SYNTHESIS, CHARACTERIZATION AND EVALUATION OF POLYMER-IRON OXIDE HYBRID NANOSYSTEMS FOR TARGETING AND IMAGING APPLICATIONS

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by

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Submitted

In fulfillment of the requirements of the degree of

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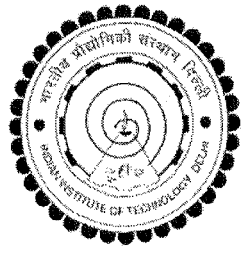
to the



Indian Institute of Technology Delhi
August 2012

Dedicated to my Parents

CERTIFICATE

This is to certify that the thesis entitled **"Synthesis, Characterization and Evaluation of Polymer-Iron Oxide Hybrid Nanosystems for Targeting and Imaging Applications"** being submitted by **Ms. Shveta Mahajan** to the Indian Institute of Technology, Delhi for the award of the degree of **Doctor of Philosophy** is a record of bona fide research work carried out under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard.

The results contained in this thesis are original and have not been submitted, in part or in full, to any other University or Institute for the award of any other degree or diploma.

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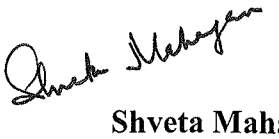

Shveta Mahajan

ABSTRACT

The use of nanoparticles in nanomedicine offers various exciting possibilities. In recent years, nanoparticles have revolutionised the approach to the systemic delivery of pharmaceutically active compounds; they provide controlled release, eliminate side-effects and maximise the therapeutic efficacy of a drug. In the case of nanoparticles used for diagnostics and imaging, the active agent may be directed to the particular cells, tissues or organs of interest by use of targeting moieties that 'home in' on the specific region.

One of the most promising candidates in medical diagnostics are the iron oxide nanoparticles, which below a certain critical value (typically in the 5-20 nm range) exhibit superparamagnetism. This thesis deals with the development of systems based on superparamagnetic iron oxide nanoparticles (SPIONs) for contrast enhancement in magnetic resonance imaging (MRI). The thesis is divided into four parts. The first part describes the synthesis and characterization of SPIONs prepared by two alternative thermal decomposition methods. The second part deals with the encapsulation of SPIONs in a micellar system and their conjugation with folic acid. The SPION-micelle systems were characterized and evaluated for receptor-mediated internalization in HeLa cells, besides magnetic targeting ability to a tumor in an *in vivo* model. The third part deals with the stabilization of SPIONs with a gelatin coating, mannosylation and the evaluation of this system for mannose receptor targeting efficacy. The fourth part describes the PEGylation of the surface of hydrophobic SPIONs, to facilitate their transfer to aqueous medium.

The first experimental chapter in this thesis describes in detail two synthetic routes for the preparation of highly crystalline SPIONs, by decomposition of iron organic precursors in organic

solvents. The first route involved decomposition of iron (III) acetylacetonate in triethylene glycol (TREG) and resulted in hydrophilic TREG-coated SPIONs [SPIO(L)]. SPIONs prepared by varying reaction conditions had particle size 4.95±1.12 nm [$SPIO_{0.5}$(L)] and 9.27±3.37 nm [$SPIO_1$(L)]. These nanoparticles were characterized by TEM, XRD, FTIR, TGA and VSM. The larger particles, designated as $SPIO_1$(L), possessed a high magnetization value of 76.8 emu/g of iron oxide (IO), while $SPIO_{0.5}$(L) had a magnetization of 55.6 emu/g of iron oxide (IO).

The second method adopted for SPION synthesis involved the thermal decomposition of iron (III) oleate in 1-octadecene in the presence of oleic acid and produced highly hydrophobic oleic acid-coated SPIONs [SPIO(B)]. These SPIONs had a small size and were highly monodisperse (diameter=5.24 nm ± 0.30 nm). They were characterized by TEM, FTIR, TGA and VSM. These too possessed a high value of magnetization (73.6 emu/g of IO).

Chapter 3 describes the preparation of SPION-polymeric hybrid micelles from $SPIO_1$(L) and a PMMA-b-pPEGMA copolymer conjugated with folic acid, for a dual targeting ability, i.e. via the folate receptor (FR) for receptor-mediated internalization and by magnetic targeting with the aid of an external magnetic field. The PMMA-b-pPEGMA copolymers were first prepared by atom transfer radical polymerization (ATRP) and characterized by GPC and ^{1}H-NMR. The polymer designated as M_1EG_1 was conjugated with folic acid (the folate-conjugated polymer is designated as FM_1EG_1). Critical micellar concentrations (CMC) were determined for all the polymers and it was found that with the length of the hydrophobic core (PMMA) remaining the same, the length of the hydrophilic block did not show any significant effect on CMC, while an increase in the length of the hydrophobic block or conjugation with folic acid led to a drastic lowering of CMC. Micelles prepared from M_1EG_1 and FM_1EG_1 were characterized by TEM,

AFM and DLS. Micelles made from M_1EG_1 had a hydrodynamic radius of 95.82 nm(PDI=0.073), while FM_1EG_1 micelles had a diameter 118.7 nm (PDI 0.108). A core-shell morphology was discernible in the TEM micrographs of the micelles. These micelles were used to prepare SPION-polymer hybrids by aqueous desolvation of a mutual solution of the SPIONs and polymer in tetrahydrofuran. The SPION-polymer micelles were characterized by TEM and MRI. T2 relaxivity was determined for $SPIO_1$(L)- FM_1EG_1 micelle cluster and was found to be 260.4 $mM^{-1}sec^{-1}$. *In vitro* cytotoxicity and uptake was evaluated in HeLa cells. The cells showed nearly 90% viability when treated with SPIONs at a concentration of 20 μg/ml (Fe) for 24 h. Internalization studies (Prussian blue quantification and confocal microscopy of Nile red loaded micelles) revealed that the folate-conjugated SPION-micelles were internalized more efficiently by the HeLa cells, which overexpress the folate-receptor, than the unconjugated formulation.

In chapter 4 the encapsulation of TREG-coated SPION in a stabilizing gelatin coat is discussed. The SPION-loaded nanoparticles were further mannosylated for mannose receptor-mediated targeting of macrophages. First the method for preparing gelatin nanoparticles (GNP) (desolvation) was optimized for pH, gelatin and crosslinker (glutaraldehyde) concentration. Particles having ~110 nm diameter could be produced and were characterized by TEM, AFM and DLS. TREG-coated SPIONs were then incubated with gelatin, the dispersion subjected to desolvation under the appropriate pH and concentration conditions and crosslinked with glutaraldehyde. The SPION-loaded gelatin nanoparticles were then derivatized with mannose. Non-mannosylated and mannosylated nanoparticles were referred to as MGNP and MN-MGNP respectively. Characterization was done by DLS, TEM and FTIR. MGNP had a hydrodynamic diameter of 163.3 nm (PDI = 0.113), while MN-MGNP exhibited an increased size of 221.4 nm (PDI = 0.095). Colloidal stability was established in water, PBS (pH 7.4), electrolyte solution

(1M NaCl), cell culture medium (DMEM) with and without serum and it was found that both MGNP and MN-MGNP were stable/non-aggregating in these media. The stability of nanoparticles in PBS over a period of several days was also established by measuring hydrodynamic diameter of MGNP and MN-MGNP in dispersions stored at 4 °C.

T2 relaxivities were also determined for MGNP and MN-MGNP by *in vitro* MR imaging, and were found to be 168.7 and 158.2 $mM^{-1}sec^{-1}$ respectively, which is comparable to commercially available agents.

Cell studies were done using the J774e murine macrophage cell line. These cells upregulate the mannose receptor. A cell viability of 92.99±2.67% and 91.13±3.35% was determined for MGNP and MN-MGNP respectively after an incubation period of 24 h at a concentration of 20 μg/ml. Cellular internalization was studied by quantifying iron oxide internalized in J774e cells by colorimetric Prussian blue assay. MN-MGNP were internalized to a greater extent in these cells than the MGNP.

The final experimental chapter described the modification of oleic acid–coated SPIONs with PEG-silanes synthesized in the laboratory. Copolymers of poly(ethylene glycol) methyl ether methacrylate (PEGME-MA, Mn=300) and 3-(trimethoxysilyl)propyl methacrylate (TMSPMA) were prepared by free-radical polymerization and characterized by GPC and FTIR. Carboxy functionality was introduced by using trimethylsilyl methacrylate (TMSMA) as one of the monomers with eventual deprotection of the trimethylsilyl groups which protect carboxy functionality. SPIONs modified with a neutral PEG silane were designated as MNP-Si-PEG, while those modified with TMSMA-containing polymers were called MNP-Si-CPEG1 and MNP-Si-CPEG2 (after deprotection of the carboxy groups). MNP-Si-CPEG2 had a greater

TMSMA content in the original polymer than MNP-Si-CPEG1. MNP-Si-CPEG1 and MNP-Si-CPEG2 were then conjugated with PEI (Mn=600) subsequently, with the PEI modified SPIONs designated as MNP-PEI1 and MNP-PEI2 respectively. The modified SPIONs were characterized by TEM, DLS, FTIR and TGA. All possessed hydrodynamic diameters of less than 10 nm. Their colloidal stability was established in different media including water, PBS, 1 M NaCl and cell culture medium (RPMI) with and without serum by measuring their UV absorption. T2 relaxivity of the sample MNP-Si-PEG was determined to be 114.8 $mM^{-1}sec^{-1}$.

In vitro studies included MTT assay and quantification of cellular uptake of the particles and were done with HeLa cells. MNP-Si-PEG, MNP-Si-CPEG1 and MNP-Si-CPEG2 were non-toxic to the cells treated for 24 h. MNP-PEI1 and MNP-PEI2 however, caused a lowering in the cell viability for the same period of incubation. Cell uptake studies by Prussian blue assay revealed that for MNP-Si-PEG and MNP-Si-CPEGs 1 and 2, SPION internalization increased as the time of incubation was increased from 1 to 24 h. With the PEI-conjugated SPIONs, cell uptake was greater after 6 h of incubation as compared to 1 h. This was, however, followed by a saturation of particle concentration within the cells.

Thus, this work demonstrates that SPIONs produced by different strategies offer versatility with respect to polymeric modification depending upon the application envisaged. The variously modified SPIONs showed good biocompatibility and cellular internalization kinetics and have potential for application as MRI contrast agents.

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ABBREVIATIONS

AFM	Atomic force microscopy
ANOVA	Analysis of variance
ATRP	Atom transfer radical polymerization
BPO	Benzoyl peroxide
CMC	Critical micellar concentration
DCC	N,N'-Dicyclohexylcarbodiimide
DLS	Dynamic light scattering
DMAP	4-Dimethylaminopyridine
DMdP	4,4'-Dimethyl-2,2'-dipyridyl
DMEM	Dulbecco's modified Eagle's medium
DMF	Dimethylformamide
DMSO	Dimethylsulphoxide
EAT	Ehrlich Ascites tumor
EBiB	Ethyl α-bromoisobutyrate
EDAC	N-(3-Dimethylaminopropyl)-N'-ethylcarbodiimide hydrochloride
FA	Folic acid
FBS	Fetal bovine serum
FCS	Fetal calf serum
FDA	Food and Drug Administration (USA)
FR-α	Folate receptor- α isoform
FT-IR	Fourier transform - Infrared spectroscopy
GNP	Gelatin nanoparticles
GPC	Gel permeation chromatography
HRTEM	High resolution transmission electron microscopy
MGNP	Magnetic gelatin nanoparticles
MMA	Methyl methacrylate
MN-MGNP	Mannosylated magnetic gelatin nanoparticles
MRI	Magnetic resonance imaging

MTT	3-(4,5-Dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide
NHS	N-Hydroxysuccinimide
NMR	Nuclear magnetic resonance
OA	Oleic acid
PBS	Phosphate buffered saline
PDI	Polydispersity index
PEG	Poly(ethylene glycol)
PEGMA	Poly(ethylene glycol) methacrylate
PEGME-MA	Poly(ethylene glycol) methyl ether methacrylate
PEI	Poly(ethyleneimine)
RES	Reticuloendothelial system
RPMI	Roswell Park Memorial Institute medium
SAED	Selected area electron diffraction
SPIO	Superparamagnetic iron oxide
SPION	Superparamagnetic iron oxide nanoparticles
TEM	Transmission electron microscopy
TGA	Thermogravimetric analysis
THF	Tetrahydrofuran
TMSMA	Trimethylsilyl methacrylate
TMSPMA	3-(Trimethoxysilyl)propyl methacrylate
TREG	Triethylene glycol
VSM	Vibrating scanning magnetometry
XRD	X-ray diffraction