

Antimicrobial activity of silver nanoparticles encapsulated in poly-*N*-isopropylacrylamide-based polymeric nanoparticles

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Abstract: In this study, we analyzed the antimicrobial activities of poly-*N*-isopropylacrylamide (pNIPAM)-based polymeric nanoparticles encapsulating silver nanoparticles (AgNPs). Three sizes of AgNP-encapsulating pNIPAM- and pNIPAM-NH₂-based polymeric nanoparticles were fabricated. Highly stable and uniformly distributed AgNPs were encapsulated within polymeric nanoparticles via in situ reduction of AgNO₃ using NaBH₄ as the reducing agent. The formation and distribution of AgNPs was confirmed by UV-visible spectroscopy, transmission electron microscopy, and inductively coupled plasma optical emission spectrometry, respectively. Both polymeric nanoparticles showed significant bacteriostatic activities against Gram-negative (*Escherichia coli*) and Gram-positive (*Staphylococcus aureus*) bacteria depending on the nanoparticle size and amount of AgNO₃ used during fabrication.

Keywords: pNIPAM, silver nanoparticles, antimicrobial activities, surface charge

Introduction

Various bacteria and fungi cause postsurgical infections. Such infections are frequently associated with biomedical implants, including prosthetic joints and fracture fixation materials.¹⁻³ Because of the slow progress of such infections, detecting them at an early stage is challenging. In the absence of an effective antibiotic, failure to treat postsurgical infections with classical antibiotics is a serious global issue.^{1,4,5} A bacterial strain carrying the *NDM-1* gene was recently reported to be resistant to strong antibiotics; thus, microbial drug resistance and the lack of effective antimicrobial agents pose great challenges.⁶

Non-conventional treatments for microbial infections include antimicrobial peptides, small molecule inhibitors, naturopathic therapy, phytotherapy, and metallic particles.⁷⁻⁹ Previously, the use of silver nanoparticles (AgNPs) was suggested for eliminating microbial infections.¹⁰ Broad-spectrum antimicrobial activities of Ag against pathogens, including both Gram-positive and Gram-negative bacteria, have been reported.^{11,12} Ag was complexed with other materials to give them with antibacterial properties. For example, the antimicrobial activity of Ag-impregnated nylon fibers against *Staphylococcus aureus* and *Candida albicans* was evaluated for wound dressing.^{13,14} AgNPs have also been used to treat *Escherichia coli* because of their ability to damage bacterial cell walls.¹⁵ Currently, AgNPs in burn ointments, wound dressings, and Ag-coated medical devices such as catheters, vascular grafts, and endotracheal tubes are used to prevent and treat bacterial infections.¹⁶⁻¹⁸

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Polymeric nanoparticles are an excellent vehicle for AgNP delivery because they can easily be modified according to the target site; moreover, their size, morphology, and surface charge can be controlled by changing the ratio of monomer to cross-linker during nanoparticle fabrication.^{19,20} Another advantage of encapsulating AgNPs inside a polymeric nanoparticle is that nanoparticles distributed in a polymeric nanoparticle show low aggregation.^{21,22} Moreover, polymeric nanoparticles reduce concerns regarding the cytotoxicity of AgNPs because the gel limits the direct exposure of a patient's cells to AgNPs and release AgNPs slowly.^{23,24} Previously, it was reported that encapsulation of AgNPs inside a polymeric nanoparticle did not affect the size and morphology of the nanocomposite.²⁵ Polymeric nanoparticles are an attractive vehicle for sustained AgNP release during local therapy because of their tunable size, numerous functional groups, thermo-responsiveness, high loading capacity, good stability, biocompatibility, and anionic charge.^{21,24,26}

In this study, we fabricated three sizes of two polymeric nanoparticle types: poly-*N*-isopropylacrylamide (pNIPAM) and pNIPAM-NH₂. In each polymeric nanoparticle, we encapsulated three different concentrations of AgNPs using a water-soluble reducing agent. We then examined the effects of polymeric nanoparticle surface charge and AgNP concentration on antimicrobial activity against Gram-negative (*E. coli*) and Gram-positive (*S. aureus*) bacteria. Our aim was to increase antimicrobial activity by encapsulating AgNPs inside a polymeric nanoparticle to limit their cell uptake and cytotoxicity. Our AgNP-encapsulated polymeric nanoparticles (AgNP-pNIPAM/pNIPAM-NH₂ nanoparticles) showed significant bacteriostatic activities against *E. coli* and *S. aureus* that were dependent on nanoparticle size and AgNO₃ concentration. The resulting AgNP-pNIPAM/pNIPAM-NH₂ polymeric nanocomposite can be developed for antimicrobial bioengineering applications.

Materials and methods

Materials

NIPAM, AgNO₃, NaOH, sodium dodecyl sulfate, and NaBH₄ were purchased from Sigma-Aldrich Co. (St Louis, MO, USA) and used after further purification through recrystallization. Ammonium persulfate (APS), *N,N*-methylenebisacrylamide (BIS), and *N*-(3-aminopropyl) methacrylamide hydrochloride (APMAAHC) were purchased from Polysciences (Warrington, PA, USA). Luria-Bertani (LB) broth medium was purchased from Oxoid (Basingstoke, UK). *E. coli* (25922) and *S. aureus* (25923) were purchased from ATCC (Manassas, VA, USA). DMEM containing glucose, phosphate-buffered saline, fetal bovine serum, penicillin G

(pen; 10,000 U/mL), streptomycin (strep; 100 µg/mL), and amphotericin B (AmB; 25 µg/mL) were purchased from GE Healthcare Life Sciences (Little Chalfont, UK). Human adipose tissue was obtained from the Korea Cancer Center Hospital under the guidelines of the Institutional Review Board at Chung-Ang University (Seoul, South Korea). MTT and DMSO were purchased from Sigma-Aldrich Co. Deionized water (DW) was used to prepare solutions and for washing. All chemicals were used as received without further purification.

Synthesis of pNIPAM/pNIPAM-NH₂ nanoparticles

pNIPAM nanoparticles were fabricated by conventional radical polymerization of NIPAM.^{28,29} Depending on the NIPAM to cross-linker ratio, three different sizes of pNIPAM nanoparticles (between 100–500 nm) were prepared. Specifically, 0.95 g of NIPAM with different amounts of BIS (0.026 g for 50:1, 0.013 g for 100:1, and 0.0065 g for 200:1) was dissolved in 195 mL of DW, and the resulting solutions were transferred into a three-necked round-bottomed flask with a constant supply of argon gas. Sodium dodecyl sulfate was added in the same ratio as BIS as a surfactant. The solution was heated to 58°C–65°C with a constant supply of argon gas for 1 h. Next, 5 mL of APS solution (0.12 g of APS dissolved in 5 mL of DW) was injected into the solution to initiate polymerization and the reaction was allowed to proceed for 4 h.³⁰ Argon gas was purged through the solution until the end of the reaction to avoid any contact with oxygen, which may intercept radicals and disrupt polymerization. The resulting dispersion was dialyzed in DW using a porous membrane (6,000–8,000 Da molecular weight cutoff) and freeze-dried. The resulting pNIPAM-based nanoparticles are referred to as G1, G2, and G3, representing the nanoparticles prepared using three NIPAM:BIS ratios (0.0065 g BIS for 200:1, 0.013 g BIS for 100:1, and 0.026 g BIS for 50:1, respectively), as shown in Figure 1A. To fabricate polymeric nanoparticles with an amine (NH₂) group, 0.065 g of APMAAHC was added to the three different NIPAM:BIS ratio reaction solutions, creating three different sizes of pNIPAM-NH₂ nanoparticles. The resulting pNIPAM-NH₂-based polymeric nanoparticles were similarly referred to as G1, G2, and G3, as shown in Figure 1B. The sizes of the prepared polymeric nanoparticles were characterized by dynamic light scattering (DLS).

Preparation of AgNP-polymeric nanoparticles

To encapsulate AgNPs inside the polymeric nanoparticles, 30 mg of each polymeric nanoparticle (ie, G1, G2, and G3

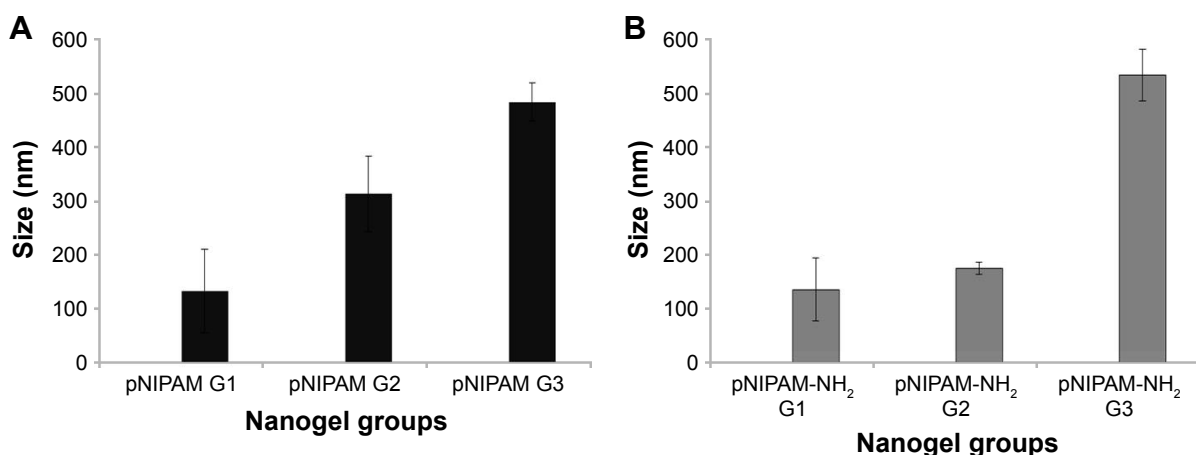


Figure 1 Average sizes of poly-*N*-isopropylacrylamide (pNIPAM) nanoparticle groups G1–G3 (A), and average sizes of pNIPAM-NH₂ nanoparticle groups G1–G3 (B).

with and without NH₂) was first incubated in 10 mM NaBH₄ solution in DW (5 mL) for 5 h. Next, the solutions were mixed with freshly prepared AgNO₃ solution (pH 7.0, 5 mL) and further incubated for 5 h at room temperature.³¹ Before use, the pH of the AgNO₃ solutions was adjusted to pH 7 with NaOH and a pH meter. The AgNO₃ and polymeric nanoparticle solutions were centrifuged at 11,000 rpm for 40 min and then washed with DW. This process was repeated three times to remove unreduced Ag⁺ or excess AgNPs located outside the polymeric nanoparticle network. Finally, 5 mL of DW was added to each sample before storing it at 8°C. After washing, the AgNP pNIPAM/pNIPAM-NH₂ nanoparticle composites were characterized by UV-visible spectroscopy, transmission electron microscopy (TEM), and inductively-coupled plasma optical emission spectrometry (ICP-OES). The overall fabrication scheme was described in Figure 2.

Characterization of AgNP-encapsulating polymeric nanoparticles

The sizes of three fabricated pNIPAM and pNIPAM-NH₂ polymeric nanoparticles were determined by DLS using a Zetasizer Nano ZS (Malvern Instruments, Malvern, UK). The mean particle diameter (z-average) and particle size distribution (polydispersity index) were measured at 25°C. The spectral absorption of the three AgNP-encapsulating pNIPAM and pNIPAM-NH₂ nanoparticle size groups was

assessed using a UV-visible spectrophotometer (SynergyTM HT reader, BioTek Instruments, Winooski, VT, USA) in the range of 300–600 nm.²⁷ All experiments were performed in triplicate to determine mean and SD values. The compositions of the resulting AgNP-encapsulating pNIPAM and pNIPAM-NH₂ nanoparticle size groups were determined by ICP-OES. The morphological characteristics of the AgNP-encapsulating pNIPAM and pNIPAM-NH₂ nanoparticle groups were observed by high-resolution TEM (JEM 3010, JEOL, Tokyo, Japan). For TEM, a drop of AgNP-encapsulating polymeric nanoparticles solution in DW was placed on a copper grid and allowed to dry at room temperature, and then placed in the sample holder of the TEM instrument and analyzed.

Assessment of antimicrobial activity

Liquid culture

The antimicrobial activities of the prepared AgNP-polymeric nanoparticles against *E. coli* and *S. aureus* were investigated. All bacterial cultures were performed in LB broth. To promote the transition of bacterial cultures into the exponential growth phase, single colonies of *E. coli* or *S. aureus* were transferred to separate flasks containing LB broth and incubated overnight at 37°C with shaking at 175 rpm, and then diluted to 10⁸ CFU/mL based on the OD at 600 nm (OD₆₀₀=1). To evaluate the antimicrobial activities of the AgNP



Figure 2 Schematic diagram of the synthesis of silver nanoparticle (AgNP)-encapsulated poly-*N*-isopropylacrylamide (pNIPAM)-based nanoparticle platforms. **Abbreviations:** APS, ammonium persulfate; RT, room temperature; SDS, sodium dodecyl sulfate.

pNIPAM/pNIPAM-NH₂ nanoparticle size groups, 40 µL of each polymeric nanoparticle-AgNP composite (G1, G2, and G3 with and without NH₂) were added to 160 µL of bacterial suspension (10⁸ CFU/mL) during the exponential growth phase in 96-well plates, and the samples were incubated at 37°C. Pure cultures were used as positive controls and culture media without cells were used as a negative control. All groups were cultured in triplicate. Bacterial growth was monitored by determining the OD of the bacterial suspension at 600 nm⁴ and the OD₆₀₀ values were recorded at 0, 1, 2, 3, 4, 5, and 24 h of incubation.

Plate diffusion method

To investigate the antimicrobial activity of AgNPs encapsulated in nanogels on solid media, *E. coli* and *S. aureus* (1×10⁶ cells/mL) were cultured on MH agar plates and the plates were dried at room temperature. A well, 8 mm in diameter, was made in each plate by gel puncture. Next, 1 mg/mL of each nanogel with AgNPs was dissolved in autoclaved distilled water and 0.5 mL of this solution was applied to the plates. Each test was performed in triplicate and a pure bacterial culture was used as a control. The plates were incubated at 37°C for 24 h. Antimicrobial activity was measured as the average diameter (mm) of the zone of inhibition around each well.³²

X-ray photoelectron spectroscopy (XPS) analysis

XPS was performed using a Leybold LH Max 200 surface analysis system (Leybold, Cologne, Germany) operated with an Mg Kα source, 200 W. Prior to XPS analysis, all samples were thoroughly dried under vacuum. Data analysis was carried out using the Origin 8 analysis programs. The binding energy scales of the high resolution spectra were calibrated by assigning the most intense C1s high resolution peak a binding energy of 286.08 eV (C–N) and 287.58 eV (C=O). A linear function was used to model the background.

Cytotoxicity assay

The cytotoxicities of the AgNP-polymeric nanoparticles to human adipose stem cells (hASCs) were determined by the MTT assay. The study was approved by the ethical review board of Chung Ang University and prior informed consent was signed by the tissue donor. The hASCs were cultured in DMEM containing 10% fetal bovine serum and 1% antibiotic-antimycotic solution (pen/strep/AmB) at room temperature under a 5% CO₂ atmosphere in a humidified incubator. A cell suspension (80 µL; 5,000 cells/well) was mixed with 20 µL

of AgNP-polymeric nanoparticles on a 96-well plate for the MTT assay. A suspension of hASCs (80 µL) with 20 µL of DW and no nanoparticle was seeded as a positive control. In a different plate, hASC suspensions containing 20 µL of each size group of the pNIPAM and pNIPAM-NH₂ AgNP-nanoparticles were seeded. Each size group (G1, G2, and G3 with and without NH₂) was tested in triplicate.

According to the instructions from the MTT assay supplier (Sigma-Aldrich Co.), after incubating the cultures for 48 h, 10 µL of AmB solution was added to each well and incubated for 4 h. Next, 0.1 mL of isopropanol with 0.04 N hydrochloric acid was added to each well. All solutions in the wells were thoroughly mixed by repeated pipetting with a multichannel pipette. Absorbance was recorded using a Synergy™ HT microplate reader (BioTek Instruments) at 570 and 690 nm for quantification.

Statistical analysis

Absorbance data of the cytotoxicity of the AgNP-polymeric nanoparticles were expressed as the mean ± SD (n=3) in Figure 3. One-way analysis of variance (ANOVA) with Tukey's multiple comparison test was performed to determine statistical significance, by using Graphpad Prism software (La Jolla, CA, USA). A value of *p*<0.05 was considered to denote statistical significance as compared with the positive control group.

Results

Characterization of AgNP encapsulating pNIPAM and pNIPAM-NH₂ polymeric nanoparticles

The sizes of the prepared pNIPAM/pNIPAM-NH₂ polymeric nanoparticles were determined by DLS. The average sizes of the G1, G2, and G3 pNIPAM nanoparticles were 131±78, 312±71, and 483±35 nm, respectively (Figure 1A), while the average sizes of the G1, G2, and G3 pNIPAM-NH₂ nanoparticles were 135±59, 174±10, and 532±48 nm, respectively (Figure 1B).

UV-visible absorption spectrum exhibited a proper encapsulation of AgNP in polymeric nanoparticles (Figures 4 and 5). Previous studies showed that UV-visible absorption spectrum results are sensitive to the formation of AgNPs and that the absorption peaks depend on particle diameter and shape.^{25,34} The AgNP absorption band is in the 400–500 nm range.³⁵ Previous results have suggested that AgNPs of smaller diameters are obtained at larger absorption doses.³⁶ Figures 4A and 5A show the UV-visible spectra of AgNPs encapsulated in the pNIPAM and pNIPAM-NH₂

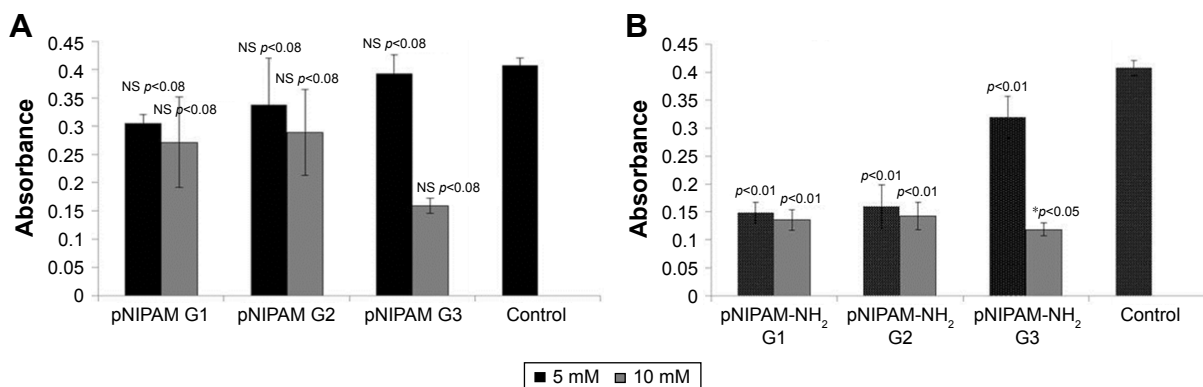


Figure 3 (A) Cytotoxicity of silver nanoparticle (AgNP)-encapsulated poly-*N*-isopropylacrylamide (pNIPAM) nanoparticle groups and **(B)** AgNP encapsulated pNIPAM-NH₂ nanoparticle groups against human adipose stem cells after 48 h.

Note: **p*-value (*p*<0.05) indicates a significant difference as compared with the control (ie, absorbance from the cell treated with no nanoparticles).

Abbreviation: NS, non significant.

AgNP-nanoparticles. The results confirmed that the AgNP fabrication process was consistent in terms of the spectral absorbance of the gels. The UV-visible spectra of our AgNP-polymeric nanoparticles showed a maximum absorbance at 437 nm, as shown in Figures 4A and 5A, which confirms

the encapsulation of AgNPs inside the polymeric nanoparticles. In previous studies, AgNPs (2–5 nm) embedded in polymer microgels exhibited the same absorption bands in poly(methylmethacrylate-co-butyl acrylate-co-acrylic acid), polyethylene imine, and silica gels.^{34,37,38} In the present

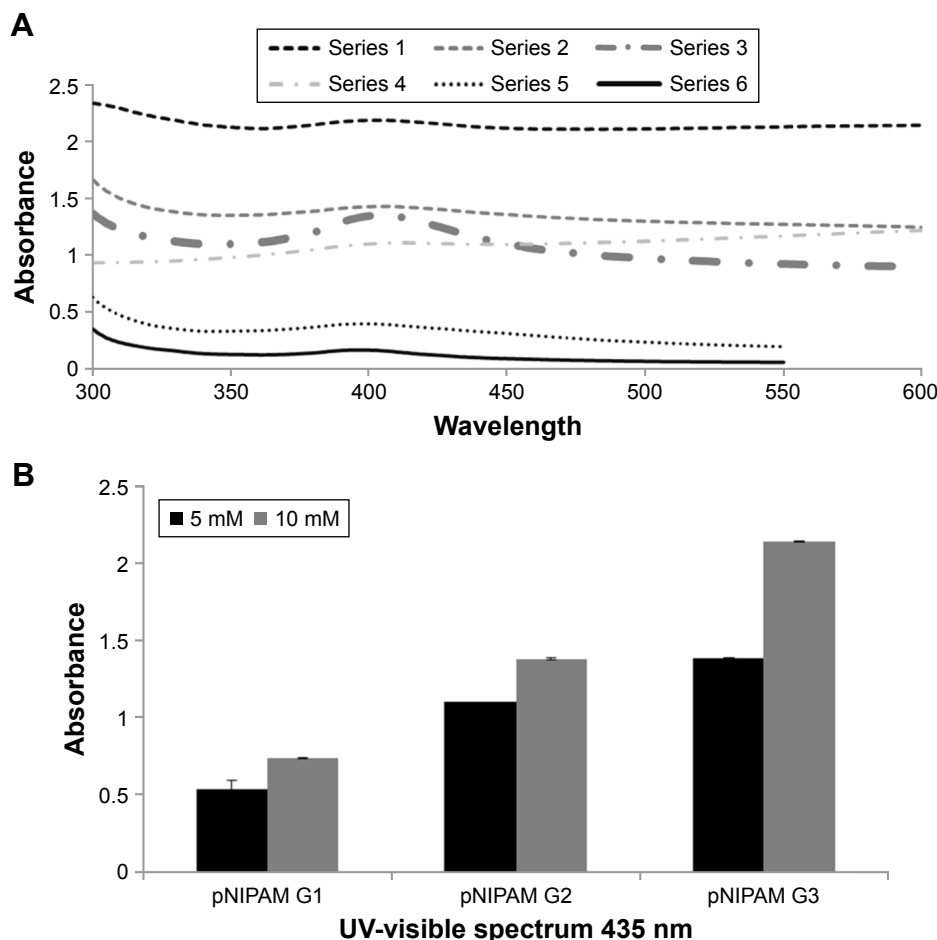


Figure 4 (A) UV-visible spectra of silver nanoparticle (AgNP)-encapsulated poly-*N*-isopropylacrylamide (pNIPAM) nanoparticle groups G1–G3, and **(B)** Ag peak absorbance at 435 nm in gels containing 5 and 10 mM concentrations of AgNO₃.

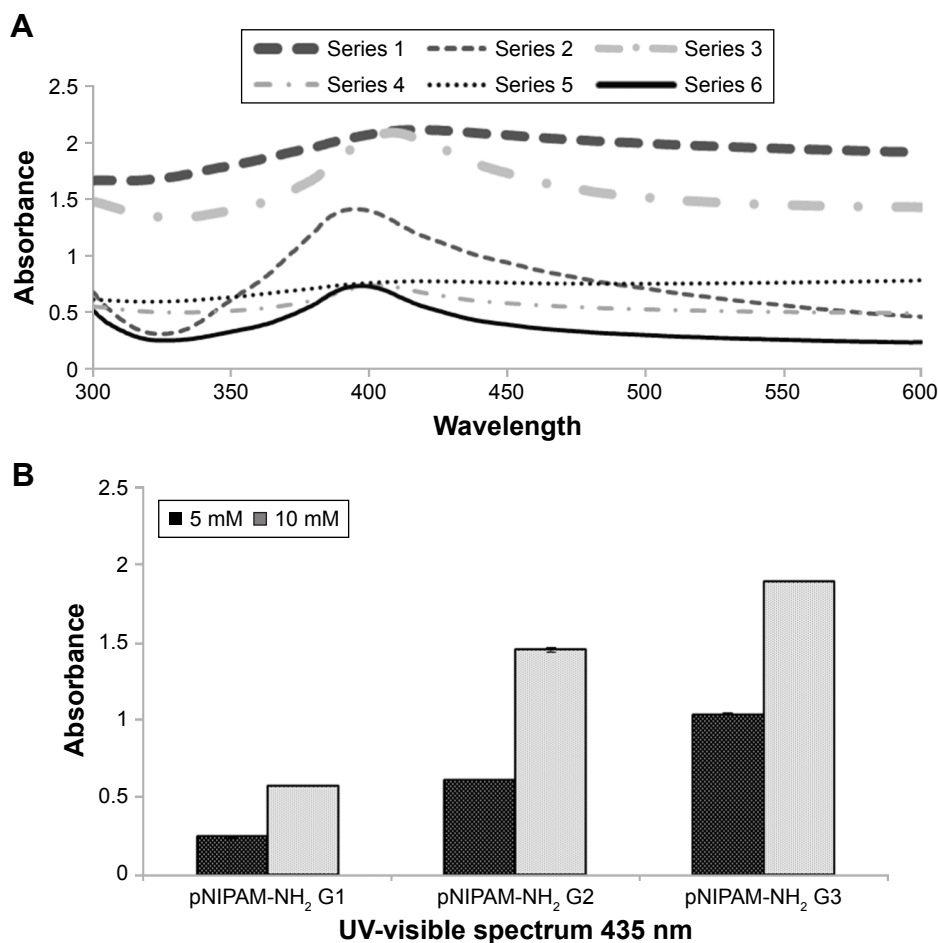


Figure 5 (A) UV-visible spectra of silver nanoparticle (AgNP)-encapsulated poly-*N*-isopropylacrylamide (pNIPAM)-NH₂ nanoparticle groups G1–G3, and **(B)** Ag peak absorbance at 435 nm in gels containing 5 and 10 mM concentrations of AgNO₃.

study, all absorption peaks were similar and all AgNP-polymeric nanoparticles showed a maximum absorption at 437 nm (Figures 4A and 5A), suggesting that the AgNPs encapsulated within the AgNP-polymeric nanoparticles are similar in size and morphology. Furthermore, the absence of a peak at 560 nm confirms that there was no AgNP aggregation or cluster formation inside the AgNP-polymeric nanoparticles.³⁹

Using the current method, we obtained a homogeneous distribution of AgNPs throughout each polymeric nanoparticle. Moreover, the Ag salts loaded in the cross-linked AgNP-polymeric nanoparticles were extensively reduced by NaBH₄, after which the color of the solution quickly changed to opaque brown.⁴⁰ These results indicate that the AgNPs were completely encapsulated within the AgNP-polymeric nanoparticles with strong localization and stabilization provided by the three-dimensional network within the polymeric nanoparticles. In contrast, polymer functional groups such as –OH, –CONH, and –COOH promote the stabilization of AgNPs through surface adsorption.²⁰ Figures 4B and 5B

show the changes in absorbance for different concentrations of AgNO₃ (5 and 10 mM) in the pNIPAM and pNIPAM-NH₂ AgNP-nanoparticles. The color of the AgNP polymeric nanoparticle solution was dependent on the concentration of AgNO₃. With the higher AgNO₃ concentration (10 mM), the color of the solution changed from light brown to dark brown, and the UV-visible spectrum peak at 437 nm was larger. The absorption peaks at 435 nm, as shown in Figures 4A and 5A, represent the characteristic peaks of surface plasmon resonance absorption by AgNPs.

Surface morphology of the resulting nanoparticles was evaluated using TEM (Figures 6 and 7). The images indicated that the morphologies for pNIPAM and pNIPAM-NH₂ AgNP-nanoparticles prepared with 5 or 10 mM AgNO₃ clearly depicted the spherical surfaces of the nanoparticles. AgNPs ranging from 1 to 35 nm in diameter were visible inside the polymeric nanoparticles (Figure S1A and B). The size of the AgNPs changed with the concentration of AgNO₃ used during fabrication, which affects the nanoparticle's internal network and surface charge.⁴ The pNIPAM-NH₂

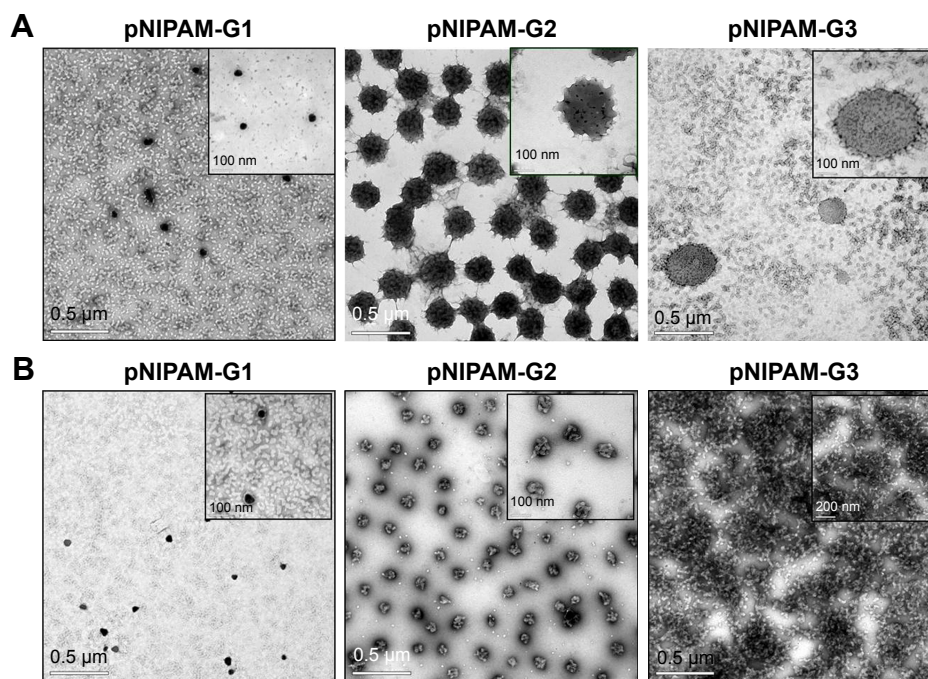


Figure 6 Representative transmission electron microscopy micrographs of silver nanoparticle (AgNP)-encapsulated poly-*N*-isopropylacrylamide (pNIPAM) nanoparticles fabricated with two different concentrations of silver salt, (A) 5 mM AgNO₃ and (B) 10 mM AgNO₃.

Note: The difference in retention of silver in nanocomposite after washing was confirmed by inductively-coupled plasma optical emission spectrometry analysis.

AgNP-nanoparticles contained larger AgNPs than the pNIPAM AgNP-nanoparticles due to the extra positive charge over the pNIPAM-NH₂ surface as shown in Figures 6 and 7.

Surface chemistry

To confirm functionalization of amine group on pNIPAM polymer, XPS analysis was performed. The XPS spectra of pNIPAM-functionalized samples are shown in Figure 8.

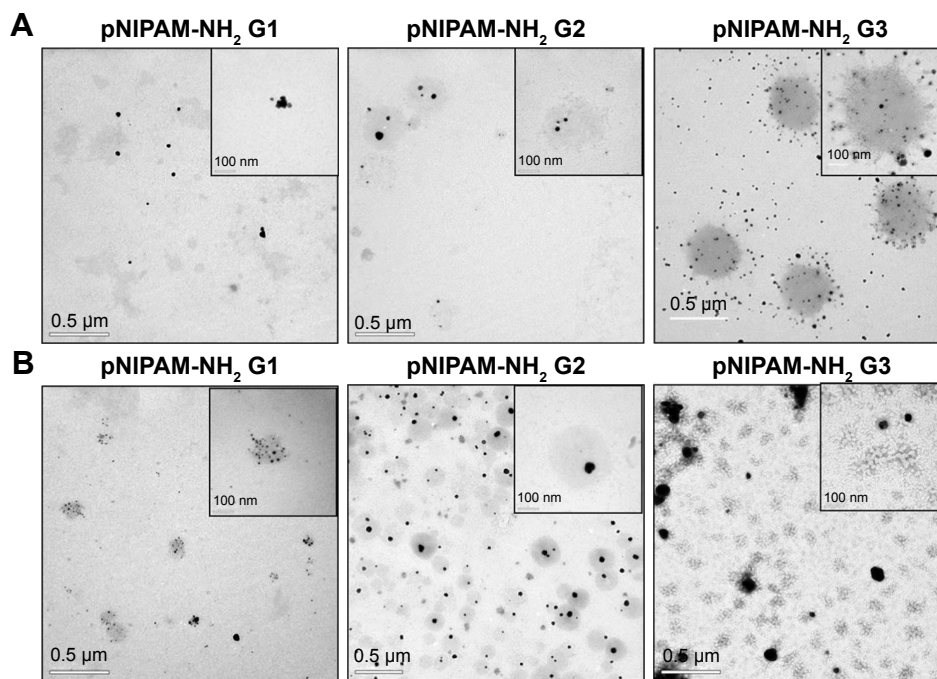


Figure 7 Representative transmission electron microscopy micrographs of silver nanoparticle (AgNP)-encapsulated poly-*N*-isopropylacrylamide (pNIPAM)-NH₂ nanoparticles fabricated with two different concentrations of silver salt, (A) 5 mM AgNO₃ and (B) 10 mM AgNO₃.

Note: The difference in retention of silver in nanocomposite after washing was confirmed by inductively-coupled plasma optical emission spectrometry analysis.

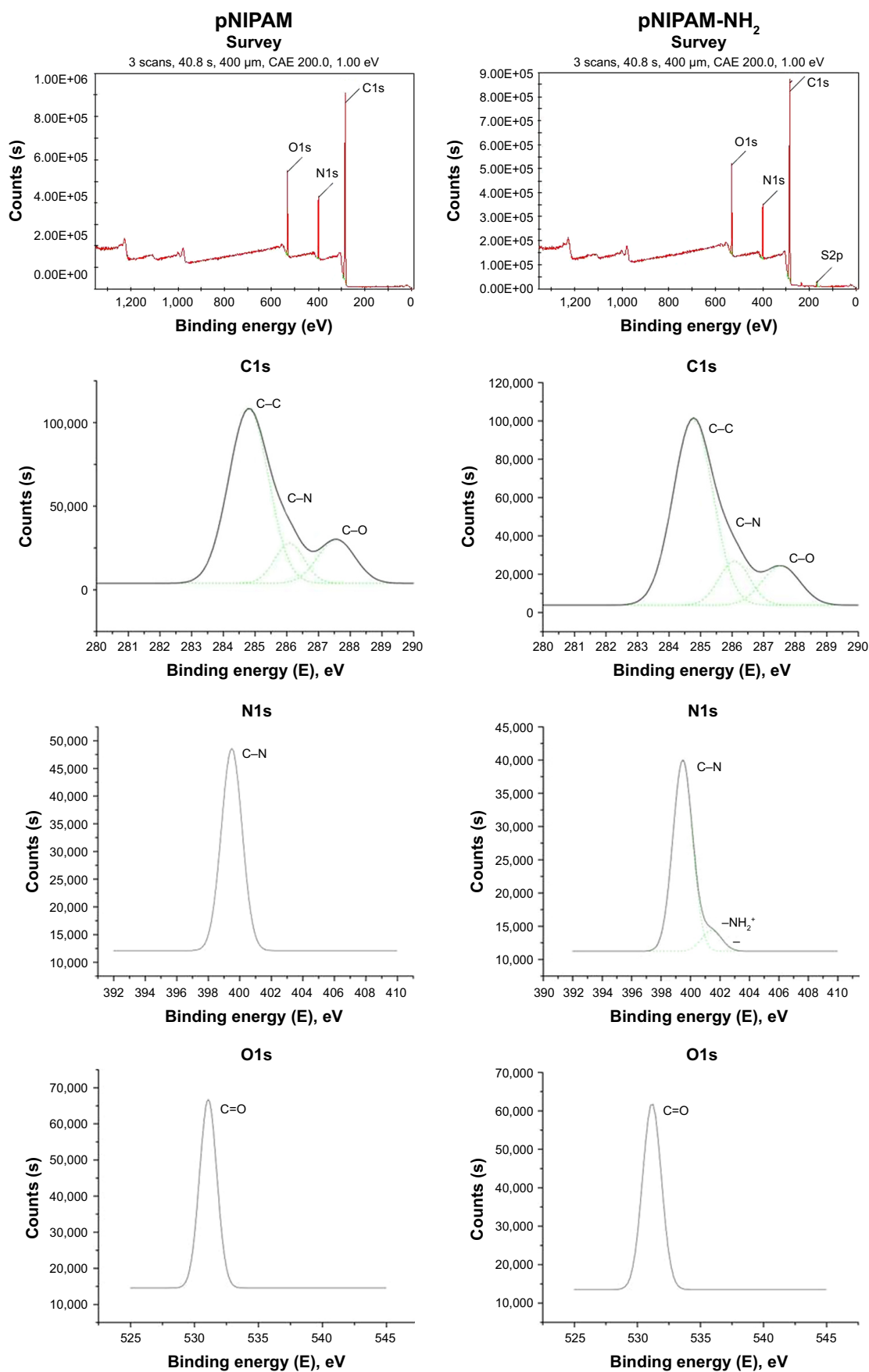


Figure 8 X-ray photoelectron spectroscopy spectra of poly-N-isopropylacrylamide (pNIPAM) (top) and pNIPAM-NH₂ (bottom), condition G1.

Notes: The curved-fitted spectra (black) are superimposed on the experimental data. The peaks of each coordination species are labeled and shown within the curve-fitted spectra.

The high resolution C1s, O1s, N1s spectra (to determine molecular bonding environment), were obtained, and done with curve fitting function in Origin software. For the C1s core-level, the typical characteristics of the amide groups comprising the backbone of the pNIPAM were recorded at 286.08 eV (C–N) and 287.58 eV (C=O), corresponding with the record at 531.08 eV (C=O) in the O1s core-level, and for the N1s core-level peaks at 399.48 eV (C–N). For pNIPAM-NH₂ nanogels, the amine group (secondary) was confirmed by the record in N1s core-level peaks 401.48 eV (–NH₂⁺–). From the XPS data, it has been confirmed that pNIPAM has been successfully functionalized with amine group. XPS analysis confirmed the presence of NH₂ on pNIPAM polymer by detecting the typical amine peak composing the backbone of the pNIPAM chain.

Antimicrobial activity of AgNP-polymeric nanoparticles

The antibacterial activities of the pNIPAM and pNIPAM-NH₂ AgNP-nanoparticles were evaluated against *E. coli* (Figures 9 and 10) and *S. aureus* (Figures 11 and 12). Briefly, for liquid culture, we added 40 μ L of each AgNP-pNIPAM/pNIPAM-NH₂ nanoparticle to 160 μ L of bacterial suspensions in LB broth during the exponential growth phase and monitored further bacterial growth by measuring the OD₆₀₀ at 0, 1, 2, 3, 4, 5, and 24 h of culture. To evaluate antimicrobial activity on solid culture, a 1×10^6 cells/mL suspension of bacterial cells was cultured on an MH agar plate. An 8 mm punch was made on agar gel and 0.5 mg of

(1 mg/mL) AgNP-pNIPAM/pNIPAM-NH₂ nanocomposite was loaded in the punch. The zone of inhibition for each set of composites was recorded after 24 h of incubation at 37°C. Our AgNP-pNIPAM/pNIPAM-NH₂ nanoparticles showed significant antimicrobial activities against both tested strains, but appeared more potent against *E. coli* (Figures 9 and 10) than previously reported.^{41,42} The overall antimicrobial activities of all size groups (G1, G2, and G3) of the pNIPAM and pNIPAM-NH₂ AgNP-nanoparticles in liquid culture against *E. coli* were similar (Figures 9 and 10A–C), but in the solid culture, the difference between the zone of inhibitions was more size-dependent (Figures 9 and 10D). The average diameter of the zones of inhibition caused by the pNIPAM-AgNP G1, G2, and G3 groups against *E. coli* were 48 ± 2 , 36 ± 6.08 , and 28 ± 2 mm and were higher than those against *S. aureus* (24 ± 2.64 , 20 ± 4.58 , 16 ± 2.64 mm). In contrast, for pNIPAM-NH₂ AgNP with *E. coli*, the zones of inhibition for the G1, G2, and G3 groups were 58 ± 8.71 , 50 ± 4.35 , and 30 ± 1 mm, respectively, while against *S. aureus* they were 27 ± 2 , 22 ± 1 , and 20 ± 4.35 mm. The overall and pNIPAM-NH₂ AgNP antimicrobial effects were slightly higher, and differences in the antimicrobial activity at the last time point were observed because of their different AgNP concentrations and additional NH₂ group over the surface of the nanocomposite (Table 1). In addition, the antimicrobial effects of both types of AgNP-pNIPAM/pNIPAM-NH₂ nanoparticles against *S. aureus* (Figures 11 and 12) were lower than those for *E. coli*.

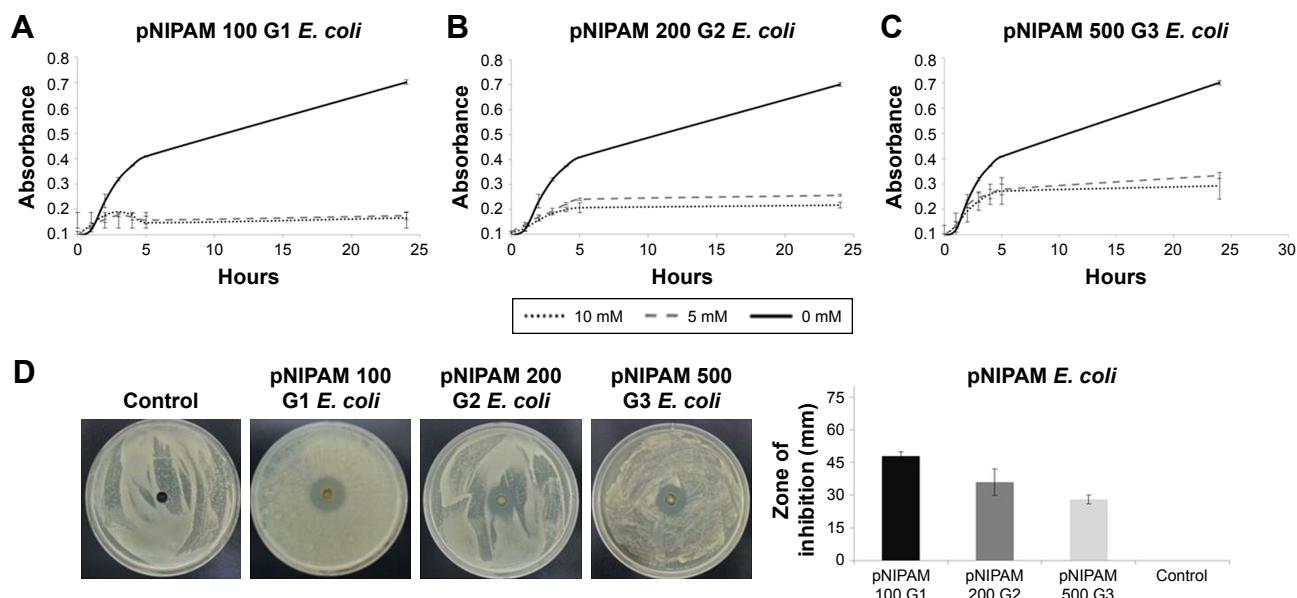


Figure 9 Antimicrobial activities of silver nanoparticle (AgNP)-encapsulated poly-*N*-isopropylacrylamide (pNIPAM) nanogel size groups G1–G3 against *Escherichia coli* (*E.coli*). **Notes:** (A) Liquid culture of *E. coli* with pNIPAM G1. (B) Liquid culture of *E. coli* with pNIPAM G2. (C) Liquid culture of *E. coli* with pNIPAM G3. (D) Solid culture of *E. coli* with control (pure growth), pNIPAM G1–G3 and average diameter of zone of inhibition (mm) graph.

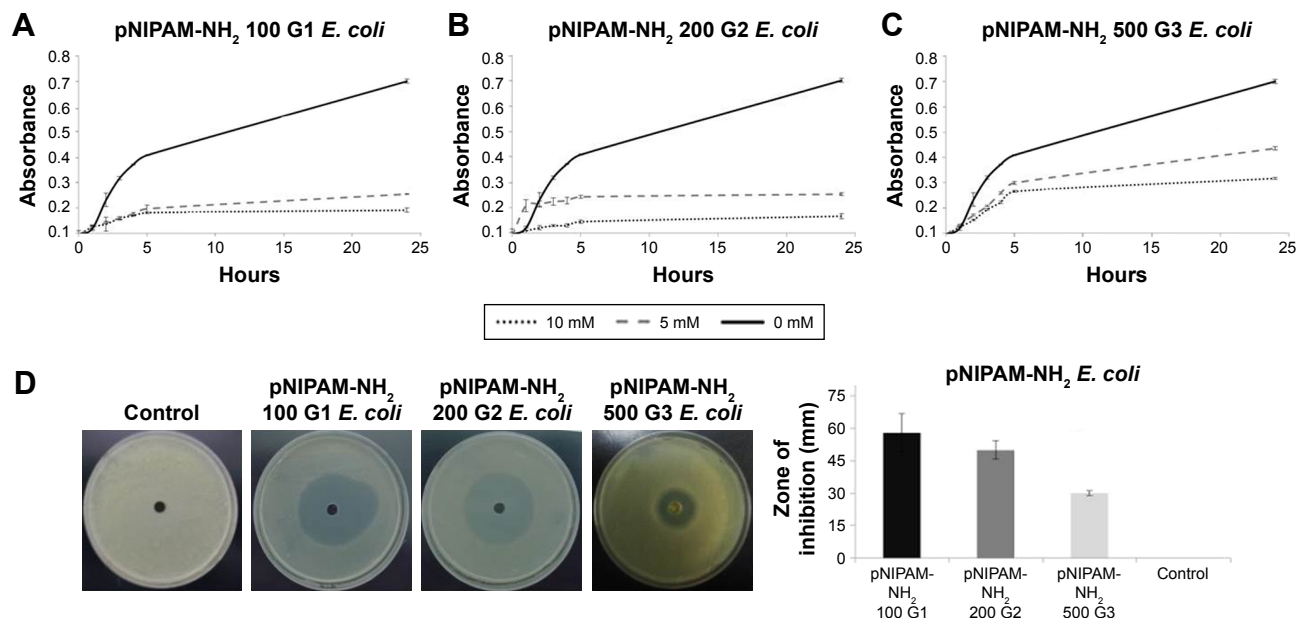


Figure 10 Antimicrobial activities of silver nanoparticle (AgNP)-encapsulated poly-N-isopropylacrylamide (pNIPAM)-NH₂ nanogel size groups G1–G3 against *Escherichia coli* (*E. coli*).

Notes: (A) Liquid culture of *E. coli* with pNIPAM-NH₂ G1. (B) Liquid culture of *E. coli* with pNIPAM-NH₂ G2. (C) Liquid culture of *E. coli* with pNIPAM-NH₂ G3. (D) Solid culture of *E. coli* with control (pure growth), pNIPAM-NH₂ G1–G3 and average diameter of zone of inhibition (mm) graph.

In vitro cytotoxicity of AgNP-polymeric nanoparticles

One of the purposes of this study was to reduce the cytotoxicity of AgNPs in human cells. To evaluate the cytotoxicity of AgNP-polymeric nanoparticles, MTT assays with hASCs were performed. Figure 3 shows the in vitro cytotoxicities

of pNIPAM and pNIPAM-NH₂ AgNP-nanoparticles in three size groups (G1, G2, and G3) against hASCs after 48 h. The results showed that smaller AgNP-polymeric nanoparticles had higher cytotoxicity (Figure 3). The cytotoxicities of the pNIPAM and pNIPAM-NH₂ AgNP-nanoparticles were higher in the AgNP-nanoparticles fabricated with the highest

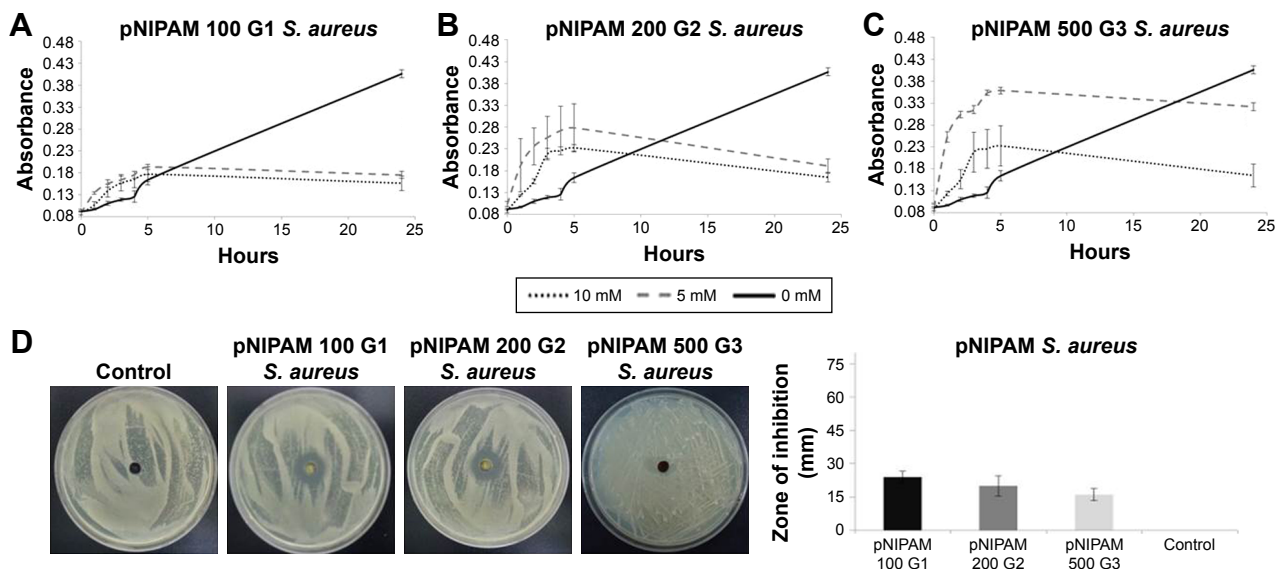


Figure 11 Antimicrobial activities of silver nanoparticle (AgNP)-encapsulated poly-N-isopropylacrylamide (pNIPAM) nanogel size groups G1–G3 against *Staphylococcus aureus* (*S. aureus*).

Notes: (A) Liquid culture of *S. aureus* with pNIPAM G1. (B) Liquid culture of *S. aureus* with pNIPAM G2. (C) Liquid culture of *S. aureus* with pNIPAM G3. (D) Solid culture of *S. aureus* with control (pure growth), pNIPAM G1–G3 and average diameter of zone of inhibition (mm) graph.

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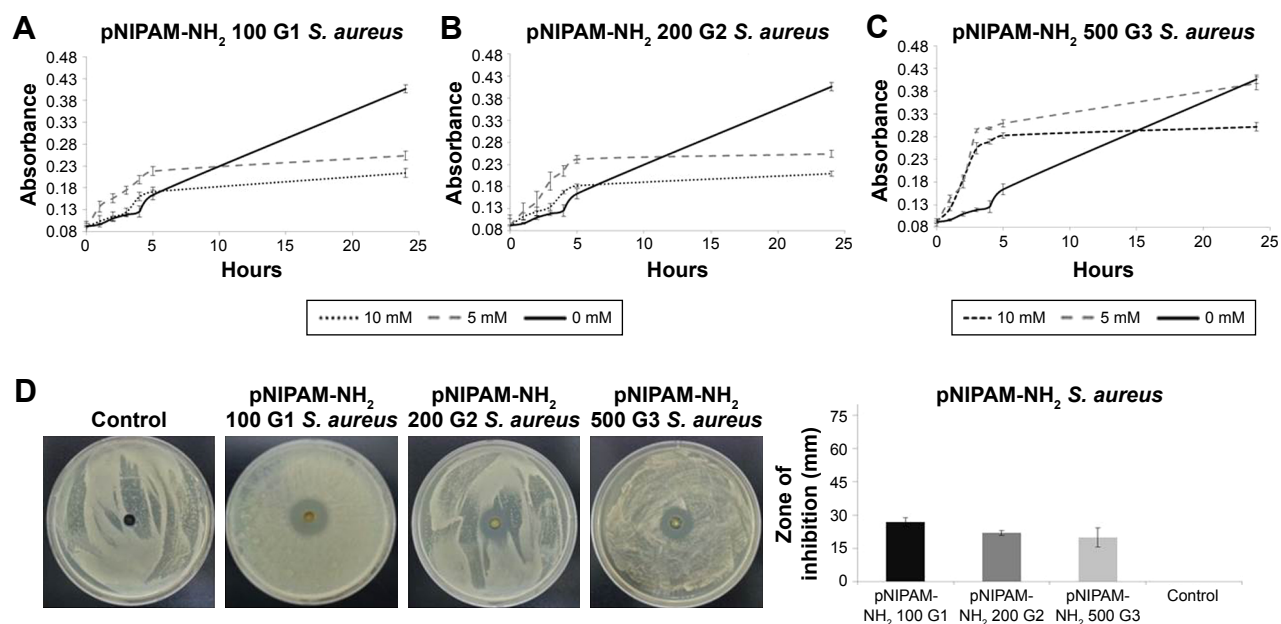


Figure 12 Antimicrobial activities of silver nanoparticle (AgNP)-encapsulated poly-*N*-isopropylacrylamide (pNIPAM)-NH₂ nanogel size groups G1–G3 against *Staphylococcus aureus* (*S. aureus*).

Notes: (A) Liquid culture of *S. aureus* with pNIPAM-NH₂ G1. (B) Liquid culture of *S. aureus* with pNIPAM-NH₂ G2. (C) Liquid culture of *S. aureus* with pNIPAM-NH₂ G3. (D) Solid culture of *S. aureus* with control (pure growth), pNIPAM-NH₂ G1–G3 and average diameter of zone of inhibition (mm) graph.

concentration of AgNO₃ (10 mM). The largest (G3) AgNP-polymeric nanoparticles showed the lowest cytotoxicity, as smaller AgNP-polymeric nanoparticles have a greater ability to penetrate biological membranes because of their high surface area to charge ratio.³² In addition, pNIPAM-NH₂ AgNP-nanoparticle groups showed higher cytotoxicities than pNIPAM AgNP-nanoparticles, despite their lower Ag⁺ concentration (Table 1). This may be because of the addition of the NH₂ surface charge as confirmed by XPS surface analysis (Figure 8).

Discussion

Characterization of AgNP-polymeric nanoparticles

AgNP-encapsulating pNIPAM/pNIPAM-NH₂ polymeric nanoparticles were synthesized by two step processes:

1) synthesis of pNIPAM/pNIPAM-NH₂ nanoparticles via polymerization of NIPAM with the aid of BIS and APS, and 2) encapsulation of AgNPs inside of resulting polymeric nanoparticle networks using AgNO₃ solutions. DLS analysis revealed that an increase of NIPAM:BIS ratios increased the particle size of both pNIPAM and pNIPAM-NH₂ nanoparticles (Figure 1). The differences in size between the pNIPAM and pNIPAM-NH₂ nanoparticles were caused by the presence of the comonomer APMAAHC.³² It is also speculated that addition of an NH₂ group to pNIPAM-NH₂ by using the APMAAHC comonomer resulted in extra hindrance and repulsion between consecutive NH₂ groups over the surface of nanogels, slightly increasing the nanogel size.³³ These results indicate that polymeric nanoparticle size can be modulated by changing the monomer to cross-linker ratio.

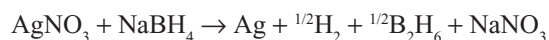
Table 1 Retention of silver after washing of pNIPAM and pNIPAM-NH₂ AgNP-nanoparticles as determined via ICP-OES analysis

Name of group	Concentration (Ag) µg/µL	Name of group	Concentration (Ag) µg/µL
pNIPAM-AgNPs G1 10 mM	0.01656	pNIPAM-NH ₂ -AgNPs G1 10 mM	0.01347
pNIPAM-AgNPs G1 5 mM	0.01271	pNIPAM-NH ₂ -AgNPs G1 5 mM	0.01068
pNIPAM-AgNPs G2 10 mM	0.0182	pNIPAM-NH ₂ -AgNPs G2 10 mM	0.01473
pNIPAM-AgNPs G2 5 mM	0.01335	pNIPAM-NH ₂ -AgNPs G2 5 mM	0.01219
pNIPAM-AgNPs G3 10 mM	0.02165	pNIPAM-NH ₂ -AgNPs G3 10 mM	0.0183
pNIPAM-AgNPs G3 5 mM	0.01541	pNIPAM-NH ₂ -AgNPs G3 5 mM	0.01327

Abbreviations: pNIPAM, poly-*N*-isopropylacrylamide; AgNP, silver nanoparticle; ICP-OES, inductively-coupled plasma optical emission spectrometry.

Similar to a previous study, the intensity of the spectral peaks in our study increased with the increase in AgNO_3 concentration, but the absorption peak positions remained at the same wavelengths.⁴³ In addition, broad peaks were observed for the AgNP-polymeric nanoparticles with larger AgNPs (Figures 4A and 5A). Our results are similar to those in a recent study that clearly revealed the formation of broad absorption peaks with an increase in the size of either pure AgNPs or AgNPs encapsulated in NIPAM-*N,N*-methylenebis-acrylamide (NIPAM-MBA) gels.²⁶ In contrast, a plasmon absorption increment in the UV-visible spectrum indicates the formation of a greater number of nanoparticles.²⁵ In our study, the pNIPAM AgNP-nanoparticles (Figure 4B) exhibited slightly higher absorption values than the pNIPAM-NH₂ AgNP-nanoparticles (Figure 5B). These differences might be due to the differing retention of AgNPs inside the AgNP-nanoparticles after washing and the differences in Ag concentrations, as shown in the ICP-OES characterization in Table 1.

The histograms in Figure S1A and B indicate variations in AgNP size; however, the diameters of approximately 85% of the AgNPs were in the range of 1–10 nm. The TEM micrographs also show that the AgNPs were highly dispersed inside the AgNP-polymer nanoparticles and were mostly spherical in shape. Hence, optimization of the experimental conditions, including pH, the concentration of AgNO_3 , nanoparticle size, and surface charge can achieve monodispersity and uniformity of shape.⁴⁴ Our aim was to obtain a uniform size distribution of AgNPs inside the AgNP-polymeric nanoparticles, and the method used produced ultra-small AgNPs with a well-controlled size distribution using NaBH_4 as the reducing agent. The chemical reaction for the NaBH_4 reduction of AgNO_3 is:



The main advantage of this in situ AgNP fabrication technique is that it provides size-controlled, uniformly sized, and homogeneously distributed nanoparticles inside a polymeric nanoparticle without the addition of a further stabilizer.⁸ This is confirmed in Figures 5 and 6, which show that the nanoparticles were evenly distributed within the polymeric chain network. As expected, we observed homogeneous distributions of AgNPs throughout the AgNP-polymeric nanoparticles, even though there was a rapid reduction of Ag^+ into AgNPs by NaBH_4 .²⁵

Changing the size or alignment of AgNPs may be possible by modifying the polymeric nanoparticle network

architecture.^{13,45} This could be achieved by varying the ratio of monomer to cross-linker used when preparing the nanoparticle. Our results showed that the AgNPs formed in AgNP-polymeric nanoparticles with different monomer:cross-linker ratios were uniformly spherical and well dispersed, but they had different sizes depending on the size of the polymeric nanoparticle.

Antimicrobial activity

Most orthopedic infections are attributed to *Staphylococcus* spp., and *S. aureus* is the leading pathogen causing biomedical implant-related infections. *S. aureus* is often carried on the skin or in the nose of healthy people and readily adheres to host proteins (eg, fibrinogen, fibronectin) on biomaterials.⁴ Such adherence can lead to the formation of a biofilm that protects the pathogen against antimicrobial agents. *S. aureus* is among the most frequently reported pathogens causing deep infections in hospitals. *E. coli* represents a diverse group of bacteria that reside in the intestines. Many *E. coli* strains are harmless, but some can cause diarrhea or illness outside the intestinal tract. In this study, we selected both *E. coli* and *S. aureus* to test the broad-spectrum antibacterial activities of our AgNP-pNIPAM/pNIPAM-NH₂ nanoparticles.

The results in Figures 9–12 exhibited the antimicrobial effects of our nanoparticle system against both *E. coli* and *S. aureus*. Interestingly, a higher antimicrobial effect against *E. coli* than *S. aureus* might be due to the structural difference in bacterial cell walls. The difference in the effect of Ag on Gram-negative and Gram-positive bacteria may lie in the structure of their cell walls. Gram-negative bacteria are encased in a thin, negatively charged outer lipopolysaccharide layer (7–8 nm thickness), whereas Gram-positive bacterial cell walls consist of a thick, highly cross-linked rigid peptidoglycan layer (20–80 nm thickness). The higher protection afforded by the Gram-positive cell wall may inhibit or prevent the bactericidal effect of AgNP-pNIPAM/pNIPAM-NH₂ nanoparticles. The greater susceptibility of Gram-negative bacteria to AgNP-pNIPAM/pNIPAM-NH₂ nanoparticles may also involve effects on bacterial signal transduction (ie, phosphorylation). Moreover, negative charges on lipopolysaccharides are attracted to the weak positive charge on AgNP-pNIPAM/pNIPAM-NH₂ nanoparticles.⁴⁶ Independently of bacterial type, the antibacterial properties of AgNP-pNIPAM/pNIPAM-NH₂ nanoparticles increased at higher concentrations of AgNO_3 . However, polymeric nanoparticle size had a greater effect on antibacterial activity than AgNO_3 concentration, and thus the smallest AgNP-pNIPAM/pNIPAM-NH₂ nanoparticles

had the greatest antibacterial activities against both bacterial strains (Figures 9–12).

The antibacterial properties of our AgNP-polymeric nanoparticles were size-dependent. Smaller nanoparticles have a greater surface area to volume ratio and can more easily penetrate biological surfaces.^{47,48} Our results showed that smaller G1 and G2 AgNP-polymeric nanoparticles had better antimicrobial activities than G3 AgNP-polymeric nanoparticles. The smaller AgNP-polymeric nanoparticles enable Ag-NPs to easily penetrate the cell wall, and their large surface area per mass brings a large number of atoms into contact with the ambient environment, resulting in an antibacterial material that is readily available to react with the components of bacterial cells.^{40,32}

In particular, AgNP-polymeric nanoparticles with a high Ag content showed increased antimicrobial properties toward *E. coli* and *S. aureus*. The pNIPAM AgNP-nanoparticles showed a higher retention of Ag content after washing than the pNIPAM-NH₂ AgNP-nanoparticles (Table 1). The antimicrobial properties of AgNP-polymeric nanoparticles allow researchers to tune their use for specific applications. For instance, to prevent biofilm formation, a highly diffusive bactericidal agent loaded into a polymeric nanoparticle may be the most appropriate means of infection prevention. This tunable feature of AgNP-polymeric nanoparticles enables optimization of Ag release for specific clinical uses and infection types, allowing targeted drug delivery that can minimize complications with the use of antimicrobial agents.⁴⁹ Based on our results, AgNP-polymeric nanoparticles exhibit antimicrobial properties and may be useful in various biomedical applications.

In vitro cytotoxicity

The differences in cytotoxicity among AgNP-polymeric nanoparticles may arise from their different concentrations of Ag and different surface charges; eg, the high cytotoxicity of the AgNP polymeric nanoparticle containing 10 mM AgNO₃ is governed by its high concentration of Ag⁺ (Table 1). This is supported by the observation that pNIPAM and pNIPAM-NH₂ nanoparticles do not, on their own, exhibit cytotoxicity against hASCs.¹⁰ The use of a lower concentration of AgNO₃ (5 mM) in both types of AgNP-polymeric nanoparticles resulted in a significantly higher survival of hASCs. Thus, our AgNP-polymeric nanoparticles developed using 5 mM AgNO₃ are suitable for contact with human tissues (Figure 3). The results suggest that cytotoxicity can be further reduced by optimizing the surface charge, in this case by adding NH₂ surface charge.

In conclusion, chemical synthesis methods for preparing AgNPs have been investigated in recent studies, with particular attention given to modifying their size and shape distributions. In the present study, the average sizes of the pNIPAM AgNP-nanoparticles were 131±78, 312±71, and 483±35 nm, while those of the pNIPAM-NH₂ AgNP-nanoparticles were 135±59, 174±10, and 532±48 nm for small, medium, and large size groups, respectively. Based on our results, AgNPs can be encapsulated within a polymer network. The AgNP-polymeric nanoparticles developed in this study showed antibacterial activities against *E. coli* and *S. aureus* that were dependent on the size and amount of AgNPs within the polymeric nanoparticle and polymeric nanoparticle's surface charge. These results suggest that our AgNP-polymeric nanoparticles can be used for antibacterial treatment to prevent postsurgical infections of biomedical implants.

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Disclosure

The authors report no conflicts of interest in this work.

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Supplementary material

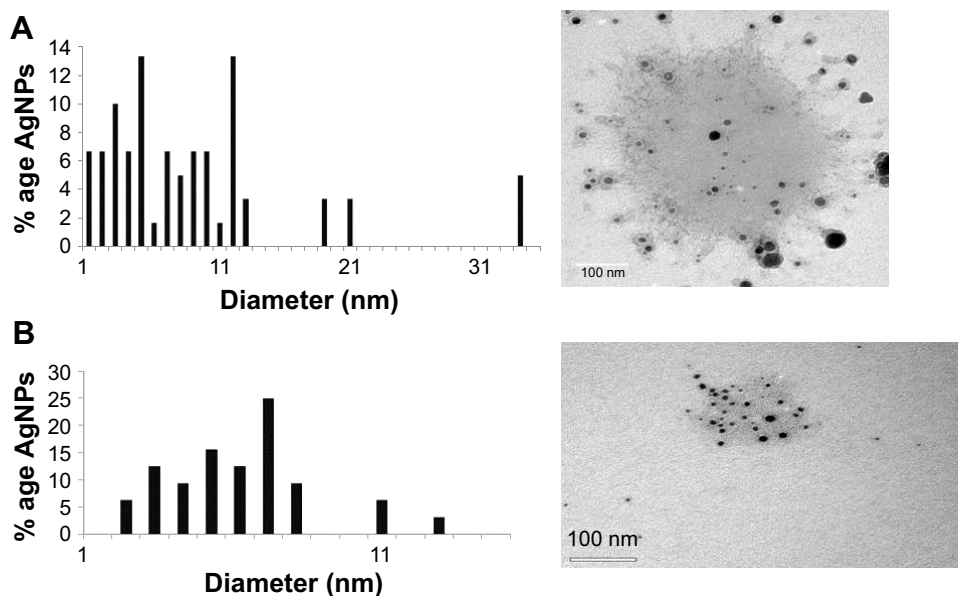


Figure S1 (A, B) Average diameter of AgNP inside the nanogels.

Abbreviation: AgNPs, silver nanoparticles.

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