned the difference between absorption bands wavelengths of two samples is not large and both samples are suitable for our aim in this study and block the region needed for CVD correction. If the size of the nanoparticles was larger than 100nm or smaller than 10nm, a large red or blue shift in absorption band wavelengths would occur. Therefore, the absorption wavelengths would not be matched to the wavelengths needed to be blocked for CVD correction. Absorbance intensity comparison shows in the 24h of immersion, the gold nanoparticles in lens deepened in 10mM solution have higher absorption intensity respect to the absorption intensity of the gold nanoparticles in the lens dunked in 25mM solution, the result is vice versa in 48h. The comparison of FWHM shows a similar trend, the band width is smaller for nanoparticles in lens immersed in 10mM solution in 24h measurements, while results of 48h measurements shows absorption band is narrower for the sample submerged in 25mM solution. These results confirm the optimum time for each concentration concluded from Fig. 5, the optimum immersion time of the sample in $HAuCl_4$ solution depends on the solution concentration, the lower concentration the smaller optimum immersion time.

In the next step of the experiment, two lenses that were dipped in the 25mM $HAuCl_4$ solution, were transferred to new environments to investigate their stability. One of them was transferred to the lens washing solution, and another one was transferred to the buffer saline solution (the solution that lens was kept in it by manufactory before usage), and their spectra were recorded at different times. The results are shown in Fig. 7.

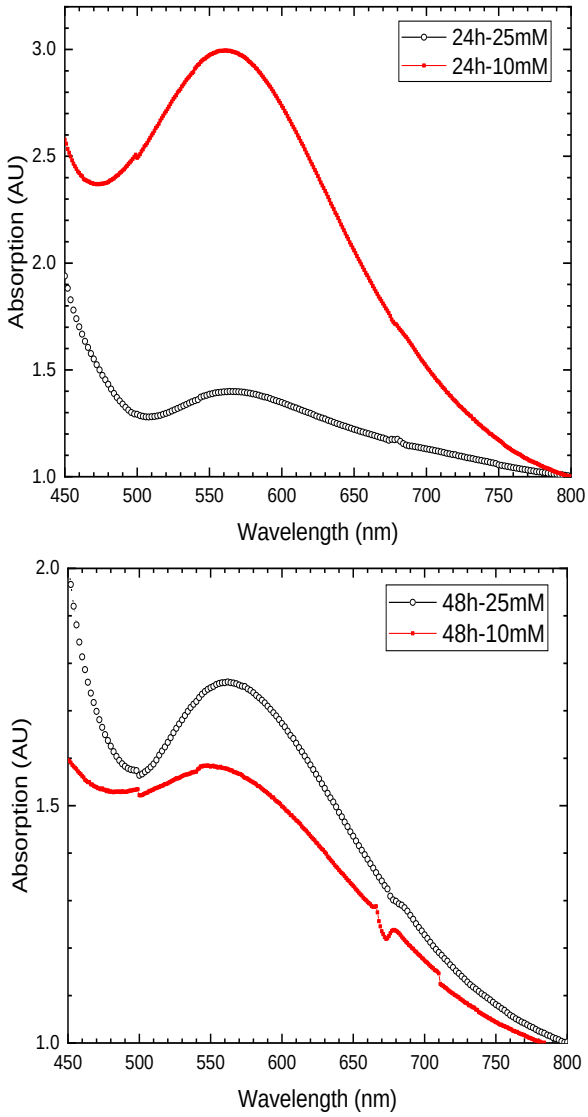

Fig. 6. Comparison of the absorption peak for the lenses in 25mM and 10mM $HAuCl_4$ solution in 24h (top) and 48h (bottom) of immersion.

For the sample translocated to the lens washing solution, the wavelength of the absorption band centered at 560nm (recorded in 72h of immersion in $HAuCl_4$ solution) was blue-shifted by 8nm when the sample was transferred to the lens washing solution. Absorption spectra were recorded after 24h, 48h, and 72h of transferring, and the wavelengths of absorption bands were constant

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during the time the sample was kept in the lens washing solution and for all spectra, it centered at 552nm.

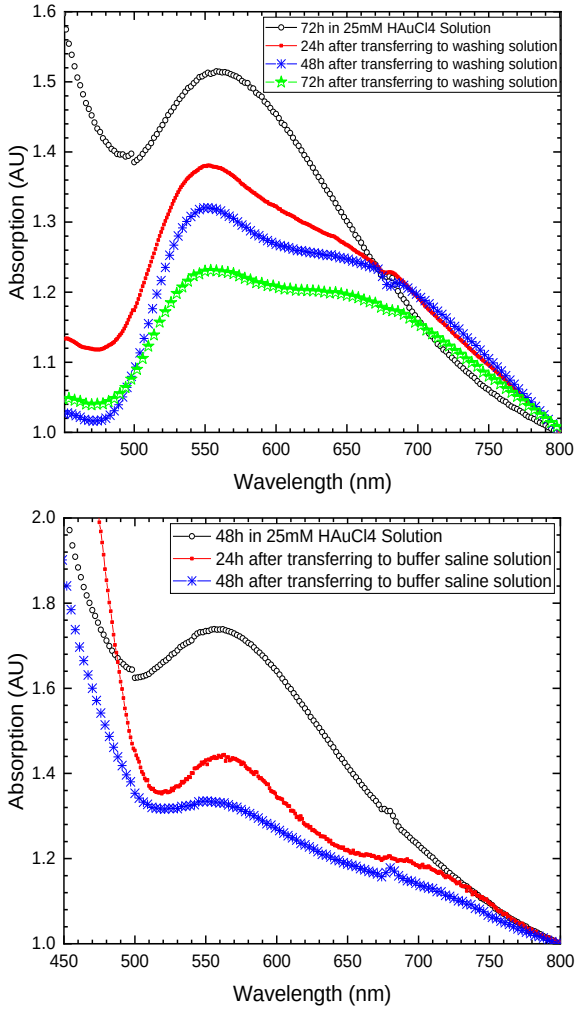

Fig. 7. Absorption spectra of the sample transferred to lens washing solution (top) and buffer saline solution (bottom).

However, the spectra of the displaced sample show another band has arisen centered around 630nm. So, it can be concluded the nanoparticles that were slightly bigger than the rest agglomerated to the larger nanoparticles and are responsible of the peak at 630nm. The smaller particles remained unchanged in the sample and the original absorption peak centered at 560nm was slightly blue-shifted by transferring and centered at 552nm. It seems the size of these small particles is smaller than the average particles' size in the original sample, so the absorption band was blue shifted. Spectra depict translocating the sample to the lens washing solution caused the absorbance intensity to be reduced. However, by increasing the time after relocating while the intensity of both bands decreased, the ratio of the second band to the first band increased by the time which shows the number of agglomerations increased. FWHM of the first absorption band of the transferred sample is smaller than the FWHM of the original sample absorption band that confirms smaller particles are not agglomerated and are responsible for that blue-shift. However, both the first and the second bands in transferred sample spectra were widened by increasing the time after transferring. SEM and TEM were recorded after one week of translocating of the samples to the washing solution and they show the size of the nanoparticles is around 100nm. However, according to the spectra belong to transferred samples and emerging of the new band at 630nm, it can be concluded the size of the primary nanoparticles (before relocating) were smaller, it is confirmed by TEM images of nanoparticles in the immersed lens in $HAuCl_4$ solution for 48h. As it has been mentioned earlier, the size of the primary nanoparticles was less than 50nm.

For the sample transferred after 48h to the buffer saline solution, the center of the peak is almost constant after 24h of transferring (red-shifted by 3nm) and the absorption band show blue-shift by 7nm after 48h of transferring to the buffer saline solution, similar to another sample translocated to the lens washing solution. The spectra of the sample transferred to the saline buffer solution also show the second band centered around 675nm that means the agglomeration of the bigger nanoparticles when the sample relocated to the saline buffer solution, but the smaller nanoparticles did not agglomerate, same as the sample transferred to the lens washing solution. The intensity of the absorption peak reduced when the sample was transferred to the buffer saline solution. The absorbance intensity for both bands decreased by increasing the time after relocating, although the ratio of decreasing the intensity of the first band is larger than the intensity decreasing ratio of the second band, it shows agglomeration of the nanoparticles by the time, however it is very slow. Similar to the previous sample, FWHM of the first absorption band of the transferred

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sample to the saline buffer solution is narrower than the width of original sample absorption band (because of the unchanged small particles and agglomeration of large particles that caused emerging the second absorbance band at longer wavelengths); however, both first and second bands became wider by increasing the time after transferring.

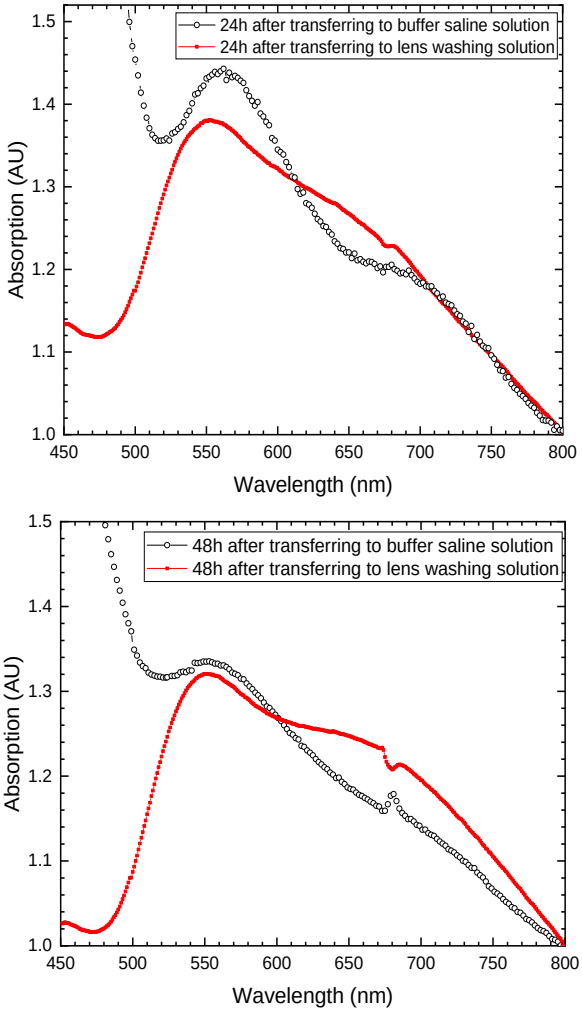

Fig. 8. Comparison of absorption spectra of the samples transferred to lens washing solution and buffer saline solution 24h (top) and 48h (bottom) after displacement.

The absorption spectra for the samples transferred to the lens washing solution and buffer saline solution have been compared 24h and 48h after transferring, the results are shown in Fig. 8.

As it can be seen in Fig. 8, in both displaced samples to the new environments by decreasing the absorption intensity of the peak around 560nm the second band arose in the longer wavelengths. The second absorption band of the sample transferred to buffer saline solution has a longer wavelength than the one transferred to the lens washing solution which shows its nanoparticles agglomerated to the bigger clusters. Comparing FWHM of the first absorption bands with each other measured 24h after relocation shows this band in the spectrum of the sample transferred to the buffer saline solution is slightly narrower than the band belong to the transferred sample to the washing solution, while 48h after relocation the first absorption band of the sample in buffer saline solution became much wider than the one in the lens washing solution.

To investigate whether these lenses with dispersed plasmonic gold nanoparticles in them are a suitable replacement to the tinted glasses and lenses or not, their optical properties need to be compared. The vision spectra of CVD patients overlap around 560nm, so the wavelengths between 540nm to 580nm should be filtered. It is important to avoid blockage other wavelengths and altering the colors, patients can distinct properly. We have considered this parameter in our design. The results depict our samples have the absorption band centered in this wavelength and it is not a very wide band, while Vino glasses filter light from 520nm to 585nm (65nm) which is a broad absorption band [11]. As the blocked region by vino glasses is wide and also have a shift with respect to the desired wavelengths, it blocks a wide range of the wavelengths that patients do not have problem in that region, so it eliminates or alters the shades of the colors that patients can distinguish correctly. As it can be seen in Fig. 9, Enchroma glasses filter three parts of the vision spectrum which consist of the wavelengths that CVD patients have not difficulties in color distinguishing in those spectral ranges. The maximum blockage happens at 594nm, which seems it has red-shifted respect to the desired wavelengths and it has higher transmittance in the overlapped region at 560nm. As the gold nanoparticles are biocompatible and filter only the region of overlapped wavelengths in CVD patients' vision spectrum, the lenses with dispersed gold nanoparticles in them investigated in this study can be more functional and better than tinted

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glasses in CVD correction. Figure 9 compares the blocked wavelengths by VINO and Enchroma dyed glasses with lenses contained gold nanoparticles.

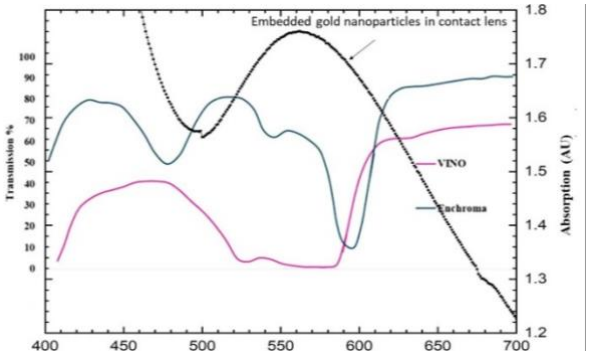

Fig. 9. Enchroma and VINO glasses spectra are compared with absorption spectrum of embedded gold nanoparticles in the soft contact lens (the graph of contact lens contain Au nanoparticles has been shown by arrow) [11, 15].

IV. Conclusion

In this study, we have investigated a new and simple method to improve color vision in CVD patients. In our method, the plasmonic gold nanoparticles have been utilized to take benefit of the extraordinary optical properties of these nanoparticles. We have dispersed the nanoparticles into the soft contact lenses to block light in the desired wavelengths range that CVD patients cannot distinguish colors in it. The wavelengths that red-green type CVD patients' vision spectra have overlap and should be eliminated ranges from 540nm to 580nm centered at 560nm. Our samples are designed to block this region in a narrow band. Compared to other glasses and lenses designed for this aim, our samples filter exactly the desired wavelengths which are narrower than the region-blocked by other devices. Also, as gold nanoparticles are biocompatible, these lenses with embedded gold nanoparticles can be a good replacement for tinted glasses and lenses.

Appendix A

The absorption spectrum of lens washing solution involved nanoparticles shows a band corresponding to gold nanoparticles absorption band (Fig. A-1).

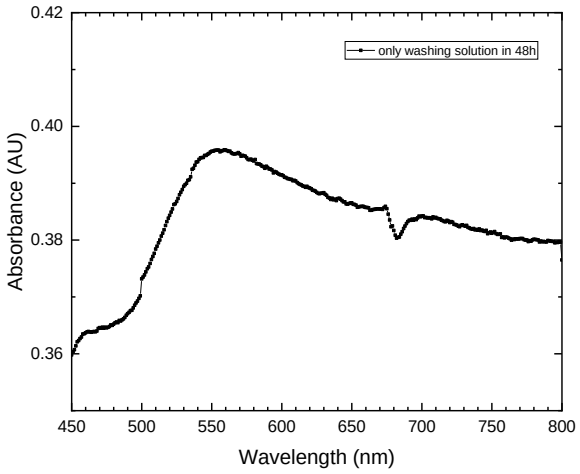

Fig. A-1. The absorption spectrum of the lens washing solution after transferring the lens with embedded nanoparticles to this solution.

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