Ferroferric oxide nanoparticles induce prosurvival autophagy in human blood cells by modulating the Beclin 1/Bcl-2/VPS34 complex

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Abstract: Magnetic iron oxide nanoparticles (NPs) are emerging as novel materials with great potentials for various biomedical applications, but their biological activities are largely unknown. In the present study, we found that ferroferric oxide nanoparticles (Fe3O4 NPs) induced autophagy in blood cells. Both naked and modified Fe3O4 NPs induced LC3 lipidation and degraded p62, a monitor of autophagy flux. And this change could be abolished by autophagy inhibitors. Mechanistically, Fe3O4 NP-induced autophagy was accompanied by increased Beclin 1 and VPS34 and decreased Bcl-2, thus promoting the formation of the critical complex in autophagy initiation. Further studies demonstrated that Fe3O4 NPs attenuated cell death induced by anticancer drugs bortezomib and doxorubicin. Therefore, this study suggested that Fe3O4 NPs can induce prosurvival autophagy in blood cells by modulating the Beclin 1/Bcl-2/VPS34 complex. This study suggests that caution should be taken when Fe3O4 NPs are used in blood cancer patients.

Keywords: iron oxide nanoparticle, autophagic pathway, anti-apoptosis

Background
Magnetic iron oxide nanomaterials are a type of novel material that have raised extensive attention because of their great biocompatibility, biodegradability, and low toxicity.1,2 With appropriate surface modifications, these materials have a promising potential for biomedical use, such as drug delivery, gene therapy, disease progress monitoring, and magnetic resonance imaging.1,2 Ferroferric oxide (Fe3O4) nanoparticles (NPs) are one such material displaying great potential for medical application; however, recent studies have demonstrated that these NPs might induce apoptosis and other cell responses.3 It was reported that Fe3O4 NP-induced apoptosis depends on the cell type. As a drug carrier, these NPs display very limited toxicity to cancer cell lines such as cervical cancer cells, but induce cytotoxicity and apoptosis in non-small lung cancer cells.3 Moreover, this activity is probably associated with the surface modifications. A recent study showed that polyacrylic acid-coated but not naked Fe3O4 NPs induce apoptosis.4

In addition to apoptosis, autophagy, another type of cell response, is frequently evoked in a self-protective manner in cells by foreign substances, such as drugs, or abnormal stress, such as irradiation and nutrient depletion. Fe3O4 NPs induce autophagy in some cells such as lung epithelial cancer cells and human brain-derived endothelial cells.5,6 But the biological responses of blood cancer cells to Fe3O4 NPs are unclear. In the present study, we investigated the effects of Fe3O4 NPs with various modifications on blood cells and found that Fe3O4 NPs induce autophagy, which protects myeloma...
cells from apoptosis induced by anticancer drugs. These results suggest caution should be taken when applying Fe₃O₄ NPs in the blood system.

**Materials and methods**

**Synthesis of Fe₃O₄ nanoparticles**

In a typical procedure,⁷ Tris(acetylacetonoato) iron(III) or Fe(acac)₃ (2 mmol), 1,2-dexadecanediol (10 mmol), oleic acid (90%) (6 mmol), oleylamine (OM) (6 mmol), and benzyl ether (20 mL) were mixed and magnetically stirred under a flow of nitrogen. The mixture was heated to 200°C for 2 hours, and then heated to 300°C for 1 hour under a blanket of nitrogen. The black-colored mixture was cooled down to room temperature. Under the ambient conditions, ethanol (40 mL) was added to the mixture, and a black material was precipitated and separated via centrifugation. The black product was dissolved in hexane in the presence of oleic acid (~0.05 mL) and oleylamine (~0.05 mL). Then the product was precipitated with ethanol and centrifuged to remove the solvent. The bare Fe₃O₄ nanoparticles were obtained for further application, such as surface modification.

**Synthesis of dopamine-polyacrylic acid-polyethylene glycol (DA-PAA-PEG) polymers**

DA-PAA-PEG polymer was synthesized following a previous protocol.⁸ Briefly, 18 mg PAA (mw=1,800, Sigma-Aldrich, 0.01 mmol) and 625 mg polyethylene glycol (PEG)-NH₂ (mw=5,000, Biomatrik Inc, 0.125 mmol) were dissolved in 2 mL dimethylformamide, into which 95.85 mg of 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide hydrochloride (EDC, 0.5 mmol) and 104.5 μL of triethylamine were added. The final mixture was stirred for another 24 hours at room temperature under the protection of nitrogen. After addition of 76.59 mg DA (50 mg), dimercaptosuccinic acid (DMSA) (50 mg), or DA-PAA-PEG (50 mg), dissolved in 1 mL of water, was slowly added into a tetrahydrofuran solution containing 200 mg bare Fe₃O₄ nanoparticles under bath ultrasonication in 30 minutes. After stirring at room temperature for 3 hours, the solvent was removed by centrifugation at 15,000 rpm. These DA, DMSA, and DA-PAA-PEG modified Fe₃O₄ NPs were referred to Fe₃O₄-DA, Fe₃O₄-DMSA, and Fe₃O₄-PEG, respectively.

**Transmission electronic microscopy and dynamic light scattering (DLS)**

Morphology and sizes of the prepared Fe₃O₄ NPs were characterized by transmission electronic microscopy (JEOL JEM-2100) as described previously.⁹ Briefly, high-resolution transmission electron microscopy operated at accelerating voltages of 200 KV were used to determine morphology of NPs. DLS was applied to analyze the hydrodynamic diameter and zeta potentials on a ZetaPALS Analyzer (Brookhaven, NY).¹⁰ The raw data were converted into zeta-potential values using the Helmholtz-Smoluchowski equation. The isoelectric point of nanoparticles in water was determined by measuring their zeta potentials and hydrodynamic diameter at the physiological pH condition.

**Cell culture**

Human leukemia cell lines (K562 and OCI-AML2) and multiple myeloma (MM) cell lines (OPM2 and RPMI-8226) were purchased from American Type Culture Collection (Washington, DC). MM cell line JNJ3 was a generous gift from Dr Aaron Schimmer (Ontario Cancer Institute, Toronto, Ontario, Canada). MM cells were cultured in Iscove’s Modified Dulbecco’s Medium (Thermo Scientific HyClone). Leukemia cells were maintained in RPMI-1640 media (HyClone). All media were supplemented with 10% of fetal bovine serum (Hyclone), 100 units/mL of penicillin and 100 μg/mL of streptomycin.

**Antibodies and chemicals**

Specific antibodies against light chain 3 (LC3), Beclin 1, p62, B-cell lymphoma 2 (Bcl-2), poly ADP-ribose polymerase (PARP), caspase-3, mammalian target of rapamycin (mTOR), phosphorylated mammalian target of rapamycin (p-mTOR), and phosphorylated protein kinase B were purchased from Cell signaling Technologies, Inc. (Danvers, MA). Antireduced glyceraldehyde-phosphate dehydrogenase (GAPDH) monoclonal antibody was purchased from Sigma (St Louis, MO). Bortezomib (BZ) was purchased from Santa Cruz, doxorubicin (Dox) and dexamethasone (Dex) were from...
Sigma, bafilomycin A1 (BafA) and 3-methyladenine (3-MA) were purchased from Sigma-Aldrich. Chemoluminescence detection system and 4’,6-diamidino-2-phenylindole (DAPI) were obtained from Beyotime Institute of Biotechnology, Nantong, People’s Republic of China. The mice were anaesthetized by an injection (Ex/Em) for DAPI and fluorescein isothiocyanate (FITC) could be induced by Fe$_3$O$_4$ NPs for 9 hours before being analyzed for the expression of LC3, Beclin 1, and Bcl-2 with specific primary antibodies.

**Immunofluorescence**

OPM2 cells (2.5×10$^5$) were plated in 12-well-plates and were treated with modified Fe$_3$O$_4$ NPs with the concentration of 100 μg/mL for 9 hours; starvation treatment was used as a positive control and dimethyl sulfoxide (DMSO) treatment was used as a negative control. OPM2 cells were then collected in cold phosphate buffer solution and transferred to glass slides using cytocentrifuge (Thermo) by a centrifuge at 800 rpm for 5 minutes. Cells were then subject to immunofluorescence analysis by staining with an anti-LC3 antibody (10 μg/mL) using a protocol as described previously. Before being analyzed on a confocal microscopy (Olympus), cells were incubated with DAPI (5 μg/mL) for 10 minutes. The wavelengths of excitation and emission (Ex/Em) for DAPI and fluorescein isothiocyanate (FITC) were 405/498 nm and 488/525 nm, respectively.

**Studies in primary blood cells**

Whole blood samples were collected in heparin-treated tubes from adult male mice (8 weeks old, 20–22 grams, provided by Shanghai Slac Laboratory Animal Co. Ltd., Shanghai, People’s Republic of China). The mice were anaesthetized by an injection of 4% chloral hydrate. Nucleated cells were then isolated from whole blood samples by a gradient centrifugation using Ficoll agent (Sigma-Aldrich) and subjected to incubation with Fe$_3$O$_4$ NPs for 9 hours before being analyzed for the expression of LC3, Beclin 1, and Bcl-2 with specific antibodies.

**Results**

**Characterization of surface-modified Fe$_3$O$_4$ NPs**

The sizes of synthesized Fe$_3$O$_4$ NPs were determined by with transmission electronic microscopy. As shown in Figures 1A, B, and C, Fe$_3$O$_4$ NPs coated with various modifications were uniformly dispersed, the average sizes of the particles were <10 nm. Further studies by DLS found the hydrodynamic sizes varied depending on the modifications. The average DLS sizes of DA- and DMSA- modified nanoparticles were 25±4 and 26±4 nm, respectively, while the PEG modification increased the average DLS size to 50±7 nm (Figure 1D). Zeta potentials of each type of Fe$_3$O$_4$ NPs in water are shown in Figure 1E. As expected, the modification affected the surface charge. Compared with the Fe$_3$O$_4$-DA and Fe$_3$O$_4$-DMSA particles, the Fe$_3$O$_4$-PEG particles carried a relative low potential, which was consistent with our previous studies. Further studies showed that these modified Fe$_3$O$_4$ NPs could dissolve in different types of solutions including water, phosphate buffered saline (PBS), RPMI-1640 cell medium, and fetal bovine serum. All solutions exhibited excellent stability in all tested physiological solutions within 24 hours (Figures 1F–H).

**Fe$_3$O$_4$ NPs induce autophagy in blood cancer cells**

NPs are not toxic to many cell types, but recent investigations showed that they can induce apoptosis and/or autophagy in certain cells, such as lung cancer cells. To find out whether the Fe$_3$O$_4$ NPs induced autophagy in blood cancer cells, leukemia cell lines (OCI-AML2 and K562) and multiple myeloma (MM) cell lines (OPM2, 8226, JN3) were treated with 100 μg/mL of Fe$_3$O$_4$ NPs with specific modifications including DA, DMSA, or PEG for 9 hours. To view autophagy induced by Fe$_3$O$_4$ NPs, the expression level of LC3-II, a phosphatidyethanolamine (PE)-conjugated form from microtubule-associated protein 1A/B-LC3 was measured because it is a common indicator of autophagy. Immunoblotting suggested that LC3-II was induced in all cells treated with Fe$_3$O$_4$ NPs (Figure 2A). This induction of LC3-II was in a time- and concentration-dependent manner (Figures 2B and C). LC3-II could be induced by Fe$_3$O$_4$ NPs at a concentration as low as 12.5 μg/mL within 9 hours (Figure 2B), or within 3 hours at the 100 μg/mL of all three types of particles (Figure 2C). To further visualize whether increased LC3-II was lipidated to the autophagosome membrane, OPM2 cells were starved or treated with each type of Fe$_3$O$_4$ NPs at 100 μg/mL for 9 hours,

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followed by immunofluorescence staining.\textsuperscript{12} As shown in Figure 2D, starvation, as predicted, led to increased LC3-II puncta appearing as green dots in the confocal microscope. Similar to starvation, Fe\textsubscript{3}O\textsubscript{4} NPs at all modifications also led to increased LC3-II puncta, a critical marker of autophagy.\textsuperscript{12,14} Therefore, Fe\textsubscript{3}O\textsubscript{4} NPs probably induce autophagy in blood cancer cells.

**Fe\textsubscript{3}O\textsubscript{4} NPs-induced autophagy is blocked by inhibitors of autophagy or lysosomes**

It is well known that autophagy can be blocked by specific autophagy inhibitors or lysosome inhibitors.\textsuperscript{15} To further confirm Fe\textsubscript{3}O\textsubscript{4} NPs-induced autophagy, myeloma cell line OPM2 was treated with Fe\textsubscript{3}O\textsubscript{4} NPs alone or along with 3-MA, an inhibitor of autophagy, or bafilomycin A1 (BafA), a lysosome inhibitor.\textsuperscript{15} As shown in Figure 3, Fe\textsubscript{3}O\textsubscript{4} NPs induced LC3-II and decreased p62. When 3-MA was added, the changes of LC3-II and p62 by Fe\textsubscript{3}O\textsubscript{4} NPs were abolished (Figures 3A, B, and C). In contrast, BafA increased the protein levels of both LC3-II and p62. Because p62 degradation is a hallmark of the autophagy flux and an important biomarker of autophagy,\textsuperscript{16} the effects of 3-MA and BafA on the protein level of p62 further demonstrated that Fe\textsubscript{3}O\textsubscript{4} NPs-induced autophagy in blood cancer cells.

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**Figure 1** Characterization of various surface modifications of superparamagnetic nanoparticles.

Notes: TEM images of (A) Fe\textsubscript{3}O\textsubscript{4}-DA, (B) Fe\textsubscript{3}O\textsubscript{4}-DMSA, and (C) Fe\textsubscript{3}O\textsubscript{4}-PEG. (D) DLS size of Fe\textsubscript{3}O\textsubscript{4}-DA, Fe\textsubscript{3}O\textsubscript{4}-DMSA, and Fe\textsubscript{3}O\textsubscript{4}-PEG in water solution; (E) Zeta potential of the Fe\textsubscript{3}O\textsubscript{4}-DA, Fe\textsubscript{3}O\textsubscript{4}-DMSA, and Fe\textsubscript{3}O\textsubscript{4}-PEG in water solution. Photos of (F) Fe\textsubscript{3}O\textsubscript{4}-DA, (G) Fe\textsubscript{3}O\textsubscript{4}-DMSA, and (H) Fe\textsubscript{3}O\textsubscript{4}-PEG in various solutions: water, phosphate buffered saline (PBS), RPMI-1640 cell medium, and fetal bovine serum (FBS) from left to right.

Abbreviations: DA, dopamine; DMSA, dimercaptosuccinic acid; DLS, dynamic light scattering; Fe\textsubscript{3}O\textsubscript{4}, ferroferric oxide; PEG, polyethylene glycol; TEM, transmission electronic microscopy.
Fe₃O₄ NPs induce autophagy in blood cells

Fe₃O₄ NPs target the Beclin 1/VPS34/Atg14 complex

Autophagy is mediated by a series of important cell signaling pathways. Its initiation is triggered by nutrient depletion via the mTOR signaling, while the elongation of autophagosomes is mainly modulated by the Beclin 1/VPS34/autophagy-related gene (Atg14) complex. To find out the mechanisms involved in Fe₃O₄ NPs-induced autophagy, we first evaluated the protein kinase B/mTOR signaling after Fe₃O₄ NPs treatment for 9 hours in which time Fe₃O₄ induced autophagy as shown in Figures 2 and 3. However, immunoblotting revealed that mTOR activation was not affected by Fe₃O₄ NPs after this treatment (Figure 4A), suggesting the mTOR signaling pathway might not be a major target of these types of nanoparticles.

**Figure 2** Fe₃O₄ NPs upregulate LC3-II expression and induce LC3 lipidation.

**Notes:** (A) Multiple myeloma cells (JJN3, 8226, OPM2) and leukemia cells (AML2 and K562) were treated with Fe₃O₄ NPs with different surface modifications. LC3-II was evaluated by immunoblotting against a specific antibody. (B) LC3-II was induced in OPM2 cells by Fe₃O₄ NPs in a concentration-dependent manner. (C) LC3-II was induced in OPM2 by Fe₃O₄ NPs in a time-dependent manner. (D) Multiple myeloma cells OPM2 was treated with different Fe₃O₄ NPs for 9 hours, followed by immunofluorescent analysis with a specific antibody against LC3-II. LC3-II puncta were observed by a confocal microscopy. Starvation (Starv.) was used as a positive control.

**Abbreviations:** DA, dopamine; DAPI, 4′,6-diamidino-2-phenylindole; DMSA, dimercaptosuccinic acid; Fe₃O₄, ferroferric oxide; GAPDH, glyceraldehyde-phosphate dehydrogenase; LC3, light chain 3; Merge, LC3 and DAPI; NPs, nanoparticles; Peg, polyethylene glycol.
Because 3-MA, an inhibitor of VPS34, blocked autophagy induced by Fe₃O₄ NPs, it suggests that the VPS34 complex might play a key role in this autophagy. VPS34 acts by forming a complex with Beclin 1, Atg14, and other proteins to promote elongation of autophagosomes; therefore, we next evaluated the expression levels of the components in the VPS34 complex. Immunoblotting revealed that Beclin 1, VPS34, and Atg14 were induced while the Bcl-2, a negative modulator of Beclin 1, VPS34, and Atg14 were induced while the Bcl-2, a negative modulator of Beclin 1, was decreased by these NPs (Figure 4B). And these changes were time- and concentration-dependent (Figures 4C and D). We next checked the protein levels of Atg14 and Beclin 1 after cells were treated for 3 to 24 hours and found that both Beclin 1 and Atg14 maintained a high level throughout this period, which was consistent with LC3-II expression. These results thus suggested the VPS34/Beclin 1 complex was important for Fe₃O₄ NP-induced autophagy.

Fe₃O₄ NPs prevent myeloma cell apoptosis induced by anticancer drugs

Autophagy has been proposed to deliver a survival or a death signal depending on the context and stress of cells. To evaluate the effects of autophagy on cell apoptosis, we first measured cell proliferation in the presence of these chemically modified Fe₃O₄ NPs. It showed that these Fe₃O₄ NPs had no effects on cell proliferation even at a concentration up to 2 g/mL (data not shown). PARP and caspase-3, both of which are common hallmarks of cell apoptosis, were not cleaved by Fe₃O₄ NPs at 100 μg/mL (Figure 5A). To confirm the effects of these NPs on cell apoptosis, OPM2 cells were treated with antmyeloma drug BZ, Dex, or Dox. Among these three drugs, BZ was the most potent one and could activate marked apoptotic signaling evidenced by activated PARP and caspase-3 at a low nano concentration (Figures 5B, C, and D). Compared with BZ, Dox and Dex were less potent; therefore, the cleaved form of caspase-3 was not markedly increased at current concentrations of Dex and Dox (Figures 5B, C, and D). In contrast, both cleaved PARP and caspase-3 in BZ-treated cells were markedly decreased by all three modified nanoparticles (Figure 5). Therefore, this experiment indicated that Fe₃O₄ NP-induced autophagy probably exhibited an antiapoptotic or a prosurvival function at least in blood cancer cells.

Bare Fe₃O₄ NPs induce prosurvival autophagy

Above studies demonstrated that these Fe₃O₄ NPs with various chemical modifications were able to induce autophagy in blood cancer cells. We wondered whether these modifications might be important for the autophagy induced by these Fe₃O₄ NPs. To find out, we next examined the effects of bare Fe₃O₄ NPs on autophagy in the same cell line – OPM2. As shown in Figures 6A and B, bare Fe₃O₄ NPs induced the expression of both LC3-II and Beclin 1 in a concentration- and time-dependent manner. Similar to the chemically modified Fe₃O₄ NPs, bare Fe₃O₄ NPs also led to degradation of p62, which could be abrogated by the autophagy inhibitor 3-MA or lysosome inhibitor BafA (Figure 6C). Notably, these bare Fe₃O₄ NPs also displayed antiapoptotic activity by decreasing the cleavage of caspase-3 and PARP (Figure 6D). Therefore, these studies showed that Fe₃O₄ NPs induced autophagy probably independent of the surface modifications.

Fe₃O₄ NPs induce autophagy in primary blood cells

Lastly, we questioned whether these Fe₃O₄ NPs induce autophagy in healthy blood cells. To this end, myeloid and lymphoid cells isolated from mice were incubated with Fe₃O₄ NPs for 9 hours. Similar to the effects of Fe₃O₄ NPs on blood...
Fe₃O₄ NPs induce autophagy in blood cells

Discussion

The present study showed that Fe₃O₄ NPs, both bare and surface modified forms, induce autophagy in both healthy and malignant blood cells although they failed to provoke apoptosis in these cells, which was confirmed by the increased LC3-II expression, LC3-II containing puncta, the degradation of the protein p62, upregulation of the Beclin 1/VPS34/Atg14 complex, and the cleavage of apoptotic markers PARP and caspase-3.

Autophagy is a conserved cellular response to the changes in their living circumstances, and it is usually activated by various chemical, physical, or biological stresses. Upon activation, autophagy can act as a cell survival mechanism or as a route to cell death depending on the circumstances. For example, in the deprivation of nutrients, cells are undergoing autophagy, which recycles...
essential amino acids or fatty acids for their survival. Although some nanoparticles are believed to be biocompatible, it may vary depending on the nature of nanoparticles themselves and the cell types. For example, silica nanoparticles and CdSe/ZnS quantum dots can induce autophagy in A549 cells in synapse, respectively. In our present study, we found Fe$_3$O$_4$ NPs activate autophagy in both normal and malignant blood cells. Nanoparticle-induced autophagy may be associated with the core nanoparticle or the surface modifications because sometimes the surface modifications lead to activated biological activities of the particles. A recent study showed that polystyrene nanoparticles with amino groups (PS-NH2) but not with carboxyl groups (PS-DMSA) rapidly induce autophagy in human leukemia cells, which suggests the surface modifications are important for autophagy induction. In our study, all bare, negatively and positively modified Fe$_3$O$_4$ NPs induce autophagy, suggesting that the surface coating on Fe$_3$O$_4$ NPs may not be a key factor in terms of autophagy induction.

There are three major pathways to regulate autophagy initiation: (1) the mammalian target of rapamycin (mTOR) that negatively regulates autophagy; (2) the Beclin1/VPS34/Atg14 complex and (3) two ubiquitin-like conjugation processes that generate membrane-bound protein complexes, promoting the formation of LC3-conjugated autophagosome.

In our study, we found that inhibition of mTOR by Fe$_3$O$_4$ NPs is not marked, suggesting that mTOR signaling control is not critical for autophagy induced by Fe$_3$O$_4$ NPs. Because 3-MA can partly abolish Fe$_3$O$_4$ NP-induced autophagy, the Beclin1/VPS34/Atg14 complex might be involved in the induction of autophagy induced by Fe$_3$O$_4$ NPs. This hypothesis is also supported by the induction of Beclin1 and Atg14 and by the decreased Bcl-2 expression even at 24 hours after treatment with Fe$_3$O$_4$ NPs. Notably, these changes are accompanied by increased LC3-II and decreased p62. Beclin 1 is the

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**Figure 5** Fe$_3$O$_4$ NPs abolish apoptosis induced by anticancer drugs.

**Notes:** (A) OPM2 cells were treated indicated nanoparticles (100 μg/mL) for 9 hours, followed by measurement of PARP and caspase-3, hallmarks of apoptosis. (B) OPM2 cells were cotreated with Fe$_3$O$_4$ DA, (C) Fe$_3$O$_4$-DMSA, or (D) Fe$_3$O$_4$-PEG and Dex (20 μM), BZ (20 nM), or Dox (0.5 μM) for 9 hours, followed by analysis of PARP and caspase-3.

**Abbreviations:** BZ, bortezomib; DA, dopamine; Dex, dexamethasone; Dox, doxorubicin; DMSA, dimercaptosuccinic acid; Fe$_3$O$_4$, ferroferric oxide; GAPDH, glyceraldehyde-phosphate dehydrogenase; NPs, nanoparticles; PARP, poly aDP-ribose polymerase; PEG, polyethylene glycol.
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mammalian homologous of yeast Atg6, which plays a key role in the process of autophagy. In intact cells, Beclin 1 forms a complex with Bcl-2; therefore Bcl-2 acts as an inhibitor of autophagy. In the stimulations of autophagy, the protein level of Beclin 1 is increased while that of Bcl-2 is decreased, Beclin 1 thus dissociates from Bcl-2, and, in turn, it binds to and forms an active complex with VPS34 and Atg14 and promotes the progression of autophagy.

In our study, Fe₃O₄ NPs decreased the expression of Bcl-2 but increased the expression of both Beclin 1 and Atg14 in a time- and concentration-dependent manner, further suggesting autophagy induced by these Fe₃O₄ NPs are highly associated with the Beclin 1/Bcl-2/Atg14/VPS34 complex.

Lastly, Autophagy is considered to induce a double-faced effect on cell activity (e.g. cell death or survival), depending on the context. We found that the Fe₃O₄ NPs prevent cytotoxicity induced by some anticancer drugs such as BZ, suggesting that these NPs prefer to display a prosurvival effect and that autophagy induced by these NPs

Figure 6 Bare Fe₃O₄ NPs induce prosurvival autophagy.

Notes: (A) OPM2 cells were treated with bare Fe₃O₄ NPs in different concentrations for 9 hours or (B) 100 µg/mL of bare Fe₃O₄ NPs at indicated time periods followed by LC3 and Beclin 1 analyses. (C) OPM2 cells were treated with bare Fe₃O₄ NPs alone or along with 3-MA or BafA for 9 hours, followed by LC3 and p62 analysis. (D) OPM2 cells were treated with bare Fe₃O₄ NPs alone or along with anticancer drugs Dex (20 µM), BZ (20 nM), or Dox (0.5 µM) for 9 hours, followed by analysis of apoptotic biomarkers PARP and caspase-3.

Abbreviations: 3-MA, 3-methyladenine; BafA, bafilomycin A1; BZ, bortezomib; Dex, dexamethasone; Dox, doxorubicin; Fe₃O₄, ferroferric oxide; GAPDH, glyceraldehyde-phosphate dehydrogenase; LC3, light chain 3; NPs, nanoparticles; PARP, poly ADP-ribose polymerase.

Figure 7 Fe₃O₄ NPs induce autophagic signaling in normal peripheral blood cells.

Notes: Nucleated cells isolated from peripheral blood of male mice were incubated with Fe₃O₄ NPs (100 µg/mL) for 9 hours followed by immunoblotting against LC3, Beclin 1, and Bcl-2 with specific antibodies.

Abbreviations: Bcl-2, B-cell lymphoma 2; DA, dopamine; DMSA, dimercaptosuccinic acid; Fe₃O₄, ferroferric oxide; GAPDH, glyceraldehyde-phosphate dehydrogenase; LC3, light chain 3; NPs, nanoparticles; PEG, polyethylene glycol.
assists to recycle amino acids and other nutrients essential for cell survival. Notably, this effect was also observed in other healthy and malignant cells. Because the blood system is probably the most exposed system to these NPs in their medical application, either as a contrast in imaging or a format in preparation of anticancer drugs, caution should be taken especially when these NPs are used for blood cancer patients.

In summary, our study demonstrated that FeO₄ NPs can induce the autophagy in blood cells by regulating the Beclin 1/Bcl-2/Atg14/VPS34 complex. FeO₄ NPs are not toxic but display prosurvival activity in blood cells. Whether these particles affect other systems is yet to be determined.

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Disclosure

None of the authors has a conflict of interest with this work.

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