Silver sulfide nanoparticles for photodynamic therapy of human lymphoma cells via disruption of energy metabolism

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Recently, studies on the application of light-responsive semiconductor nanomaterials for photodynamic therapy (PDT) of non-solid tumors have attracted tremendous attention. Herein, 6.98 nm Ag₂S nanoparticles (Ag₂S NPs) with excellent aqueous dispersibility, stability, and biocompatibility were synthesized by a facile strategy without any post-modification. In vitro studies indicated that Ag₂S NPs could significantly inhibit the growth of human lymphoma cells (Raji cells) compared with hepatoma carcinoma cells (Hep G2 cells) under light irradiation. Further studies revealed that Ag₂S NPs could specifically induce the accumulation of intracellular reactive oxidative species in Raji cells under light irradiation, and induce significant disruption of energy metabolism. This finding provides inspiration for the potential application of Ag₂S semiconductor nanoparticles as a photosensitizer to significantly and specifically treat human lymphoma through PDT.

1 Introduction

Photodynamic therapy (PDT) is known as a non-invasive therapeutic method for efficient treatment of cancers due to its repeatability without cumulative toxicity, minimal invasiveness, and improved quality of life for the patient. Owing to the critical role of photosensitizers in PDT treatment, there is much interest in exploiting superior photosensitizers to enhance the curative duration of PDT. Although traditional organic photosensitizer molecules, such as rhodamine, porphyrin, and their derivatives, ensure effective execution of PDT, some properties still need to be improved: for example, enhanced retention times or resistance to photobleaching. In addition, complicated synthesis and functionalization steps can be barriers to their practical application.

Some inorganic nanomaterials possess intrinsic photodynamic properties for killing tumor cells by photochemical reactions, which are similar to organic photosensitizers, through their inherent light-absorption abilities. Different from organic photosensitizers, the enhanced permeability and retention of inorganic nanomaterials may offer better opportunities for phototherapy applications. However, most studies on inorganic photosensitizers have mainly focused on organic-inorganic hybrid nanomaterials and up-conversion of nanoparticles, which have to overcome complicated syntheses for energy conversion efficiency. Recently, some semiconductor nanoparticles (SCNPs) with superior photosensitive properties have been used for photodynamic therapy, including Cd- and Pb-based SCNPs, because they emit in the visible and near-infrared region. However, the high toxicity of lead and cadmium hinders their potential application. Moreover, the lack of in-depth understanding of the response of SCNPs to PDT does not help in their effective use in correlative nanomaterials for PDT. Thus, it is urgent to explore alternative inorganic photosensitizers with low toxicity and improved efficiency.

Some studies have indicated that, due to the absence of toxic metal ions and the ultralow solubility product constant \( K_{sp} = 6.3 \times 10^{-50} \), Ag₂S exhibits excellent biocompatibility and a wide range of applications in many fields, including bio-imaging, fluorescent detection of molecules and metal ions, electronics, catalysis, and energy conversion. In particular, Ag₂S NPs have attracted increasing attention as a result of their fascinating optical properties. However, little is known about the application of Ag₂S nanoparticles (Ag₂S NPs) as a photosensitizer for PDT, especially to treat non-solid tumors such as lymphoma, which is more aggressive and chemotherapy-resistant than solid tumors.

Based on these considerations and using bovine serum albumin (BSA) as stabilizer, we utilize a facile strategy to synthesize crystalline Ag₂S nanoparticles with good water dispersibility. The as-prepared Ag₂S NPs can be used directly as a photosensitizer to significantly inhibit the growth of human lymphoma cells under light irradiation. This can be ascribed to accumulation of intracellular reactive oxygen species (ROS) and the corresponding disruption of energy metabolism. The results
indicate that Ag₂S NPs might be used as a photosensitizer to specifically and significantly treat human lymphoma through PDT.

2 Experimental section

Chemicals

Silver nitrate (AgNO₃), thioacetamide (TAA), and BSA were purchased from Sigma Chemical Co. (USA). Reactive oxygen species assay kit was purchased from Beyotime Biotechnology (Shanghai, China). Fetal bovine serum (FBS), EMEM medium, DMEM medium, trypsin, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazoliumbromide (MTT), and annexin V-FITC/PI double-staining assay kit were purchased from Becton Dickinson and Company.

Preparation of Ag₂S/BSA NPs

AgNO₃ was dissolved in double-distilled water (ddH₂O) and mixed with BSA solution, then moderately stirred for 6 h to ensure complete chelation of Ag⁺ with BSA. Then, TAA was dissolved in ddH₂O and slowly injected into the Ag⁺-BSA mixed solution under nitrogen flow, then allowed to stand for 24 h at 25 °C. Finally, the sample (Ag₂S/BSA NPs) was collected and dried under vacuum.

Characterization

The morphology and size of the Ag₂S NPs were characterized by HRTEM (JEOL JEM-2100). The Fourier transform infrared (FT-IR) spectra were recorded in the range 4000–400 cm⁻¹ (Bio-Rad FTS-40 FT-IR spectrometer). The crystal phase of the Ag₂S/BSA NPs was determined using an X-ray diffractometer (Bruker AXS, Germany) with graphite-monochromatized CuKα radiation (λ = 0.15406 nm) in the 2θ range 20–70°. UV-vis absorption spectra were recorded on a Shimadzu UV-1700 spectrometer. Zeta potentials in phosphate buffer solution (PBS), H₂O, serum or DMEM, were measured using a Nano-ZS instrument. Photoluminescence (PL) measurements were carried out on a HITACHI FP-6500 spectrophotometer.

Cell culture and evaluation of cytotoxic effects

Human hepatoma (Hep G2) and lymphoma (Raji) cells were purchased from the Cell Bank of the Chinese Academy of Sciences, Shanghai, China. The cells were incubated in DMEM or EMEM medium under 5.0 wt%/vol CO₂ at 37 °C. Fetal bovine serum (FBS), EMEM medium, trypsin, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT), and annexin V-FITC/PI double-staining assay kit were purchased from Becton Dickinson and Company.

Annexin V-FITC/PI double-staining assay

Hep G2 cells and Raji cells (1 × 10⁵ cells per ml) were cultured for 24 h. Then, the cells were exposed to Ag₂S NPs for 12 h under dark or light irradiation. As control, cells without treatment with Ag₂S NPs were prepared. After treatment, the cells were harvested. The apoptotic and necrotic evaluation was quantified by flow cytometric analysis.

Confocal microscopy analysis

Hep G2 cells and Raji cells (1 × 10⁵ cells per ml) were incubated in a confocal dish for 12 h. Then, the cells were treated with Ag₂S NPs. An FV1200 spectral confocal microscope (Olympus, Japan) was used to image cells in one-photon mode. As control, the untreated cells were imaged.

Evaluation of intracellular internalization of Ag₂S NPs

Hep G2 cells and Raji cells (1 × 10⁵ cells per ml) were treated by Ag₂S NPs for 12 h under dark or light irradiation. Subsequently, all of the cells were continually exposed under dark for 6 h. After treatment, the cells were digested with concentrated nitric acid for 2 h. As control, the cells without treatment with Ag₂S NPs were prepared. Then, the intracellular concentrations of Ag⁺ were analyzed by inductively coupled plasma-mass spectrometry (ICP-MS) (ELAN DRC-e, PerkinElmer SCIEX).

Flow cytometric analysis and confocal microscopy imaging analysis of intracellular ROS

2',7'-Dichlorofluorescin diacetate (DCFH-DA) was utilized to evaluate intracellular ROS levels. Briefly, after incubation with Ag₂S NPs for 12 h under dark or light irradiation, the cells (1 × 10⁶ cells per ml) were further exposed to DCFH-DA for 2 h. Subsequently, cells were continually exposed under dark for another 6 h. As control, the cells without treatment with Ag₂S NPs were prepared. After treatment, the cells were harvested. The fluorescence of intracellular ROS was analyzed by flow cytometry. Meanwhile, cell imaging was carried out using a FV1200 spectral confocal microscope.

Photostability of Ag₂S NPs

To evaluate the photostability of the Ag₂S NPs, the photoluminescence and UV-Vis absorbance of Ag₂S NPs were continually monitored every 2 h under dark or light irradiation.

Glycolysis metabolism evaluation by Seahorse extracellular flux (XF-96) analyzer

The glycolytic capacity was determined for Raji cells using the Seahorse XF-96 analyzer. Cells were incubated for 24 h and treated with Ag₂S NPs under dark or light irradiation. Then, cellular oxygen consumption rates (OCRs) were measured as follows. Cells were washed with Seahorse assay media supplemented with fresh sodium pyruvate and glucose and incubated at 37 °C without CO₂ for 1 h. Oligomycin (1 μM), carbonyl cyanide-3-trifluoromethoxyphenylhydrazone (FCCP) (0.5 μM), and rotenone/antimycin A (1 μM) were sequentially added into each well. Then, the amount of oxygen consumption for adenosine triphosphate (ATP) production (coupling efficiency), the level of proton leak (non-ATP-linked oxygen consumption), the maximal respiration capacity, and the level of nonmitochondrial respiration were measured.
3 Results and discussion

Synthesis and characterization of silver sulfide nanoparticles

Silver sulphide nanoparticles (Ag$_2$S NPs) were synthesized using BSA as a stabilizer by a facile method. First, silver nitrate aqueous solution was gently mixed with BSA aqueous solution to construct the chelating system. Then, the chelating system was mixed with freshly prepared TAA aqueous solution to prepare Ag$_2$S NPs. The X-ray diffraction (XRD) pattern was recorded and used to demonstrate formation of the silver sulfide. The diffraction peaks with 2$\theta$ values at 31.52°, 34.38°, and 36.81° (Fig. 1a) can be indexed to the (−112), (−121) and (121) planes of acanthite Ag$_2$S. From the HRTEM images shown in Fig. 1b, the as-prepared Ag$_2$S comprises well-dispersed nanoparticles with an average diameter of ~6.98 nm. The lattice fringe spacing in the HRTEM image was determined as 0.294 nm (see Fig. 1c), corresponding to the (−112) plane of acanthite Ag$_2$S.

The zeta potentials of Ag$_2$S NPs in ddH$_2$O, FBS, PBS, and DMEM medium were determined to be −24.74, −26.78, −21.48, and −31.21 mV, respectively. Therefore, these results reveal the excellent stability of the Ag$_2$S NPs under physiological conditions when the Ag$_2$S NPs are dispersed into different media. The FT-IR spectroscopic analysis results indicate the presence of BSA in the as-prepared Ag$_2$S NPs. From the FT-IR spectra shown in Fig. 2a, compared with Ag$_2$S NPs, absorption bands of N–H stretching (3193 cm$^{-1}$) and amide bands (1662, 1539, and 1399 cm$^{-1}$) were detected in the spectrum of BSA. In the spectrum for Ag$_2$S NPs the absorption bands for N–H stretching are observed to shift to lower wavenumber (3193 to 3133 cm$^{-1}$) and the amide bands obviously shift to higher/lower wavenumber (1684, 1507, and 1400 cm$^{-1}$), suggesting the presence of BSA in Ag$_2$S NPs and the interaction of silver sulfide with BSA.

From the ultraviolet-visible (UV-vis) absorption characterization (Fig. 2b), silver sulfide nanoparticles exhibit strong absorbance in the range 200–600 nm, revealing good photo absorption properties. In Fig. 2c, the fluorescence spectrum demonstrates that Ag$_2$S NPs exhibit a powerful emission peak at 483 nm (excitation wavelength: 366 nm).

Cell cytotoxicity assay

The antiproliferative effects of Ag$_2$S NPs on Hep G2 human hepatocellular carcinoma cells and Raji human lymphoma cells were evaluated under dark or light irradiation using the MTT assay. From the data shown in Fig. 3a, Ag$_2$S NPs slightly inhibit the proliferation of Hep G2 cells under dark or light irradiation. From Fig. 3b, negligible cytotoxicity was observed when Raji cells were treated with Ag$_2$S NPs in the dark. However, under light irradiation, Ag$_2$S NPs significantly inhibited the proliferation of Raji cells, compared with Hep G2 cells. The results indicate that Ag$_2$S NPs could be used as photosensitizers for PDT of human lymphoma cells, such as Raji cells.
Cellular internalization of Ag₂S NPs

In order to explore the possible reasons for the specific anticancer activities of Ag₂S NPs, the amounts of intracellular nanoparticles internalized by Hep G2 cells and Raji cells were determined through ICP-MS analysis. From the results shown in Fig. 3c, more Ag₂S NPs could be internalized by Hep G2 cells. However, the intracellular amounts of Ag₂S NPs internalized by Raji cells or Hep G2 cells do not show significant differences under dark or light irradiation. This suggests that the different efficiency for anticancer PDT of Ag₂S NPs towards Hep G2 and Raji cells is not derived from the difference in the amounts of internalized nanoparticles. Meanwhile, ICP-MS results indicate that light irradiation cannot increase the amount of Ag₂S NP internalization by Raji cells (Fig. 3c). In addition, the Ag₂S NPs cannot be specifically internalized by Raji cells or Hep G2 cells.

Because of the different antiproliferative effects of Ag₂S NPs on different cancer cells, the apoptosis-inducing effects of Ag₂S NPs on Hep G2 cells and Raji cells were determined using the annexin V-FITC/PI double-staining assay through flow cytometry analysis. From Fig. 4a–c it can be seen that the apoptosis of Hep G2 cells cannot be induced by Ag₂S NPs, either under dark or light irradiation. Fig. 4d–f shows that Ag₂S NPs, also, cannot induce apoptosis and necrosis of Raji cells under dark irradiation. However, Ag₂S NPs could significantly induce apoptosis and necrosis (30%) of Raji cells under light irradiation. These results suggest that the considerable antiproliferative effects of Ag₂S NPs on Raji cells are relevant to apoptosis.

Confocal microscopy images (Fig. 5a) show the luminescence intensity in Raji human lymphoma cells from Ag₂S NPs. The bright-field images and overlay of confocal luminescence show that luminescence can be observed in the cytoplasm but not in the membrane surface and nucleus. In Fig. 5b–e, the UV-vis and fluorescence spectra of Ag₂S NPs do not show obvious changes when illuminated for different periods of time, revealing their good photostability.

Confocal microscopy images indicate that Ag₂S NPs cannot induce generation of intracellular ROS in Hep G2 cells when treated under dark or light irradiation (Fig. 6a–c). For Raji cells, the control cells and the cells treated with Ag₂S NPs...
under dark exhibit only negligible green fluorescence (Fig. 7a and b). These results suggest that the intracellular level of ROS is very low when cells are treated with Ag$_2$S NPs under dark irradiation. However, in contrast, strong green fluorescence was observed in Raji cells treated with Ag$_2$S NPs under light irradiation (Fig. 7c), revealing the presence of high levels of intracellular ROS. These results indicate that high levels of intracellular ROS can be specifically generated by Raji cells upon treatment with Ag$_2$S NPs under irradiation, which was further quantified by flow cytometric analysis. From Fig. 7d, compared with control cells, the fluorescence level of DCFH from the Raji cells treated with Ag$_2$S NPs under dark does not show strong enhancement. However, after treatment with Ag$_2$S NPs under light irradiation, the fluorescence level from Raji cells increases sharply. This confirms that treatment of Raji cell Ag$_2$S NPs under light illumination can induce generation of intracellular ROS in Raji cells, which is critical for PDT of cancer cells.

To understand the photodynamic response of Raji cells treated with Ag$_2$S NPs in depth, the OCR, an indicator of mitochondrial respiration, was determined to evaluate the effects of different treatments on the mitochondrial function of cancer cells. From the results shown in Fig. 8, compared with untreated Raji cells, the basal respiration, maximal respiration, and spare capacity of Raji cells decreased significantly when treated with Ag$_2$S NPs under light irradiation. However, the cells treated with Ag$_2$S NPs under dark were not influenced. These results reveal that Ag$_2$S NPs under light irradiation could give rise to disruption of energy metabolism.

Conclusions
In summary, aiming to find alternatives for inorganic photosensitizers that have low toxicity and improved efficiency as sole
and direct photosensitizers for PDT, Ag$_2$S/BSA hybrid nanoparticles with stable water dispersibility were prepared by a facile method, and without complicated modification. The Ag$_2$S NPs with good solubility can be used directly as photosensitizers to significantly inhibit the growth of human non-solid tumors cells, such as human lymphoma cells, under light irradiation. This can be explained by accumulation of intracellular ROS. Furthermore, this study indicates a mechanism whereby Ag$_2$S NPs damage mitochondrial function and disrupt energy metabolism, which could be used for sole and direct application to photodynamic therapy for human lymphoma cells.

**Conflicts of interest**

There are no conflicts to declare.

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