Inhibitory effect of magnetic $\text{Fe}_3\text{O}_4$ nanoparticles coloaded with homoharringtonine on human leukemia cells in vivo and in vitro

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Abstract: Homoharringtonine (HHT), a natural cephalotaxine alkaloid, has been used in the People’s Republic of China for treatment of leukemia for >3 decades. Here, we employed magnetic $\text{Fe}_3\text{O}_4$ nanoparticles (MNP-$\text{Fe}_3\text{O}_4$) to improve the therapeutic effect of HHT and investigated its biological effects. Within a certain range of concentrations, the HHT-MNP-$\text{Fe}_3\text{O}_4$ showed a more enhanced inhibitory effect on the selected myeloid leukemia cell lines than HHT alone. Compared with HHT, HHT-MNP-$\text{Fe}_3\text{O}_4$ could induce more extensive apoptosis in leukemia cells, which also showed more pronounced cell arrests at G0/G1 phase. HHT-MNP-$\text{Fe}_3\text{O}_4$ enhanced antitumor activity by downregulating myeloid cell leukemia-1, which could inhibit the activation of caspase-3 and poly-ADP-ribose polymerase. In vivo experiments using tumor-bearing animal models showed that the mean tumor volume with HHT-MNP-$\text{Fe}_3\text{O}_4$ was significantly smaller than that with HHT alone (193±26 mm$^3$ versus 457±100 mm$^3$, $P<0.05$), while the mean weight was 0.67±0.03 g versus 1.42±0.56 g ($P<0.05$). Immunohistochemical study showed fewer myeloid cell leukemia-1-stained cells in mice treated with HHT-MNP-$\text{Fe}_3\text{O}_4$ than with the controls. These findings provide a more efficient delivery system for HHT in the treatment of hematological malignancy.

Keywords: leukemia, magnetic nanoparticles, magnetic $\text{Fe}_3\text{O}_4$ nanoparticles, HHT

Introduction

Myeloid leukemia, a type of leukemia involving myeloid tissue, is a heterogeneous group of clonal disorders characterized by an abnormal proliferation of myeloid stem/progenitor cells and subsequent bone marrow failure. Although a majority of these patients can achieve complete remission by current chemotherapies, most of these patients may ultimately relapse within a certain limited period. Hence, there is a largely unsatisfied need for more effective drugs for the patient population with treatment failure or relapse.

Homoharringtonine (HHT), a kind of Chinese traditional medicine, is a compound derived from the Cephalotaxus genus. HHT was first isolated in the 1970s and was found to have natural antitumor and antileukemic activities in vitro and in vivo studies. HHT was initially considered as one of the most effective choices for patients with acute myelocytic leukemia (AML) and chronic myelogenous leukemia (CML) who failed with interferon alpha (IFN-α) therapy and could not tolerate hematopoietic stem cell transplantation. However, after the tyrosine kinase inhibitor imatinib mesylate was recommended as the standard therapy for patients with CML, the attention toward HHT began to decrease. Recently, a few encouraging findings demonstrated that HHT played a critical role in the treatment of patients who failed with imatinib therapy, especially those with tyrosine kinase inhibitor-insensitive T315I mutation.
Materials and methods

Cell culture

The myeloid leukemia cell lines HL60, K562, NB4, and SHI-1 were obtained from the Shanghai Cell Culture Institute (Shanghai, People’s Republic of China). All but SHI-1 cell lines were cultured in RPMI-1640 (SHI-1 cell line in Iscoves modified Dulbecco medium), containing 100 U/mL penicillin and 10% fetal bovine serum. All cell lines were incubated in a humidified atmosphere containing 5% CO₂ at 37°C. Total viable cells were assessed using the trypan blue staining.

Materials

HHT was obtained from Shaanxi Sciphar Biotechnology Co., Ltd (Shanxi Province, People’s Republic of China). Oleic acid-coated iron oxide NPs were obtained from Jiangsu Key Laboratory for Biomaterials and Devices (Southeast University, Nanjing, People’s Republic of China). Other reagents used included cell counting kit-8 (Sigma Chemicals, Perth, Australia), Annexin V–fluorescein isothiocyanate Apoptosis Detection Kit (KeyGEN Biotech, Nanjing, People’s Republic of China), Cell Cycle Detection Kit (Beyotime Institute of Biotechnology, Jiangsu, People’s Republic of China), Transwell insert chambers (Costar®, Corning Inc., Corning, NY, USA), matrigel-coated membrane inserts (BD Biosciences, San Jose, CA, USA), and 1% methylcellulose lysis buffer (RIPA lysis buffer, Beyotime Institute of Biotechnology). Monoclonal antibodies, including those for caspase-3, PARP, Mcl-1, and β-actin, were supplied by Santa Cruz Biotechnology Inc. (Dallas, TX, USA). All reagents were of analytical grade.

Preparation of HHT-MNP-Fe₃O₄

A two-step method reported previously was used for the synthesis of oleic acid-coated iron oxide NPs.²² HHT and oleic acid-coated iron oxide NPs were dissolved in tetrahydrofuran at a ratio of 1:5 (w/w) for preparation of HHT-MNP-Fe₃O₄. The mixture was slowly added into 1% polyoxyethylene-polyoxypolyethylene copolymer solution under sonication, and the resulting suspension was stirred for 6 hours to evaporate tetrahydrofuran. Finally, the resulting suspension was filtered and lyophilized. The drug loaded in MNP-Fe₃O₄ was 10.71 wt% (HHT-to-iron weight ratio). The free drug was separated from loaded drug by retrodialysis method and quantified by high-performance liquid chromatography.²²²³ The morphology of MNP-Fe₃O₄ after rehydration was observed using a transmission electron microscope. The hydrodynamic diameter and size distribution of MNP-Fe₃O₄ were examined using a dynamic light scattering instrument and analyzed by
Brookhaven Instruments NanoDLS Particle Sizing Software. To determine the kinetics of HHT release from HHT-MNP-Fe$_3$O$_4$ NPs, 1 mL of the HHT-MNP-Fe$_3$O$_4$ NPs was placed into a dialysis bag (8,000–12,000 Da) and submerged into 10 mL of pH 7.4 PBS (with 0.5% Tween-80) at 37°C with stirring for 48 hours. At 12 hours, 24 hours, 36 hours, and 48 hours, 1 mL of buffer was withdrawn and replaced with the same volume of buffer. The concentration of HHT was determined by high-performance liquid chromatography.\textsuperscript{23}

**Animal model**

**Subcutaneous tumor model**

Female athymic nude mice, aged 5 weeks and weighing 20±2 g, were purchased from the Shanghai Laboratory Animal Center, People’s Republic of China. SHI-1 cells (1×10$^5$ cells per mouse) were inoculated subcutaneously to mice at the left axilla (designated as day 0). Mice were randomly divided into four groups. Tumors were measured by a vernier caliper on alternate days and their volume ($V$) were calculated as $V = d \times D/2$ where $d$ and $D$ represent the shortest and the longest diameter of the tumor in mm, respectively. When the tumor reached a mean size of 100 mm$^3$, the mice were injected with 2.5 mg/kg HHT or HHT-MNP-Fe$_3$O$_4$. The treatment was carried out three times without interval in 3 days by the tail vein. Tumor volume was measured at days 7, 14, 21, and 28 to evaluate the drug effect. At day 28, mice were killed and the tumors were fixed in 10% neutral formalin, desiccated, and then embedded in paraffin for immunohistochemical analysis. The statistics of experiment results were calculated by one-way analysis of variance and Student’s t-test. $P<0.05$ was chosen as significance level for all analyses performed.

**Results**

**Physicochemical and properties of HHT-MNP-Fe$_3$O$_4$**

As shown in Figure 1A, the polymeric micelles were generated by the hydrophobic interaction of the polyoxyethylene–polyoxypropylene copolymer chain and oleic acid on the surface of iron oxide NPs. The average core size of these HHT-NPs determined by transmission electron microscope was 11.2 nm (Figure 1B). The average hydrodynamic diameter of HHT-NPs for three batches determined by dynamic light scattering was 57.3±2.2 nm (Figure 1C), which covered both the core–shell and its aqueous layer. Moreover, the polydispersity index of HHT-NPs is 0.119. The drug release from NPs at 12 hours, 24 hours, 36 hours, and 48 hours was 7.2%±2.1%, 19.2%±3.5%, 26.7%±5.4%, and 46.2%±3.9%, respectively. The results show that the release rate of HHT from HHT-MNP-Fe$_3$O$_4$ NPs is very slow and a sustained release would be expected in vivo.

**Effect of HHT-MNP-Fe$_3$O$_4$ on leukemia cell lines in vitro**

Four cell lines (K562, HL-60, SHI-1, and NB4) were employed to test the growth inhibition and cytotoxicity of HHT-MNP-Fe$_3$O$_4$. After treating with HHT at various concentrations for 24 hours, 36 hours, and 48 hours, NB4 was the cell line most sensitive to HHT treatment (Figure 2A). The mean IC$_{50}$ values for HHT-induced NB4 in three independent experiments were 0.022 µM, 0.014 µM, and 0.09 µM at 24 hours, 36 hours, and 48 hours, respectively (Figure 2B). So, we chose NB4 cells as the experiment subject in vitro. HHT-MNP-Fe$_3$O$_4$ demonstrated antitumor activity against NB4 cells in a dose-dependent manner (Figure 2C). Furthermore, HHT-MNP-Fe$_3$O$_4$ displayed a higher inhibition ratio compared with HHT at a dose of 0.015625–0.125 µM ($P<0.05$).

The morphological features of HE-stained NB4 were characterized under an optical microscope (Figure 3A). After treating with HHT and HHT-MNP-Fe$_3$O$_4$ at the dose of 0.015625 µM for 24 hours, there were typical apoptotic morphological changes such as formation of apoptotic bodies, nuclear fragmentation, and karyopyknosis found in NB4 cells. These apoptotic changes were more evident with HHT-MNP-Fe$_3$O$_4$ when compared with HHT alone. The ultrastructural morphology of NB4 cells was analyzed using a transmission electron microscope (Figure 3B).
The invagination of the cell membrane and visible black particles inside were observed in NB4 cells treated with MNP-Fe$_3$O$_4$, while the cellular membrane in the control group was intact. A large number of intracellular vacuoles without black particles, loosing chromatins, and swollen lysosomes were observed for NB4 cells treated with HHT. The similar phenomena but with visible black particles could be observed for NB4 cells treated with HHT-MNP-Fe$_3$O$_4$.

The apoptosis rate of NB4 cells induced by HHT-MNP-Fe$_3$O$_4$, which consisted of 0.0078125 µM HHT, was significantly higher than that induced by HHT alone at the dose of 0.0078125 µM for 24 hours (18.4% versus 10.73%; $P<0.05$; Figure 4A). This indicated that MNP-Fe$_3$O$_4$ could enhance HHT-induced apoptosis. The 24-hour HHT-MNP-Fe$_3$O$_4$ treatment resulted in a more cell arrest of NB4 cells at G0/G1 phase when compared with treatment with HHT alone. Furthermore, for the MNP-Fe$_3$O$_4$-loaded HHT group, the proportion of G0/G1 cells was increased from 47.83%±1.42% to 60.4%±1.26% ($P<0.05$; Figure 4B). Moreover, the number of colonies of NB4 cells treated with HHT-MNP-Fe$_3$O$_4$ was more than that with the HHT group (19.7±3.2 versus 25.9±4.3, $P<0.05$, Figure 4C).

Western blotting showed that higher protein levels of cleaved caspase-3 and PARP were observed in the HHT-MNP-Fe$_3$O$_4$ group when compared with the HHT group, which may account for the higher inhibition ratio of HHT-MNP-Fe$_3$O$_4$ (Figure 4D). The decreased levels of Mcl-1 protein in NB4 cells treated with HHT-MNP-Fe$_3$O$_4$ showed statistical significance compared with that with HHT alone ($P<0.05$). Therefore, the downregulation of Mcl-1 may result in marked degradation of cleaved caspase-3 and PARP.

Tumor-bearing animal models

The mean tumor volume for the mice treated with HHT-MNP-Fe$_3$O$_4$ was significantly smaller than that with HHT alone (193±26 mm$^3$ versus 457±100 mm$^3$, $P<0.05$, Figure 5A). The tumor weight for those with HHT-MNP-Fe$_3$O$_4$ was significantly smaller than with HHT alone. For the HE staining, the normal tumor cells with clear cell morphology and more chromatins were observed in the control group and the MNP-Fe$_3$O$_4$ group. It suggests a flourishing tumor growth. A large number of necrotic cells and vacuoles were observed in tumors in mice treated with HHT-MNP-Fe$_3$O$_4$. 

Figure 1 Construction of HHT-NPs.
Notes: (A) HHT-NPs that are constructed by the hydrophobic interaction between the polyoxyethylene–polyoxypropylene copolymer chain and oleic acid (OA) on the surface of iron oxide NPs; (B) transmission electron microscopy images of HHT-NPs after rehydration with water; and (C) hydrodynamic diameter of HHT-NPs after rehydration with water.
Abbreviations: HHT, homoharringtonine; NPs, nanoparticles.
whereas only limited necrotic tumor cells could be seen in those with HHT alone (Figure 5B).

The findings with regard to the proportion of blast cells in peripheral blood from the BABL/C mice demonstrated less residual tumor cells in the HHT-MNP-Fe$_3$O$_4$ group than in the HHT group (0.09 ± 0.05 versus 0.23 ± 0.04, Figure 5C). Although Mcl-1 protein level in the spleen collected from the mice implied the antitumor efficacy of HHT and HHT-MNP-Fe$_3$O$_4$, the level of this protein was notably lower in the HHT-MNP-Fe$_3$O$_4$ group than in the HHT group (0.17 ± 0.057 versus 0.31 ± 0.061, Figure 5D). These results suggested that HHT-MNP-Fe$_3$O$_4$ had higher antitumor activity than HHT in vivo.

**Discussion**

HHT, a natural cephalotaxine alkaloid, has been used in the People’s Republic of China for treatment of leukemia for >30 years. As reported previously, HHT in combination with Ara-C could induce a complete remission rate of 39%–60% in elderly patients with AML.

In a recent randomized Phase III trial (ChiCTR-TRC-06000054), HHT combined with cytarabine and aclacinomycin resulted in a CR rate of 73%, whereas HHT combined with cytarabine and daunorubicin in young patients with newly diagnosed AML resulted in a CR rate of 67%.

Because of its dramatic toxicity, the use of HHT is limited in the treatment of severe diseases. Moreover, the poor solubility results in poor bioavailability and low absorption of HHT. Meanwhile, the NPs can act as a universal drug carrier system for systemic administration of water-insoluble anticancer drugs. So, we chose MNP-Fe$_3$O$_4$ as a drug delivery vector for HHT, aiming to increase its antitumor activity in vitro and in vivo.

**Figure 2** The inhibitory effect of different HHTs on growth of myeloblastic leukemia cell lines in vitro.

**Notes:** (A) $IC_{50}$ of HHT on K562, HL-60, SHI-1, and NB4 in vitro; (B) the inhibitory effect of MNP-Fe$_3$O$_4$ on growth of NB4 for 24 hours; and (C) the inhibitory effect of different dosage forms of the drug on growth of NB4 for 24 hours.

**Abbreviations:** HHT, homoharringtonine; MNP-Fe$_3$O$_4$, magnetic Fe$_3$O$_4$ nanoparticles.
The effect of growth inhibition of HHT-MNP-Fe$_3$O$_4$ was stronger than that of HHT alone as demonstrated by the significant difference between the two groups in cell proliferation and apoptosis. Apoptosis is triggered from the activation of caspases, including caspase-3, caspase-8, and caspase-9, which were situated at several key positions in the apoptotic pathways. PARP, as one of the essential substrates, was activated by caspase-3 and caspase-7, which promoted the DNA strand breaks. Mcl-1, as a representative prosurvival protein of the Bcl-2 family, protects tumor cells from apoptosis in the setting of hematologic malignancies. HHT is a molecule targeting the A-site cleft of eukaryotic ribosome, which then results in the decreased expression of Mcl-1. The introduction of MNP-Fe$_3$O$_4$(HHT-MNP-Fe$_3$O$_4$) may improve the biological effect of HHT on Mcl-1, resulting in lower tumor cells proliferation and higher apoptosis rate than HHT alone.
Based on the earlier mentioned findings, we further investigated the antitumor efficacy in vivo of HHT-loaded NPs in tumor-bearing mice. The different magnitudes of necrosis were observed for the different dosage forms as the animals treated with HHT-MNP-Fe₃O₄ exhibited larger necrotic area than those with HHT alone. Immunohistochemical study showed that the Mcl-1-stained cells from the mice in the HHT-MNP-Fe₃O₄ group were fewer than those from the controls receiving blank MNP-Fe₃O₄ or HHT alone. The earlier mentioned data confirmed that the expression of Mcl-1 was lower in the tumor tissue treated with HHT-MNP-Fe₃O₄, which was consistent with the result of Western blotting. The superior anticancer effect of HHT-MNP-Fe₃O₄ might be associated with the stability of NPs in blood circulation, slow release to tumor site, the effective cellular uptake, and cooperative effect of HHT and NPs.

Figure 4 The impact of HHT-MNP-Fe₃O₄ on NB4 cells versus HHT. 
Notes: NB4 cells were treated with different drugs: control, 1.875 µg/mL MNP-Fe₃O₄, 0.0078125 µM hhT, and 0.0078125 µM hhT + 1.875 µg/mL MNP-Fe₃O₄. (A) Apoptosis and (B) cell cycle of NB4 cells treated with different drugs for 24 hours was detected by flow cytometry (FCM); (C) the ability of colony-forming of NB4 treated with different drugs for 6 hours; (D) the expression level of PARP, Caspase-3 and Mcl-1 protein in NB4 cells treated by different drugs was detected by western blot.

Abbreviations: HHT, homoharringtonine; Mcl-1, myeloid cell leukemia-1; MNP-Fe₃O₄, magnetic Fe₃O₄ nanoparticles; PARP, poly-ADP-ribose polymerase; FCM, flow cytometry.
Figure 5 The impact of HHT-MNP-Fe₃O₄ on SHI-1 cells versus HHT in vivo.

Notes: (A) Tumor volume and body weight changes after anticancer treatment with different drug formulations in the subcutaneous model; (B) histological assay of tumors of SHI-1 tumor-bearing mice that received different treatments; (HE, 40× magnifications); (C) the proportion of blast in the peripheral blood of erythroleukemia implanted in BABL/C mice with treatments of different drug strategies (400×, Wright staining); (D) images of histological changes of different drug strategies in treatments of erythroleukemia implanted in BABL/C mice model. Brown and blue stains represent Mcl-1 and nuclei in immunohistochemical assay, respectively.

Abbreviations: HE, hematoxylin–eosin; HHT, homoharringtonine; Mcl-1, myeloid cell leukemia-1; MNP-Fe₃O₄, magnetic Fe₃O₄ nanoparticles.
The toxicity of HHT-MNP-Fe₃O₄ may cause some concern. However, in most studies about its in vivo toxicity, Fe₃O₄ NPs have been shown to be associated with low toxicity in the human body. It is primarily due to the fact that they can be degraded and cleared from circulation by the endogenous iron metabolic pathways. Iron released from NPs is metabolized in the liver and subsequently used in the formation of red blood cells or excreted via kidneys. A study comparing several metal oxide NPs demonstrated iron oxide NPs to be safe and nontoxic <100 mg/mL. Another study on normal, glial, and breast cancer cells revealed that the toxicity of Fe₃O₄ NPs coated with a bipolar surfactant is concentration dependent, with the particles being nontoxic in the concentration range of 0.1–10 mg/mL, whereas cytotoxic at 100 mg/mL. Therefore, it is possible to find a safe concentration range for Fe₃O₄ NPs without triggering adverse cellular response.

Conclusion
We designed a drug delivery vector for HHT. HHT-MNP-Fe₃O₄ had cooperative effect in suppression of tumor cell growth both in vivo and in vitro. The HHT-MNP-Fe₃O₄ could enhance the therapeutic efficiency by reducing the expression of Mc-1 and activating caspase-3 and PARP. Here, we pay attention to the potential of MNP-Fe₃O₄ and HHT, which can enhance the antitumor effect, and hope the designed anticancer drugs based on this research can be used in future clinical practice. Moreover, our study may provide a promising platform of the codelivery system as a component of combination therapy in the treatment of hematological malignancies.

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Disclosure
The authors report no conflicts of interest in this work.

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