Synergistic effect of magnetic nanoparticles of Fe$_3$O$_4$ with gambogic acid on apoptosis of K562 leukemia cells

Abstract: Gambogic acid (GA) has a significant anticancer effect on a wide variety of solid tumors. Recently, many nanoparticles have been introduced as drug-delivery systems to enhance the efficiency of anticancer drug delivery. The aim of this study was to investigate the potential benefit of combination therapy with GA and magnetic nanoparticles of Fe$_3$O$_4$ (MNPs-Fe$_3$O$_4$). The proliferation of K562 cells and their cytotoxicity were evaluated by MTT assay. Cell apoptosis was observed and analyzed by microscope and flow cytometry, respectively. Furthermore, realtime polymerase chain reaction and Western blotting analyses were performed to examine gene transcription and protein expression, respectively. The results showed that MNPs-Fe$_3$O$_4$ dramatically enhanced GA-induced cytotoxicity and apoptosis in K562 cells. The typical morphological features of apoptosis treated with GA and MNPs-Fe$_3$O$_4$ were observed under an optical microscope and a fluorescence microscope, respectively. The transcription of caspase-3 and bax gene in the group treated with GA and MNPs-Fe$_3$O$_4$ was higher than that in the GA-alone group or MNPs-Fe$_3$O$_4$-alone group, but the transcription of bcl-2, nuclear factor-$\kappa$B, and survivin degraded as did the expression of corresponding proteins in K562 cells. Our data suggests a potential clinical application of a combination of GA and MNPs-Fe$_3$O$_4$ in leukemia therapy.

Keywords: gambogic acid, magnetic nanoparticles of Fe$_3$O$_4$, traditional Chinese medicine, K562 leukemia cells, apoptosis

Introduction

A major problem of cancer therapy is the side effects of chemotherapy. Minimizing side effects and maximizing efficacy is a major goal in the development of tumor treatment. Gambogic acid (GA), a naturally occurring brownish orange resin called gamboge, possesses diverse biological effects such as anti-inflammatory and antioxidant actions. Preclinical research revealed that a therapeutic dose of GA could inhibit the growth of a wide variety of tumor cells, including hepatoma, pulmonary carcinoma, gastric cancer, and breast cancer cells. How GA mediates the growth of these tumor cells is not fully understood, but GA has been shown to induce apoptosis, arrest cell cycles, and downregulate bcl-2, nuclear factor-$\kappa$B, and survivin degraded activity. Preclinical research revealed that a therapeutic dose of GA did not inhibit the proliferation of bone marrow, peripheral blood leucocyte count, or phagocytotic function of macrophage in tumor-bearing mice. Because of its broad spectrum anticancer actions, satisfactory therapeutic effect, and good tolerance, GA is a promising candidate in anticancer drugs.

Another key problem for tumor treatment is the reducing sensitivity of tumor cells to cytotoxic drugs. Thus, many polymer nanospheres and nanoparticles have been introduced as drug-delivery systems to enhance the efficiency of anticancer drug
delivery based on the ability to target specific locations in the body.17 The most promising materials are magnetic nanoparticles. Magnetic nanoparticles of Fe₃O₄ (MNPs-Fe₃O₄), a biocompatible and superparamagnetic nanomaterial with satisfactory chemical stability and low toxicity, are widely used for targeted-drug carriers with target-orientation and sustained-release properties.18

Our study aims to evaluate the potential benefit of combination therapy with GA and MNPs-Fe₃O₄ for leukemia and whether MNPs-Fe₃O₄ could promote the apoptosis induced by GA. To elucidate the mechanisms possibly involved, we also measured the expression of apoptosis-related genes and proteins, including caspase-3, bax, bcl-2, NF-κB, and survivin.

**Materials and methods**

**Main reagents**

GA (Kanion Pharmaceutical Co., Ltd, Jiangsu, China) was dissolved in dimethyl sulfoxide (DMSO; Sigma Aldrich, St. Louis, MO), stored at −20 °C, and then diluted as needed in RPMI 1640 medium (Gibco/BRL, Carlsbad, CA). MTT was purchased from Sigma Aldrich. Monoclonal antibodies including caspase-3, bax, bcl-2, NF-κB, survivin, and β-actin were purchased from Santa Cruz Biotechnology (Santa Cruz, CA). MNPs-Fe₃O₄ (State Key Lab of Bioelectronics, Nanjing, China) were well distributed in RPMI 1640 medium (Sijiqing, Hangzhou, China) by using ultrasound treatment in order to obtain MNPs-Fe₃O₄ colloidal suspension. GA conjugated with MNPs-Fe₃O₄ was prepared by mechanical absorption polymerization at 4 °C for 48 hours.

**Cell lines and culture conditions**

K562 cells, derived from human leukemic cells from a chronic myeloid leukemia patient in blastic crisis and constantly preserved in our laboratory, were cultured in RPMI 1640 medium containing 10% (v/v) heat-inactivated new-born calf serum (Sijiqing, Hangzhou, China) by using ultrasound treatment to obtain MNPs-Fe₃O₄ colloidal suspension. GA conjugated with MNPs-Fe₃O₄ was prepared by mechanical absorption polymerization at 4 °C for 48 hours.

**Cell viability assay**

Cytotoxicity was determined by the MTT assay. K562 cells (8 × 10⁴/mL) were incubated into 96-well flat-bottomed plates (Costar, Charlotte, NC). Different concentrations of GA were added into these cells and cultured at 37 °C for 24, 48, and 72 hours, respectively. To determine the optimum synergistic effect of MNPs-Fe₃O₄, different concentrations of MNPs-Fe₃O₄ were used synephymally with or without GA in graded concentrations. Briefly, 20 μL MTT (5 mg/mL) was added to each well and incubated at 37 °C for 4 hours. The formazan was dissolved with 150 μL dimethyl sulfoxide (Sigma Aldrich) and the reduction of MTT was quantified by absorbance at 570 nm using a plate reader (Model 550; Bio-Rad Laboratories, Tokyo, Japan). The inhibition ratio (IR) of cells was determined as follows: (1 − A<sub>treated group/A<sub>control group> × 100%. The 50% inhibiting concentration (IC<sub>50> was defined as the concentration required for 50% inhibition of cell growth.

**Apoptosis assay by flow cytometer**

Quantification of apoptotic cells was performed using an Annexin-V-FITC Apoptosis Detection Kit (KenGen, Nanjing, China) according to the manufacturer’s instructions. After incubation in a medium containing different drugs at 37 °C for 48 hours, the cells were collected and suspended in 500 μL of binding buffer, and 5 μL Annexin-V-fluorescein isothiocyanate (FITC) and 5 μL propidium iodide (PI) were added at room temperature in the dark for 15 minutes. Analyses were performed by FACSscan flow cytometer (Becton Dickinson, Sunnyvale, CA). The cells in the FITC-positive and PI-negative fraction were regarded as apoptotic cells.

**Cell morphological assessment**

After being cultured in RPMI-1640 containing 6 mg/L GA, 0.6 mg/L GA conjugated with 10 mg/L MNPs-Fe₃O₄ or without GA at 37 °C for 48 hours, K562 cells were collected and smeared. Some films were stained with Wright’s stain to observe the morphological changes of apoptosis cells by optical microscope; others were fixed with methanol for 15 minutes, stained with fluoresce dye DAPI (Santa Cruz Biotechnologies), and then observed under a fluorescence microscope (IX51; Olympus, Tokyo, Japan) with a peak excitation wave length of 340 nm.

**Quantitative real-time PCR (QPCR) analysis**

As described before, K562 cells (8 × 10⁴/mL) were treated, harvested, and then total RNA was isolated using Trizol reagent (Invitrogen Life Technologies, Carlsbad, CA) according to the manufacturer’s protocol. The reverse transcription reactions were performed using SuperScript™ II reverse transcriptase (Invitrogen Life Technologies) and the newly synthetic cDNA was amplified within target and control sequences (primer sequences for caspase-3 (270 bp) forward, 5′-GCTATTTGTGAGCCTGGTGTG-3′ and reverse, 5′-TGTTTCCCTGCAGGTGGTG-3′; Bax (114 bp) forward, 5′-TTTTGCTTCAGGGTTTCATC-3′
and reverse, 5'-GACACTCGCTCAGCTTCTTG-3'; Bel-2 (452 bp) forward, 5'-GGGAGAACAGGGTGACATAA-3' and reverse, 5'-CCACCGAACTCAAGGAAGG-3'; NF-κB (227 bp) forward, 5'-TCGTTTCCGT ATGTATGT-3' and reverse, 5'-CCCTGGGTCCACGATTTA-3'; Survivin (255 bp) forward, 5'-CAAGGACCACCAGCATCTC-3' and reverse, 5'-CCAAGGTGTTATCTTCGAATC-3'; GAPDH (205 bp) forward, 5'-GGATTTGGTCGTATTG-3' and reverse, 5'-GAAGATGTGGTGATGGGATT-3'). QPCR was performed by monitoring in real-time the increase of fluorescence of SYBR green 1 dye (Takara, Shiga, Japan) with Rotor-Gene 3000 (Corbett Research, Sydney, Australia). The relative gene copy number was calculated by the concentration-CT standard curve method and normalized using the average expression of GAPDH.

Western blot analysis
In order to examine the expression of caspase-3, bax, bcl-2, NF-κB, and survivin, we next performed Western blot analysis on whole cell protein extracted from cells treated for 48 hours as described previously. In brief, total protein was isolated on ice and subjected to 10% sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE) gels using modified radio immunoprecipitation assay buffer, and transferred to a polyvinylidene difluoride membrane (Bio-Rad). Western blotting was performed with a 1:1000–1200 dilutions of monoclonal antibodies against either anti-human caspase-3, bax, bcl-2, NF-κB, surviving, or β-actin anti-body in 5% nonfat dry milk, and then with horseradish peroxidase-conjugated goat anti-rabbit (1:5000) as a secondary antibody. The band was detected by using an enhanced chemiluminescence detection system (Amersham, Buckinghamshire, UK).

Statistical analysis
All data were presented as means ± standard deviation in triplicate and analyzed using SPSS software (v. 15.0; SPSS Inc., Chicago, IL). The difference among various groups was analyzed by ANOVA test, and P values of less than 0.05 were considered significant.

Result
Synergistic effect on cytotoxicity of K562 cells
The MTT assay revealed that GA inhibited the survival of K562 cells in a dose- and time-dependent manner and the IC_{50} was 1.13 mg/L (Figure 1). Furthermore, it was observed that the addition of MNPs-FeO_{3} did enhance the inhibition of GA to K562 cells, and 10 mg/L MNPs-FeO_{3} reduced the IC_{50} value of GA to 0.72 mg/L (P < 0.05) (Figure 2), suggesting MNPs-FeO_{3} with GA have a synergistic effect on K562 cells.

Synergistic effect on apoptosis of K562 cells
Only (7.1% ± 3.23%) apoptosis of K562 cells were observed under 10 mg/L MNPs-FeO_{3}, there was no significant changes compared to the control group (6.1% ± 1.67%) (P > 0.05). The apoptosis of K562 cells induced by 0.6 mg/L GA for 48 hours was (35.2% ± 3.37%) (P < 0.05), while combination of GA with 10 mg/L MNPs-FeO_{3} increased to (48.7% ± 1.47%) (P < 0.05) (Figure 3), which indicated that MNPs-FeO_{3} could enhance GA-induced apoptosis.

Morphological changes of K562 Cells
The morphological changes of K562 cells by optical microscope were shown in Figure 4. K562 cells in control group displayed normal, healthy shape demonstrated by the clear skeletons (Figure 4A); After treatment with 0.6 mg/L GA and 10 mg/L MNPs-FeO_{3} for 48 hours, typical cytomorphological features of apoptosis in K562 cells were evident, such as cell shrinkage, chromatin condensation, margination, and presence of apoptotic bodies (Figure 4B); While large dose of GA led K562 cells to necrosis (Figure 4C).

Under the fluorescence microscope, the nucleolus changes of K562 cells were observed (Figure 5). K562 cells in control group were stained equably blue fluorescence, indicating that the chromatin equably distributed in nucleolus (Figure 5A), but 0.6 mg/L GA led a few K562 cells to display chromatin condensation and nucleolus pyknosis (Figure 5B). After incubated with 0.6 mg/L GA and 10 mg/L MNPs-FeO_{3} for
48 hours, the cells emitting bright fluorescence increased and displayed the typical phenomena of apoptosis including chromatin condensation, nucleolus pyknosis, and nuclear fragmentation (Figure 5C).

**Transcription of caspase-3, bax, bcl-2, NF-κB and survivin by QPCR**

10 mg/L MNPs-Fe$_3$O$_4$ could not influence the expression of caspase-3, bax, bcl-2, NF-κB, and survivin mRNA, but the synergia of 0.6 mg/L GA and 10 mg/L MNPs-Fe$_3$O$_4$, for 48 hours could dramatically upregulate the transcription of caspase-3 and bax mRNA in K562 cells ($P < 0.05$), surpassing the effects of 0.6 mg/L GA alone (Figure 6C) ($P < 0.05$). Meanwhile, the co-treatment of agents mentioned above for 48 hours seemed to induce degradation of bcl-2, NF-κB, and survivin mRNA on K562 cells ($P < 0.05$), also surpassing the effects of GA (0.6 mg/L) alone ($P < 0.05$).

**Expression of caspase-3, bax, bcl-2, NF-κB, and survivin protein by Western blot**

Based on computer-assisted image analysis, it seems that caspase-3, bax, bcl-2, NF-κB, and survivin proteins in K562 cells treated with 10 mg/L MNPs-Fe$_3$O$_4$ had no significant changes when compared to control group ($P > 0.05$). However, the level of caspase-3 and bax proteins in K562 cells treated with 0.6 mg/L GA dramatically elevated, compared to control group ($P < 0.05$) (Figure 7). Furthermore, these two kinds of proteins, whose genes were upregulated in 0.6 mg/L GA and 10 mg/L MNPs-Fe$_3$O$_4$ group in K562 cells (Figure 6), were more than those of 0.6 mg/L GA alone ($P < 0.05$). Reversely, compared with the control group, the level of other three proteins in cells after co-treatment as described previously was lower than those of 0.6 mg/L GA alone ($P < 0.05$) (Figure 7).

**Discussion**

Although many chemotherapy drugs are used clinically, the overall survival of leukemia patients is still unsatisfactory. The majority of chemotherapy medicines have serious adverse effects in addition to their clinical effects. Patients find these side effects hard to tolerate, which often causes chemotherapy failure. GA differs from other anticancer drugs as it is an apoptotic inducer from traditional Chinese medicine. It can induce tumor cell death selectively without toxicity to normal tissue, which offers...
a unique prospect in the development of new antitumor medicine.\textsuperscript{4,19} Apoptosis is an important metabolic step in regulating the number of cells and their growth. If apoptosis is blocked, the metabolism will become disordered and tumors will develop and grow.\textsuperscript{20} Most anticancer agents exert their anticancer effects by inducing apoptosis.\textsuperscript{21} Recently, MNPs-Fe\textsubscript{3}O\textsubscript{4} are widely used for targeted-drug carriers to enhance the efficiency of anticancer drug delivery based on the ability of target-orientation and sustained-release properties.\textsuperscript{18} Our previous studies have demonstrated the synergistic effect of MNPs-Fe\textsubscript{3}O\textsubscript{4} with anticancer drug on the intracellular accumulation in leukemia cells.\textsuperscript{22–28} Thus, in the present study, we wanted to demonstrate the potential synergistic effects of MNPs-Fe\textsubscript{3}O\textsubscript{4} and GA on apoptosis in leukemia cells.

Data from our cytotoxicity assay showed that MNPs-Fe\textsubscript{3}O\textsubscript{4} enhanced the toxicity of GA in K562 cells and the addition of MNPs-Fe\textsubscript{3}O\textsubscript{4} decreased the IC\textsubscript{50} of GA in K562 cells. This phenomenon is consistent with our previous studies that reported that less than 20 mg/L of MNPs-Fe\textsubscript{3}O\textsubscript{4} did not influence the multiplication of K562 cells.\textsuperscript{26} We also investigated the synergistic effects of GA with MNPs-Fe\textsubscript{3}O\textsubscript{4} on the apoptosis of K562 cells. The addition of 10 mg/L MNPs-Fe\textsubscript{3}O\textsubscript{4} caused the apoptotic percentage of K562 cells induced by 0.6 mg/L GA for 48 hours to increase by 14.4%. Our outcomes clearly indicate that a MNPs-Fe\textsubscript{3}O\textsubscript{4}-drug delivery system can decrease the IC\textsubscript{50} of GA and enhance apoptosis in leukemia cells.

In order to check whether the effects of MNPs-Fe\textsubscript{3}O\textsubscript{4} combining with a small dose of chemotherapeutic agent was...
different from the effects of a large dose of chemotherapeutic agent on K562 cells, we demonstrated that the K562 cells in 0.6 mg/L GA and 10 mg/L MNPs-Fe$_3$O$_4$ group for 48 hours showed a typical morphological features of apoptosis under the optical microscope, while 6 mg/L GA led cells to necrosis. This effect supports our previous assumption. Meanwhile, the cells incubated with 0.6 mg/L GA and 10 mg/L MNPs-Fe$_3$O$_4$ displayed the typical apoptosis under the fluorescence microscope, compared with that of 0.6 mg/L alone. These results suggest that a combination of MNPs-Fe$_3$O$_4$ and GA could be a feasible candidate in the development of anticancer drugs.

Apoptosis is the consequence of a series of precisely regulated events that are frequently altered in tumor cells. In general, the sequence of events has been broadly categorized into two pathways: the extrinsic pathway, which involves the activation of the tumor necrosis factor (TNF)/Fas death receptor family and the intrinsic pathway, which involves the mitochondria. In both pathways, an apoptotic death stimulus results in the activation of caspases, the major executioners of this process, either directly or via activation of the mitochondrial death program. It is well known that caspase-3 is the most characterized effector caspase, and its activation leads to the final stages of cellular death by proteolytic dismantling of a large variety of cellular components on one hand, and activation of proapoptotic factors on the other hand. Our study showed that GA combined with MNPs-Fe$_3$O$_4$ dramatically upregulated the transcription and expression of caspase-3 in K562 cells. This result supports the promotion of GA-induced apoptosis by MNPs-Fe$_3$O$_4$ was related to the level of genes and proteins expression.

In tumor cells, apoptosis can be induced either by activation of molecules upstream of apoptosis signaling or by inhibition of antiapoptotic factors. Survivin, a member of the inhibitor of apoptosis protein (IAP) family, is overexpressed in virtually every human cancer. In several tumor cell lines, the presence of survivin correlates with resistance to apoptosis and is associated with increased malignancy. Previous in vitro studies showed that inhibition of survivin restored or enhanced the cytotoxicity of chemoreagents, and animal studies showed a superb efficacy against xenografts using an adenoviral strategy targeted to survivin. At present, survivin is validated as a cancer therapeutic target. Our data showed that the expression of antiapoptotic genes such as bcl-2, survivin of K562
cells were significantly downregulated after co-treatment of GA with MNPs-Fe$_3$O$_4$, whereas the expression of bax was upregulated. Bax and bcl-2 both belong to the bcl-2 family. Overexpression of Bax has been shown to accelerate cell death, while overexpression of antiapoptotic proteins such as bcl-2 represses the death function of bax. Thus, the ratio of bcl-2/bax might be a critical factor of a cell’s threshold for undergoing apoptosis. Although bcl-2 and survivin are both apoptosis inhibitors, they work through different pathways in the regulation of cell apoptosis. The antiapoptotic protein bcl-2 mainly inhibits the mitochondrial pathways while survivin directly blocks the processing and activation of effector caspase-3 and caspase-7, which commonly acts downstream of both apoptosis signaling pathways, which suggests that MNPs-Fe$_3$O$_4$ loaded with GA induced cell apoptosis through various pathways.

NF-κB is a transcription factor, which regulates the expression of several genes whose products are involved in tumorigenesis. Apoptosis and tumorigenesis are known to be regulated by NF-κB-regulated gene products. The transcription factor NF-κB involves the extrinsic death receptor signaling pathway of apoptosis. Suppression of NF-κB activation promotes TNF-induced apoptosis. As our results showed, GA combined with MNPs-Fe$_3$O$_4$ induced the degradation of NF-κB genes and proteins in K562 cells. We presumed that they inhibited the activation of NF-κB and worked through downregulated NF-κB-regulated gene products involved in antiapoptosis such as IAP1, IAP2, bcl-2, Bcl-xL, and TRAF1.

Kasibhatla and colleagues reported an undiscovered link between transferrin receptor (TfR) and the rapid activation of apoptosis. GA binding to TfR induced a unique signal leading to rapid apoptosis of tumor cells. TfR, the molecular target for GA, was significantly overexpressed in different types of cancers. However, GA bound to the TfR independent of the transferring-binding site. Binding of GA to TfR activated the apoptosis cascade rapidly by using caspase-8 and the mitochondrial pathway. They also demonstrated that GA and transferrin bound to independent sites on the receptor and it appeared that GA was not competed by transferring. Yong Yang and colleagues proved that GA not only banded to transmembrane protein TfR, but also permeated the cell membrane and distributed in the cell matrix. Apart from the “extrinsic” pathway, they hypothesized that the intrinsic mitochondrial pathway for the activation of caspases might also be involved in GA-induced apoptosis. In our research, GA combined with MNPs-Fe$_3$O$_4$ induced apoptosis not only through influencing the regulatory factors in the intrinsic mitochondrial pathway such as bax and bcl-2, but also through regulating the transcription factor NF-κB involved in the extrinsic death receptor signaling pathway in apoptosis. We hypothesized that both pathways might be involved in apoptosis induced by the combination of MNPs-Fe$_3$O$_4$ with GA. Besides, in our study, a significant change was observed in apoptosis of K562 cells after GA combined with MNPs-Fe$_3$O$_4$, which obviously surpassed the effects of GA alone. We supposed that in addition to binding to TfR and stimulating a unique signal of rapid apoptosis, GA loaded on MNPs-Fe$_3$O$_4$ also permeated the cell membrane through binding to the transferring-binding site of TfR and the endocytosis, which were potential routes into cells for MNPs-Fe$_3$O$_4$. Our assumption should be proven by future research.

In conclusion, our study demonstrates for the first time that MNPs-Fe$_3$O$_4$ can promote apoptosis induction of GA in vitro in leukemic cells, and the synergistic effect of that composite on apoptosis induction may owe to the regulation of various proliferative and antiapoptotic gene products, including caspase-3, bax, bcl-2, NF-κB, and survivin. Thus, it may be possible that a combination of MNPs-Fe$_3$O$_4$ and GA may be a sufficient and less toxic method in leukemia therapy.
Acknowledgments
This work was supported by 863 Project of People’s Republic of China (No. 2007AA0222007) National Nature Science Foundation of People’s Republic of China (No. 30740062, 30872970) and Special-purpose Science Research Foundation for High School (No. 20070286042). The authors report no conflicts of interest in this work.

References


