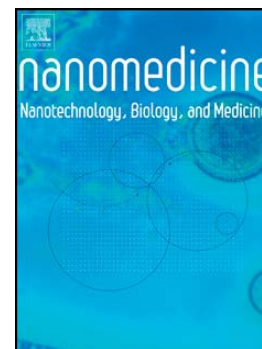


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Assessment of *in vivo* Systemic Toxicity and Biodistribution of Iron-doped Silica Nanoshells

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Abstract

Silica nanoparticles are an emerging class of biomaterials which may be used as diagnostic and therapeutic tools for biomedical applications. In particular, hollow silica nanoshells are attractive due to their hollow core. Approximately 70% of a 500nm nanoshell is hollow, therefore more particles can be administered on a mg/kg basis compared to solid nanoparticles. Additionally, their nanoporous shell permits influx/efflux of gases and small molecules. Since the size, shape, and composition of a nanoparticle can dramatically alter its toxicity and biodistribution, the toxicology of these nanomaterials was assessed. A single dose toxicity study was performed *in vivo* to assess the toxicity of 500nm iron-doped silica nanoshells at clinically relevant doses of 10-20 mg/kg. This study showed that only a trace amount of silica was detected in the body 10 weeks post-administration. The hematology, biochemistry and pathological results show that the nanoshells exhibit no acute or chronic toxicity in mice.

Keywords: Silica nanoparticles, toxicity, biodistribution, biomaterials, toxicology, nanomaterials

Abbreviations: ICP-OES, inductively coupled plasma optical emission spectroscopy; IV, intravenous; mesoporous silica nanoparticle, MSN; Tetramethyl orthosilicate, TMOS; energy dispersive X-ray spectroscopy, EDX; complete blood count, CBC; haematoxylin and eosin, H&E; scanning electron microscopy, SEM; high intensity focused ultrasound, HIFU; alanine transaminase, ALT; alkaline phosphatase, ALP; blood urea nitrogen, BUN; phosphate buffered saline, PBS; SiO₂, silica; Fe-SiO₂, iron-silica

Background

Silica (SiO₂) nanomaterials have gained much attention due to their broad range of potential biomedical applications which include bio-imaging, drug delivery, biosensors, and therapeutic ablation.¹⁻³ Characteristics that make SiO₂ nanoparticles a promising material are their well-established surface modification chemistry, high surface area, large pore volume, high stability in storage, and *in vivo* stability.^{4,5} Furthermore, porous SiO₂ nanoshells have gained considerable interest as *in vivo* imaging agents due to their potential to improve cancer diagnosis and their ability to provide guidance during surgery.⁶⁻⁸ SiO₂ nanoshells can be used as carriers for contrast agents such as a fluorophore,^{9,10} perfluorocarbon,^{8,11} and superparamagnetic material.¹²⁻¹⁴

Many studies have evaluated the toxicity of various SiO₂ nanoparticle formulations. The size, shape, morphology, charge, and surface properties of a nanoparticle can dramatically affect its biodistribution and toxicology.³ For instance, solid SiO₂ materials with amorphous particle morphology may cause hemolysis of red blood cells, which raises concerns regarding their safety in the clinic.^{15,16} Yu *et al.* (2011) investigated the impact of SiO₂ nanoparticle design on cellular toxicity and hemolytic activity up to 500 µg/ml by evaluating the effect of geometry, size, porosity, and surface charge of SiO₂ nanoparticles *in vitro*.¹⁷ It was shown that the toxicity of SiO₂ nanoparticles is influenced by surface charge and pore size and that cellular toxicity is cell-type dependent. Their studies showed that solid nonporous nanoparticles had a far greater

hemolytic activity compared to mesoporous silica nanoparticles (MSNs), which showed no hemolytic toxicity for all geometries, at doses below 100 µg/mL.

Several in-vivo studies have been performed to assess the toxicity of SiO₂ nanoparticles. They show that SiO₂ nanoparticles can cause inflammatory responses and hepatotoxicity which are influenced by factors such as dose, particle size, surface area, charge, and particle formulation^{9, 17-21}. For example, Yu *et al.* investigated the acute toxicity of 120 nm spherical MSNs when administered intravenously (IV)²²; the maximum tolerated dose for these particles was 30 mg/kg. Nishimori *et al.* investigated the relationship between particle size and toxicity using nonporous spherical SiO₂ particles with diameters of 70 nm, 300 nm and 1000 nm²³. Their findings showed that 70 nm nanoparticles induced liver injury at 30 mg/kg, while 300 nm and 1000 nm SiO₂ particles exhibited no biochemical or histological tissue damage even at 100 mg/kg. This shows that the size of the nanoparticle can significantly alter the toxicity even for the same particle formulation.

The biodistribution of nanoparticles provides some information of the excretion and degradability of the administered particles. Several studies have examined the biodistribution of SiO₂ particles, which have shown them to primarily accumulate in mononuclear phagocyte system (MPS) organs such as the liver, lungs and spleen. Studies have shown that SiO₂ nanoparticles can be excreted from the body; the excretion is influenced by particle formulation, size, dose, and surface modification, among other factors^{4, 11, 24, 25}. It is expected that these factors will also influence the toxicity.

Before new nanomaterial formulations can be applied safely in a clinical setting, their biocompatibility and biodistribution need to be assessed. Despite the numerous studies of the toxicology of various forms of SiO₂ nanoparticles, the toxicity of each formulation must be

assessed before being translated to the clinic, since nanoparticle properties depend strongly on their composition, size, shape, and surface chemistries²⁰. In the present study, the toxicity and long-term biodistribution of calcined 500 nm SiO₂ nanoshells and Fe-SiO₂ nanoshells, which have been shown to be biodegradable *in vitro*, are investigated when administered IV to mice at a clinically relevant dose. One attractive characteristic of hollow SiO₂ nanoshells is that due to their hollow core, more particles can be administered on a per mass basis. Approximately 70% of the nanoshell is hollow, therefore, on average an equivalent of 3X more particles can be administered on a mg/kg basis compared to solid nanoparticles of the same size. The particles are calcined, which offers long term stability for storage, and their nanoporous shell wall permits influx and efflux of drugs, gases, and other small molecules. These characteristics allow for this platform to potentially be used as an ultrasound contrast agent or for drug delivery.⁶⁻⁸ Other platforms such as solid nanoparticles cannot carry gases due to their solid core, therefore solid nanoparticles do not have color Doppler ultrasound capabilities. In addition, 500nm nanoshells have demonstrated to have good ultrasound imaging capabilities which is partly the reason why their toxicity is being evaluated in this study. By understanding the toxicology effects of new nanomaterial formulations, nanoparticles can be designed for decreased toxicity thereby creating more efficacious and safe therapeutic and diagnostic agents.

Materials and Methods

Materials

Tetramethyl orthosilicate (TMOS) was purchased from Sigma Aldrich Corp (St. Louis, Missouri). 500 nm amino-polystyrene beads were acquired from Polysciences Inc (Warrington, Pennsylvania). Iron (III) ethoxide was acquired from Gelest Inc (Moorisville, Pennsylvania). Potassium hydroxide was purchased from Fischer-Scientific (Pittsburg, Pennsylvania). 500 mM aqueous KOH was obtained by dissolving the KOH pellets in Milli-Q water. Nitric acid (HNO₃)

was provided by EMD (Billerica, Massachusetts) at 67 – 70% purity and 1% HNO₃ was prepared by diluting the stock HNO₃ with MilliQ water. The multi-element standard solution for silicon calibration was provided by SPEX CertiPrep (Metuchen, New Jersey). The yttrium standard solution for internal calibration was purchased from Agilent Technologies (Santa Clara, California). Blood collection tubes coated in either heparin or EDTA were purchased from BD Biosciences (Franklin Lakes, New Jersey).

Six week old female Swiss Webster mice were provided by Charles River Laboratories, weighing between 20-25 grams each. Mice were fed a commercial pelleted diet (Harlan Tekland) and kept at 22°C in UCSD approved animal housing with a 12 hour light/dark cycle. All animal care and procedures were approved by the UCSD Institutional Animal Care and Use Committee. All animals in these studies were treated with humane care.

Methods

Nanoshell Synthesis

Fe-SiO₂ and pure SiO₂ nanoshells were synthesized as previously reported.^{6, 7} Fe-SiO₂ nanoshells were synthesized by mixing of 2.7 ul of TMOS, 10 ul of iron ethoxide (20 mg/ml in ethanol), and 50 ul of amino-polystyrene templates in 1 ml of absolute ethanol for 5 hours on a vortex mixer at 3000 RPM. After mixing, the particles are centrifuged and washed three times in ethanol and left to dry overnight. Dry particles were then calcined for 18 hours at 550 C. Pure SiO₂ particles were synthesized by mixing 3 ul of TMOS and 50 ul of polystyrene templates in 1 ml of absolute ethanol for 5 hours. After mixing, the particles were centrifuged and washed three times in ethanol and left to dry overnight. The dry particles were subsequently calcined for 18 hours at 550 °C. Particle synthesis and quality was confirmed by scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The diameter and shell thickness of nanoshells was quantified by measuring the diameter and length of the shell

thickness taken from high resolution TEM images and analyzed using ImageJ. The percentage of hollow space occupied by the nanoshells was determined by calculating the volume of the hollow nanoshell using the outer diameter and subtracting the volume of the inner diameter of the nanoshell. SEM images were acquired using a FEI/Phillips XL30 FEG ESEM with an accelerating voltage of 10 kV. Energy dispersive X-ray spectroscopy (EDX) was performed on the same Oxford EDX attachment and analyzed with INCA software. TEM images were acquired using a JEOL 1200 EX II TEM.

Single Dose Toxicity

A single dose toxicity study was performed over the course of 10 weeks in healthy female Swiss white mice. Four groups were compared ($n = 10$) to determine if the nanoshells had any measureable toxicity. Group 1 received a 100 μ l injection of Fe-SiO₂ nanoshells at 4 mg/ml (approximately 20 mg/kg), group 2 received 100 μ l of SiO₂ nanoshells at 4 mg/ml, group 3 received 100 μ l of SiO₂ nanoshells at 2 mg/ml (approximately 10 mg/kg) which is the particle number/ml equivalent of group 1 (Fe-SiO₂ at 4mg/ml), and group 4 was a control group which received no particles. All injections were performed IV *via* the tail vein. 100 μ l of blood was drawn with a submandibular lancet from each mouse weekly for the first four weeks and then biweekly for the following six weeks. From each group, 5 mice had their blood allocated into vacutainer tubes containing EDTA for Complete Blood Count (CBC) analysis and the other 5 mice had their blood allocated into vacutainer tubes contain heparin for serum chemistry analysis. CBC and Serum Chemistry analyses were performed by UCSD Animal Care Program Diagnostic Laboratory and STAT Labs. After 10 weeks, the animals were sacrificed. Three animals from each group were used for long-term biodistribution studies, and the remaining animals were used for pathological investigation after sectioning and H&E staining.

Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES Analysis)

ICP-OES was used to detect nanoshells retained in mouse organs. One mouse was injected with 100 μ l of a 4 mg/mL aqueous nanoshell solution. Control mice were sacrificed 24 hours after the mice received the nanoshell injection, and the organs were collected. To analyze the organs for silicon content, the organs were incubated in 7 ml of aqueous 500 mM KOH and bath sonicated for 48 hours. 0.5 ml of each digested sample was drawn out and acidified using 2.5 ml of 1% HNO₃. The samples were centrifuged for 15 minutes at 3000 rpm, and 0.5 ml of a 300 ppb yttrium standard solution was added to each 2.5 ml aliquot of a supernatant sample. The samples were finally briefly centrifuged immediately before ICP-OES analysis as described in a previous study²⁶.

Histological Analysis

Tissue samples were fixed in 10% formalin and submitted to the UCSD histology core facility for paraffin block processing, sectioning and Hematoxylin and Eosin (H&E) staining. The slides were imaged using a Nikon Eclipse E600 microscope. The slides were randomized and analyzed by the Chief of Pathology and Laboratory Medicine at the VA Medical Center, La Jolla. Focal inflammation was quantified by counting the number of inflammatory foci per organ for each group.

Statistical Analysis

Serum chemistry and hematology markers were compared by using multiple unpaired two-tailed t-tests to determine statistical significance ($\alpha = 0.05$). Mean values were calculated for each time point in order to perform multiple t-tests as described by J. N. Matthews, *et al.*²⁷ Statistical analysis was performed by using GraphPad Prism software version 6. A total number of 5 mice per group were used for the study.

Results

Characterization of Nanoshells

The SiO₂ and Fe-SiO₂ nanoshells were hollow and spherical in shape with an average diameter of 497 nm ± 13 and 455 nm ± 14, respectively, as shown by SEM and TEM in **Figure 1**. The images show that the SiO₂ and Fe-SiO₂ nanoshells are fairly uniform in size with no visible holes, cracks, or other deformations. The diameters and shell thicknesses of nanoshells were determined by using TEM images. The incorporation of iron does not greatly affect the shell thickness or morphology compared to pure SiO₂ nanoshells; the shell thickness for Fe-SiO₂ was 27 nm ± 4 and 33 nm ± 5 for SiO₂ nanoshells. EDX showed that Fe-SiO₂ nanoshells have an average 5 mol % of iron doped into the nanoshell matrix. The incorporation of iron makes the nanoshells biodegradable in human serum, and attractive for biomedical applications.²⁸ Serum transferrin has been shown to bind to the iron-doped nanoshells, which may induce degradation and dissolution of any residual nanoshells that are not excreted from the body²⁹. In addition, 500nm Fe-SiO₂ nanoshells may be filled with gases giving them ultrasound capabilities as shown in **Figure 2**.

Single Dose Acute Toxicity

The 500 nm nanoshells evaluated in this study have been developed for use as contrast agents when filled with perfluoropentane gas or as ablative agents when combined with high intensity focused ultrasound (HIFU).^{2, 6, 30} It is important to thoroughly evaluate the toxicity of new compounds before the translation to clinical trials. Therefore, the acute toxicity of SiO₂ and Fe-SiO₂ nanoshells was assessed in order to evaluate their safety *in vivo*. Mice received an IV injection of 400 µg of SiO₂ (20 mg/kg), 400 µg of Fe-SiO₂ (20 mg/kg), 200 µg of SiO₂ (10 mg/kg), or Phosphate Buffered Saline (PBS). 10 mg/kg was assessed for SiO₂ because it is the equivalent of the Fe-SiO₂ by particle concentration. Blood was collected over the course of 10 weeks and serum chemistry and hematology analysis was performed.

Nanoparticles have been shown to have different pharmacological actions when administered IV, depending on factors such as size, shape, charge, and composition. In particular, nanoparticles usually preferentially accumulate in the liver.³ Therefore it is important to evaluate if nanoparticle administration affects liver function. For serum chemical analysis, albumin, bilirubin, alanine transaminase (ALT), and alkaline phosphatase (ALP) were evaluated to assess hepatic function as shown in **Figure 3**. The serum chemistry levels for mice which received Fe-SiO₂ or SiO₂ did not differ significantly from the control group. Multiple t-tests were performed for statistical analysis and all groups showed no statistically significant difference between the control and nanoshell dosed groups ($\alpha = 0.05$). This data indicates that a systemic dose of 20 mg/kg (4mg/ml) of SiO₂ or Fe-SiO₂ nanoshells show no acute hepatic toxicity over the course of 10 weeks.

Nanoparticles have been shown capable of being cleared through the renal system.⁴ Therefore blood urea nitrogen (BUN) and creatinine were measured to determine if IV administration of 500 nm SiO₂ and Fe-SiO₂ nanoshells alters renal function. Pancreatic function was also assessed by measuring amylase and glucose as shown in **Figure 4**. The SiO₂ nanoshell group had a significantly higher serum creatinine levels compared to the control group ($p=0.003$ for 4mg/ml $p=0.01$ for 2mg/ml). However, for all groups the values were still within the normal range for serum creatinine values reported by Charles River for female Swiss Webster mice.

Serum analytes such as sodium (Na), potassium (K), calcium (Ca), and phosphorus (P) were measured in order to evaluate any electrolyte imbalances of mice post injection as shown in **Figure 5**. There was a significantly higher serum Na levels for mice that received Fe-SiO₂ when compared to the control group ($p= 0.002$). Nevertheless, when compared to Na values reported by Charles River, the Na values measured in this study fell within the normal range of the 95%

confidence interval. Overall, the general health of mice administered with Fe-SiO₂ and SiO₂ nanoshells IV was unaffected by the particles.

Amorphous SiO₂ particles have been shown to cause hemolysis of red blood cells which raise safety concerns about their use in the clinic.^{15, 16} The interaction of SiO₂ nanoparticles and blood components impacts cellular toxicity and hemolytic activity, which depend on different nanoshell formulations such as composition, size, and charge. Therefore, hematology analysis of 500 nm Fe-SiO₂ and SiO₂ nanoshells was performed in order to assess blood chemistry, blood-forming organs, and blood diseases. Neutrophils, lymphocytes, hemoglobin (Hb), and eosinophils were measured to assess hematological abnormalities after nanoshell administration over the course of ten weeks and as a potential indicator of an immune or inflammatory reaction, as shown in **Figure 6**. Other analytes such as monocytes, red blood cells (RBC), nucleated RBCs/100WBC, mean corpuscular volume (MCV), mean corpuscular hemoglobin concentration (MCHC), and mean platelet volume (MPV) were also measured (**See Figure S1**). There was no significant difference observed between Fe-SiO₂ nanoshells, SiO₂ nanoshells at 2 mg/ml or 4 mg/ml, and the PBS vehicle group for any of the analytes. In addition, all measured values fell within the 95% CI values reported by Charles River. These findings are a good indication that SiO₂ and Fe-SiO₂ nanoshells are generally safe when administered systemically at the indicated doses. It is likely that the physical characteristics of the nanoshells including their hollow core, surface composition, and size contributed to their low toxicity.

Haematoxylin and eosin (H&E) histological analysis was performed on liver, lung, kidney, spleen, muscle, and heart tissue samples 10 weeks after administration of Fe-SiO₂ or SiO₂ nanoshells to check for inflammation or any abnormalities, as shown in **Figure 7**. The pathology revealed some mild chronic inflammation in the liver, lung, and kidney in all groups as evidenced by focal lymphocytic infiltrates. Representative sections show lymphocytic infiltrate

in the perisinusoidal distribution in the liver, peri-bronchial in the lung, and peri-vascular in the kidney. Histological analysis was also performed on the brain and showed no pathological changes when compared to the PBS control (See **Figure S2**). The number of mice with focal inflammation in each group was not significantly different in mice treated with nanoshells when compared to mice injected with PBS as summarized in **Table 1**.

In addition, the organs of naive mice which has no isoflurane anesthesia exposure nor blood drawn were evaluated. Mild focal inflammation was observed in the lung and kidney, and acute inflammation was observed in the liver which shows that mild inflammation is typical in naive Swiss mice as shown in **Figure 7e**. Similarly, Plummer *et al.*³¹ showed that the control group as well as rats exposed to inhaled isoflurane anesthesia for a prolonged period of time showed hepatic focal inflammation suggesting that mild focal inflammation is often observed in healthy laboratory rodents. It is possible that repeat bleeding and isoflurane anesthesia are probable factors contributing to increased focal inflammation observed in our experimental and PBS control mice groups.³²

No multinucleated cells were observed in the spleen. No abnormalities were noted for any of the H&E sections and no apparent differences were observed between mice treated with Fe-SiO₂ or SiO₂ nanoshells and the PBS group. The number of inflammatory foci was quantified to evaluate the degree of focal inflammation per group as shown in **Figure 8**. There were no significant differences between groups treated with Fe-SiO₂ or SiO₂ nanoshells and the control group. These results showed that there was no significant damage to major organs (liver, lungs, heart, kidney, and spleen) when compared to control mice. This indicates that Fe-SiO₂ and SiO₂ nanoshells can potentially be safely used in the clinic by IV dosing at the given doses.

The biodistribution of Fe-SiO₂ and SiO₂ nanoshells was performed 24 hours or 10 weeks after systemic administration, and ICP-OES was used to measure the amount of elemental Si in each organ, as shown in **Figure 9**.

For SiO₂ nanoshells, 42% of total injected nanoshells accumulated in the liver, which is consistent with previous studies.⁷ It is important to note that nearly 57% of the total injected dose was not detected in any organs or the blood 24 hours after administration; this may be due to excretion. After 10 weeks post administration, only 2% of nanoshells were detected in the liver. Similarly, the biodistribution of Fe-SiO₂ was studied 24 hours and 10 weeks post-injection. Interestingly, when SiO₂ nanoshells were doped with iron, only 5% of the total injected dose was present in the liver, while 8% was detected in the lungs. Nearly 88% of the total injected dose was undetectable in the organs or the blood after only 24 hours. After 10 weeks post administration, only 4% of nanoshells were detected in organs, mostly in the liver.

In a previous study, whole body scintigraphy in a mouse showed that after IV administration, a large portion of Fe-SiO₂ and SiO₂ nanoshells localized in the liver when monitored immediately post injection and at 1 hour, 24 hours, and 72 hours.⁷ After 72 hours, organ gamma counting showed a substantial amount of signal in the liver, and some in the kidney and spleen, but very little signal was detected elsewhere. The results in the present study show that the nanoshells are retained mostly by the liver and suggest that incorporation of iron can alter the biodistribution of SiO₂ nanoshells. These findings show that fewer nanoshells were retained within 24 hours when they were doped with iron. It is postulated that iron doping leads to transferrin interactions in the body which may lead to faster biodegradation as seen in previous studies²⁸.

Discussion

The kidney is capable of removing molecules from the blood by filtering particles through the glomerular capillary wall, also known as glomerular filtration. Renal filtration depends on surface charge and size, where molecules with a hydrodynamic diameter greater than 8 nm are typically not capable of glomerular filtration and therefore are not excreted *via* the renal system^{33, 34}; however, some studies have suggested that particles larger than 8 nm can be excreted through the urine.⁴ Nevertheless, it is highly unlikely that a large number of intact 500 nm SiO₂ nanoshells are being excreted in the urine unless the particles were first broken down to smaller components before renal excretion.

The liver catabolizes particles in the blood through phagocytosis followed by biliary excretion.³⁴ Phagocytic Kupffer cells, specialized macrophages located in the liver, are highly effective at recognizing and removing unwanted substances from the blood, including nano- and microparticles. Kupffer cells selectively phagocytose opsonized particulates which have been coated with complement proteins for recognition.^{35, 36} Particles are subsequently metabolized and excreted as bile *via* the biliary system. Passage through the liver can make metabolites smaller and more polar which can result in reabsorption in the blood leading to excretion *via* the renal system however, renal clearance is observed at lower rates. In the present study, it is most likely that the particles are being cleared *via* the hepatic system. It is hypothesized that iron incorporation can alter the uptake, metabolism, and clearance of the nanoshells. It is probable that the interaction of serum proteins is different for Fe-SiO₂ and SiO₂ nanoshells, which may result in a different extent of opsonization for each formulation. The altered surface protein coating of the Fe-SiO₂ nanoshells may change the extent of Kupffer cell phagocytosis and hepatic excretion.

The main site of transferrin synthesis is in the liver.³⁷ Transferrin is an iron transport protein that delivers Fe^{3+} from the duodenum and macrophages to all tissues by circulating in the blood.³⁸ Human transferrin binds iron as Fe^{3+} with a high affinity; therefore, the incorporation of Fe^{3+} into the SiO_2 nanoshell structure likely facilitates the decomposition of Fe- SiO_2 nanoshells by degradation, which results in hepatic clearance. The biodegradation of Fe- SiO_2 in FBS and human serum was shown in previous studies,²⁸ consistent with the *in vivo* results shown in the present study. More recent studies show that Fe- SiO_2 nanoshells undergo binding/endocytosis in cells that overexpress the transferrin receptor and that their uptake can be blocked with addition of holotransferrin.²⁹ This suggests that the surface of the Fe- SiO_2 nanoshells may also be bound to transferrin *in vivo*. Not only are hepatocytes involved in iron metabolism, but the liver endothelium has been shown to be rich in the transferrin receptor, which enhance endocytosis of the Fe- SiO_2 nanoshells.³⁹⁻⁴¹ The liver endothelium has an increasingly recognized role in biliary excretion.⁴²

A small percentage of Fe- SiO_2 nanoshells was observed in the lung, whereas only trace amounts of non-doped SiO_2 nanoshells were seen. Previous studies have shown that SiO_2 nanoparticles can cause an inflammatory response in the lung.³³ Kusaka *et al.* showed that 30 nm SiO_2 nanoparticles administered intratracheally to mice caused more severe lung inflammation than did 3000 nm SiO_2 particles.⁴³ The present study shows that there was no additional long-term lung damage after 500 nm Fe- SiO_2 and SiO_2 nanoshells were administered IV when compared to the control group, which may be due to their larger size and/or the difference in route of administration. Several studies have been performed in order to assess the toxicity of SiO_2 nano- and microparticles^{11, 25, 44, 45 46} which showed that the SiO_2 particle biodistribution depends on several factors such as charge, size, and surface modification.

These nanoshells are expected to be used as contrast agents for cancer diagnosis or for ultrasound guidance during surgery. In previous studies, the nanoshells have shown to be stationary markers *in vivo* and can be imaged intermittently over the course of 10 days in a tumor-bearing mouse model, and continuously for 45 minutes when administered intratumorally.³⁰ In the event that the nanoshells escape the tumor or are administered IV, this study has shown that the nanoshells show no apparent systemic toxicity and can be safely cleared from the body after a single dose. In addition, these nanoshells may also be used in combination with HIFU for ablative therapy.²

These results show that the nanoshells presented in this study are safe when administered systemically allowing exploitation of the hollow structure and calcined shells. Approximately 70% of the nanoshell is hollow, therefore, on average an equivalent of 3X more particles can be administered on a mg/kg basis compared to solid nanoparticles of the same size. The particles are calcined, which offers long term stability for storage, and their nanoporous shell wall can permit influx and efflux of drugs, gases, and other small molecules. Although future pharmacokinetic studies including blood circulation and clearance should be performed, this study indicates that 500 nm nanoshells are safe when administered IV at the doses studied.

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Figure Captions

Figure 1. SEM and TEM images of 500nm a) Fe-SiO₂ and b) SiO₂ nanoshells.

Figure 2. 500nm SiO₂ and Fe-SiO₂ nanoshells have ultrasound imaging capabilities under color Doppler and CPS mode.

Figure 3. Serum chemistry analysis for hepatic function. Mice were injected with 100 µl of Fe-SiO₂ nanoshells at 4mg/ml (●), SiO₂ at 4mg/ml (▲), SiO₂ nanoshells at 2mg/ml (▼), or PBS (■). Albumin, bilirubin, alanine transaminase (ALT), and alkaline phosphatase (ALP) were measured in mice over the course of 10 weeks to evaluate hepatic function. Serum chemistry did not differ significantly between control and treated groups. Data is shown as average ± SD, where n=5.

Figure 4. Serum chemistry analysis for renal and pancreatic function. Mice were injected with 100 µl of Fe-SiO₂ nanoshells at 4mg/ml (●), SiO₂ at 4mg/ml (▲), SiO₂ nanoshells at 2mg/ml (▼), or PBS (■). Blood urea nitrogen (BUN), creatinine, glucose and amylase were measured in mouse serum over the course of 10 weeks to evaluate general renal and pancreatic function. Serum chemistry did not differ significantly between control and treated groups. Data is shown as average ± SD, where n=5.

Figure 5. Serum chemistry analysis for electrolyte imbalance. Mice were injected with 100 μ l of Fe-SiO₂ nanoshells at 4mg/ml (●), SiO₂ at 4mg/ml (▲), SiO₂ nanoshells at 2mg/ml (▼), or PBS (■). Sodium, potassium, calcium, and phosphorus, were measured in mouse serum over the course of 10 weeks to evaluate electrolyte imbalance. Serum chemistry did not differ significantly between control and treated groups. Data is shown as average \pm SD, where n=5.

Figure 6. Mouse hematology. Mice were injected with 100 μ l of Fe-SiO₂ nanoshells at 4mg/ml (●), SiO₂ at 4mg/ml (▲), SiO₂ nanoshells at 2mg/ml (▼), or PBS (■). Blood was collected over the course of 10 weeks and hematology tests were performed to assess blood, blood-forming organs, and blood diseases. No significant difference was observed between Fe-SiO₂ nanoshells, SiO₂ nanoshells, and PBS control. Data is shown as average \pm SD, where n=5.

Figure 7. Histological analysis of Fe-SiO₂ and SiO₂ nanoshells. A single dose acute toxicity study was performed over the course of 10 weeks in healthy female Swiss white mice. Five groups were compared to determine if the nanoshells had any measureable toxicity; a) Fe-SiO₂ (400 μ g), b) SiO₂ (400 μ g), c) SiO₂ (200 μ g) d) PBS e) and naive group. Images are shown at 100X. Mild focal inflammation is observed in the liver, lung and kidney for all groups. Arrows are pointing to inflammation foci.

Figure 8. Quantification of focal inflammation in liver, lung, and kidney. Focal inflammation was quantified by counting the total number of focal inflammation foci for each mouse and computing the average per group. Multiple t-tests showed no statistical significance (ns) when compared to the control group.

Figure 9. Biodistribution of SiO₂ after IV administration. 500 nm SiO₂ nanoshells and Fe-SiO₂ nanoshells were administered IV to mice. Mice were sacrificed and organs were collected 24 hours or 10 weeks post-treatment. ICP-OES analysis was used to detect silica content in each organ. High accumulation of SiO₂ nanoshells was observed 24 hours post administration, and clearance occurred after 10 weeks. Fe-SiO₂ nanoshells showed reduced uptake in the liver but some uptake in the lung after 24hours. Both SiO₂ and Fe-SiO₂ showed very low levels of detectable silica in organs 10 weeks after administration. Data is shown as average \pm SD.

Table 1. Inflammation in major mouse organs. Pathological evaluation of mouse liver, lung, kidney, spleen, muscle, heart, and brain showed mild inflammation in the liver, lung, and kidney of all groups. The percentage of mice which showed at least one focal point of inflammation in each organ is summarized per organ (n=5 per group). Multiple t-test analysis showed no statistical significance when compared to the control group.

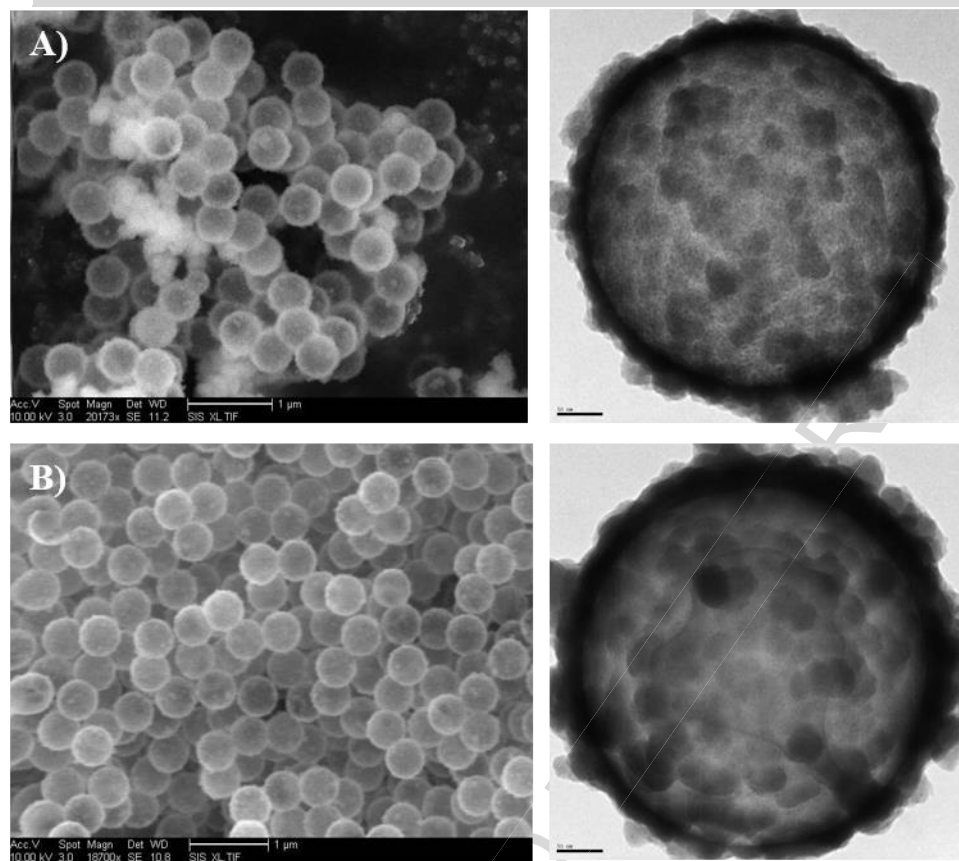


Fig. 1

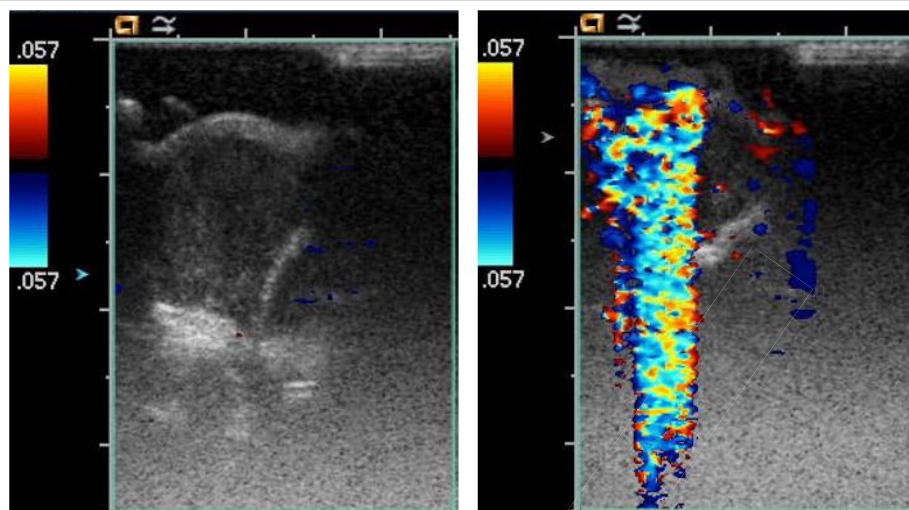


Fig. 2

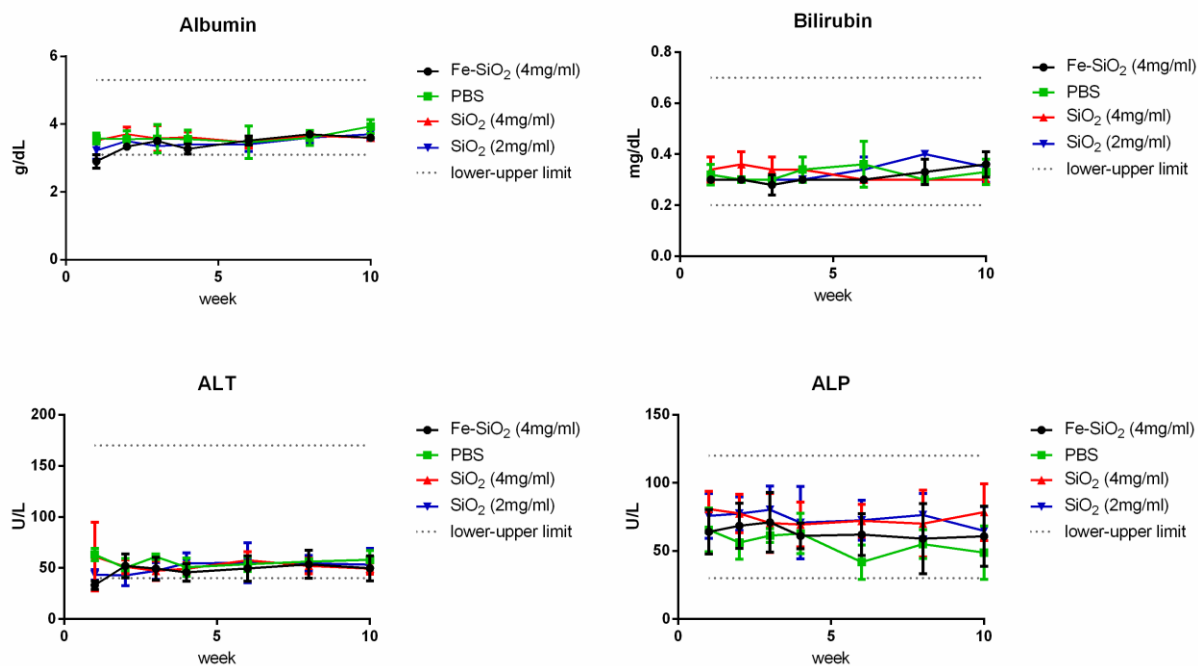


Fig. 3

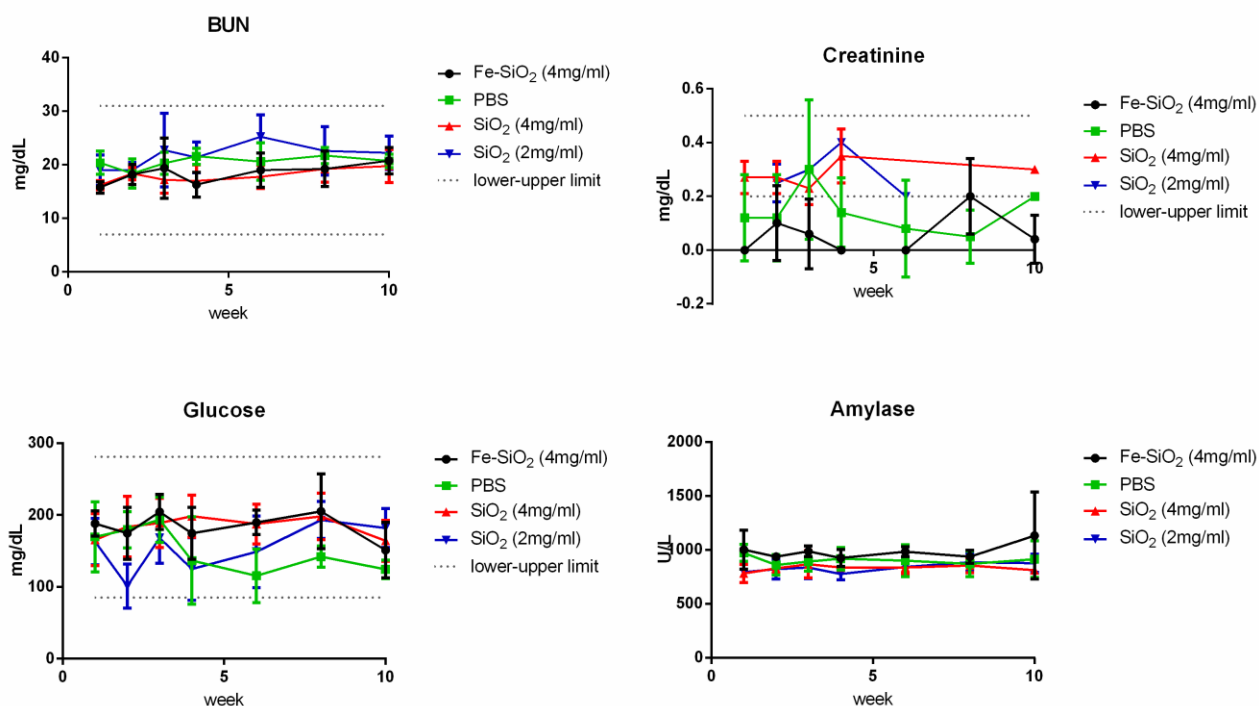


Fig. 4

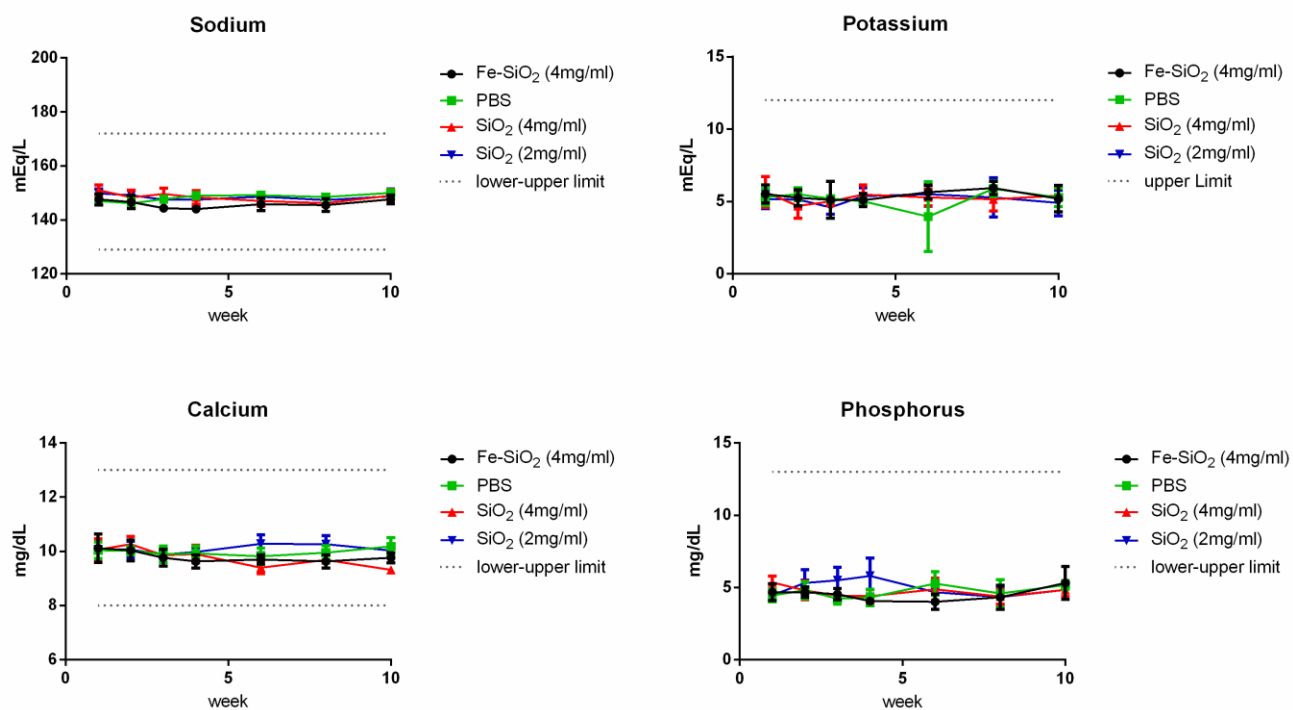


Fig. 5

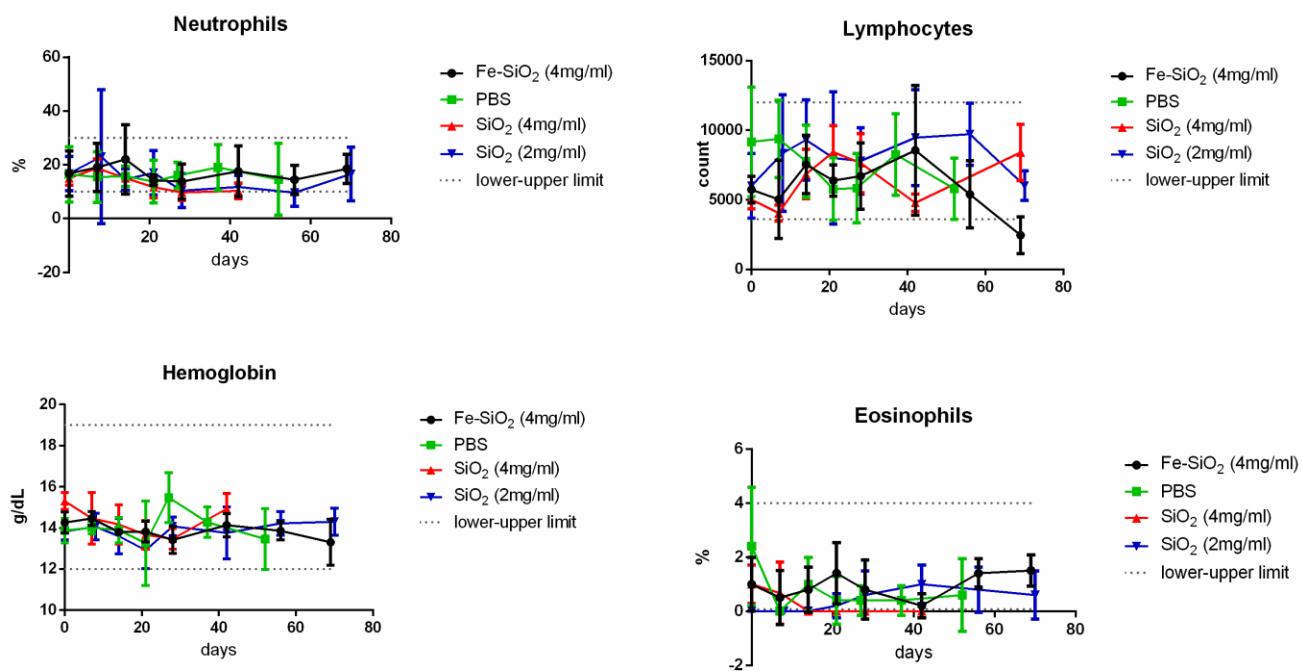


Fig. 6

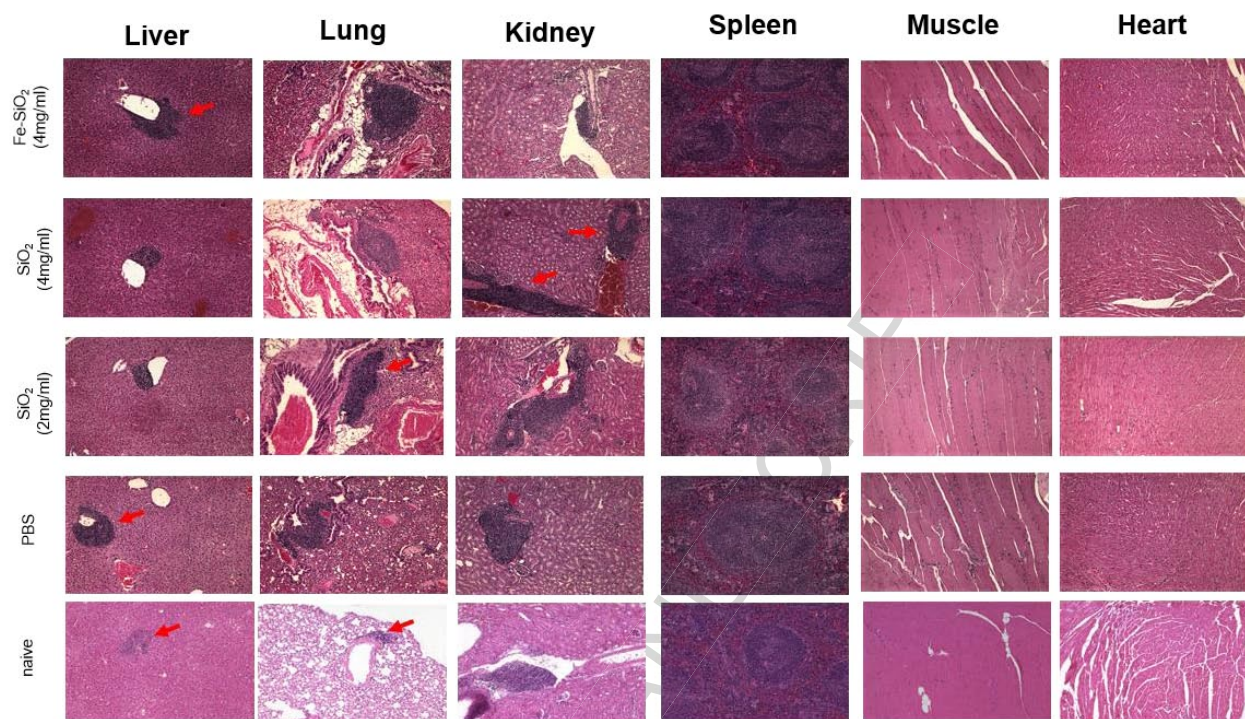


Fig. 7

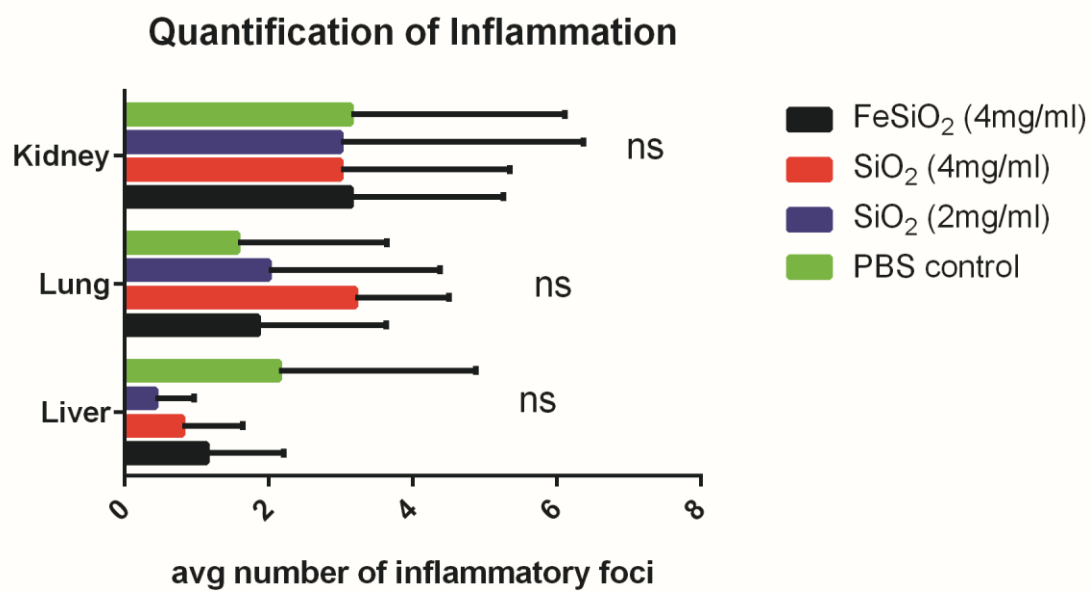


Fig. 8

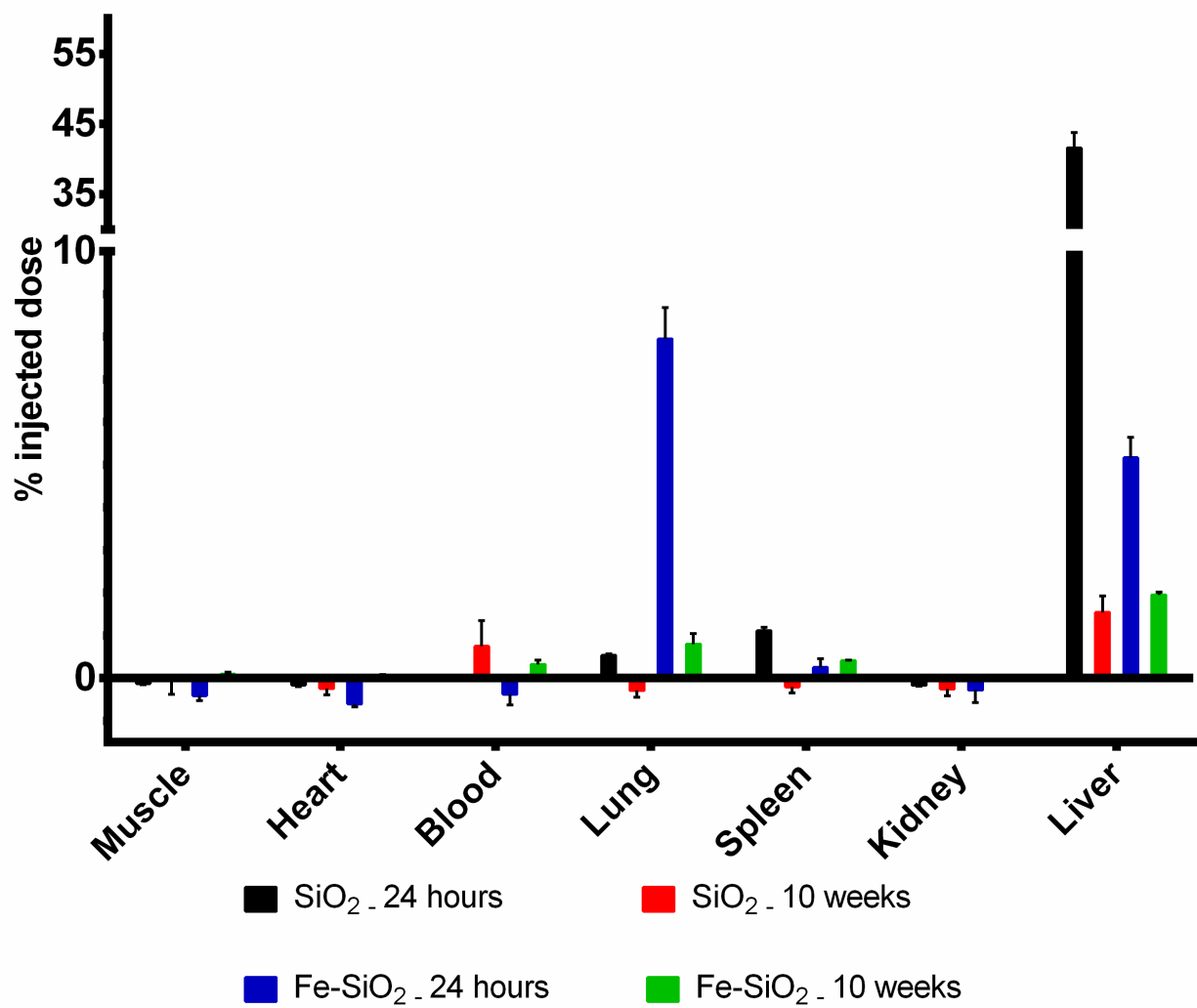


Fig. 9

Table 1

	Liver	Lung	Kidney	Spleen	Muscle	Heart	Brain
Fe-SiO₂ (4mg/ml)	71%	71%	86%	0%	0%	0%	0%
SiO₂ (4mg/ml)	60%	100%	100%	0%	0%	0%	0%
SiO₂ (2mg/ml)	43%	71%	86%	0%	0%	0%	0%
PBS	71%	57%	71%	0%	0%	0%	0%

Graphical Abstract

Many studies have evaluated the toxicity of various silica nanoparticle formulations. The size, shape, morphology, charge, and surface properties of a nanoparticle can dramatically affect its biodistribution and toxicology. In the present study, 500nm hollow silica nanoshells showed no acute or chronic toxicity in mice after intravenous administration. In addition, the nanoshells were retained mostly by the liver and were undetectable after 10 weeks. Incorporation of iron altered the biodistribution of SiO_2 nanoshells.

