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Cytotoxic effect of magnetic iron oxide nanoparticles synthesized via seaweed aqueous extract

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Abstract: Magnetic iron oxide nanoparticles (Fe_3O_4 MNPs) are among the most useful metal nanoparticles for multiple applications across a broad spectrum in the biomedical field, including the diagnosis and treatment of cancer. In previous work, we synthesized and characterized Fe_3O_4 MNPs using a simple, rapid, safe, efficient, one-step green method involving reduction of ferric chloride solution using brown seaweed (*Sargassum muticum*) aqueous extract containing hydroxyl, carboxyl, and amino functional groups mainly relevant to polysaccharides, which acts as a potential stabilizer and metal reductant agent. The aim of this study was to evaluate the in vitro cytotoxic activity and cellular effects of these Fe_3O_4 MNPs. Their in vitro anticancer activity was demonstrated in human cell lines for leukemia (Jurkat cells), breast cancer (MCF-7 cells), cervical cancer (HeLa cells), and liver cancer (HepG2 cells). The cancer cells were treated with different concentrations of Fe_3O_4 MNPs, and a MTT (3-[4,5-dimethylthiazol-2-yl]-2,5 diphenyl tetrazolium bromide) assay was used to test for cytotoxicity, resulting in an inhibitory concentration 50 (IC_{50}) value of $23.83 \pm 1.1 \mu\text{g/mL}$ (HepG2), $18.75 \pm 2.1 \mu\text{g/mL}$ (MCF-7), $12.5 \pm 1.7 \mu\text{g/mL}$ (HeLa), and $6.4 \pm 2.3 \mu\text{g/mL}$ (Jurkat) 72 hours after treatment. Therefore, Jurkat cells were selected for further investigation. The representative dot plots from flow cytometric analysis of apoptosis showed that the percentages of cells in early apoptosis and late apoptosis were increased. Cell cycle analysis showed a significant increase in accumulation of Fe_3O_4 MNP-treated cells at sub-G1 phase, confirming induction of apoptosis by Fe_3O_4 MNPs. The Fe_3O_4 MNPs also activated caspase-3 and caspase-9 in a time-response fashion. The nature of the biosynthesis and therapeutic potential of Fe_3O_4 MNPs could pave the way for further research on the green synthesis of therapeutic agents, particularly in nanomedicine, to assist in the treatment of cancer.

Keywords: green synthesis, seaweed water extract

Introduction

Nanoscience and nanotechnology have elegant potential across a broad spectrum of cancer research, including diagnostic, monitoring, and therapeutic strategies, and provide novel approaches in these areas.¹ Some nanocarriers, like liposomes, dendrimers, micelles, carbon nanotubes, and nanoparticles, have been used to help in the diagnosis and theranostics of certain types of cancers.^{2,3} The green approach to synthesis of nanoparticles using plant materials, such as reducing and capping agents, could be considered attractive in nanobiotechnology. When compared with mechanical strategies, this technology is safe, simple, nontoxic, efficient, and environmentally friendly, and also provides efficacious single-pot reactions without the need for additional surfactants or capping agents.⁴

Due to their superparamagnetic behavior and surface modification properties, iron oxides are considered to be capable candidates in cancer therapy.⁵ A novel

approach to biosynthesis of iron oxide magnetic nanoparticles (Fe_3O_4 MNPs) is to make nanoparticles using natural products, such as plant extracts, to reduce metal ions, which are readily scalable and nontoxic compared with physical and chemical methods.⁶

Synthesis of iron oxide in the presence of an oxidant creates several forms of iron oxides that involve magnetite (Fe_3O_4) and hematite ($\alpha\text{-Fe}_2\text{O}_3$), which among them can be found a beneficial application of magnetite type iron oxide nanoparticles as a main subject for biomedical research.⁷ The unique magnetic properties of iron oxide nanoparticles mean decreased drug expenditure and drug administration, and improved efficacy of diagnosis, targeting, and treatment of tumors.⁸

The biocompatibility of Fe_3O_4 MNPs makes them suitable for biomedical application, such as in cellular therapy, tissue repair, drug delivery, and magnetofection.⁹ Recent investigations have focused on developing methods that synthesize magnetic nanoparticles with vast potential including size, charge, stability, shape, and morphology.¹⁰ In general, because of influence aggregation behavior, colloidal stability, cytotoxicity nanoparticles surface coatings are considered a critical subject of study.¹¹ The biodistribution of these nanoparticles in vivo is greatly affected by their surface coating properties and the influence of an external magnetic field. In addition, a number of biocompatibility assays have been performed for polysaccharide-coated magnetic nanoparticles, due to concerns regarding the risks and benefits of magnetic nanoparticles and related technologies to human health and the environment.

Using Fe_3O_4 MNPs in the treatment of cancer, Ling et al reported on superparamagnetic iron oxide nanocrystals concurrently loaded with docetaxel, a chemotherapeutic anticancer drug, and assessed their efficacy as an anticancer agent. The targeted nanoparticles were seen to have an antiproliferative effect in PC3 prostate cancer cells on cytotoxicity assay. The IC_{50} value for iron nanoparticles loaded with docetaxel was 1.46-fold and 1.57-fold lower than that of docetaxel after 48 hours and 72 hours of treatment. Furthermore, the nanoparticles alone did not have any significant cytotoxic effect on PC3 cells, suggesting that a drug encapsulated in nanoparticles develops increased cytotoxicity in a time-dependent and dose-dependent manner.¹²

Khan et al evaluated the cytotoxic effects of Fe_3O_4 MNPs in A549 human lung epithelial cancer cells and normal IMR-90 lung fibroblasts. In their study, cancerous and normal cells were exposed to various concentrations of Fe_3O_4 MNPs (1–100 $\mu\text{g}/\text{mL}$) for 24 hours and 48 hours. Their

findings showed that Fe_3O_4 MNPs had significant cytotoxic effects on A549 human lung cancer cells, but not on normal IMR-90 human lung fibroblasts.¹³ Recent studies have also confirmed the fact that bioactive compounds obtained from macroalgae can increase the chances of discovery of novel and versatile pharmaceutical agents with promise in cancer research, diagnostics, and treatment.¹⁴

As mentioned in previous reports,¹⁵ seaweed is a subgroup of macroalgae and an available food source in many countries, traditionally those in south-east Asia.¹⁶ Seaweed contains a number of potentially biologically active ingredients, including polysaccharides, proteins, lipids, vitamins, soluble fiber, and minerals, with multiple medical applications in cancer,¹⁷ inflammation,¹⁸ allergy,¹⁹ diabetes,²⁰ thrombosis,²¹ and obesity (by bringing down the caloric value of the diet),²² and may be useful in the reduction of lipid absorption and risk of cardiovascular disease,²³ hypertension,²⁴ and other degenerative diseases.²⁵ These biomedical applications of seaweed are mainly due to its functional groups, which act as capping agents in a green single-step process. Polysaccharides are the main constituent of biopolymers in seaweed water extract, and have been found to be strong stabilizers enabling increased biocompatibility. Further, they confer chemical functionality to nanostructures such as Fe_3O_4 MNPs.²⁶

In a previous study,²⁷ we synthesized and characterized Fe_3O_4 MNPs using a brown seaweed (*Sargassum muticum*) extract via the green method. The aim of this study was to investigate the cytotoxic effects of Fe_3O_4 MNPs prepared by green biosynthesis on various human cancer cell lines using a number of experimental methods.

Materials and methods

Materials

Specimens of the brown seaweed, *Sargassum muticum*, were obtained from coastal waters in the Persian Gulf. All aqueous solutions were made using distilled deionized water.

Cell cultures

All cancer cell lines were purchased from the American Type Culture Collection (ATCC, Rockville, MD, USA), maintained in Roswell Park Memorial Institute 1,640 medium (ATCC) supplemented with L-glutamine 2 mM and 10% fetal bovine serum (ATCC), with 100 U/mL penicillin and 100 $\mu\text{g}/\text{mL}$ streptomycin (Sigma-Aldrich, St Louis, MO, USA) according to the ATCC protocol, and cultured and grown in 75 cm^2 culture flasks (TPP Techno Plastic Products, Trasadingen, Switzerland) at 37°C in an incubator with a humidified atmosphere of 95% air and 5% CO_2 (Binder

GmbH, Tuttlingen, Germany). The cultures were frequently examined under an inverted microscope (MICROS, Sankt Veit an der Glan, Austria) for confluency and viability.

Methods

Preparation of *S. muticum* extract

As mentioned in our previous study,²⁷ the seaweed specimens were washed and stored at -20°C . To make the extract, seaweed samples (about 1 g) were ground, freeze-dried, and boiled with distilled deionized water (100 mL) in an Erlenmeyer flask, with constant stirring for 15 minutes. The extract was then cooled to room temperature, filtered, and stored at -20°C before use.

Preparation and characterization of Fe₃O₄ MNPs

Fe₃O₄ MNPs (Figure 1) have been prepared and well characterized previously by our group.²⁷

Cytotoxicity assay

The antiproliferative effect of Fe₃O₄ MNPs on various cancer cell lines and a normal Chang liver cell line was quantified using a 3-(4,5-dimethylthiazol-2-yl)-2,5 diphenyl tetrazolium bromide (MTT) kit (Sigma-Aldrich) according to the standard method.²⁸ Briefly, cells were allowed to grow in a 75 cm² cell culture flask (TPP Techno Plastic Products, Switzerland) until 95% confluent. The cells were then seeded into each well of a 96-well microculture plate (TPP Techno Plastic Products) at a concentration of 1×10^5 cells/mL and treated with Fe₃O₄ MNPs at various concentrations. After incubation for 72 hours at 37°C in a 5% CO₂ incubator (Binder GmbH), 25 μL of a 5.5 mg/mL MTT solution was added to each well, covered with aluminum foil, and incubated for a further 3 hours in the dark. Immediately afterwards, the medium was aspirated and the remaining purple formazan was lysed with MTT solution. The assay was performed in triplicate.

The optical density was then measured at 570 nm using an enzyme-linked immunosorbent assay universal microplate reader (Biotech Inc., USA). The inhibitory concentration 50 (IC₅₀) value was determined from the absorbance versus concentration curve. Dimethyl sulfoxide 0.1% was used as the negative control.

Acridine orange/propidium iodide assay

Fe₃O₄ MNP-induced death of Jurkat cells was investigated using the acridine orange/propidium iodide double-staining method according to the standard procedure²⁹ followed by examination under a fluorescence microscope (Leica, Tokyo, Japan) with Leica Q Fluoro software (Leica) installed. The Jurkat cells were plated at a concentration of 1×10^6 cells/mL in a 25 cm² culture flask (TPP Techno Plastic Products), exposed to Fe₃O₄ MNPs at the IC₅₀, and incubated at 37°C in a 5% CO₂ incubator for 24, 48, and 72 hours. Next, the cells were centrifuged at $200 \times g$ (Universal 320R Centrifuge, Andreas Hettich GmbH & Co.KG, Tuttlingen, Germany) for 10 minutes and the supernatant was discarded. The cells were then washed twice with phosphate-buffered saline after centrifuging at $200 \times g$ for 10 minutes to remove the remaining medium. About 10 μL of the cell pellets were stained with a 10 μL fluorescent dye mixture containing equal volumes (100 $\mu\text{g}/\text{mL}$) of acridine orange and propidium iodide for 2 minutes. Approximately 10 μL of freshly stained cell suspension was placed onto a glass slide, covered with a cover slip, and examined under a fluorescent microscope.

Annexin V-fluorescein isothiocyanate assay

Jurkat cells (1×10^6 cells/mL) were exposed to the nanoparticles for 12, 24, and 48 hours, with untreated cells used as controls. The cells were then collected and centrifuged at $200 \times g$ (Universal 320R Centrifuge), (Andreas Hettich

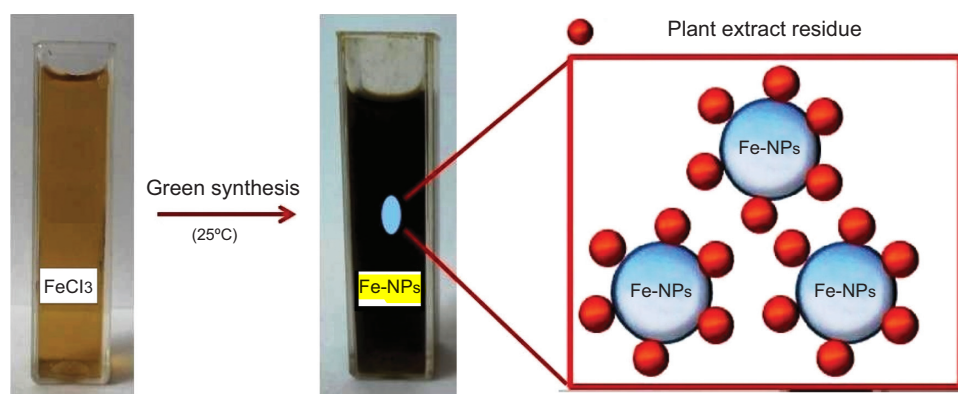


Figure 1 Magnetic iron oxide nanoparticles synthesized via brown seaweed extract.

GmbH & Co.KG) for 10 minutes to remove the medium. The cell pellets were washed twice with 1 mL of ice-cold phosphate-buffered saline, recentrifuged, and resuspended in ice-cold 1× binding buffer. Exactly 500 µL of cell suspension was transferred to a 5 mL culture tube (TPP Techno Plastic Products), to which 5 µL of Annexin V-fluorescein isothiocyanate (FITC) conjugate and 10 µL of propidium iodide were added. The cells were incubated for 15 minutes at room temperature in the dark. Finally, flow cytometry was done under laser emitting excitation light at 488 nm using a **BD FACSCalibur™** flow cytometer equipped with an argon laser (BD Biosciences, Franklin Lakes, NJ, USA). The data were analyzed using **BD CellQuest™ Pro software** (BD Biosciences).

Cell cycle assay

Flow cytometry was used to investigate the cytotoxicity of Fe₃O₄ MNPs in Jurkat cells. Briefly, Jurkat cells (2.0×10⁶ cells/mL) were cultured with the IC₅₀ of Fe₃O₄ MNPs and incubated for 24, 48, and 72 hours. The cells were harvested by centrifugation at 1,500 rpm for 5 minutes and washed with phosphate-buffered saline. Next, 600 µL of 70% ice-cold ethanol were added to the cell pellets, which were then kept at -20°C overnight. A 1 mL volume of phosphate-buffered saline was added and spun down at 1,500 rpm for 5 minutes to remove the ethanol. The cell pellets were then washed twice with phosphate-buffered saline, stained with staining buffer containing **0.1% Triton X-100**, **10 mM ethylenediaminetetraacetic acid**, **50 µg/mL RNase A**, and **3 µg/mL propidium iodide**, and incubated in the dark on ice for 30 minutes. Flow cytometry was performed with laser emitting excitation light at 488 nm using a FACSCalibur™ flow cytometer equipped with an argon laser (BD Biosciences). The data analysis was performed using CellQuest™ Pro software.

Caspase-3 and caspase-9 assays

The activity of caspase-3 and caspase-9 in Jurkat cells treated with Fe₃O₄ MNPs was determined after 24, 48, and 72 hours using a colorimetric assay kit (BD Biosciences) according to the manufacturer's instructions without modification.

Statistical analysis

The experiments were done in triplicate, and the results are expressed as the mean ± standard deviation. The statistical analysis was done using IBM® SPSS® Statistics for Windows version 20.0 software (IBM Corp., Armonk, NY, USA). *P*-values <0.05 were considered to be statistically significant.

Results and discussion

Fe₃O₄ MNPs inhibit proliferation of human cancer cells

Observation of morphological changes in cells indicated that Fe₃O₄ MNPs inhibited proliferation of the various cancer cell lines in a dose-dependent and time-dependent manner (Figure 2A). No toxicity was seen in the normal Chang liver cell line (Figure 2B). The IC₅₀ values calculated for Fe₃O₄ MNPs in the various cancer cell lines were 23.83±1.1 µg/mL (HepG2), 18.75±2.1 µg/mL (MCF-7), 12.5±1.7 µg/mL (HeLa), and 6.4±2.3 µg/mL (Jurkat) after treatment for 72 hours. Therefore, Jurkat cells were selected for further investigation.

It is relevant to the evaluation toxicity of metal nanoparticles against cancer cells as many studies have already reported. Coradeghini et al reported that BALB/C-3T3 mouse fibroblasts at higher doses than 50 µM for 72 hours of exposure to gold nanoparticles with a thickness of 5 nm, as compared with 15 nm, induced dose-dependent cytotoxicity. They reported that the size of gold nanoparticles is an important indicator of potential application in the biomedical field.³⁰ Another recent study reported that different types of iron oxide nanoparticles demonstrate diverse biological activity as a result of versatile surface coating. Novotna et al

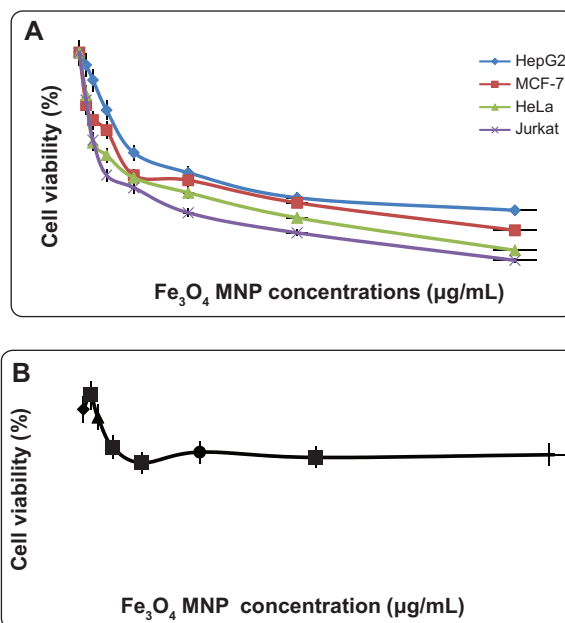


Figure 2 (A) The cytotoxic effect of Fe₃O₄ MNPs on various cancer cell lines after 72 hours of treatment evaluated by mitochondrial activity using the MTT assay. Each point represents the mean value of three replicates. **(B)** The cytotoxic effect of Fe₃O₄ MNPs on a normal Chang human liver cell line after 72 hours of treatment evaluated with MTT assay. Each point represents the mean value of three replicates.

Abbreviations: Fe₃O₄ MNPs, magnetic iron oxide nanoparticles; MTT, 3-(4,5-dimethylthiazol-2-yl)-2,5 diphenyl tetrazolium bromide.

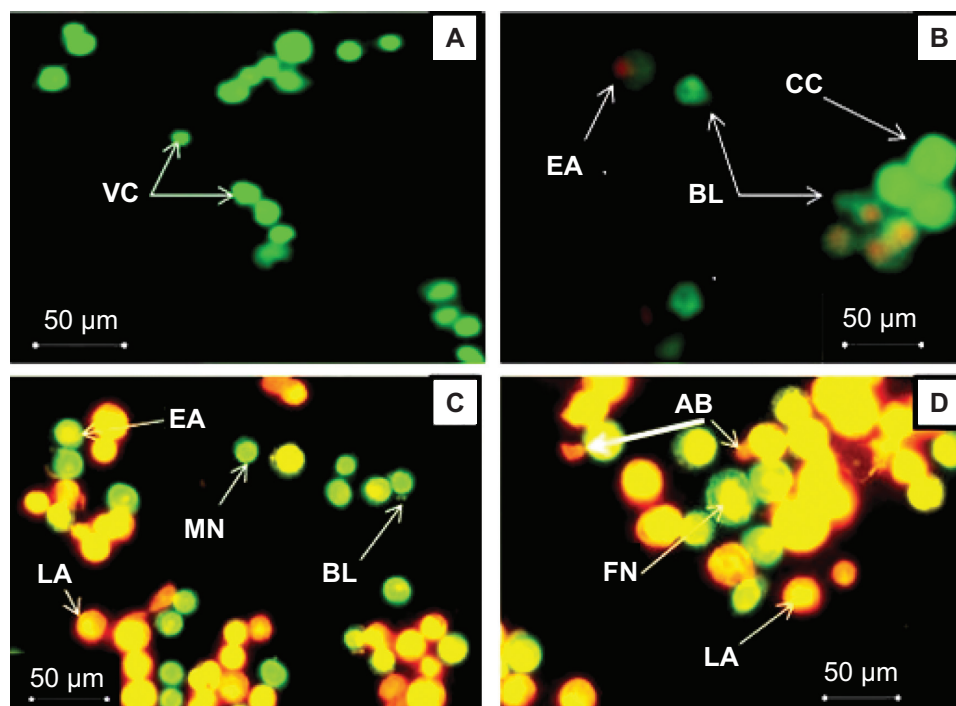


Figure 3 Fluorescent micrographs of acridine orange/propidium iodide double-stained Jurkat cells treated with Fe₃O₄ MNPs. (A) Untreated cells showing normal cell structure, (B) early apoptotic cells after 24 hours of treatment showing membrane blebbing and chromatin condensation, (C) blebbing and nuclear margination after 48 hours of treatment, and (D) DNA fragmentation and apoptotic body formation after 72 hours of treatment.

Abbreviations: VC, viable cells; EA, early apoptotic cells; CC, chromatin condensation; BL, membrane blebbing; MN, margined nucleus; FN, fragmented nucleus; LA, late apoptotic cells; AB, apoptotic body; Fe₃O₄ MNPs, magnetic iron oxide nanoparticles; DNA, deoxyribonucleic acid.

examined the effect of superparamagnetic iron oxide nanoparticles on human bone marrow mesenchymal stromal cells from two donors, ie, hBMSCs-1 and hBMSCs-2. Their results showed only hBMSCs-2 were sensitive to these nanoparticles; however, increased oxidative injury to lipids, proteins, and DNA was detected in cells from both donors.³¹

Schweigera et al reported on Fe₃O₄ MNPs stabilized with poly(ethyleneimine)-g-poly(ethylene glycol) and branched poly(ethyleneimine). They also evaluated the cytotoxic effects of polymer-coated iron oxide nanoparticles in A549 epithelial adenocarcinoma cells. Their findings for cell viability showed that poly(ethyleneimine) layered onto iron oxide nanoparticles comparable with free poly(ethyleneimine) polymer produced significant cytotoxicity.¹¹

Quantification of apoptosis using acridine orange/propidium iodide double-staining

Induction of apoptosis is a useful strategy in the treatment of cancer. Several cellular and molecular biological features can be demonstrated in apoptotic cells, including cell shrinkage, DNA fragmentation, and activation of the caspase cascade. The cytotoxicity of Fe₃O₄ MNPs was evaluated by inhibition of cell growth. When the growth-inhibited cells were stained with acridine orange/propidium iodide, apoptotic cell

death was observed in a time-dependent and dose-dependent manner in all cultures (Figure 3).

Intact membranes exclude propidium iodide, but allow uptake of acridine orange, which binds to double-stranded DNA and fluoresces green under 488 nm excitation. Untreated cells show diffuse green fluorescence, while apoptotic cells (containing condensed chromatin material) show clumps of intense green fluorescent spots within the cell. Characteristic condensation patterns observed were the crescent shape at the periphery of the nucleus and at the more numerous round clumps.

Annexin V-FITC assay

The apoptotic effect induced by the Fe₃O₄ MNPs was investigated further by determining the percentage of apoptotic cells using flow cytometric analysis with Annexin V/propidium iodide double-staining. Annexin V-positive/propidium iodide-negative staining indicated cells in early apoptosis due to the strong affinity of A-FITC for phosphatidylserine, which transports from the inner leaflet of the plasma membrane to the outer surface of the membrane during early apoptosis. On the other hand, Annexin V-negative/propidium iodide-positive staining indicates necrotic cells, since propidium iodide, which cannot pass through an intact cell membrane,

penetrates the compromised membranes of cells that are dead or in late apoptosis, and binds to nucleic acids. Meanwhile, Annexin V-negative/propidium iodide-negative staining indicates viable cells and Annexin V-positive/propidium iodide-positive staining indicates cells in late apoptosis. The representative dot plots for the flow cytometric analysis comparing untreated cells and treated cells (at 12, 24, and 48 hours) showed an increase in the percentages of cells in early apoptosis and late apoptosis (Figure 4 and

Table 1). In addition, exposure to Fe_3O_4 MNPs resulted in a slight decrease in the amount of viable cells at 12, 24, and 48 hours. These results suggest that the antiproliferative effect of Fe_3O_4 MNPs on Jurkat cells results from induction of cell apoptosis.

Cell cycle assay

In cells treated with agents that induce apoptosis, a sub-population of cells appears before the G1 peak and is

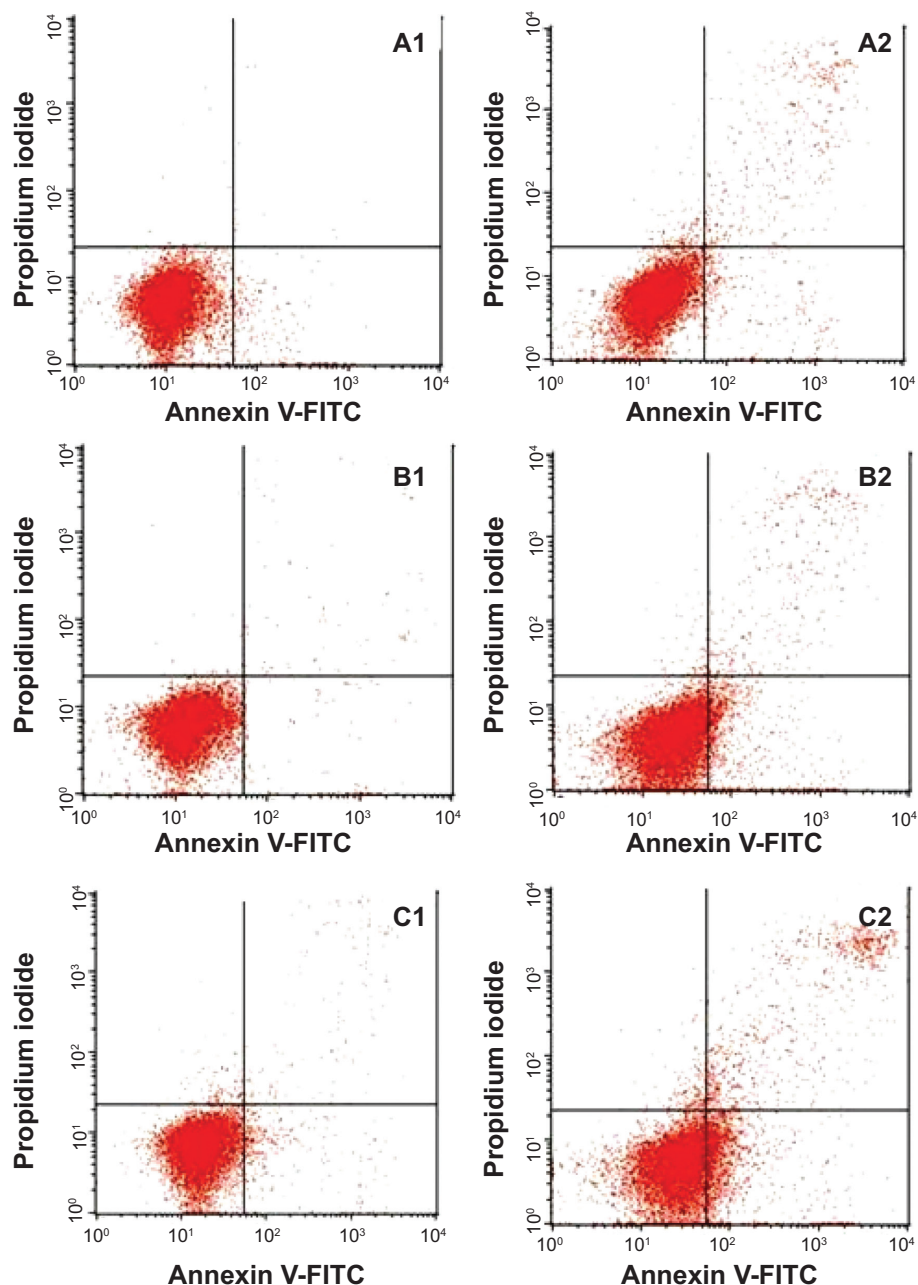


Figure 4 Flow cytometric analysis of induction of apoptosis in Jurkat cells by Fe_3O_4 MNPs after staining with FITC-conjugated Annexin V and propidium iodide. (A1–C1) Untreated (control) Jurkat cells after 12, 24, and 48 hours of incubation, respectively. (A2–C2) Effects of 12, 24, and 48 hours of treatment with Fe_3O_4 MNPs, respectively. **Abbreviations:** Fe_3O_4 MNPs, magnetic iron oxide nanoparticles; Annexin V-FITC, annexin V-conjugated fluorescein isothiocyanate.

Table 1 Flow cytometric analysis of Jurkat cells treated with Fe₃O₄ MNPs

Cells (%)						
Cell Condition	Control 12 hours	Treated 12 hours	Control 24 hours	Treated 24 hours	Control 48 hours	Treated 48 hours
Viable cells	95.54±0.11	89.59±0.26	93.33±0.55	85.29±0.16	93.78±0.26	74.98±0.33
Early apoptosis	1.77±0.14	4.75±0.61*	1.98±0.57	8.00±0.38*	3.15±0.41	15.04±0.52*
Late apoptosis/necrosis	2.69±0.34	5.66±0.95**	4.69±0.50	7.71±0.82**	3.07±0.25	9.98±0.50**

Notes: The cells were stained with FITC-conjugated Annexin V and propidium iodide, then incubated at 37°C for 12, 24, and 48 hours. Values are expressed as the mean ± standard deviation of three different experiments. The data were analyzed using post hoc comparison test-one way analysis of variance, and means were compared by Tukey's B test. *Significant ($P < 0.05$) increase in early apoptotic cells in Fe₃O₄ MNP-treated groups compared with untreated controls. **Significant ($P < 0.05$) increase in late apoptotic/necrotic cells in Fe₃O₄ MNP-treated groups compared with untreated controls.

Abbreviations: Fe₃O₄ MNP, magnetic iron oxide nanoparticles; FITC, fluorescein isothiocyanate.

referred to as the sub-G1 peak. This is believed to be the result of endonuclease activation and subsequent leakage of DNA from the cells. Necrotic cells do not show an immediate reduction in DNA content, so a distinction can be made. As shown in Figure 5 and Table 2, the sub-G1 population, indicating apoptotic cells, increased in

a time-dependent manner from 10.10±0.28 24 hours after exposure to Fe₃O₄ MNPs to 20.0±0.20 after 48 hours and 23.85±0.56 after 72 hours. Regulation of the cancer cell cycle is a potential strategy in the development of anticancer drugs. Xia et al showed a shift of cell distribution into the G2/M phase, which was enhanced by Fe₃O₄ MNPs.³²

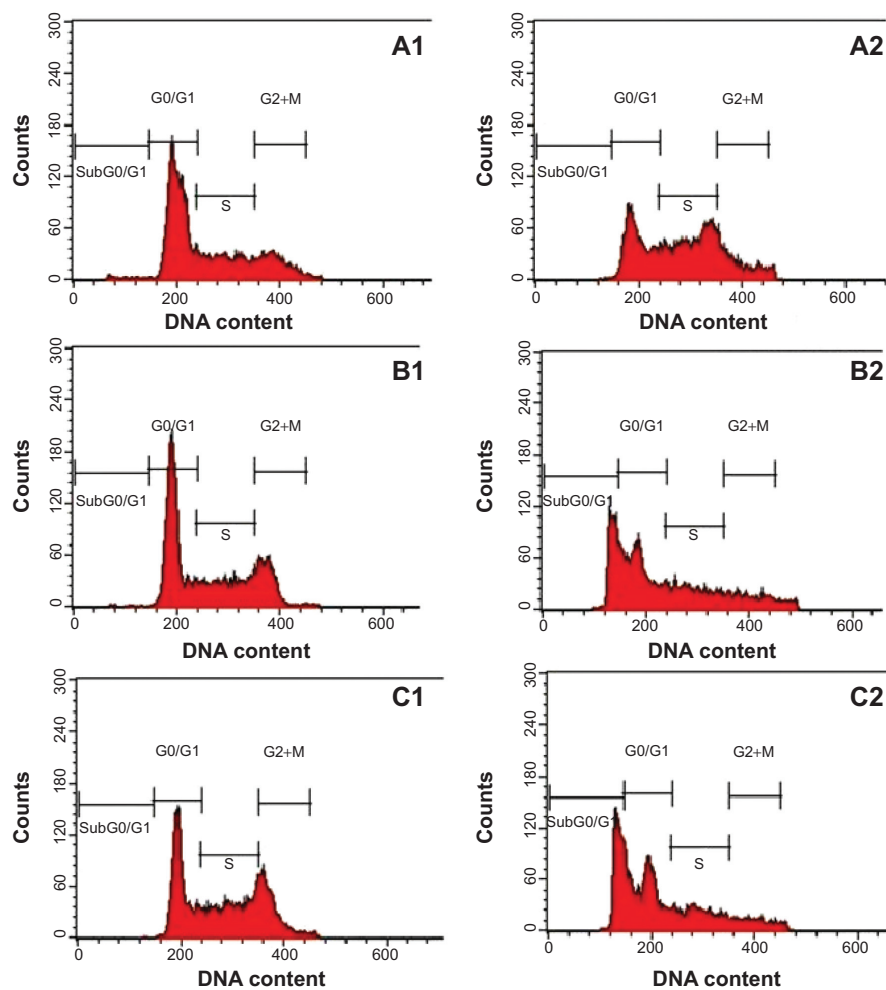


Figure 5 Cell cycle analysis of Jurkat cells treated with Fe₃O₄ MNPs after staining with propidium iodide. (A1–C1) Untreated Jurkat cells treated for 24, 48, and 72 hours, respectively. (A2–C2) Effects of 24, 48, and 72 hours of exposure of Jurkat cells to Fe₃O₄ MNPs, respectively. G0/G1, G2/M, and S indicate the cell phase, and sub-G0/G1 refers to the proportion of apoptotic cells.

Abbreviation: Fe₃O₄ MNPs, magnetic iron oxide nanoparticles; DNA, deoxyribonucleic acid.

Table 2 Flow cytometric analysis of Jurkat cells treated with Fe₃O₄ MNPs

Cells (%)	Control		Treated		Control		Treated	
Cell cycle phases	24 hours	24 hours	48 hours	48 hours	72 hours	72 hours	72 hours	72 hours
G0/G1	56.25±0.06	33.44±0.45	51.13±0.29	42.61±0.52	37.64±0.32	45.68±0.68		
G2/M	17.85±0.76	18.29±0.41	20.16±0.26	12.29±0.35	24.22±0.22	10.06±0.93		
Synthesis	24.91±0.06	38.23±0.33	29.24±0.06	22.93±0.12	38.95±0.61	21.35±0.18		
Sub G0/G1	0.98±0.23	10.10±0.28*	0.20±0.34	20.0±0.20*	0.02±0.46	23.85±0.56*		

Notes: The cells were stained with propidium iodide and incubated at 37°C for 24, 48, and 72 hours. Values are expressed as the mean ± standard deviation of three different experiments. The data were analyzed using post hoc comparison test-one way analysis of variance, and means were compared by Tukey's B test. *Significant (*P*<0.05) increase of cells in sub-G0/G1 phase in Fe₃O₄ MNP-treated groups compared with untreated controls.

Abbreviation: Fe₃O₄ MNP, magnetic iron oxide nanoparticles.

Our data indicate that the sub-G1 population, ie, apoptotic cells, increased in a time-dependent manner, whereas other researchers have reported cells arrested in G1/S and in both G1/S and G2/M.³² These conflicting results suggest that there may be fundamental differences between cell types.

Caspase assay

The apoptotic effect of Fe₃O₄ MNPs was also examined by determining caspase-3 and caspase-9 activity relative to varying concentrations of protein content for cells treated with the IC₅₀ of Fe₃O₄ MNPs. Our results show that enzyme activity increased in a time-dependent manner, as shown in Figure 6 and Table 3.

Apoptosis is orchestrated by a family of cysteine proteases known as caspases. The main effectors of apoptosis encompass proteases from the caspase family, which reside as latent precursors in most nucleated animal cells. Fourteen mammalian caspases have been identified, three of which (caspase-3, caspase-6, and caspase-7) are

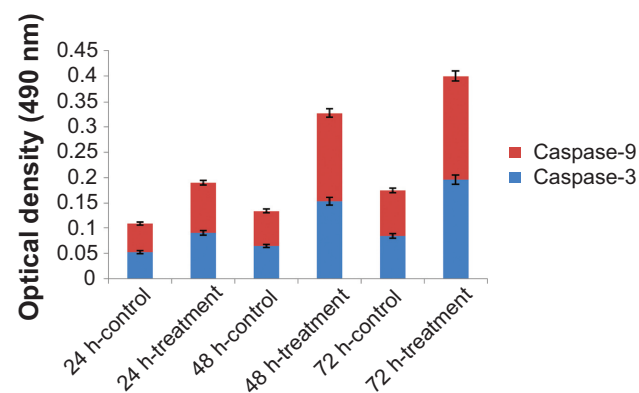


Figure 6 Effect of treatment with Fe₃O₄ MNPs on caspase-3 and caspase-9 activity in Jurkat cells. The values represent the mean ± standard deviation of three independent experiments. Significant differences (*P*<0.05) in caspase-3 and caspase-9 activity were found between the treated and control groups.

Abbreviation: Fe₃O₄ MNPs, magnetic iron oxide nanoparticles.

thought to coordinate the execution phase of apoptosis by cleaving multiple structural and repair proteins. Pathways to caspase-3 activation have been identified, which are either dependent on or independent of release of mitochondrial cytochrome c and caspase-9 function. Caspase-3 is required for the typical hallmarks of apoptosis, and is necessary for apoptotic chromatin condensation and DNA fragmentation in all cell types examined. Thus, caspase-3 is essential for certain processes associated with dismantling of the cell and the formation of apoptotic bodies. However, it may also function before or at the stage when commitment to loss of cell viability is made. As shown in Figure 7, Fe₃O₄ MNPs increased the activity of caspase-9 and caspase-3 in a time-dependent manner. According to studies of caspase activity, several distinct pathways exist, resulting in induction of apoptosis by Fe₃O₄ MNPs. In our study, we noted that Fe₃O₄ MNPs activated caspase-3 and caspase-9 in a time-response manner.

Conclusion

Fe₃O₄ MNPs with different sizes and characteristics have been developed and widely investigated in a number of biomedical applications. Stabilizing molecules, as well as preventing the formation of aggregation, were critical for controlling the chemical reactions and consequently provided dependable well dispersed size and consistency. In this study, we investigated the toxicity of Fe₃O₄ MNPs in human leukemia (Jurkat) cells. Our results show that exposure of Jurkat cells to Fe₃O₄ MNPs results in significant cytotoxicity, with an apoptotic response, but not in a normal Chang liver cell line, providing new opportunities for safe delivery of Fe₃O₄ MNPs and application in anticancer therapy.

Acknowledgment

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Table 3 Spectrophotometric analysis of caspases in Jurkat cells treated with Fe₃O₄ MNPs for 24, 48, and 72 hours

Cells %	24 hours		48 hours		72 hours	
Caspase	Control	Treated	Control	Treated	Control	Treated
Caspase-3	0.057±0.003	0.095±0.001*	0.068±0.010	0.158±0.025*	0.080±0.095	0.199±0.055*
Caspase-9	0.059±0.001	0.102±0.009*	0.07±0.081	0.179±0.016*	0.095±0.039	0.207±0.031*

Notes: Values are expressed as the mean ± standard deviation of three different experiments. The data were analyzed using post hoc comparison test-one way analysis of variance, and means were compared by Tukey's B test. *Significant ($P < 0.05$) increase in apoptotic cells in Fe₃O₄ MNP-treated groups compared with untreated controls.

Abbreviation: Fe₃O₄ MNP, magnetic iron oxide nanoparticles.

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Disclosure

The authors report no conflicts of interest in this work.

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