Synthesis of Hyperbranched Amphiphilic Polyester and Theranostic Nanoparticles thereof

2-12-2013

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SYNTHESIS OF HYPERBRANCHED AMPHIPHILIC POLYESTER AND THERANOSTIC NANOPARTICLES THEREOF

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Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 662 days.

Appl. No.: 12/417,017
Filed: Apr. 2, 2009

Provisional application No. 61/041,624, filed on Apr. 2, 2008.

Int. Cl.
C08G 63/00 (2006.01)
C07C 6/00 (2006.01)
C07C 27/10 (2006.01)

U.S. Cl. .......................... 528/271; 562/400; 568/700

Field of Classification Search ....................... None
See application file for complete search history.

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ABSTRACT
A method of making a hyperbranched amphiphilic polyester compound includes drying under vacuum a mixture of 2-(4-hydroxybutyl)-malonic acid and p-toluene sulphonic acid as catalyst. The vacuum is then released with a dry inert gas after drying. The dried mixture is heated under the inert gas at a temperature sufficient for polymerization. The inert gas is evacuated while continuing to heat the mixture. The formed polymer is then dissolved in dimethylformamide and precipitated out by adding methanol. Modifications of the method yield nanoparticles of polyesters having properties suited for coencapsulating fluorescent dyes together with therapeutic drugs, resulting in theranostic nanoparticles, that is, nanoparticles useful in both therapeutic treatments and diagnostic methods.

12 Claims, 29 Drawing Sheets
(18 of 29 Drawing Sheet(s) Filed in Color)
FIG. 1
FIG. 2
FIG. 4
FIG. 6
FIG. 7
FIG. 9
FIG. 10
FIG. 11
FIG. 14
FIG. 15
FIG. 17
FIG. 18
FIG. 19
**FIG. 20**

A. Zeta Potential Distribution

- Zeta potential (mV): -54.5

B. Zeta Potential Distribution

- Zeta potential (mV): 10.33

[Diagrams showing Zeta potential distributions with corresponding chemical structures.]
FIG. 21
FIG. 22
FIG. 23

Absorbance vs Wavelength (nm)

- DIR-Folate HBPE PNP's
- HBPE
- Folic acid (355 nm)
- DiR (755 nm)
FIG. 25
FIG. 26
FIG. 29
FIG. 30
SYNTHESIS OF HYPERBRANCHED AMPHIPHILIC POLYESTER AND THERANOSTIC NANOPARTICLES THEREOF

RELATED APPLICATION

This application claims priority from co-pending provisional application Ser. No. 61/041,624, which was filed on 2 Apr. 2008.

STATEMENT OF GOVERNMENT RIGHTS

Development of the present invention was supported, at least in part, by a grant from the U.S. Government. Accordingly, the Government may have certain rights in the invention, as specified by law.

FIELD OF THE INVENTION

The present invention relates to the field of nanotechnology and, more particularly, to nanoparticles useful as carriers of fluorescent dyes for diagnostic purposes and therapeutic drugs for treatment of disease; these dual-purpose particles are also known as “theranostic nanoparticles.”

BACKGROUND OF THE INVENTION

Polymer science has traditionally focused on linear polymers or cross-linked linear polymers, resulting in a wide variety of materials implemented in most facets of daily life. Recent progress in polymer sciences has resulted in the development of dendrimers and most recently hyperbranched polymers consisting of branched structures with high numbers of reactive groups in their periphery. The syntheses of these multifunctional dendritic (branched) polymers hold great promise for targeted delivery of drugs, therapeutics, diagnostics and imaging. The perfectly branched structures called dendrimers are constructed by an iterative and complex reaction sequence involving protection-deprotection steps whereas hyperbranched polymers, the less perfect structures, are made by one step polymerization reaction. Recent advances in nonviral drug delivery and cancer chemotherapy have revealed biocompatible branched polymers like polyethyleneimine (PEI) and starburst PAMAM as effective drug delivery systems, which can mimic naturally occurring biological transport systems such as lipoproteins and viruses. Unlike linear polymers which are produced from divalent AB type monomers, dendritic macromolecules are produced from polyvalent ABn monomers (n≥2), giving rise to its branching and multiple-end structures.6-8 Dendritic polymers have gained large interest in recent years because of their highly branched structures facilitating efficient encapsulation of guest molecules and having many attractive features such as improved solubility, reactivity, structure architecture, biocompatibility, low viscosity and low crystallinity compared to those of linear polymers of same molecular weight. Therefore, the creation of new and highly branched polymeric nanostructures with multifunctional capabilities is central to the development of novel materials with applications in various fields ranging from drug delivery, immunosays, microelectrodes, coating and nanocomposites. Polymeric nanoparticles and nanocomposites with dual fluorescent, magnetic and therapeutic properties will have a huge impact in medicine, particularly in cancer diagnosis and treatment, where novel targeted multifunctional polymeric nanoparticles can be developed to obtained spatiotemporal information about disease stage and progress of a therapeutic regime. 12-14 Hence, there has been substantial interest in developing smart therapeutic and selective polymeric vehicles for targeted treatment of various diseases, preventing toxicity to healthy tissues.

SUMMARY OF THE INVENTION

With the foregoing in mind, the present invention advantageously provides methods for making hyperbranched amphiphilic polyester compounds. These polymers may be used to generate nanoparticles having one or more hydrophobic pockets and a hydrophilic outer surface. The polymeric nanoparticles (PNPs) may be used as carriers for a hydrophobic near-infrared fluorescent dye and/or a therapeutic drug. The PNPs are biodegradable and, having been modified with appropriate chemical groups along their outer surface, are readily taken into cells, thus providing an ideal vehicle for delivery of therapeutic drugs. Since the PNPs may carry both a fluorescent dye and a therapeutic drug, they can be tracked optically via the dye and simultaneously deliver the drug to predetermined cells. The capability of having both a therapeutic modality and a diagnostic modality may be identified as “theranostic.”

A method of the present invention includes making a hyperbranched amphiphilic polyester compound. The method includes drying under vacuum a mixture of 2-(4-hydroxybutyl)-malonic acid and p-toluene sulfonic acid as catalyst. Then, releasing the vacuum with a dry inert gas after drying. The method continues by heating the dried mixture under the inert gas at a temperature sufficient for polymerization. The method proceeds by evacuating the inert gas while continuing to heat the mixture, then dissolving the formed polymer in dimethylformamide. Finally, the method ends after precipitating the dissolved polymer by adding methanol.

In the method, drying may comprise a mixture of 2-(4-hydroxybutyl)-malonic acid and p-toluene sulfonic acid in approximately a 100:1 molar ratio. Also, drying under vacuum preferably comprises a high vacuum and the inert gas is argon gas. The heating is preferably at a temperature of approximately 150°C, which promotes polymerization. The heating may continue for approximately two hours. Evacuating is most preferably conducted slowly at approximately 0.2 mmHg for about one hour while maintaining the polymerization temperature. After polymerization, the method may further comprise purifying the polymer by separating the precipitate, washing it with methanol and drying it in a vacuum.

The described method may be modified to make aminated PNPs. This is accomplished by dissolving the precipitated polymer in anhydrous dimethylformamide (DMF), adding 1,1′-carbonyldimidazole drop-wise to form a reaction mixture and incubating the reaction mixture at room temperature for approximately one to two hours. This method continues by adding ethylenediamine in anhydrous DMF drop-wise and continue incubation of the reaction mixture at room temperature for approximately 24 hours, then precipitating the reaction mixture in methanol, separating the precipitate and drying in a vacuum to obtain a purified hyperbranched polyester amine.

Yet another modification of the described method is useful for making propargylated PNPs. This modification includes dissolving the precipitated polymer in anhydrous dimethylformamide (DMF), adding 1,1′-carbonyldimidazole drop-wise to form a reaction mixture, incubating the reaction mixture at room temperature for approximately one to two hours, then adding propargyl chloride in anhydrous DMF drop-wise and continue incubation of the reaction mixture at room tem-
The invention additionally includes a polymeric nanoparticle consisting essentially of the polymer HBPE (5), the nanoparticle also having a hydrophobic near-infrared fluorescent dye encapsulated therein. The dye may be selected from the group consisting of Dil, DiR and DiD. Additionally, this PNP may include a therapeutic drug coencapsulated with said fluorescent dye and, particularly, an anti-cancer drug such as azidothymidine.

Another polymer included in the invention is one having a molecular structure according to the formula shown for HBPE-EDA (6).

Moreover, the invention further includes a polymeric nanoparticle consisting essentially of the polymer HBPE-EDA (6) and a hydrophobic near-infrared fluorescent dye encapsulated therein. As noted above, the dye may be selected from the group consisting of Dil, DiR and DiD and the PNP may also include a therapeutic drug coencapsulated with said fluorescent dye.

The other modification of the presently disclosed method is useful for making a polymer having a molecular structure according to the formula shown for HBPE-PA (7), as set forth below.

Included in the invention is a polymeric nanoparticle consisting essentially of the polymer HBPE-PA (7) and a hydrophobic near-infrared fluorescent dye encapsulated therein. In this polymeric nanoparticle the dye may be selected from the group consisting of Dil, DiR and DiD, and there may also be a therapeutic drug coencapsulated with said fluorescent dye. The therapeutic drug preferably comprises an anti-cancer drug, for example, azidothymidine or 25 wherein the anti-cancer comprises paclitaxel.

Those skilled in the art will recognize that while certain hydrophobic near-infrared fluorescent dyes have been given as examples, other dyes having similar properties would also be predictably useful in the invention. The same prediction can be expected to hold for therapeutic drugs other than the ones given here as examples; as long as the drug exhibits sufficient hydrophobicity to nest in the hydrophobic pocket formed by the polymer in the nanoparticle, the drug should be of use in the invention. These dyes and drugs as known to the skilled by their properties are, therefore, intended to be included within the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Office upon request and payment of the necessary fee.

Some of the features, advantages, and benefits of the present invention having been stated, others will become apparent as the description proceeds when taken in conjunction with the accompanying drawings, presented for solely for exemplary purposes and not with intent to limit the invention thereto, and in which:

FIG. 1 illustrates, according to a method of the invention, the facile synthesis of amphiphilic hyperbranched polyester (HBPE, 5) and corresponding polyester-amine (HBPE-EDA, 6) polymer, which are highly branched, globular, and biodegradable in nature; the polymeric backbone of HBPE was synthesized by melt polymerization of the monomer 4, which can be easily made from commercially available diethylmalonate 1 and bromobutyl acetate (2) in two simple steps, hence the synthesis of 5 is cost-effective; the corresponding amminated polymer can be synthesized via conjugation of ethylendiamine using 1,1'-carbonyldiimidazole (CDI) coupling; the resulting amphiphilic and dendritic polymers (5 and 6) contain inner hydrophobic domain (aliphatic chains), surrounded by a hydrophilic outer shell (carboxylic or amine groups), which after self assembly in water result in a stable nanoparticle suspension which can encapsulate hydrophobic dyes and drugs;

FIG. 2 shows a schematic representation of the structure of dendritic polyester (HBPE 5) and corresponding formation of polymeric nanoparticles via solvent diffusion method; using this method, a series of hydrophobic drugs and dyes can be encapsulated in one pot; these polymeric nanoparticles are highly dispersed in water and stable in a wide range of buffered solutions under physiological conditions; both click chemistry, carbodiimide chemistry and other conjugation chemistries can be used for the functionalization of these polymeric nanoparticles with small molecule like antibodies, proteins, oligonucleotides and other targeting agents to generate a nanoparticle-ligand library;

FIG. 3 presents an overall schematic representation of the preparation of functional polymers and polymeric nanoparticles (PNPs); polymer 5 was synthesized following the melt polymerization technique; PNPs were synthesized using the solvent diffusion method and were stable in water and other aqueous buffer solutions; carbodiimide chemistry has been followed for the synthesis of functional polymers (6 and 7) using 1,1'-carbonyldiimidazole (CDI), as a water insoluble
carboxylic acid groups; not surprisingly, the zeta potential of the non-aminated polymeric nanoparticles is negative (A, \( \zeta = -54.5 \) mV), whereas a dramatic increase in the polymer’s molecular weight was observed when high vacuum was applied; moreover, when the evacuation was continued for more than 2 h, the resulting polymers were found to be insoluble in all the solvents; the average molecular weight of polymer (5) was \( M_w = 42,000, \) PD = 1.6; FIG. 10 is a TGA thermogram trace of polyester 5 at a heating rate of 10°C/min in air; the thermogram obtained is typical of an aliphatic hyperbranched biopolymer; the hyperbranched polymer exhibits a moderate thermal stability; thermal decomposition of the polymer was initiated at \( 210°C \); at \( 225°C \), the polymer has only lost about 2.5% of its weight, mainly due to evaporation of the volatile compounds (such as \( \mathrm{H}_2\mathrm{O}, \) CHCl\(_3\) and DMF), before the induction of its thermal decomposition of the polymer was initiated at \( 210°C \); at \( 225°C \), the polymer has only lost about 2.5% of its weight, mainly due to evaporation of the volatile compounds (such as \( \mathrm{H}_2\mathrm{O}, \) CHCl\(_3\) and DMF), before the induction of its thermal degradation; approximately a 10% weight loss occurred at \( 250°C \); FIG. 11 shows in A) the chemical structure of DiiD and DiR; these dyes are water insoluble in nature and are primarily used to visualize cell membranes; and in B) a photographic image showing an aqueous (PBS) suspension of HBPE nanoparticles encapsulating the corresponding dyes (8a-c); similarly, one can encapsulate a hydrophobic drug or a combination of drug and dye; highly dispersed dyes/drugs encapsulated polymeric nanoparticles are stable in wide range of solvents under physiological conditions. The fluorescence of the resulting dye-encapsulated polymeric nanoparticles is bright and is not accompanied by any significant quenching upon encapsulation of photobleaching upon prolonged imaging; FIG. 12 shows the hydrodynamic diameters of the nanoparticles as measured by dynamic light scattering (DLS) instrument; measurement data shows the average hydrodynamic diameter of the particles are ranging between approximately 90±20 nm; FIG. 13 presents Scanning Electron Microscope (SEM) images of the polymeric nanoparticles showing an average diameter ranging from 115±25 nm, in accordance with the DLS data shown in FIG. 12; remarkably, the black rectangular box in the image indicates that the nanoparticles are spherical in shape, as expected; FIG. 14 depicts FT-IR spectra of the final monomer 4 (Acid), HBPE 5 (Polymer) and the dye encapsulating PNPs 8a, demonstrating presence of dye within the PNP; the presence of a FT-IR band at 1728 cm\(^{-1}\) for the ester group indicates the formation of the hyperbranched polyester from the monomer (band at 1710 cm\(^{-1}\) for aliphatic carboxylic acid group); the band at 1675 cm\(^{-1}\) is attributed to a conjugated alkene group, confirming the encapsulation of the dye inside a hydrophobic cavity of the PNP; FIG. 15 is UV/Vis spectra of the dye (Dil, DiiD, DiR)-encapsulating PNPs (8a-c), showing the presence of the NIR dyes with absorption maxima at 552, 650 and 755 nm, respectively; FIG. 16 shows the characteristic fluorescence emission spectra of dye encapsulating polymeric nanoparticles (8a-c) in DI water; the fluorescence intensity maxima of these nanoparticle solutions at 570 nm, 675 nm and 780 nm indicate the presence of NIR dyes Dil, DiiD and DiR, respectively, in the hydrophobic domain of the polymeric nanoparticles; no changes in fluorescence intensity or quenching of the dyes was observed upon encapsulation and subsequent storage of the nanoparticles at 4°C for months, demonstrating the high fluorescence stability of these dye encapsulated polymeric nanoparticles; note the multiple imaging capability using 3 different wavelengths; FIG. 17 are UV/Vis is spectra of the Dil dye encapsulating PNPs (8a) and the dye alone; a blue shift (by 10 nm) was observed in the UV/Vis absorption maxima in the case of Dil encapsulating PNP, which confirmed the presence of the dye within the hydrophobic domain of the PNP; FIG. 18 depicts the blue shift (23 nm) in the fluorescence emission of Dil encapsulating HBPE nanoparticles (8a) as compared to free dye; this is due to both van-der Walls (hydrophobic) and electronic interactions of the dye with the polymeric cavity, confirming the presence of dye inside the polymeric cavity; FIG. 19 shows a photo-stability study of the Dil encapsulating PNPs (8a) and Dil alone in solution in the presence of UV light, demonstrating the stability of the dye when encapsulated inside the polymeric cavity compared to the free dye; FIG. 20 shows the electrophoretic potential (zeta potential) of the synthesized polymeric nanoparticles; the zeta potential of the non-aminated polymeric nanoparticles is negative (A, \( \zeta = -54.5 \) mV), as expected, due to the presence of surface carboxylic acid groups; not surprisingly, the zeta potential of the aminated polymeric nanoparticles is positive (B, \( \zeta = +10.33 \) mV), where the low positive value indicates the partial amination of the nanoparticles with the presence of less number of free carboxylic groups than amine groups at the surface; FIG. 21 presents cell internalization studies using Xenogen’s IVIS 50; in these experiments either carboxylated (negative, 8b) or aminated (positive, 9b) nanoparticles were incubated with cells from the A549 lung cancer cell line; in these representative studies, near infrared DiR encapsulated nanoparticles were used, although similar results were observed with DiD and Dil; as expected, internalization was
observed only when the positively charged aminated DiR nanoparticles were used, as judged by the near infrared fluorescence coming from the cell pellets on FIG. 21B; note that when carboxylated nanoparticles are used (FIG. 21A), the fluorescence remains in the supernatant; these results demonstrate that cationic nanoparticles are a better candidate for the cell internalization studies and for cell tracking studies. In addition, it shows the capability of imaging in the near infrared;

FIG. 22 is a UV/Vis spectrum of the folate-clicked, DiR-encapsulating PNP's 11a, showing the presence of both the encapsulated dye (553 nm) and surface clicked with folate (354 nm); similar results were obtained for the paclitaxel- and Dil-encapsulating PNP's 11d, prepared for targeted cancer therapy;

FIG. 23 shows an UV/Vis spectrum of the folate-clicked, DiR-encapsulating PNP's 11b, showing the presence of both the encapsulated DiR (755 nm) and surface clicked with folate (355 nm);

FIG. 24 shows bar graphs acknowledging the potential biomedical applications of the synthesized PNP's; we evaluated their cytotoxicity, through the MTTi assay; first, we examined the potential in vitro differential cytotoxicity of carboxylated, aminated, and folate-decorated Dil-containing PNP's, using a lung carcinoma (A549) cell line; results indicated that the carboxylated and folate-conjugated PNP's exhibited nominal cellular cytotoxicity (less than 4% compared to the control), whereas the aminated PNP's induced cell death to approximately 10% of the cell population (FIG. 24a); indeed, the folate-decorated Dil and paclitaxel co-encapsulating PNP's 11d induced a significant reduction in cell viability, as more than 50% of the cell population underwent cell death (FIG. 24b); furthermore, as most lung carcinomas exhibit aberrant telomerase activity, leading to cell immortalization, we encapsulated the reverse transcriptase inhibitor AZT in PNP's 11e; we found that folate-decorated Dil and AZT co-encapsulating PNP's induced significant cell death, as previously reported in literature via inhibition of telomerase activity (FIG. 2b); overall, these data suggest that the induction of cell death is mainly mediated by either paclitaxel or AZT, and not by the fluorophores; control cells were treated with 1×PBS; average values of four measurements are depicted ± standard error;

FIG. 25 shows a confocal laser-scanning microscopic image of A549 lung cancer cells incubated with Dil dye-encapsulated carboxylic nanoparticles (8a); dye encapsulated nanoparticles are incubated with the cells for 6 h; result shows no internalization of the nanoparticles into the cytoplasm, which demonstrates that the anionic (carboxylic groups at surface) polymeric nanoparticles are not the appropriate candidate for cell internalizations; instead, only cell membrane stained with the dye (outer red lines); the nucleus stained with DAPI (blue color);

FIG. 26 shows a confocal laser-scanning microscopic image of A549 lung cancer cells incubated with Dil dye-encapsulated aminated polymeric nanoparticles (9a); internalization of the nanoparticles into the cytoplasm was observed, which demonstrates that the cationic (amine groups at surface) polymeric nanoparticles are the appropriate candidate for cell internalizations; the nucleus stained with DAPI (blue color);

FIG. 27 depicts a confocal laser-scanning microscopic image of A549 lung cancer cells incubated with Dil dye-encapsulated folate-immobilized polymeric nanoparticles (11a); the particles were incubated with the cells for 6 h; internalization of the nanoparticles into the cell was observed, demonstrating the presence of folate receptor in the A549 cancer cells and therefore inducing a folate-receptor mediated internalization;

FIG. 28 provides a confocal laser-scanning microscopic image of A549 lung cancer cells incubated with folate modified nanoparticles (11d) encapsulating both a hydrophobic dye (Dil) and a hydrophobic anti-cancer drug (paclitaxel); the nanoparticles were incubated with the cells for 6 h; neither the fluorescence intensity of the dye, nor the cytotoxic effects of the anti-cancer drug are affected when encapsulated in the polymeric nanoparticle; experiments show that paclitaxel-induced mitotic arrest results in apoptotic cell death of lung carcinoma cells (A549);

FIG. 29 is a confocal laser-scanning microscopic image of A549 lung cancer cells incubated with folate modified nanoparticles (11e) encapsulating both a hydrophobic dye (Dil) and a hydrophobic anti-HIV drug (AZT); the nanoparticles were incubated with the cells for 6 h; these experiments show that AZT-induced mitotic arrest results in apoptotic cell death of lung carcinoma cells (A549);

FIG. 30 provides an assessment of the PNP-cell association via flow cytometry, where 1) absence of fluorescence emission is observed in control mock-treated cells (1×PBS), in b) presence of the dyes-loaded non-aminated PNP's (8a) is observed, in c) aminated (9a) and d) folate-decorated (11a) nanoparticles interact more profoundly with the cells, as indicated by higher levels of fluorescence emission; and FIG. 31 shows drug (paclitaxel) and dye (Di!) release profiles of functional PNP's (11d) in PBS (pH=7.4) at 37° C.; release of paclitaxel (A & B) and Dil (C & D) were observed in the presence of an esterase enzyme (A & C) and at pH 4.0 (B & D); these results indicate that the PNP's are degradable in the presence of the esterase enzyme and at low pH; a controlled release of drug and dye was observed.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which preferred embodiments of the invention are shown. Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention pertains. Although methods and materials similar or equivalent to those described herein can be used in the practice or testing of the present invention, suitable methods and materials are described below. Any publications, patent applications, patents, or other references mentioned herein are incorporated by reference in their entirety. In case of conflict, the present specification, including any definitions, will control. In addition, the materials, methods and examples given are illustrative in nature only and not intended to be limiting. Accordingly, this invention may be embodied in many different forms and should not be construed as limited to the illustrated embodiments set forth herein. Rather, these illustrated embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Other features and advantages of the invention will be apparent from the following detailed description, and from the claims.

Herein, we report the synthesis of novel biodegradable hyperbranched polyesters and their use for the synthesis of cell-permeable polymeric nanoparticles that encapsulate hydrophobic dyes and drugs for dual optical imaging and therapeutic applications. To date, no one has made bio-compatible polymeric nanoparticles from diethylmalonate
based hyperbranched polyester. The design and synthesis of diethylmalonate-based AB₃ monomer is novel and tuned in such a way that the resulting polymer will have three-dimensional molecular architecture with hydrophobic interior and hydrophilic segments at the surface (amphiphilic). Selective mono-C-alkylation of diethylmalonate using a mild basic condition and followed by hydrolysis of the monomer was performed to develop a new, water-soluble AB₃ monomer for the synthesis of the hyperbranched polyester. We have employed a melt polymerization technique using para-toluene sulfonic acid [p-TSA] as a catalyst to synthesize the novel aliphatic and biodegradable hyperbranched polyester. We hypothesized that the presence of AB₃ branching point and a hydrophobic butyl chain in the monomer structure could be able to generate a highly branched and hydrophobic polymer. As a proof-of-principle, the resulting polyester was highly branched, amphiphilic, having carboxylic acid groups at the surface and obtaining a three-dimensional architecture with hydrophobic cavity. Therefore, compare to the conventional linear polymers, our branched polyester is amorphous, amphiphilic, soluble, biodegradable, highly surface functional and has cavities for effective encapsulation of guest molecules, which suggest its versatility in biomedical applications. Post-functionalization of this water insoluble polyester has been done using carbodiimide chemistry resulting in cationic and clickable hyperbranched polyester.

A solvent diffusion method has been adopted for the synthesis of polymeric nanoparticles (PNPs) where the hydrophobic areas assemble together to minimize contact with the aqueous environment, while exposing the hydrophilic segments containing carboxylic acid groups at the surface in aqueous solution. This results in the formation of carboxyl functionalized spherical polymeric nanoparticles in water containing inner hydrophobic domains that can encapsulate hydrophobic molecules such as dyes and drugs. Note that, this is the first example of development of hyperbranched polyester based polymeric nanoparticles using solvent diffusion method. Experimental data showed the effective encapsulation of various hydrophobic near infrared (NIR) dyes and a therapeutic drug without significant precipitation or reduction of the fluorescence properties. The fluorescence of the resulting PNP is bright and stable, allowing the imaging of cells without significant photo-bleaching. Click chemistry has been used for the synthesis of folate decorated PNP for the targeted cancer therapy. Finally, we have been able to encapsulate either a hydrophobic antitumor drug (Paclitaxel) or, a nucleoside analog reverse transcriptase inhibitor (AZT) for the treatment of HIV and AIDS, along with near infra red fluorescent dyes (DiI or DiR) into the folate decorated PNP for targeted drug delivery and imaging. We have used human lung carcinoma (A549) and normal cardiomyocytes (hKc2) cell lines throughout all in vitro studies. We have assessed MTT assay to determine the cytotoxicity of our functional PNP. Results showed Taxol® and AZT encapsulated PNP were toxic to the cancerous cell lines, whereas, dye encapsulated polymeric fluorophores were non-toxic. These results were corroborated with confocal microscopic studies and FACS analysis. The PNP degradation and controlled drug and dye release experiments were performed under enzymatic and low pH environments. Most importantly, we are successful in animal imaging using mice model, in vivo, with the NIR dye (DiR and DiI) encapsulated PNP for animal imaging applications.

Therefore, our present protocol is capable of creating a library of multifunctional theranostic (therapeutics and optical diagnostics) polymeric nanoparticles for biomedical applications including (a) encapsulated chemotherapeutic agents (Taxol® and AZT) for HIV and cancer therapy, (b) surface functionality (folic acid ligand) for cancer targeting, (c) "click"-chemistry-based conjugation of targeting ligands, (d) encapsulated NIR dyes for fluorescent imaging capabilities and (e) thermechanical applications including luminescent, conductive, magnetic or radioprotecting of the corresponding polymeric-metallic nanocomposites.

Results and Discussion

Synthesis and Characterization of Biodegradable Hyperbranched Polymers

The amphiphilic hyperbranched polyester (HBPE 5) was rationally designed for the development of thermo-sensitive PNPs (nanoparticles providing both a therapeutic agent and a diagnostic modality), by employing strategies of nanoparticle formconstruction and dye encapsulation in one process. FIGS. 1-2 show our synthetic strategy, leading to the formation of a novel, water-soluble, AB₃ monomer which upon polymerization gives rise to the water insoluble, biodegradable polymer 5, capable of encapsulating dyes/drugs for therapeutic applications. The melt polymerization technique was followed for the polymer synthesis, where we observed that at the initial stages of polymerization, oligomers and low molecular weight polymers were obtained. However, upon applying vacuum, a high molecular weight polymer (Mₘ = 42,000, PD = 1.6) was formed (FIG. 9). The resulting polyester was highly branched, having carboxylic acid groups at the surface and obtaining a three-dimensional architecture with hydrophobic cavity. Hence contrary to conventional linear polymers, our branched polyester is amorphous, amphiphilic, soluble, highly surface functional, biodegradable and has a cavity for effective encapsulation of guest molecules, which suggest its versatility in biomedical applications. Through thermal gravimetric analysis (TGA), we determined that the polymer exhibits moderate thermal stability (10% weight loss at 250°C in air), which is typical for a biodegradable polymer (FIG. 10). The polymer was further characterized using spectroscopic and chromatographic techniques (FIGS. 5-8). Subsequently, the presence of free carboxylic acid groups at the surface prompted the generation of a library of functional polymers using carbodiimide chemistry. We used 1,1'-carboxyldimidazole (CDI), as a water insoluble carbodiimide, and either ethylenediamine or propargylamine for the synthesis of surface-amininated cationic polymer (HBPE-EDA 6) and clickable polymer, respectively (HBPE-PA 9, FIG. 3). Hence, the former surface-aminated polymer may be a good candidate for non-specific cell internalization, whereas, the latter one might be a platform for targeted therapy due to the facile conjugation of specific cellular receptor ligands, such as folic acid, via click chemistry (FIG. 4).

Polymeric Nanoparticle (PNP) Synthesis and Drug/Dye Encapsulation

In order to prepare functional PNP, a modified solvent diffusion method was used, where the nanoparticle formation and guest molecule encapsulation in the hydrophobic cavity took place in one-pot. The amphiphilic polymer and hydrophobic guests were dissolved in anhydrous dimethylformamide (DMF) and added drop-wise to water under continuous stirring, driving both the self-assembly and encapsulation processes and resulting in the synthesis of functional PNP. The resulting PNP were highly stable in separate solution for more than a year, without significant reduction in the fluorescent emission of the encapsulated dyes and can be concentrated without significant precipitation. Therefore, near infra red dye (DiI, DiR and DiI) encapsulated PNP (8a-e and 9a-e) were synthesized from the corresponding carboxylated and aminated polymers (HBPE 5 and HBPE-EDA 6, respectively). Alternatively, the aminated PNP (9a-
c) can be prepared from the carboxylated PNPs (8a-c) using water soluble carbodiimide, EDC, [1-ethyl-3-(3-dimethylamino)propyl]carbodiimide hydrochloride] and ethylenediamine (FIG. 3). Amination of these nanoparticles was confirmed by an overall surface charge (ζ-potential) measurement, where a positive surface potential was obtained in the case of aminated PNPs (FIG. 20). Propargylated PNPs were also synthesized with [Di dye (10a), DiR dye (10b), DiD (10c)] Dil and with anti-cancer drug paclitaxel (10d) and with AIZ (10e) using the above strategy. These PNPs (10a-e) are very important synthon for the synthesis of a library of functional PNPs via click chemistry. To demonstrate the applicability of click chemistry in this system, the alkyn-azide click was engineered to occur at the interface between the propargylated carboxylic acid corona of the PNPs and the aqeous phase in which the azide-functionalized ionic acid is dissolved. Therefore, folate-decorated PNPs (11a-e) were prepared using this 1,3-dipolar cycloaddition reaction, click chemistry, mediating the targeted drug delivery to cancer cells that express the folate receptor (FIG. 4).

Polymeric Nanoparticle Characterization

The approximate hydrodynamic diameter of the PNPs was determined through Dynamic Light Scattering (DLS), ranging from 100±20 nm, which was similar to that of the unmodified nanoparticles (FIG. 12). Well-formed spherical PNPs were observed by scanning electron microscopy (SEM, FIG. 13) and the average diameter of these PNPs was 115±25 nm, demonstrating a direct correlation with the DLS data. Remarkably, the black rectangular box in the SEM image indicates that the shape of the nanoparticles was spherical as expected from the structure of the original polymer HBPE 5. The formation of hydrophobic micromdomains and the encapsulation of NIR dyes inside the PNPs were confirmed by fluorescence measurement of free Dil dye and encapsulated Dil in PNPs (8a, FIG. 18). In this experiment, Dil dye was dissolved in DMF and allowed to evaporate at room temperature and then dispersed in water. A blue shift (by 23 nm) was observed in the fluorescence emission of Dil-encapsulated HBPE nanoparticles (570 nm) as compared to the free non-encapsulated Dil dye (593 nm) in water. This indicated the presence of the dye inside the electronic environment of the polymer’s cavity, confirming the presence of hydrophobic micromdomains in the PNPs. Similar results were obtained from UV/Visible spectroscopy studies, where a blue shift was observed for the encapsulated Dil (FIG. 17), further confirming the entrapment of the dye inside the cavity. Interesting results were obtained from Fourier Transform Infra Red (FTIR) spectroscopy (FIG. 14), and these corroborated the formation of PNPs encapsulating the Dil dye. The presence of the aliphatic alkenes’ characteristic band at 1675 cm⁻¹ indicated the encapsulation of Dil via conjugated double bonds inside the nanoparticle cavity. Subsequently, we prepared three different dye (Dil, DiR and DiD) containing PNPs (8a, 8b and 8c, respectively) from the polymer 5 as shown in FIG. 3 and FIG. 15. Characteristic fluorescence emission spectra of the dye-encapsulated PNPs in PBS buffer are shown in FIG. 16. The fluorescence intensity maxima of these nanoparticles were at 570, 675 and 780 nm, indicating the presence of the NIR dye Dil, DiR and DiD, respectively, within the hydrophobic domain of the PNPs. These functional fluorophore-containing PNPs were highly stable in aqueous solution (FIG. 11). Next, NIR dye and paclitaxel co-encapsulated folate-clicked PNPs (11a-e) were characterized by UV/Vis spectroscopy (FIGS. 22-23).

In Vitro Cytotoxicity

Having in mind the potential biomedical applications of the synthesized PNPs, we evaluated their cytotoxicity, through the MTT assay. First, we examined the potential in vitro differential cytotoxicity of carboxylated, aminated, and folate-decorated Dil-containing PNPs, using a lung carcinoma (A549) cell line. Results indicated that the carboxylated and folate-conjugated PNPs exhibited nominal cellular cytotoxicity (less than 4% compared to the control), whereas the aminated PNPs induced cell death to approximately 10% of the cell population (FIG. 24a). Considering these findings, the potential use of these PNPs in imaging and drug delivery applications, either in vitro or in vivo, is anticipated. Hence, we examined if PNPs can be used for targeted drug delivery, by examining the cytotoxic efficacy of PNPs co-encapsulating Dil and the hydrophobic chemotherapeutic agent paclitaxel. Indeed, the folate-decorated Dil and paclitaxel co-encapsulating PNPs induced a significant reduction in cell viability, as more than 50% of the cell population underwent cell death (FIG. 24b). Furthermore, as most lung carcinomas exhibit aberrant telomerase activity, leading to cell immortality, we encapsulated the reverse transcriptase inhibitor AIZ in PNPs. We found that folate-decorated Dil and AIZ co-encapsulating PNPs induced significant cell death, as previously reported in literature via inhibition of telomerase activity (FIG. 24b). Overall, these data suggest that the induction of cell death is mainly mediated by either paclitaxel or AIZ, and not by the fluorophore. Specifically, the enhanced in vitro cytotoxicity of the folate-decorated Dil and paclitaxel co-encapsulating PNPs in A549 cells hints the successful targeting of carcinomas that overexpress the folate receptor on their plasma membrane. Furthermore, these results suggest that the co-encapsulation of a fluorophore and a therapeutic agent in our PNPs can be utilized for cellular targeting, such as in cancer or anti-HIV CD4⁺-specific therapeutic regimes, visualization of the drug’s homing and monitoring of tumor regression in clinical studies.

In Vitro Cellular Uptake of PNPs

To demonstrate the capability of our functional PNPs to be internalized by cells and eventually exert specific intracellular activity, various preparations of PNPs were incubated with lung carcinoma cells (A549) for 6 h. Confocal images showed that there was no internalization of the non-aminated PNPs, but only the cell membranes were found to be stained with the red Dil dye (outer red lines. FIG. 25). This demonstrates the proof-of-concept that the anionic (carboxylic groups at surface) PNPs are not appropriate candidates for cell internalization. To further corroborate this concept, we used A549 cells treated with aminated PNPs encapsulating Dil (9a). Contrary to the carboxylated PNPs, there was strong internalization of the cationic surface PNPs (FIG. S26). Notably, these PNPs did not affect cellular integrity and nuclear stability, failing to trigger apoptosis, even after 12 h of incubation. Hence, these results strongly support the notion that cationic (surface amine groups) PNPs are better vehicles for cell internalization. Subsequently, we performed in vitro cellular uptake studies, utilizing a Xenogen IVIS system. Similar results to the confocal studies were obtained. Specifically, aminated PNPs were found intracellularly, as fluorescent emission was recorded from the cell pellet. On the other hand, there was absence of fluorescence emission from the pellet of cells treated with non-aminated PNPs, suggesting lack of PNP internalization (FIG. 21, IVIS images). Similar results were obtained from other synthesized PNPs (8b-c and 9b-c) through the IVIS setup, in line with the confocal microscopy observations.

Then, we investigated the targeting potential of our PNPs and cellular uptake of the folate-clicked PNPs (11a), comparing these PNPs with the corresponding carboxylated ones (8a). Confocal microscopy revealed the effective uptake of the folate-functionalized PNPs by A549 cells (FIG. 27), in contrast to the carboxylated ones (FIG. 25). The enhanced...
cellular uptake of the folate-decorated PNPs may be attributed to folate-receptor mediated internalization. Accordingly, through confocal studies, we observed that the efficiency of folate-decorated PNPs uptake significantly improved upon increasing the incubation time, while no cytotoxic effects were observed via the MTT assay. Hence, the enhanced time-dependent uptake and retention of these PNPs is likely due to folate-receptor recycling, which is typical of constitutive nutrient receptor endocytic trafficking. Subsequently, to demonstrate the folate-clicked PNPs’ (11a) proof-of-concept theranostic capability towards cancer cells, we used Dil and paclitaxel co-encapsulating PNPs (10d). Then, the surface propargyl groups were clicked with azide-functionalized folic acid, in order to achieve targeted drug delivery with optical imaging capability for spatiotemporal monitoring. Lung carcinoma cells overexpressing the folate receptor were treated with these PNPs (11d). After a 3 h-long incubation, confocal microscopic examination revealed cellular internalization and induction of paclitaxel-mediated mitotic arrest (FIG. 28), in accordance to the literature. This illustrates that paclitaxel’s therapeutic efficacy was preserved, despite its PNP encapsulation. Furthermore, treatment with paclitaxel-containing PNPs triggered dramatic cellular morphological changes after 12 h of incubation, leading to cell death. Furthermore, as most lung carcinomas exhibit aberrant telomerase activity, leading to cell immortality, we encapsulated the reverse transcriptase inhibitor AZT in PNPs. We found that folate-decorated Dil and AZT co-encapsulating PNPs induced significant cell death, as previously reported in literature via inhibition of telomerase activity (FIG. 29). These observations strongly support the importance of encapsulating this potent anti-tumor agent within the polymeric cavity and targeting its delivery, in order to prevent damaging non-transformed cells and healthy tissue. Taken together, these findings support the principle that folate-decorated PNPs can target and deliver chemotherapeutic agents to folate-receptor-overexpressing carcinomas, while visualizing the drug’s homing. Thus by modifying the targeting moiety at the theranostic PNPs’ surface, other carcinomas or ailing cells may be targeted tailoring the therapeutic regime, while obtaining important spatiotemporal information for clinical decision making.

Flow Cytometric Assessment of PNPs Uptake

To corroborate the PNPs cellular uptake ability, a detailed flow cytometry analysis was performed with functional PNPs (8a, 9a and 11a) and A549 cells. Specifically, through flow cytometry, we determined the Dil-derived cell-associated fluorescence emission in a quantifiable fashion. As shown in FIG. 30a, limited fluorescence emission was observed from cells treated with the carboxylated PNPs (8a). This indicated nominal cell association of these carboxylated PNPs (8a), when compared to the control non-treated cells (FIG. 30b) where there was lack of fluorescence emission. This is in accordance with the data from the confocal and IVIS studies, confirming the observation that the anionic surface of the nanoparticles interacts with the cell’s plasma membrane. Contrary to this and similar to the confocal microscopic observations, cells incubated with amino PNPs (9a) showed three-fold higher fluorescence emission and binding activity when compared to the control mock-treated cells, as shown in FIG. 30c. Similar to other cationic small molecules and peptides, the interaction of the surface-localized positive charge of the amino PNPs with the negatively charged cell membrane facilitated the association of the PNPs with the cell membrane at the extracellular milieu and the subsequent cellular uptake and retention, as observed through previously discussed in vitro studies. Interestingly, upon clicking the carboxylated PNPs with folic acid, a higher cell-associated fluorescence emission was observed (FIG. 30d). Notably, the profound cellular uptake of the folate-decorated PNPs (11a), being comparable to the aminated ones, is attributed to the specific folate-receptor-mediated internalization and intracellular retaining. Overall this indicates that the specific targeting of PNPs through targeting moieties, such as folate, is feasible and equally efficient as the non-specific electrostatic-mediated uptake of cationic entities, rendering targeted PNPs useful for potential in vivo applications.

Drug/Dye Release Study of Functional PNPs

The therapeutic application of our polymeric nanoparticles is influenced by the rate of release of the encapsulated drug from the polymeric cavity. To evaluate 11d’s drug release profile, enzymatic (esterase) and low-pH degradation experiments were performed. Results indicate a fast release of the drug (paclitaxel) from the nanoparticle 11d upon esterase incubation, reaching a plateau within 4 hours (FIG. 31A). A similar release profile of the drug was observed at pH 4.0, reaching a plateau within 4.5 hours (FIG. 31B). No significant release of the drug was observed from nanoparticles incubated in PBS, pH 7.4. These results demonstrate the stability of the polymeric nanoparticles during storage (PBS), and their cargo release only after cellular uptake via either esterase-mediated degradation or in acidified lysosomes. Only after folate-receptor-mediated uptake did the PNPs 11d become cytotoxic upon intracellular release of the therapeutic agent. Interestingly, even slower release of the dye was observed, both upon esterase incubation and at pH 4.0 (FIGS. 31C and 31D). However, no release of the dye was observed at normal physiological pH (7.4). The observed differential release of the drug vs. the dye from PNPs may be attributed to the drug’s (paclitaxel) size and hydrophobic nature.

EXPERIMENTAL SECTION

Materials

Anhydrous DME, DMSO, 3-(4,5-Dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT), 1,1’-Carbonyldimidazole (CDI), N-hydroxysuccinimide (NHS), AZT (azidotubulin), dyethylmaleate and other chemicals were purchased from Sigma-Aldrich and used without further purification. Near Infra Red dyes (Dil—D282, DiD—D7757, and Dil—D12731) and 4’,6-diamidino-2-phenylindole (DAPI—D1306) were purchased from Invitrogen, whereas the EDC (1-Ethyl-3-[3-dimethylaminopropyl]carbodiimide hydrochloride) was obtained from Pierce Biotechnology. The folate-receptor-overexpressing human lung carcinoma cell line A549 (CCL-185) was obtained from ATCC. Dialysis membranes were obtained from Spectrum Laboratories. Acetonitrile, tetrahydrofuran and other solvents were purchased from Fisher Scientific and used as received, unless otherwise stated.

Instrumentation

Infrared spectra were recorded on a PerkinElmer Spectrum 100 FT-IR spectrometer. UV/Vis is spectra were recorded using CARY 300 Bio UV/Vis is spectrophotometer. Fluorescence spectra were recorded on a NanoLog Horiba jobin Yvon fluorescence spectrophotometer. NMR spectra were recorded on a MERCURY 300 MHz spectrometer using the TMS/solvent signal as an internal reference. Gel permeation chromatography (GPC) results were obtained using JASCO MD 2010 Plus instrument with PD 2020 light scattering Precision Detector. Thermo gravimetric analyses (TGA) were performed on a SETARAM, Mettler TC11 instrument with sample sizes 10-20 mg. All the experiments were done using a heating rate of 10°C/min in air. Atomic Force Microscopic
(AFM) images were obtained from Dimension 3100 Atomic Force Microscope from Veeco Digital Instruments. Confocal images were taken on a Zeiss Axioskop 2 mot plus confocal microscope. Flow Cytometry experiments were performed using a BD FACSCalibur multiparameter flow cytometer system from BD Biosciences. MTT study has been done using BIO-TEK Synergy H1T multi-detection microplate reader. Dynamic light scattering (DLS) studies were done using a PDDLS/CoolHatch 40T instrument using Precision Deconvolve 32 software and SEM images were taken using Jeol 6400F scanning electron microscope. IVIS experiments were done using IVIS 50 imaging system from Xenogen imaging technologies. Analytical Thin Layer Chromatography (TLC) section from BD Biosciences. MTT study has been done using a BD BIO-TEK HT multi-detection microplate reader.

Synthesis of 4-bromobutyl acetate (2): Tetrahydrofuran (12.2 mL, 148.4 mmol) and potassium bromide (21.1 g, 176.5 mmol) were added in a 250 mL round bottom flask containing 150 mL acetonitrile. The reaction mixture was cooled to 0°C followed by drop-wise addition of acetyl chloride (11 mL, 155.1 mmol). Subsequently, the mixture was brought to room temperature, where it was continuously stirred for 36 h. The reaction mixture was poured in water and extracted with ethyl acetate. The organic layer was washed with water, dried over Na₂SO₄, and concentrated to obtain the pure product as a colorless liquid.

Yield: 24.3 g (85%). bp: >250°C. ¹H NMR (300 MHz, CDCl₃, δ ppm, J Hz): 1.79 (m, 2H), 1.92 (m, 2H), 2.03 (s, 3H), 3.46 (t, 2H, J = 6.6), 4.08 (t, 2H, J = 7.7), 2.05 (s, 3H), 3.34 (t, 1H, J = 6.6), 4.22 (q, 2H, J = 7.2). ¹³C NMR (75 MHz, CDCl₃, δ ppm): 14.06, 20.79, 23.74, 28.25, 28.25, 51.84, 61.27, 63.89, 169.31, 171.11. IR (CHCl₃): 2982, 1725. TGA: 90% weight loss at 250°C.

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Synthesis of polyacrylamide nanomaterials Dye-encapsulating PNPs (8-10): Solvent diffusion method. Different near IR dye (Dil, DiR or DiD) solutions were prepared by mixing 5 µL of the dye aliquot (0.014 g, 0.25 mmol) was used as the starting material.}

General procedures for the synthesis of functional polymeric nanoparticles Dye-encapsulating PNPs (8-10): Solvent diffusion method. Different near IR dye (Dil, DiR or DiD) solutions were prepared by mixing 5 µL of the dye aliquot (0.014 g, 0.25 mmol) was used as the starting material. The resulting polymer-dye mixture in DMF was added drop-wise to deionized water (5 mL) with constant stirring at room temperature forming dye encapsulated polymeric nanoparticles. The nanoparticle solution was dialyzed (using 6-8 K
molecular weight cut off dialysis bag) three times against deionized water and phosphate buffered saline (PBS) solution.

Paclitaxel (Taxol®) and Dil co-encapsulating polymeric nanoparticles 10d: Taxol® (5 µL, 1 mg/mL) and Dil dye (5 µL, 10 µg/µL) were taken in an Eppendorf Tube® containing propargylated polymer (7, 0.025 g) in 500 µL DMF and followed the solvent diffusion method as described above.

AZT and Dil co-encapsulating polymeric nanoparticles 10e: AZT (azidothymidine) was dissolved in DMF to a final concentration of 1 mg/mL. The polymers (5 or 7, 0.025 g) were dissolved in 250 µL of DMF using a vortexer. Subsequently, AZT (5 µL, 1 mg/mL) and Dil (5 µL, 10 µg/mL) were added to the polymer solutions, followed by vortexing. The resulting polymer-AZT-Dil mixture in DMF was added drop-wise to deionized water (5 mL) with continuous stirring at room temperature. The reaction mixture was then centrifuged and dialyzed (using 6-8 K molecular weight cut off dialysis bag, against deionized water and phosphate buffered saline) three times against deionized water and phosphate buffered saline (PBS) solution.

Synthesis of Aminopropylazide 12: Chloropropyl amine (7.0 g, 75.26 mmol) and sodium azide (14.23 g, 225.81 mmol) were taken in a 100 mL round bottom flask containing 40 mL of distilled water and heated at 80°C for 20 h. The reaction mixture was concentrated via a rotavapor using high vacuum, and 2 g of KOH was added to it and then extracted by using diethyl ether. Subsequently, the reaction mixture was dried over anhydrous sodium sulphate and concentrated. Then, the mixture was purified through flash column chromatography using 4% ethyl acetate in petroleum ether as an eluant, in order to obtain the pure aminopropylazide.

Yield: 5.1 g (68%). 1H NMR (300 MHz, CDCl3, δ ppm): 1.26 (bs, 2H), 1.81 (m, 2H), 2.80 (t, 2H), 3.38 (t, 2H). IR (CHCl3) 3307, 2941, 2089, 1663, 1433, 1370, 1259, 1242, 1075, 1026, 818, 760 cm⁻¹.

Synthesis of azide-functionalized folic acid 13: 1,1'-carbonyldimidazole (0.022 g, 0.014 mmol) was taken in an Eppendorf Tube® containing folic acid (0.05 g, 0.011 mmol) in anhydrous DMF (2 mL) and incubated for 2 h at 35°C. To this we added aminopropylazide (0.014 g, 0.014 mmol) in anhydrous DMF (100 µL) and incubated it for 24 h at room temperature. The reaction mixture was then centrifuged and washed to remove excess starting materials. Finally, we dissolved the azide-functionalized folic acid in 1 mL of DMF. The presence of a band at 2091 cm⁻¹ in the IR spectrum and a UV absorbance shoulder at 354 nm confirmed the formation of azide-functionalized folic acid.

Yield: 100%. 1H NMR (400 MHz, DMSO-d6, δ ppm): 1.61 (m, 2H), 1.65 (m, 2H), 1.90 (m, 2H), 2.19 (t, 2H), 2.78 (t, 2H), 4.18 (q, 1H), 4.21 (d, 2H), 6.62 (d, 2H), 7.59 (d, 2H), 8.58 (s, 1H). FT-IR (Nujol): 3024, 2097, 1603, 1492, 1375, 1291, 1248, 1180, 1122, 1062, 950, 844, 755, 696 cm⁻¹.

Synthesis of folate-functionalized PNP's 11a-e: click chemistry.

The propargylated polymeric nanoparticles 10a-e (0.025 g, 6x10⁻⁹ mmol) in bicarbonate buffer (pH=8.5) were taken to an eppendorf containing catalytic amount of Cul (0.11 µg, 6x10⁻⁹ mmol) in 250 µL of bicarbonate buffer, vortexed for 30 seconds. To this was added azide-functionalized folic acid (13, 0.005 g, 6x10⁻⁹ mmol) in DMSO and the reaction was incubated at room temperature for 12 h. The final reaction mixture was purified by dialysis using 6-8 K molecular weight cut off dialysis bag, against deionized water and phosphate buffered saline (PBS) solution. The purified functional PNP's (11a-e) were stored in refrigerator for further characterization.

Cell Culture and Cell Viability Studies

Lung carcinoma cells (A549) were grown in Kaighn's modification of Ham's F12 medium (F12K—Cellgro), supplemented with 5% fetal bovine serum (Hitt-Inactivated FBS—Cellgro), L-glutamine, streptomycin, amphotericin B, and sodium bicarbonate. The cells were maintained at 37°C, 5% CO₂ in a humidified incubator. We used the MTT assay in order to assess potential cytotoxic effects upon in vitro administration of the drug/dye-encapsulating functional HBPE nanoparticles. Specifically, lung carcinoma cells (3000 cells/well) were seeded in 96-well plates, and were incubated with the nanoparticles for 3 hours at 37°C. Then, each well was washed three times with 1xPBS and treated with 20 µL MTT (5 mg/mL) and incubated for 2 hours. The resulting formazan crystals were dissolved in acidified isopropanol (0.1 N HCl) and the absorbance was recorded at 570 nm and 590 nm (background), using a Synergy HT multi-detection microplate reader (Biotek). These experiments were performed in triplicates.

Cellular Internalization

Initially, in vitro uptake and internalization of the PNP's was assessed through fluorescence laser-scanning confocal microscopy, using a Zeiss LSM 510 confocal microscope. Specifically A549 cells (10⁴) were incubated for the stated time period with the corresponding PNP preparation in a humidified incubator (37°C, 5% CO₂). Subsequently, the cells were thoroughly washed three times with 1xPBS and fixed with a 10% formalin. Nuclear staining with DAPI was performed as recommended by the supplier. Then, multiple confocal images were obtained, achieving a representative view of the cell-PNP interaction. Confirmation of the confocal studies was facilitated through FACS and IVIS analyses. For FACS, 10⁵ lung carcinoma cells were incubated for 6 hours with the corresponding PNP preparation. Then the cells were detached from the culture dish with 0.05% trypsin, and the resulting pellet was resuspended in 1 mL culture media. The cell suspension underwent flow cytometric analysis, using a BD FACS Calibur system, in order to quantify the cellular uptake of the synthesized PNP's. For the IVIS analysis, 10⁵ lung carcinoma cells were incubated for 6 hours with the corresponding PNP preparation, and then the supernatant was collected in eppendorf tubes. Subsequently, we thoroughly washed the cells with 1xPBS and detached them, as stated above. The resulting pellets were resuspended in 1 mL culture media. All Eppendorf Tubes® were examined simultaneously on a Xenogen IVIS system, using the following filters sets: DsRed (500-550 nm/575-650 nm for Dil), Cy5.5 (615-665 nm/695-770 nm for DiD) and ICG (710-760 nm/810-875 nm for DiR). All experiments were performed in triplicates.

In Vitro Drug/Dye Release

The in vitro drug/dye release studies were carried out using a dynamic dialysis technique at 37°C. Briefly, 100 µL of PNP's (11d) are incubated with a porcine liver esterase (20U/L) inside a dialysis bag (MWCO 6000-8000), which is then placed in a PBS solution (pH 7.4). The amount of guest (dye or drug) molecules released from the nanoparticle into the PBS solution was determined at regular time intervals by taking 1 mL aliquots from the PBS solution and measuring the fluorescence intensity at 575 nm for Dil and 372 nm for Taxol®. The concentration of the either dye or drug was calculated using a standard calibration curve. The cumulative
fraction of release versus time was calculated using the following equation:

\[
\text{Cumulative release (\%)} = \frac{[\text{guest}]_{t}}{[\text{guest}]_{\infty}} \times 100
\]

Where \([\text{guest}]_{t}\) is the amount of guest released at time \(t\), \([\text{guest}]_{\infty}\) is the total guest present in the guest encapsulated PNP.

Accordingly, in the drawings and specification there have been disclosed typical preferred embodiments of the invention and although specific terms may have been employed, the terms are used in a descriptive sense only and not for purposes of limitation. The invention has been described in considerable detail with specific reference to these illustrated embodiments. It will be apparent, however, that various modifications and changes can be made within the spirit and scope of the invention as described in the foregoing specification and as defined in the appended claims.

REFERENCES CITED


That which is claimed:
1. A method of making a hyperbranched amphiphilic polyester compound, the method comprising:
- heating the dried mixture under the inert gas at a temperature sufficient for polymerization;
- precipitating the reaction mixture in methanol, separating the precipitate and drying in a vacuum to obtain a purified hyperbranched polyester amine.

2. The method of claim 1, further comprising:
- washing with methanol and drying in a vacuum.

3. The method of claim 1, wherein drying under vacuum is conducted at approximately 0.2 mmHg.
4. The method of claim 1, wherein the inert gas is argon gas.
5. The method of claim 1, wherein heating is at a temperature of approximately 150°C.
6. The method of claim 1, wherein heating continues for approximately two hours.
7. The method of claim 1, wherein evaporation is conducted at approximately 0.2 mmHg for about one hour while maintaining the polymerization temperature.
8. The method of claim 1, further comprising purifying the polymer by separating the precipitate, washing with methanol and drying in a vacuum.
9. The method of claim 1, further comprising:
- dissolving the precipitated polymer in anhydrous dimethylformamide (DMF);
- adding 1,1-carboxyldimidazole drop-wise to form a reaction mixture;
- precipitating the reaction mixture at room temperature for approximately one to two hours;
- dissolving ethylenediamine in anhydrous DMF drop-wise and continue incubation of the reaction mixture at room temperature for approximately 24 hours; and
- precipitating the reaction mixture in methanol, separating the precipitate and drying in a vacuum to obtain a purified hyperbranched polyester amine.
10. The method of claim 1, further comprising:
- dissolving the precipitated polymer in anhydrous dimethylformamide (DMF);
- adding 1,1-carboxyldimidazole drop-wise to form a reaction mixture;
- incubating the reaction mixture at room temperature for approximately one to two hours;
- dissolving propargyl chloride in anhydrous DMF drop-wise and continue incubation of the reaction mixture at room temperature for approximately 24 hours; and
- precipitating the reaction mixture in methanol, separating the precipitate and drying in a vacuum to obtain a purified hyperbranched propargylated polyester amine.
11. A method of making a hyperbranched amphiphilic polyester compound, the method comprising:
- drying a mixture of 2-(4-hydroxybutyl)-malonic acid and a p-toluene sulphonic acid catalyst under vacuum;
- heating the vacuum-dried mixture in the presence of an inert gas to a polymerization temperature and maintaining the polymerization temperature for a predetermined period of time;
- evacuating the inert gas while continuing to heat the vacuum-dried mixture; and
- producing the hyperbranched amphiphilic polyester compound during heating, the polyester compound having a butyl group core from which a plurality of polyester branches extend, the polyester branches terminating in at least one carboxylic acid group;
- purifying the hyperbranched amphiphilic polyester compound by dissolving the hyperbranched amphiphilic polyester in a first solvent; and
- precipitating the hyperbranched amphiphilic polyester compound in a second solvent.

dissolving the formed polymer in dimethylformamide; and
precipitating the dissolved polymer by adding methanol.
12. A method of making a hyperbranched amphiphilic polyester compound, the method comprising:
drying a mixture of 2-(4-hydroxybutyl)-malonic acid and a p-toluene sulphonic acid catalyst under vacuum;
introducing an inert gas to the dried mixture;
heating the dried mixture under the inert gas at a temperature sufficient for polymerization;
evacuating the inert gas while continuing to heat the dried mixture;
generating the hyperbranched amphiphilic polyester compound from the dried mixture, the hyperbranched amphiphilic polyester compound having a hydrophilic periphery surrounding a hydrophobic interior, the hydrophobic interior having a plurality of polyester branches that extend from a common butyl core, the periphery having a plurality of carboxylic acid groups that are attached to the terminal ends of the polyester branches; and
purifying the hyperbranched amphiphilic polyester compound by dissolving the hyperbranched amphiphilic polyester compound in a first solvent; and precipitating the hyperbranched amphiphilic polyester compound in a second solvent.

* * * * *
It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Specifications:

Column 1, Lines 13-16: Cancel the text “Development of the present invention was supported, at least in part, by a grant from the U.S. Government. Accordingly, the Government may have certain rights in the invention, as specified by law.” and replace it with the following:

--The invention was made with government support under grant 5K01CA101781 awarded by the National Institutes of Health. The government has certain rights in the invention.--

Signed and Sealed this Twenty-eighth Day of May, 2013

Teresa Stanek Rea
Acting Director of the United States Patent and Trademark Office
It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

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-- This invention was made with government support under CA101781 awarded by the National Institutes of Health. The government has certain rights in the invention. --

This certificate supersedes the Certificate of Correction issued May 28, 2013.

Signed and Sealed this
Eleventh Day of February, 2014

Michelle K. Lee
Deputy Director of the United States Patent and Trademark Office