

Synthesis of polymer-grafted gold nanoparticles via gamma radiation^{*})

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Abstract: The research focused on the synthesis of polytetrafluoroethylene (PTFE) grafted with gold nanoparticles (AuNP). The Turkevich method, one of the common techniques of AuNP synthesis, was used to obtain an AuNP solution with a nanoparticle size of 20 nm. The PTFE-AuNP samples were subsequently irradiated and the absorbed doses were 0.5, 2, 5, 10 and 20 kGy. It was noticed that samples irradiated with 0.5 and 2 kGy were less stable and less concentrated than samples irradiated with higher doses due to aggregation and formation of precipitation after 30 days.

Keywords: gold nanoparticles, polymer, grafting, radiosensitizers.

Synteza polimerów szczepionych nanocząstkami złota z wykorzystaniem promieniowania gamma

Streszczenie: W artykule omówiono technikę syntezy poli(tetrafluoroetyleny) (PTFE) szczepionego nanocząstkami złota (AuNP). Metodą Turkevicha, jedną z powszechnie stosowanych technik syntezy AuNP, uzyskano roztwór AuNP o wielkości cząstek 20 nm. Próbkę roztworu PTFE-AuNP były następnie naświetlane promieniowaniem gamma; zaabsorbowane dawki promieniowania wyniosły 0,5, 2, 5, 10 oraz 20 kGy. Stwierdzono, że w przypadku dawek 0,5 i 2 kGy roztwór był mniej stabilny, a stężenie nanocząstek było niższe niż w przypadku wyższych dawek. Wiązało się to z agregacją i precypitacją nanocząstek po upływie 30 dni od naświetlania.

Słowa kluczowe: nanocząstki złota, polimer, szczepienie, radiouczulacze.

Gold has generally been a precious metal since the beginning of human civilization and is versatile in every aspect of daily life from currency and jewellery to industry as well as medicine. Gold nanoparticles (AuNP) are one of the materials that provide benefits in the engineering of nanomaterials for radiotherapy, diagnostics, and even theranostics due to their shape and size-dependent properties [1], strong surface Plasmon resonance properties [2, 3], and excellent biocompatibility [4].

Various approaches can be used to produce gold nanoparticles such as the Turkevich method [5], Brust-Schiffrin [6], seed-mediated growth [7] and others with

each having its advantages and disadvantages. The Turkevich method was chosen for this study because it can produce spherical AuNPs of size 10 nm up to 30 nm and its monodispersity is in a satisfactory range. Another advantage of this method is that the citrate ions take on a double role, acting as a reducing agent and a stabilizing agent [8]. This method can also be used to produce AuNP with a size of more than 30 nm but the polydispersity of the AuNP solution will be higher and the quality of its spherical shape will also be affected [9].

Monodisperse AuNP solution can provide clearer diagnostic results [10] and precise delivery of ionizing radiation in radiotherapy [11] compared to polydisperse AuNP solution. To exploit these advantages, this study takes the approach through centrifugation method to produce a monodisperse AuNP solution. There are various ways to separate AuNP solutions according to size such as size exclusion chromatography [12] and gel electrophoresis [13]. However, each of these methods is time consuming and requires secondary chemical modifications to the nanoparticles.

Polymer grafted AuNP as radiosensitizing agent has a great potential in the scientific community and medi-

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cal sector. The booming of research and study related to AuNP in recent years could lead to its usage in medical practice in just around the corner. The type of polymers and way to synthesize them together with grafting to or from AuNP are limitless and each and every one of them has unique characteristics and benefit that could be reaped for more precise and targeted radiotherapy. Polymer-grafted gold nanoparticles improve the issue of AuNP in biological media by ensuring good dispersibility and long-term stability [14].

When the size of particle decreases, the wavelength of SPR related absorption shifts to shorter, bluer wavelength (blueshift) and vice versa [15]. By altering the form or size of the AuNP, the SPR could be controlled, resulting in particles with specific optical properties for various applications [16]. Based on this phenomenon, the wavelength of a particular AuNP solution could determine the approximate size of AuNP particles inside it [9].

EXPERIMENTAL PART

Materials

All flasks were washed with aqua regia solution before use to clean them out of contaminants such as precious metal substrates [17]. Aqua regia was produced by mixing hydrochloric acid and concentrated nitric acid (both obtained from Sigma-Aldrich) with a volume ratio of 3:1. The materials used to synthesize gold nanoparticles were chloroauric acid (HAuCl_4) (99.995% trace metal basis) and dehydrated trisodium citrate (Na_3Ct), both obtained from Sigma-Aldrich. Deionized water was also used in each procedure. All materials listed were used directly without additional purification.

AuNP synthesis

In synthesizing of gold nanoparticles (AuNP), 100 ml of 0.5 mM HAuCl_4 solution in a volumetric flask and 1.0 wt% of Na_3Ct solution were prepared. The flask containing HAuCl_4 solution was heated continuously by a heating plate and stirred rapidly with a magnetic stirrer. When the HAuCl_4 solution reached its boiling point (100°C), 4.13 ml of Na_3Ct solution was rapidly injected into the HAuCl_4 solution [9]. AuNP synthesis was completed when there were no changes of suspension's color. This particular reaction could take 2 to 5 minutes, depending on the molar ratio (MR). Finally, the samples were allowed to cool down to room temperature.

PTFE-AuNP synthesis

The PTFE solution was added to AuNP solution in molar ratio of 10:1 (PTFE:AuNP) and after that was bubbled with nitrogen for 15 minutes to remove possible dissolved gases. Gammacell 220 from Nordion, a fully self-contained research irradiator that provides high-intensity gamma radiation, was used to irradiate the PTFE-AuNP samples with doses 0.5, 2, 5, 10 and 20 kGy. 2 ml of each irradiated sample was centrifuged at 7,000 g-force for 30 minutes using Eppendorf F-45-12-11 [18]. The centrifugation process increased the concentration of PTFE-AuNP and the PTFE-AuNP pellets were thereafter redispersed to receive washed PTFE-AuNP solution.

The optical properties of AuNP were examined via ultraviolet-visible (UV-Vis) spectrometry using Lambda 35 from Perkin Elmer after being left on shelf for 30 days. Samples were prepared in a U-shaped bottom ultraviolet (UV) quartz cuvette by diluting 1 ml of PTFE-AuNP solu-

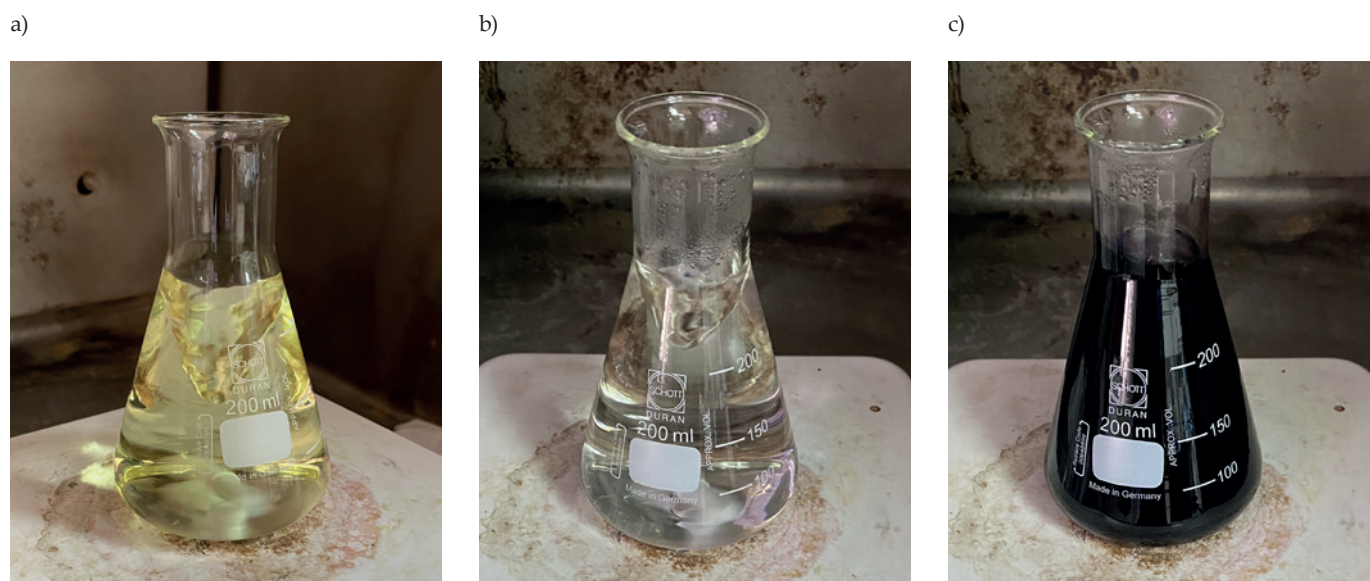


Fig. 1. The changes of HAuCl_4 solution color: a) yellow (before AuNP synthesis reaction took place), b) clear solution (first stage of AuNP synthesis), c) deep purple (after fourth stage of AuNP synthesis)



Fig. 2. Final red wine color of washed PTFE-AuNP solution

tion with 3 ml of ionized water. The wavelength used in measurements was 300 to 800 nm.

RESULTS AND DISCUSSION

Color changes in synthesized AuNP

According to the recent study by Polte *et al.* [19], the reason of color changes during synthesis of AuNP solution are the three phases of AuNP synthesis, from rapid nucleation through random attachment to intraparticle ripening observed under various reaction circumstances.

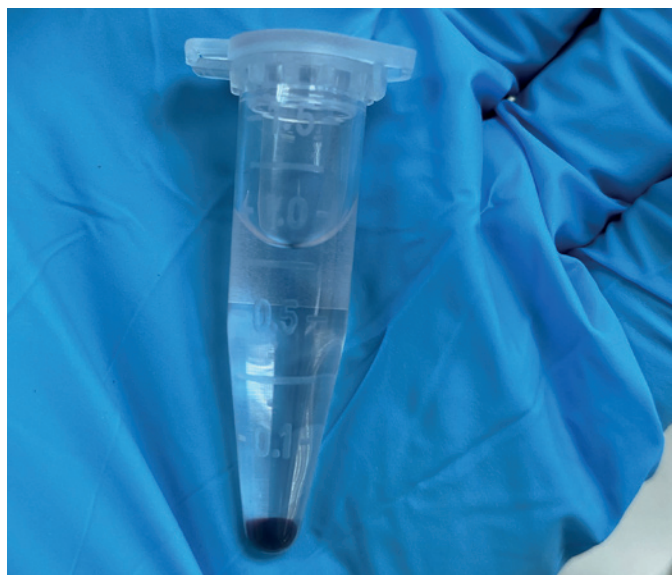
These three phases of AuNP could be demonstrated as a four-step nucleation and growth process, with the initial phase splitted into two steps [19]. The initial color of HAuCl_4 solution was yellow due to no reaction taking place (Fig. 1a). After addition Na_3Ct into HAuCl_4 solution, the transition from yellow to clear solution was observed (Fig. 1b) and could be explained by a rapid production of small nuclei (first stage) and afterwards either the nuclei coalescing [9] or Ostwald ripening [20] into larger particles (second stage). At the third stage, additional coalescence and continuous gold precursor reduction promoted the particles' slow growth of diffusion. In the last stage, the color of AuNP solution turned into deep purple (Fig. 1c), and later into red wine color (Fig. 2), when the particles grew rapidly reaching their final size, as a result of complete consumption of the precursor species [21].

On the way of centrifugation process it was possible to extract PTFE-AuNP pellet (Fig. 3a) and isolate them from contaminants in the supernatant obtained in the PTFE-AuNP solution. Similar observations are described by S.K. Balasubramanian *et al.* [18], who separated AuNP colloids in form of pellets and purified from non-AuNP components (supernatant) using two rounds of centrifugation of 1 ml of freshly synthesized AuNP solution at different centrifugation forces [18]. The washed solution of PTFE-AuNP (Fig. 3b) was obtained by redispersion of PTFE-AuNP pellets in ionized water of its original volume.

Ultraviolet-visible spectrophotometry (UV-Vis)

In Figure 4, the results of researches on optical absorbance of PTFE-AuNP solution using ultraviolet-visible spectrophotometry (UV-Vis) are presented. At 520 nm a peak was observed, which suggested that the size of

a)



b)



Fig. 3. Isolated PTFE-AuNP pellets (a) and washed PTFE-AuNP solution after redispersion of pellets in water (b)

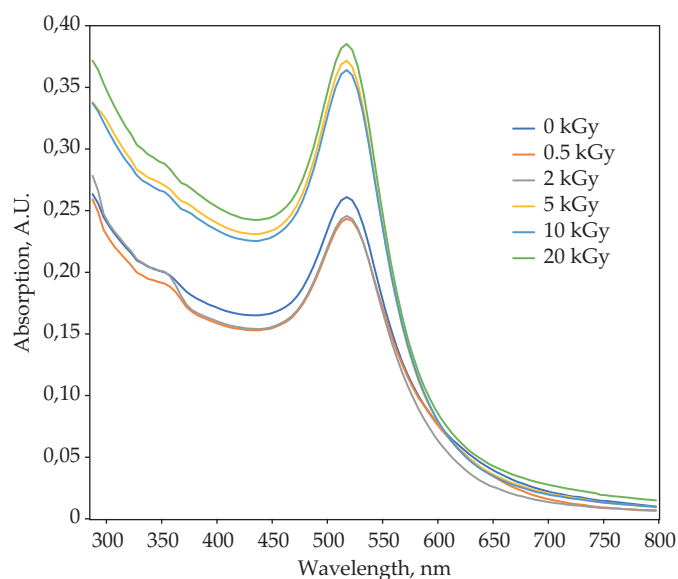


Fig. 4. Optical absorbance of PTFE-AuNP samples irradiated with various doses, the difference in curves between low and high doses could be observed

the obtained PTFE-AuNP particles was approximately 20 nm. The similar findings were done by Li *et al.*, who obtained size of particles AuNP equal 20 nm using TEM analysis and noticed 520 nm band in UV-Vis [22]. In addition, Xing *et al.* synthesized graphene oxide/AuNP composite (GO/AuNP) and reported the absorption peak at 520 nm (UV-Vis) for 20 AuNP as well [23].

Current study showed the difference in optical absorbance of PTFE-AuNP samples irradiated with 0.5 and 2 kGy dose (Fig. 4) compared to other doses. The difference in curves could be explained by aggregation of PTFE-AuNP which occurred at lower doses (0.5 and 2 kGy) and was verified by visible precipitation in samples irradiated with 2 kGy (Figs. 5b and 5c). The irradiation doses were found not to have a significant influence on the size of PTFE-AuNP obtained in this study. The absorption peak was found to retain at 520 nm regardless the doses used (Fig. 4). Non-irradiated AuNP were well diffused, despite some aggregation (Fig. 5a), while no aggregation was visible in PTFE-AuNP samples irradiated with 5, 10 and 20 kGy (Figs. 5d, 5e and 5f). Le Goas *et al.* noticed that irradiated with 4 and 20 kGy of gamma radiation poly(methacrylic acid)-grafted AuNP (PMAA-AuNP) and poly(2-hydroxyethylmethacrylate-meth-

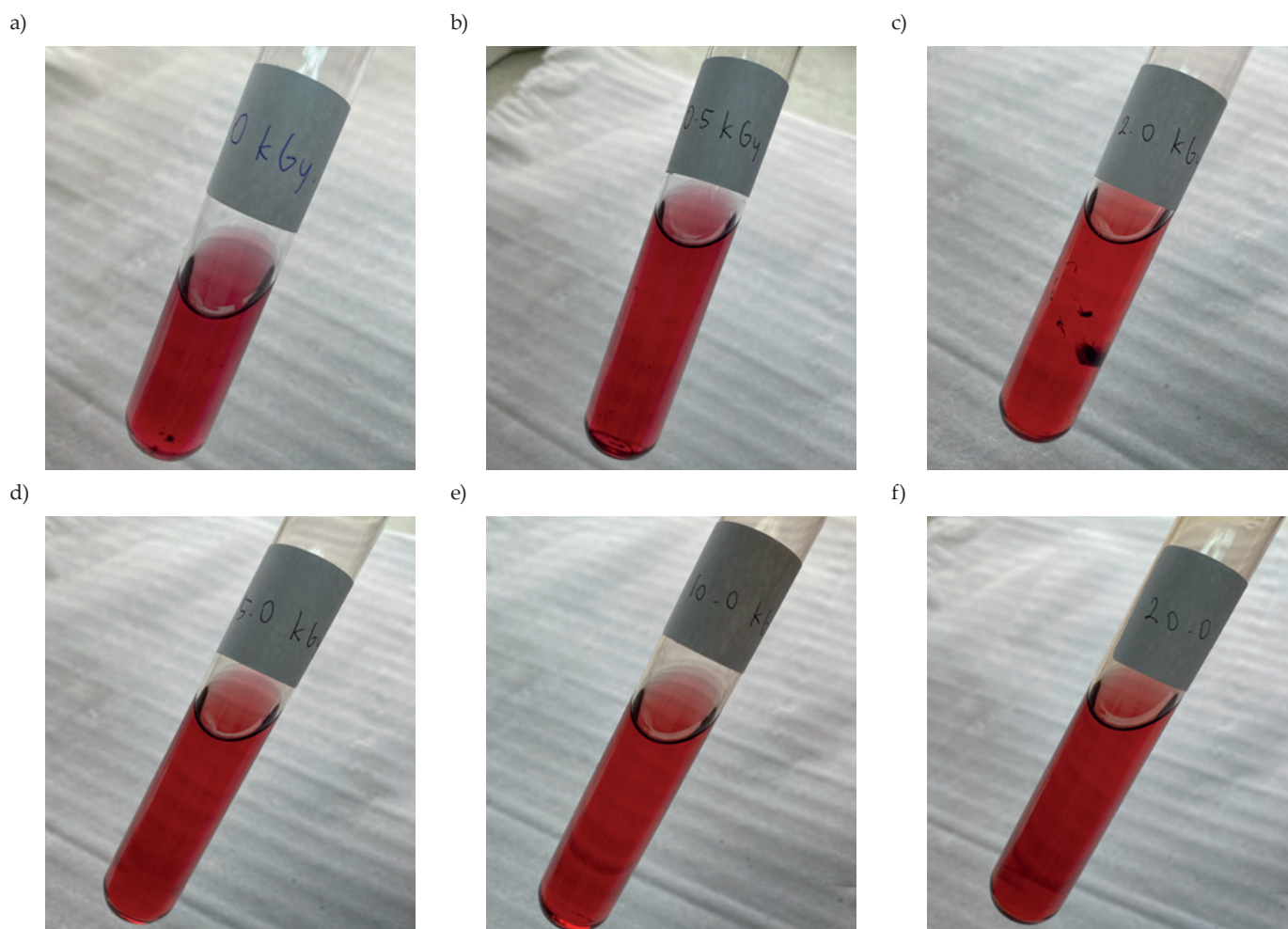


Fig. 5. PTFE-AuNP solution samples: non-irradiated (a) and irradiated with dose of b) 0.5 kGy (low aggregation), c) 2 kGy (high aggregation), d) 5 kGy, e) 10 kGy, f) 20 kGy

acrylic acid)-grafted AuNP [P(HEMA-MAA)-AuNP] exhibited no aggregation under TEM analysis [14].

CONCLUSION

This study shows that the four-step mechanism of AuNP synthesis could be seen via naked eye by observing its color changing. The UV-Vis data obtained showed that the size of PTFE-AuNP particles produced was 20 nm with 520 nm absorption peak value. With absorbed dose of 0.5 and 2 kGy, long-term shelf life was lower compared to 5, 10 and 20 kGy due to more visible aggregation within 30 days. Overall, the Turkevich method is one of simple methods to synthesize 20 nm AuNP and centrifugation provides quick and reliable washing of AuNP solution. Future research regarding mechanism of grafting polymer to AuNP surface would be explored.

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