

Surface Initiated Atom Transfer Radical Polymerization of *N*-Hydroxysuccinimide Methacrylate from Magnetite Surface as Precursor for Functional Polymer Shell

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Recently, there has been much increased interest in surface coating of magnetic nanoparticles with organic shell materials for various electronics and biomedical applications.^{1,2} These applications include high-density magnetic recording, ferrofluid, magnetic resonance imaging, magnetic targeting drug delivery and so on.^{3–7} In these applications, the organic shell act not only as a stabilizing agent, but also to confer functionality, such as biocompatibility and molecular recognition.^{6–8} Densely packed organic reactive shell is required to produce highly stable functional magnetic nanoparticles.

Several methods have been developed to prepare polymer coating on nanoparticles surface.^{9–12} Recently, surface initiated atom transfer radical polymerizations (ATRP) were successfully applied to prepare densely packed polymer layer onto magnetic nanoparticles.^{13,14} The advantage of ATRP to surface-initiated polymerization is that it is relatively easy to perform in a living fashion.^{12,15} With applying the living polymerization, densely packed polymer layers with controlled chain lengths can be fabricated onto various nanoparticles surface.^{13–17} However, for a successful ATRP measurement, it is necessary to examine various experimental conditions such as temperature, ligand, catalyst, and solvent depending on monomer in use.¹⁸ One of the most difficult examples is ATRP of acrylamide derivatives because amide group can coordinate with copper catalyst and/or their propagating radical undergo SN₂ substitution, both of which result in polymerization termination.¹⁹ Recently, some successful ATRP's of acrylamide derivatives have been reported, however several restrictions such

as ligands and solvent availability are existed.^{20,21} To overcome this problem, we report here a method to coat magnetite nanoparticles with a precursor reactive polymer shell, which gives a platform to introduce a series of functional polymer shell of amine derivatives by substitution reaction.

In this study, we have applied surface initiated ATRP technique to synthesize poly(*N*-hydroxysuccinimide methacrylate) (pSucMA)-coated magnetite (Fe₃O₄) nanoparticles (Fe₃O₄-pSucMA) to synthesize precursor polymer (pSucMA) onto nanoparticles surface. The pSucMA can be converted to desired functional polymer-shell by simple substitution reaction of succinimide groups with functional amine derivatives. Tetradecylamine was used as an example to fabricate nanoparticles coated with polymethacrylamide shell to perform the feasibility of the reaction. Previously, we have reported that *N*-alkylmethacrylamide polymers form a stable condensed monolayer at the air-water interface by a two-dimensional network based on hydrogen bonding between amide groups and giving well-defined polymer sheets by Langmuir-Blodgett (LB) method.²² The nanoparticle coated by alkylmethacrylamide polymer shell will be expected to form highly ordered monoparticle layer with a help of the network based on hydrogen bonding of the amide groups.

EXPERIMENTAL

Materials

All reagents were purchased from TCI, unless otherwise mentioned and used as received.

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Synthesis of Magnetite Nanoparticles with ATRP Initiator

Monodisperse oleic acid stabilized Fe_3O_4 nanoparticles were prepared by the high temperature solution-phase reaction.²³ To introduce ATRP initiator onto magnetite nanoparticles surface the particles were dispersed in a 1 M of 2-methyl-2-bromo-isobutyric acid (BrIBA) of hexane solution. The dispersion was stirred for 72 h at room temperature under nitrogen atmosphere.²⁴ The nanoparticles bound with initiator (Fe_3O_4 -BrIBA) were separated by centrifugation. The product was washed three times with hexane to remove excess free initiator from the nanoparticles surface and dried under vacuum.

Surface Initiated ATRP of *N*-Hydroxysuccinimide Methacrylate onto Nanoparticles Surface

N-Hydroxysuccinimide methacrylate (SucMA) was synthesized from the condensation of *N*-hydroxysuccinimide and methacryloyl chloride.²⁵ The ligand, *N*-(*n*-propyl)-2-pyridylmethanamine, was prepared as described elsewhere.²⁶ The ATRP of SucMA onto nanoparticles surface was carried out by modifying the reported process.²⁷ Fe_3O_4 -BrIBA nanoparticles (40 mg) were mixed with 3 mL of dehydrated dimethylsulfoxide (DMSO) containing SucMA (0.7 g, 3.8 mmol), CuBr (0.018 g, 0.12 mmol) (Aldrich 99.99%), and *N*-(*n*-propyl)-2-pyridylmethanamine (34 μL , 0.23 mmol). The polymerization was carried out at 70 °C for 12 h under argon atmosphere. After cooling to room temperature, the solvent was removed under vacuum and acetone was added to precipitate out the Fe_3O_4 -pSucMA nanoparticles. The precipitated Fe_3O_4 -pSucMA were washed three times with acetone and dried under vacuum.

Conversion of pSucMA to Polymethacrylamide onto Magnetite Surface

The prepared Fe_3O_4 -pSucMA nanoparticles were mixed with anhydrous tetrahydrofuran (THF) (5 mL) under argon atmosphere and tetradecylamine (TDA) (2 mmol) was added into the solution. The solution was heated at 50 °C for 8 h. After cooling to room temperature, the solvent was removed and the poly-tetradecylmethacrylamide (pTDMA)-coated Fe_3O_4 particles (Fe_3O_4 -pTDMA) were precipitated in methanol and rinsed several times to remove unreacted amine.

Measurements

The microscope images of the nanoparticles were measured by a transmission electron microscopy (TEM, JEOL, JEM-3010) at an accelerating voltage 300 kV. FT-IR spectra were measured with a JASCO FT/IR-230 using KBr pellet. UV-vis absorption spec-

tra were measured by a Hitachi, U-3000 spectrophotometer. The number average molecular weight (M_n) and polydispersity index (M_w/M_n) were determined by a Toyo Soda, gel permeation chromatography (GPC) with TSK-gel Super-HM-M column system using polystyrene standard. Thermogravimetric analysis (TGA) was carried out by a thermogravimetric analyzer (RIGAKU, TG-DTA-2850) under Ar in the temperature range of 30–800 °C with an increasing rate of 10 °C/min.

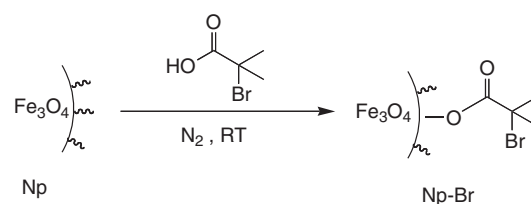
RESULTS AND DISCUSSION

Preparation of Fe_3O_4 Nanoparticles

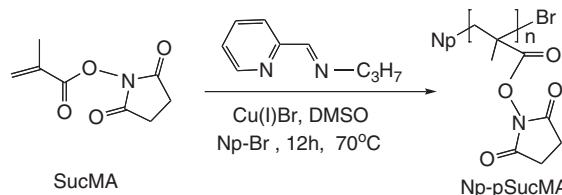
The magnetite nanoparticles were prepared by a high temperature solution-phase reaction that has already proven to be effective procedure for the preparation of highly uniform magnetic nanoparticles.²³ The TEM image of the magnetite nanoparticles showed an average diameter of 4–5 nm with small deviation. These nanoparticles were used in the following modification reaction with ATRP.

Preparation of BrIBA-coated Fe_3O_4 Nanoparticles

The coating of magnetite nanoparticles with SucMA polymer was carried out by a two steps reaction shown in Scheme 1. First, an ATRP initiator was introduced onto the magnetite surface by ligand-exchange reaction. The oleic acid and oleyl amine coated magnetite nanoparticles were dispersed in a 1 M of BrIBA/hexane solution and stirred for 72 h at room temperature under nitrogen atmosphere.²⁴ After stirring for 72 h, Fe_3O_4 -BrIBA were precipitated as a yellowish powder. The exchange reaction was confirmed by FT-IR spectroscopy. Figure 1 shows



Step 1. Preparation of Fe_3O_4 -BrIBA by ligand-exchange reaction.



Step 2. Surface-initiated ATRP of SucMA on magnetite surface.

Scheme 1. Fabrication process of pSucMA shell onto magnetite nanoparticle core.

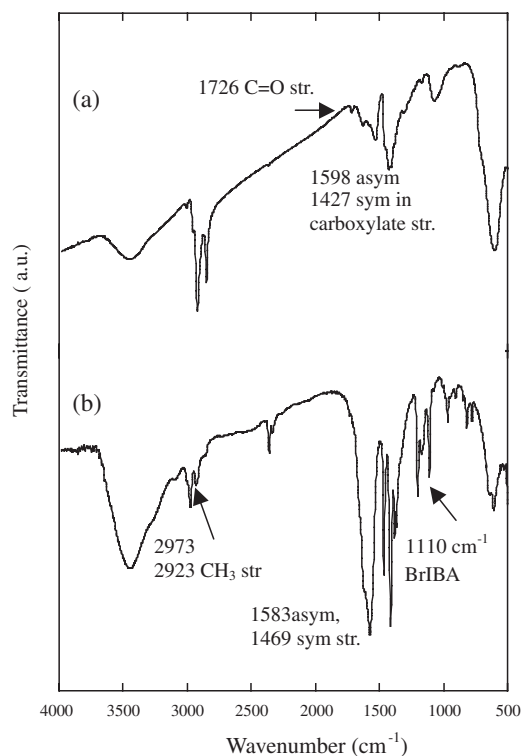


Figure 1. FT-IR spectra of oleic acid stabilized Fe_3O_4 nanoparticles before (a) and after (b) ligand exchange with BrIBA.

the IR spectra of Fe_3O_4 nanoparticles before and after ligand exchange reaction. The IR spectrum of as prepared nanoparticles shows alkyl CH_2 vibration band at 2921, 2852 cm^{-1} and carbonyl stretching vibration at 1726 cm^{-1} . The band at 1598 and 1427 cm^{-1} are assigned to asymmetric and symmetric vibration of carboxylate group, respectively. After the ligand exchange reaction, besides these alkyl CH_3 vibration band and carbonyl peaks, a new absorption peak at 1110 cm^{-1} appeared, which is assigned to the initiator of BrIBA.²⁴ The peaks at 1583 and at 1469 cm^{-1} were asymmetric and symmetric vibrations of carboxylate groups. The positions of these bands are sensitive to the chemical compositions of nanoparticles surface.²⁸ The amount of the initiator introduced onto the nanoparticles surfaces was calculated to be 2.39×10^{-6} mol per mg of nanoparticles calculated by TGA analysis.

Surface-initiated ATRP of SucMA on Magnetite Surface

The ATRP of SucMA on Fe_3O_4 -BrIBA nanoparticles as macroinitiator was carried out with a similar method described elsewhere.²⁷ The Fe_3O_4 -BrIBA nanoparticles were dispersed into dehydrated DMSO solution and then SucMA, CuBr, and *N*-(*n*-propyl)-2-pyridylmethanamine were added under argon atmosphere. The reaction solution was kept at 70 °C for 12 h. Figure 2(a) shows IR spectra of Fe_3O_4 -pSucMA

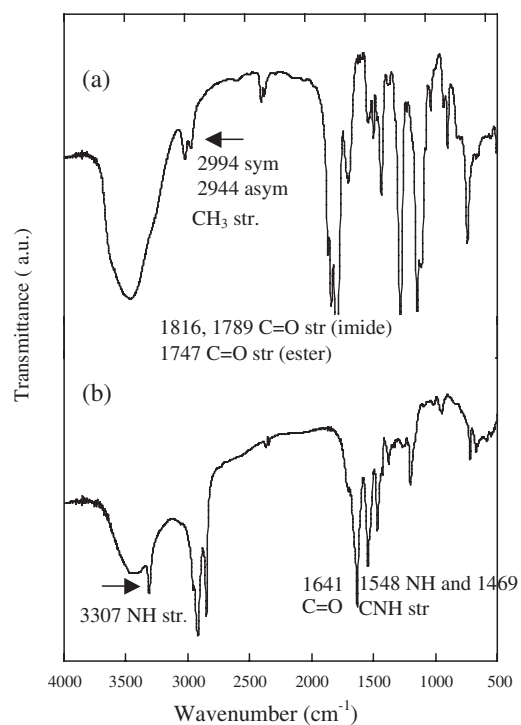
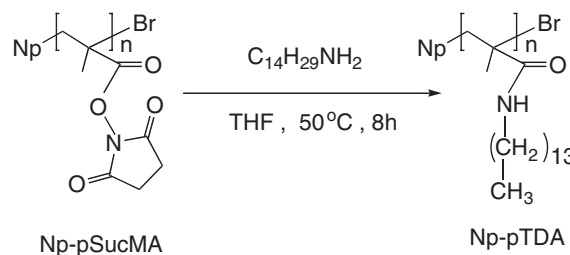


Figure 2. FT-IR spectra of Fe_3O_4 -pSucMA (a) and Fe_3O_4 -pTDMA (b).



Scheme 2. Fabrication process of pTDMA shell onto magnetite nanoparticle core by substitution reaction.

particles. The new peaks appeared at 1816 and 1789 cm^{-1} were attributed to $\text{C}=\text{O}$ stretching vibration of succinimide and at 1747 cm^{-1} for ester, which indicate that the polymerization occurred onto the magnetite surface. The bands at 2994 and 2944 cm^{-1} were from alkyl CH_3 and CH_2 stretching vibration of polymer backbone. Free polymer was not detected after removing the solvent. This means that the initiator was not detached from the nanoparticles surface. Accordingly, the polymer growth was confined at the surface of the initiator-coated nanoparticles.

Conversion of pSucMA into Polymethacrylamide onto Magnetite Surface

Finally, we prepared pTDMA shell onto nanoparticles surface from the reaction of Fe_3O_4 -pSucMA with TDA by substitution reaction shown in Scheme 2.

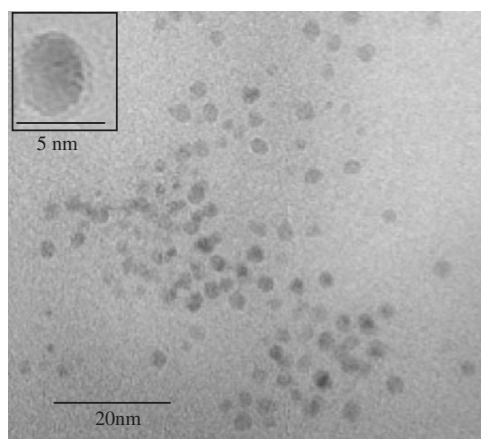


Figure 3. TEM image of Fe_3O_4 -pSucMA core-shell nanoparticles. Inset: Magnified image of one particle.

TDA was selected because we have previously mentioned that pTDMA form a stable condensed monolayer at the air-water interface by a two-dimensional network based on hydrogen bonding between amide groups.²² SucMA has an active ester group, which undergoes substitution reaction easily with primary and secondary amine derivatives.^{29,30} To synthesize Fe_3O_4 -pTDMA, TDA was added to the dispersion of Fe_3O_4 -pSucMA in THF under argon atmosphere to perform the substitution reaction. Figure 2(b) shows IR spectra of Fe_3O_4 -pTDMA after conversion with TDA. The characteristic amide absorption bands appeared at 3307 cm^{-1} for NH stretching and at 1641 cm^{-1} for C=O vibration. The appearance of bands at 1548 and 1469 cm^{-1} assigned to NH bending and CNH stretching (str.) respectively, supports the conversion of pSucMA polymer into pTDMA onto nanoparticles surface. Moreover, after the reaction with TDA both ester and C=O of imide peaks mostly disappeared. To confirm the grafted polymer stability after post polymerization reaction we have measured TGA of the polymer-coated nanoparticles before and after post-polymerization reaction. From the TGA measurement we have calculated that only 15% of polymer was detached from the Fe_3O_4 core after the post polymerization reaction.³¹

The TEM image of the Fe_3O_4 -pTDMA nanoparticles showed uniform dispersion with no aggregation of the particles (Figure 3). The pTDMA is readily observed with light contrast shell (Figure 3 Inset). The structure of these core-shell nanoparticles is supported by UV-vis, IR, and GPC measurements. Figure 4 shows the UV-vis absorption of the Fe_3O_4 -pTDMA particles in chloroform. The yellowish transparent solution showed the absorption peak at $\sim 320\text{ nm}$, which characterized the Fe_3O_4 core.³² Moreover, the particles were easily attracted with magnet, which indicates that the magnetic property of the nanoparticles

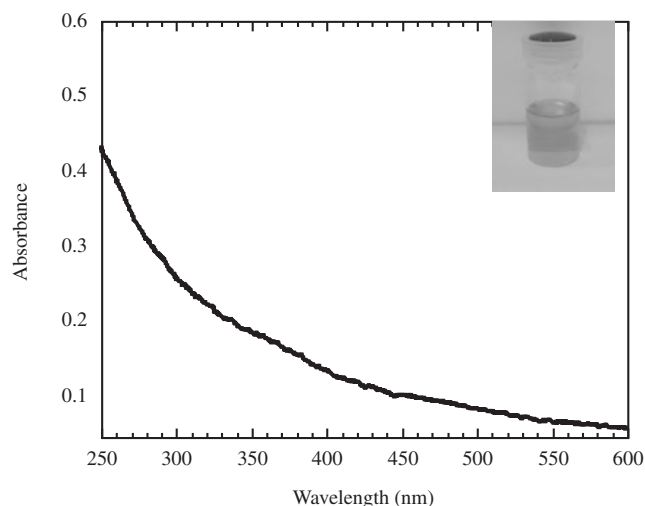


Figure 4. UV-vis spectrum of Fe_3O_4 -pTDMA core-shell nanoparticles in chloroform. Inset: Digital camera image of the sample.

is retained after polymer coating onto nanoparticles surface.

The molecular weight and polydispersity of the pTDMA shells were measured by removing pTDMA chains from the magnetite particles surface using aqueous solution of HCl.²⁴ The molecular weight was found 3500 with low polydispersity ($M_w/M_n = 1.13$), which is consistent with very thin polymer shell on nanoparticles surface observed by TEM. The IR spectrum of the cleaved polymer resembled with synthesized Fe_3O_4 -pTDMA (data not shown), which indicates pTDMA was not decompose during cleavage process. The calculated grafting density showed higher value (1.9 chain/nm^2)³³ than previously reported data (0.7 chain/nm^2)¹⁴ due to the underestimated surface area of the nanoparticles, where all the particles were assumed to be spherical with 4 nm diameter. Interestingly, the Fe_3O_4 -pTDMA formed a stable monolayer at the air/water interface. The detail will be discussed in the forthcoming report.

CONCLUSIONS

In summary, we prepared Fe_3O_4 -pSucMA nanoparticles as reactive polymer hybrid magnetite nanoparticles. The Fe_3O_4 -BrIBA nanoparticles retain its original shape after ligand-exchange reaction and can be successfully performed ATRP reaction of SucMA on nanoparticles surface. The reactive shell of the magnetite particles can be easily reacted with TDA to produce Fe_3O_4 -pTDMA nanoparticles. We believe this modification approach should be able to be used to the synthesis of other nanoparticles with increasing complexity and functionality in the polymeric shell.

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31. The amount of grafted pSucMA was found 0.7 mg per mg of nanoparticles. After post polymerization reaction the polymer loss was also found 0.7 mg per mg of nanoparticles.
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33. The amount of grafted polymer was found 2.4×10^{-7} mole per $7.34 \times 10^{16} \text{ nm}^2$ of magnetite nanoparticles when we assumed that the particles size are spherical with 4 nm diameter.