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Recent Advances in Non-viral Vectors for Gene Delivery

Xia Guo^{†,‡} and Leaf Huang^{*,†}

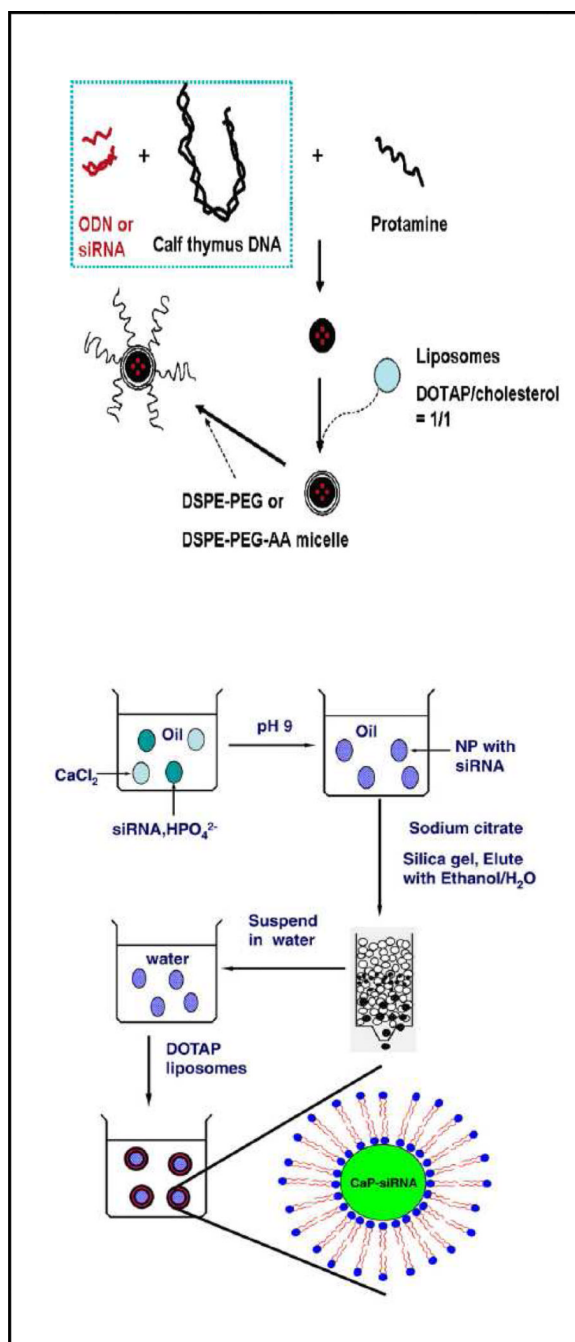
[†]Division of Molecular Pharmaceutics, Eshelman School of Pharmacy, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599, United States

[‡]School of Chemistry and Chemical Engineering, Yangzhou University, Yangzhou, Jiangsu, 225002, P.R.China

CONSPECTUS

Non-viral vectors, typically based on cationic lipids or polymers, are preferred due to safety concerns with viral vectors. So far, non-viral vectors can proficiently transfect cells in culture, but obtaining efficient nanomedicines is far from evident. To overcome the hurdles associated with non-viral vectors is significant for improving delivery efficiency and therapeutic effect of nucleic acid. The drawbacks include the strong interaction of cationic delivery vehicles with blood components, uptake by the reticuloendothelial system (RES), toxicity, targeting ability of the carriers to the cells of interest, and so on. PEGylation is the predominant method used to reduce the binding of plasma proteins with non-viral vectors and minimize the clearance by RES after intravenous administration. The nanoparticles that are not rapidly cleared from the circulation accumulate in the tumors due to the enhanced permeability and retention effect, and the targeting ligands attached to the distal end of the PEGylated components allow binding to the receptors on the target cell surface. Neutral or anionic liposomes have been also developed for systemic delivery of nucleic acids in experimental animal model. Designing and synthesizing novel cationic lipids and polymers, and binding nucleic acid with peptides, targeting ligands, polymers, or environmentally sensitive moieties also attract many attentions for resolving the problems encountered by non-viral vectors. The application of inorganic nanoparticles in nucleic acid delivery is an emerging field, too.

*To whom correspondence should be addressed. leafh@email.unc.edu. Phone: (919) 843-0736. Fax: (919) 966-0197.



Recently, different classes of non-viral vectors appear to be converging and the features of different classes of non-viral vectors could be combined in one strategy. More hurdles associated with efficient nucleic acid delivery therefore might be expected to be overcome.

In this account, we will focus on these novel non-viral vectors, which are classified into multifunctional hybrid nucleic acid vectors, novel membrane/core nanoparticles for nucleic acid delivery and ultrasound-responsive nucleic acid vectors. The systemic delivery studies are highlighted. Finally, we bring forward the prospect for nucleic acid delivery. We think a better understanding of the fate of the nanoparticles inside the cell and of the interactions between the parts of hybrid particles will lead to a delivery system suitable for clinical use. We also underscore

the value of sustained release of nucleic acid and presume making vectors targeted to cells with sustained release *in vivo* should be an interesting research challenge.

Keywords

non-viral vectors; gene delivery; liposome

Introduction

Gene therapy has been regarded as a promising and ultimate cure for many acquired and inherited life-threatening diseases, such as AIDS, cancer, genetic disorders, etc. The efficacy of a nucleic acid drug requires that the molecule be delivered to the interior of the target cell.¹ Therefore, to achieve successful gene therapy, development of a proper delivery vector is a significant factor.

The vectors for gene delivery are usually divided into two categories: viral and non-viral (or synthetic) vectors. Viruses offer greater efficiency of gene delivery, however, non-viral vectors are preferred due to safety concerns with the viral vectors.^{2,3} Synthetic vectors are typically based on cationic lipids or polymers which can complex with negatively charged nucleic acids to form particles with a diameter in the order of 100 nm. The complex protects nucleic acid from degradation by nuclease. Moreover, cellular and local delivery strategies have to deal with the need for internalization, release, and distribution in the proper subcellular compartment. In the case of DNA therapy, translocation of the DNA into the nucleus is necessary. In the case of RNA interference (RNAi), siRNA must be delivered to the RNA-induced silencing complex (RISC) in the cytoplasm. Systemic delivery strategies encounter additional hurdles, for example, strong interaction of cationic delivery vehicles with blood components, uptake by the reticuloendothelial system (RES), kidney filtration, toxicity and targeting ability of the carriers to the cells of interest.^{4,5}

Extensive efforts have been focused on overcoming these barriers and some strategies have been reviewed lately.⁴⁻¹⁴ Modifying the surfaces of the cationic non-virals can minimize their interaction with blood components, reduce RES uptake, decrease their toxicity and increase their binding affinity with the target cells. Binding of plasma proteins (also termed opsonization) is the primary mechanism for RES to recognize the circulating nanoparticles. Macrophages, such as the Kupffer cells in the liver, recognize the opsonized nanoparticles *via* the scavenger receptor. Liver, spleen and bone marrow are the major RES organs for nanoparticle clearance. PEGylation (i.e. modifying the surface with polyethyleneglycol) is the predominant method used to reduce the opsonization and aggregation of non-viral vectors and minimize the clearance by RES, leading to a prolonged circulation lifetime after intravenous (i.v.) administration.^{4,5} PEGylated nanoparticles are therefore often referred as “stealth” nanoparticles. The nanoparticles that are not rapidly cleared from the circulation will have a chance to encounter the leaky tumor vasculature and accumulate in the tumors, which is known as the enhanced permeability and retention (EPR) effect.^{4,5} However, PEG on the surface can decrease the uptake by target cells and reduce the biological activity. Therefore, to attach targeting ligand to the distal end of the PEGylated component is necessary; the ligand is projected beyond the PEG “shield” to allow binding to receptors on the target cell surface.⁴ When cationic liposome is used as gene carrier, the application of neutral helper lipid is helpful for the release of nucleic acid, besides promoting hexagonal phase formation to enable endosomal escape. Some researchers have developed neutral or anionic liposomes for systemic delivery of nucleic acids and obtained therapeutic effect in experimental animal model.^{6,7} Designing and synthesizing novel cationic lipids and polymers, and covalently or noncovalently binding gene with peptides, targeting ligands,

polymers, or environmentally sensitive moieties^{8–11} also attract many attentions for resolving the problems encountered by non-viral vectors. The application of inorganic nanoparticles (for example, metallic nanoparticles, iron oxide, calcium phosphate, magnesium phosphate, manganese phosphate, double hydroxides, carbon nanotubes, and quantum dots) in gene delivery is an emerging field, too, because they can be prepared and surface-functionalized in many different ways.^{12–14}

All these extensive efforts still yield very limited information for an effective gene therapy in clinic and obtaining efficient nanomedicines from non-viral vectors is far from evident.³ Recently, different classes of non-viral vectors appear to be converging; some novel non-viral vectors were formulated, combining the features of different classes of non-viral vectors, and hence, might be of multifunction and multipurpose. Such a strategy may not only avoid the problems associated with the stability, toxicity and protein binding, but also facilitate the targeted delivery and release of the nucleic acid from the delivery vehicle within the cell. In this account, we will focus on these novel non-viral vectors and the studies where therapeutic effect has been observed *in vivo* will be highlighted.

Multifunctional Hybrid Gene Vectors

Inorganic particles can easily be prepared and surface-functionalized. They exhibit good storage stability and are not subject to microbial attack. Some inorganic nanoparticles have been modified in different ways to develop multifunctional gene delivery systems. Two recent reviews^{13,14} discussed the strategy based on magnetic inorganic nanoparticles (such as Fe₃O₄, MnO₂, and so on) for cancer targeted delivery of nucleic acid and simultaneous diagnosis *via* magnetic resonance imaging (MRI). Here we will focus on the multifunctional gene delivery systems based on silica or gold nanoparticles.

An efficient gene delivery carrier and imaging agent for HeLa and NIH3T3 cells has been developed based on silica nanotubes (SNT, Figure 1).¹⁵ The tube structured SNTs are endowed with two physically distinct domains: the inner void and the outer surface. Different functionalization of the inner and outer surfaces of SNT could provide a facile and effective method to integrate multifunctionality. By covalently conjugating the outer surface of the SNT with cationic, low molecular weight, branched polyethylenimine (BPEI, MW 1.8K), it could easily load pDNA and transport the cargo into the cells. The inner space of the SNT was filled with a magnetic-fluorescent nanocomposite (iron oxide nanoparticles and green fluorescent quantum dots (CdSe/ZnS)). Since the walls of SNTs are transparent to long wavelength UV and visible light, the two caged materials in the inner void could be used simultaneously for imaging the cell with internalized SNT by MRI, and for monitoring intracellular movement of SNT by fluorescence. The success of this dual-modality nanoconstruct *in vitro* should be expected to drive further research *in vivo*.

Combination of two or more chemotherapeutic agents with pharmacodynamically synergistic or additive effects is effectively used in a number of cancer therapy protocols.¹⁶ In most cases, a successful drug/gene combination requires delivery of both agents at the same population of tumor cells in a coordinated manner. Because pharmacokinetics and disposition profiles of small-molecule drugs and nucleic acid drugs differ greatly, systems capable of targeted delivery of drug/gene combinations are urgently needed. Bhattarai et al¹⁷ modified mesoporous silica nanoparticles (MSN) with poly(ethylene glycol) (PEG) and poly(2-(dimethylamino)-ethylmethacrylate) or poly(2-(diethylamino)ethylmethacrylate). The particles were then loaded with a lysosomotropic agent chloroquine (CQ, which is often used to enhance transfection of non-viral gene delivery vectors *in vitro*) and complexed with plasmid DNA or siRNA. By using this polycation-modified MSN, CQ was delivered simultaneously with DNA or siRNA *in vitro*, and a significantly increased transfection and

silencing activity were observed in B16F10 cells when compared with the case using MSN not loaded with CQ. Considering the fact that when CQ was used alone *in vivo*, to achieve the necessary concentrations for enhancing transfection required toxic doses, this study hypothesized that co-delivery of CQ with plasmid DNA or siRNA in a single particle might overcome the need for systemic exposure and eventually allow *in vivo* use of CQ. However, the hypothesis has yet to be tested in animal models.

Arg-Gly-Asp peptides (RGD) are ligands for $\alpha_v\beta_3$ integrin receptors. Direct conjugation of RGD to DNA/PEI (polyethyleneimine) polyplexes can increase the transfection efficiency *in vitro*¹⁸ and *in vivo*¹⁹. However, these targeting approaches are not able to differentiate between tumors that express high levels of $\alpha_v\beta_3$ over tumors that express medium level of $\alpha_v\beta_3$ (or over cell types that express low amounts of $\alpha_v\beta_3$).^{18,19} To solve this problem, clustered Arg-Gly-Asp peptides were prepared with Au nanoparticles as template.²⁰ By introducing clustered RGD ligands on the surface of DNA/PEI polyplexes (Figure 2), improved targeting of the vector towards U87MG tumors with high levels of $\alpha_v\beta_3$ integrin expression over HeLa tumors with medium $\alpha_v\beta_3$ integrin expression was observed in tumor bearing mice after i.v. administration.²¹ This is an interesting study which exploits the enhanced avidity of multivalent binding.

McMahon et al²² synthesized biomimetic high density lipoprotein (HDL) nanoparticles based upon a gold nanoparticle template (HDL AuNPs) and found that HDL AuNPs could adsorb antisense cholesterylated DNA and regulate target gene expression in PC-3 cells *in vitro*. HDLs are natural phospholipid-rich cholesterol transporters and can deliver adsorbed cholesterylated nucleic acids to cell types targeted by HDL for gene regulation. Thus, the HDL AuNP platform can be expected for the targeted *in vivo* delivery of nucleic acid.

Polymers also played a role in developing multifunctional nucleic acid delivery systems. Using poly-L-lysine and PEI as templates, Li et al²³ combined prodrug enzyme therapy, siRNA therapy and simultaneous diagnosis by making prodrug enzyme, siRNA, MRI reporter and optical reporter into a single systemic treatment strategy for the ER/PR/Her2-neu negative MDA-MB-231 human breast cancer xenograft model. Prodrug enzyme therapy, where a drug-activating enzyme delivered to the tumor converts a nontoxic prodrug to a cytotoxic drug, is being actively investigated to minimize normal tissue damage. The prodrug enzyme in this report is bacterial cytosine deaminase (bCD) that converts the nontoxic prodrug 5-fluorocytosine (5-FC) to cytotoxic 5-fluorouracil (5-FU), and the siRNA mediates choline kinase- α (Chk- α), an enzyme significantly up-regulated in aggressive breast cancer cells. The combination of siRNA and prodrug enzyme could amplify the selective targeting of cancer cells while minimize normal tissue damage *via* i.v. administration. Meanwhile, noninvasive imaging can demonstrate effective tumor delivery of the siRNA and prodrug enzyme to determine when the prodrug should be administered, as well as detecting target down-regulation by siRNA and prodrug conversion by the enzyme. According to this report, *in vivo* MRI and optical imaging showed efficient intratumoral nanoplex delivery, and a single dose of the siRNA/prodrug enzyme containing nanoplex together with the prodrug resulted in a 6-fold increase of tumor doubling time, suggesting that image-guided combined siRNA and prodrug enzyme treatment should have significant potential to improve therapeutic efficacy and minimize normal tissue damage. This nanoplex strategy could be expected to expand to downregulate multi-drug-resistant pathways or repair enzymes and increase the efficiency of chemo- or radiation therapy *in vivo*.

Recently, as alternative strategies to deliver nucleic acids to tumors, a controlled-release system responding to the unique environments of tissues and external stimuli has been investigated. Gold nanorods have strong absorption bands in the near-infrared region, and

the absorbed light energy is then converted into heat by gold nanorods, the so-called 'photothermal effect'. Because the near-infrared light can penetrate deeply into tissues, the surface of gold nanorod could be modified with double-stranded DNA for controlled release (Figure 3).²⁴ When the dsDNA-modified gold nanorods were irradiated by near-infrared light, single-stranded DNA was released due to thermo-denaturation induced by the photothermal effect. The amount of released ssDNA was dependent upon the power and exposure time of light irradiation. Release of ssDNA was also observed in Colon-26 tumors grown in mice after light irradiation as the dsDNA modified gold nanorods were directly injected into the tumors.²⁴ Such a controlled-release system of oligonucleotide triggered by the photothermal effect could expand the applications of gold nanorods that have unique optical characteristics.²⁴

Lee et al²⁵ fabricated protease-degradable poly-L-lysine (PLL) and siRNA onto gold nanoparticles (AuNPs), by layer-by-layer fabrication, which is a gentle assembly procedure based on charge-charge interactions between positively and negatively charged polymers. The NPs are multilayered, with the outer surface layer being PLL, could deliver siRNA into tumor cells, and due to the slow degradation of PLL, the incorporated siRNA could be released gradually and showed extended gene-silencing effects without toxicity. The strategy is yet to be tested in animal models.

Novel Membrane/Core Nanoparticles for Gene Delivery

The pharmacology of a liposomal formulation of nucleic acid is largely determined by the extent to which the nucleic acid is encapsulated inside the liposome bilayer. Encapsulated nucleic acid is protected from nuclease degradation, while those merely associated with the surface of the liposome is not protected. Encapsulated nucleic acid shares the extended circulation lifetime and biodistribution of the intact liposome, while those that are surface associated adopt the pharmacology of naked nucleic acid once they disassociate from the liposome.

Liposomal encapsulation of small molecule drugs may be achieved by either "passive" or "active loading".²⁶ Unlike small molecule drugs, nucleic acids can not cross intact lipid bilayers, predominantly due to the large size and hydrophilic nature of the nucleic acid. Therefore, nucleic acids are entrapped within liposomes with conventional passive loading technologies, such as ethanol drop method (as in SALP),²⁶ reverse-phase evaporation method, and ethanol dilution method (as in SNALP).²⁶ These methods rely on the electrostatic interaction between nucleic acid and cationic lipid; the formation of liposomes and the encapsulation efficiency of nucleic acid are sensitive to changes in the ionic strength, cationic lipid, and PEG lipid content, and the scalability and reproducibility are not satisfactory.²⁶

Recently, a viruslike structure with condensed nucleic acid located inside the lipid membranes was developed.^{27,28} It was initially prepared by condensing DNA with protamine into a compact complex, followed by coating with cationic liposome to obtain LPD (liposome-polycation-DNA) nanoparticles. The compact complex formed by DNA and protamine constitutes the core of LPD. Compared with cationic liposome/DNA complex, LPD offers better protection of plasmid DNA against enzymatic digestion and gives a higher level of gene expression in mice *via* intravenous administration. The formulation was also modified for selectively delivering siRNA to receptor positive tumor cells *in vitro* and *in vivo* (Figures 4 and 5). siRNA was mixed with a carrier DNA, calf thymus DNA, before complexing with protamine, and PEG conjugated lipids were post-inserted into the outer lipid membrane to further stabilize the formulation. A targeting ligand (anisamide, a sigma-1 receptor ligand) was conjugated to the distal end of PEG for targeting sigma receptor

expressing tumor cells.^{29–33} The PEG on the LPD surface was arranged in a brush mode and thus, prevented serum opsonization and improved the chance to reach the tumor *via* EPR effect. The targeting ligand increased the delivery efficiency and tissue specificity.³⁴ Moreover, by adjusting the ratio of protamine to siRNA and calf-thymus DNA, the core could be coated with anionic liposomes (formed by DOPA, 1,2-dioleoyl-sn-glycero-3-phosphoethanolamine, and cholesterol) to form LPD-II.³⁵ Both LPD and LPD-II can systemically deliver doxorubicin (Dox) and siRNA to multiple drug resistance (MDR) tumors simultaneously. Although the same amount of siRNA and Dox delivered by targeted LPD and LPD-II showed similar levels of apoptosis induction and therapeutic efficacy in NCI/ADR tumors, LPD-II showed a lower toxicity profile, which might suggest a larger therapeutic window and potential clinical application for cancer therapy.³⁵

Metallic ions (such as Ca²⁺ and Mg²⁺) were also used to mediate and optimize lipoplex formation. Mozafari et al^{36,37} once constructed a non-viral and non-cationic gene transfer vector by incorporating plasmid DNA to the liposomes formed by DPPC (dipalmitoylphosphatidylcholine)/DCP(dicetylphosphate)/CHOL(cholesterol) liposomes, by the electrostatic mediation of Ca²⁺ ions. It is possible to get a high DNA entrapment capacity and high transfection efficiency in CHO-K1 and 16HBE14o- cells using the anionic nanolipoplex, but two or three aggregated/semi-fused vesicles were observed as a result of their complexation with DNA mediated by Ca²⁺. To avoid this drawback and still employ the affinity of calcium to the phosphate groups in nucleic acids, novel membrane/core nanoparticles for siRNA delivery was developed lately.³⁸ In this strategy, the core of LPD is replaced with the acid-sensitive nano-sized calcium phosphate (CaP), prepared by using water-in-oil microemulsions in which siRNA was entrapped. The CaP core was then coated with DOTAP (1,2-dioleoyl-3-trimethylammonium-propane chloride salt)/cholesterol liposome membrane (Figure 6). The resulting new formulation is called liposome/calcium/phosphate, or LCP. The LCP nanoparticles were further modified by post-insertion of PEG with or without anisamide. The targeted LCP nanoparticles silenced about 70% and 50% of luciferase activity for H460 cells in culture and those grown in a xenograft model, respectively. Since CaP rapidly dissolves in the acidic pH, endocytosed CaP should be disassemble in the endosomes and release its cargo into the cytoplasm. Furthermore, calcium phosphate is an inorganic component of the biological hard tissues, i.e., bone, teeth, and tendons, where it exists as carbonated hydroxyapatite. Therefore, the replacement of DNA(or siRNA)-protamine complex by calcium phosphate/DNA (or siRNA) complex may also decrease the immunotoxicity. Although calcium phosphates is a well used non-viral vector for *in vitro* transfection, their rapid aggregation hinders the application *in vivo*.^{13,39–43} Poly(ethylene glycol)-*block*-poly(methacrylic acid) was once used to stabilize CaP crystals, but only the *in vitro* gene silencing-efficacy was observed.⁴⁴ Therefore, wrapping the CaP core with a PEGylated lipid membrane not only stabilizes the core, but also promises a potential application of CaP for clinical trial.

PEI was also used to condense nucleic acid, followed by modification with liposomes.^{45,46} Although a decreased toxicity and enhanced biological activity were shown if compared with the case using nonlipidated PEI, the toxicity of PEI should be still the hurdle for its application *in vivo*.

Ultrasound-responsive Gene Vectors

Low-intensity ultrasound in combination with microbubbles has recently acquired much attention as a safe method of gene delivery. Ultrasound shows tissue-permeabilizing effect. Ultrasound-triggered delivery allows the control of the deposition of the drug from outside the patient's body using suitable force fields.^{47,48} It is non-invasive and site-specific, and

could make it possible to destroy tumor cells after systemic delivery, while leave nontargeted organs unaffected.

In ultrasound-triggered drug delivery, tissue-permeabilizing effect can be potentiated using ultrasound contrast agents, gas-filled microbubbles.⁴⁹⁻⁵¹ The use of microbubbles as gene vectors is based on the hypothesis that destruction of DNA-loaded microbubbles by a focused ultrasound beam during their microvascular transit through the target area will result in localized transduction upon disruption of the microbubble shell while sparing nontargeted areas. However, the therapeutic effect of ultrasound-targeted microbubble destruction (UTMD) is relative to the size, stability, and targeting function of microbubbles. Recently, some groups improved the properties of DNA binding microbubbles by using lipid-stabilized microbubbles. UTMD has been used to deliver genes to cells *in vitro* and *in vivo*, to treat diabetes⁵⁰, cardiovascular disease,⁵¹ and carcinoma^{52,53} in experimental animal models. Negishi et al⁵⁴ combined polyethyleneglyco-modified bubble liposomes and ultrasound exposure and developed a safe and efficient gene delivery system for skeletal muscle *via* intraperitoneal administration. More recently, Un et al⁵⁵ targeted the bubble lipoplexes with mannose and developed a DNA vaccination for metastatic and relapsed melanoma, by transfection of pUb-M, coexpressing ubiquitylated gp100 and TRP-2 (Figure 7). They reported that the vaccine effects against melanoma were sustained for at least 100 days after i.v. administration.

Besides ultrasound-mediated delivery, magnetic targeting delivery could be used for drug targeting. However, there are fundamental limitations to the use of magnetic drug targeting. Sufficient magnetic force must be exerted on the nanomagnetic carriers at the target site before they are cleared from circulation.^{56,57} Thus, magnetic nanoparticles are usually entrapped in gene vectors for imaging the delivery of nucleic acid,^{13-15, 23} as discussed above. Recently, Vlaskou et al⁵⁸ generated nucleic acid carriers that combined responsiveness to both ultrasound and magnetic fields, i.e., magnetic and acoustically active lipospheres (MAALs). The lipospheres were obtained upon shaking a mixture of soybean oil, a cationic lipid, magnetic nanoparticles (iron oxide nanoparticles), a nucleic acid, and aqueous buffer in a perfluoropropane atmosphere in a sealed vial. Although the combined application of magnetic field and ultrasound had no synergistic effect in terms of liposphere capture in the lungs, a synergistic effect of magnetic field and ultrasound was observed in site-specific plasmid deposition in a dorsal skinfold chamber model in mice after injection into the carotids. This study may indicate that gene delivery mediated by ultrasound irradiation could be improved if effective means of accumulating and retaining ultrasound microbubbles at the target sites are available.

It seems that gene therapy using microbubbles as vectors and ultrasound to direct local transfer of genes to the target site is minimally invasive and is, in theory, easily adapted to serial treatments. It may become a promising strategy that could circumvent limitations of viral gene delivery systems. However, to make it an effective therapeutic method in clinic will require further improvements of the formulation as well as the use of more advanced ultrasound-transducing device. The biocompatible shell to encapsulate the ultrasound contrast agent is mainly based on lipid compositions that are used for the preparation of liposomes. Detailed research on screening lipids and optimizing formulation is necessary.

Prospective and Perspective

Employing chemical and biological strategies to prepare multifunctional vectors to overcome hurdles associated with efficient cellular nucleic acid delivery has proven to be beneficial. It has provided exciting new nanomedicine-based strategies for gene therapy. Unfortunately, progress into clinical trials has been slow. There is insufficient knowledge of

the physicochemical and biological properties during the various phases of the transfection process. Leal⁵⁹ recently reported the development of cationic liposome-siRNA complexes with a novel cubic phase nanostructure exhibited efficient silencing with low toxicity. This finding underscores the importance of understanding membrane-mediated interactions between cationic liposome-siRNA complex nanostructure and cell components in developing cationic liposome-based gene silencing vectors. Better understandings of the fate of the nanoparticles inside the cell and of the interactions between the parts of a hybrid particle will lead to a delivery system suitable for clinical use. In addition, different cell lines show a different selectivity towards the hydrophilicity of the particle's surface when it comes to the uptake of nanoparticles. A thorough research about the interaction between cells and vectors is necessary. Escaping the rapid uptake of nanoparticles by the reticuloendothelial system is also a necessary requirement for an efficient tumor uptake of the encapsulated nucleic acid.

To date, the delivery of siRNA has predominantly utilized agents that were developed for plasmid DNA delivery. DNA and RNA are different in physicochemical properties, for example, the size, the affinity of cation, and the stiffness of the strand (resistance to condensation), etc. Plasmid DNA needs to be transported into the nucleus for gene expression, while siRNA only needs to be transferred across the plasma membrane to reach its target in the cytoplasm. The optimal carriers may be different for these two applications and delivery reagents should be specifically developed for siRNA delivery. In addition, RNA is relatively unstable. There are only a few reports so far about the sustained delivery of siRNA.⁶⁰⁻⁶² How to make vectors targeted to cells with sustained release *in vivo* should be an interesting research challenge.

Inorganic nanoparticles offer many ways to prepare systems with a defined particle size, surface functionalization, nucleic acid protection, and biocompatibility. As it is possible to finetune their nanostructure, for example, by coating them with different layers or by loading internal nanopores, their use as carriers could be extended beyond the current applications. Combination of inorganic nanoparticles with other classes of non-viral vectors should be an interesting and promising research field.

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Biographies

Xia Guo is a Full Professor of School of Chemistry and Chemical Engineering, Yangzhou University, P.R.China and currently, is a visiting scholar in University of North Carolina at Chapel Hill. She got Ph.D. in 1998 and her research is mainly in the field of colloids and interfaces.

Leaf Huang, Ph.D. is the Fred Eshelman Distinguished Professor and Chair, Division of Molecular Pharmaceutics in the Eshelman School of Pharmacy, University of North Carolina at Chapel Hill. His research has been in the area of gene therapy and targeted drug delivery. He has pioneered the liposome non-viral vector and has produced the vector for the first non-viral clinical trial in 1992. He has authored or co-authored more than 300 peer-reviewed papers and more than 120 reviews and book chapters. He is the inventor or co-inventor of 16 US and foreign patents and co-founded 5 biotech start-ups in the past.

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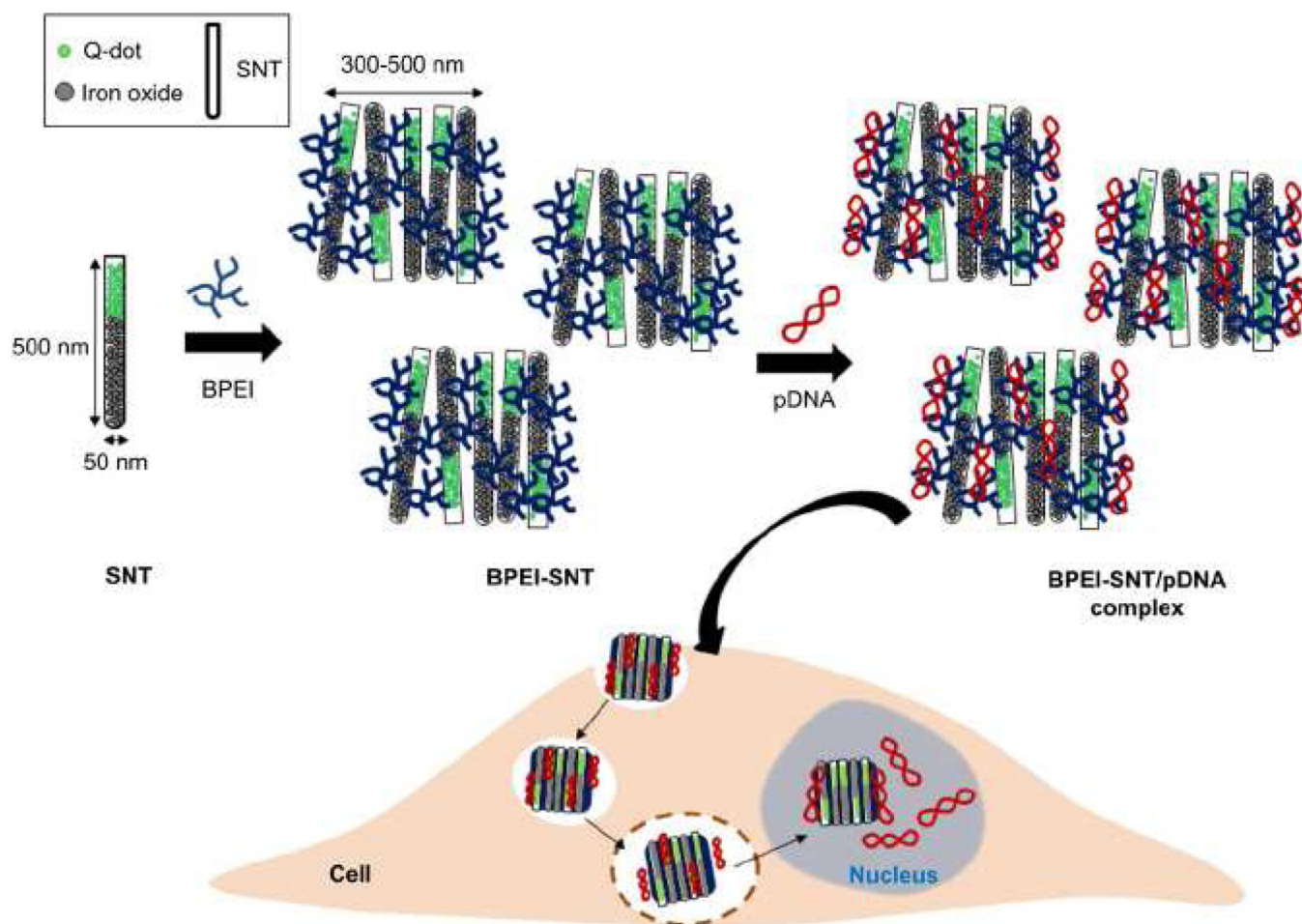


Figure 1. Schematic illustration depicting preparation of BPEI-SNT/pDNA complex. Figure is reproduced from reference [15] with permission.

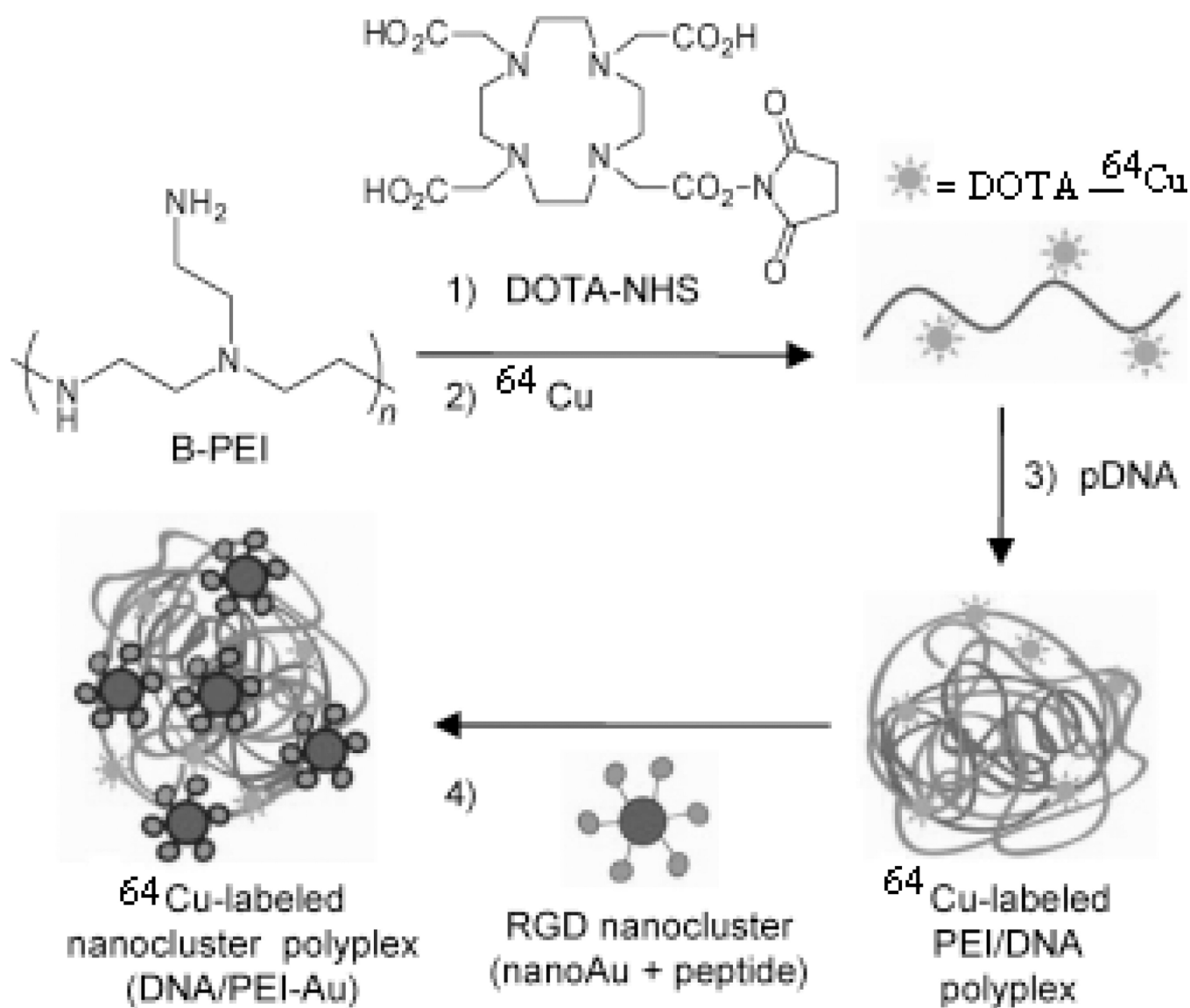


Figure 2. ^{64}Cu -labeled RGD nanocluster-modified DNA/PEI polyplexes. Figure is reproduced from reference [21] with permission.

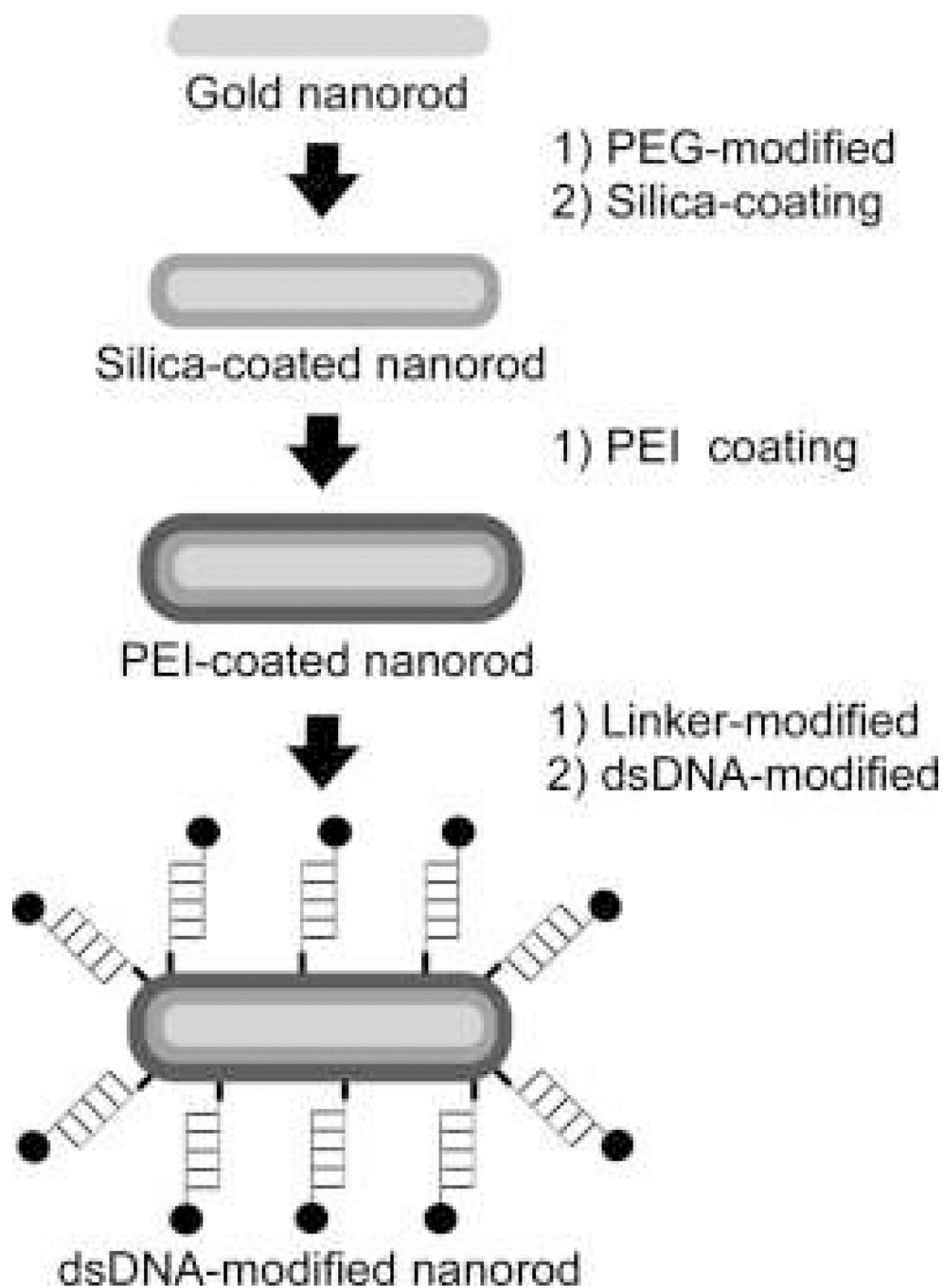


Figure 3. Preparation of dsDNA-modified gold nanorods. Figure is reproduced from reference [24] with permission.

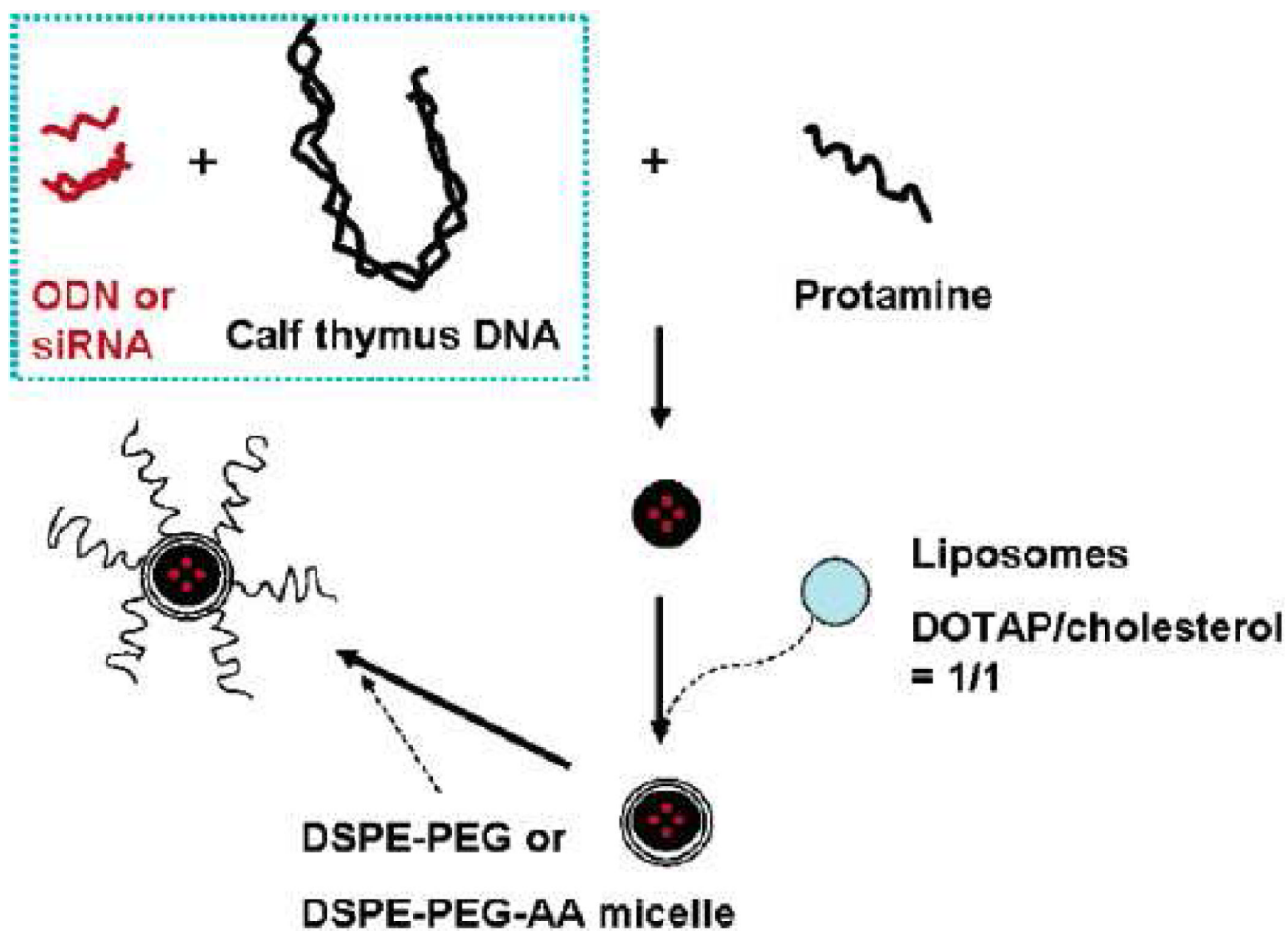


Figure 4. Illustration of preparation of PEGylated LPD. Figure is reproduced from reference [30] with permission.

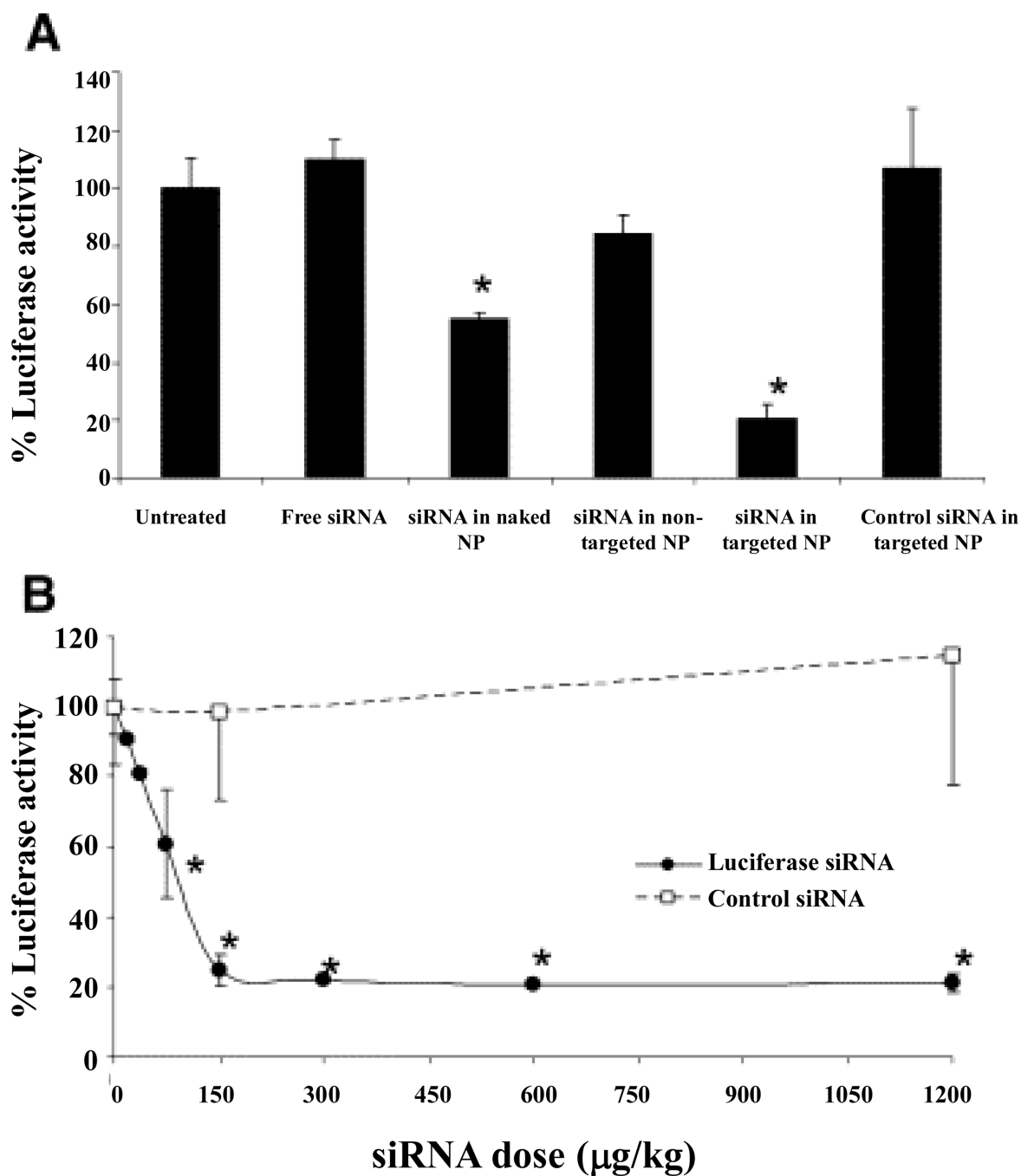


Figure 5. *In vivo* luciferase gene silencing effect of different siRNA formulations at the dose of 150 µg/kg (A) and that of the targeted NP at various doses (B). B16F10 tumor bearing mice were i.v. injected with different siRNA formulations. Data=mean±SD (n=3–8), * indicates p<0.05 compared to the untreated control. Figure is reproduced from reference [29] with permission.

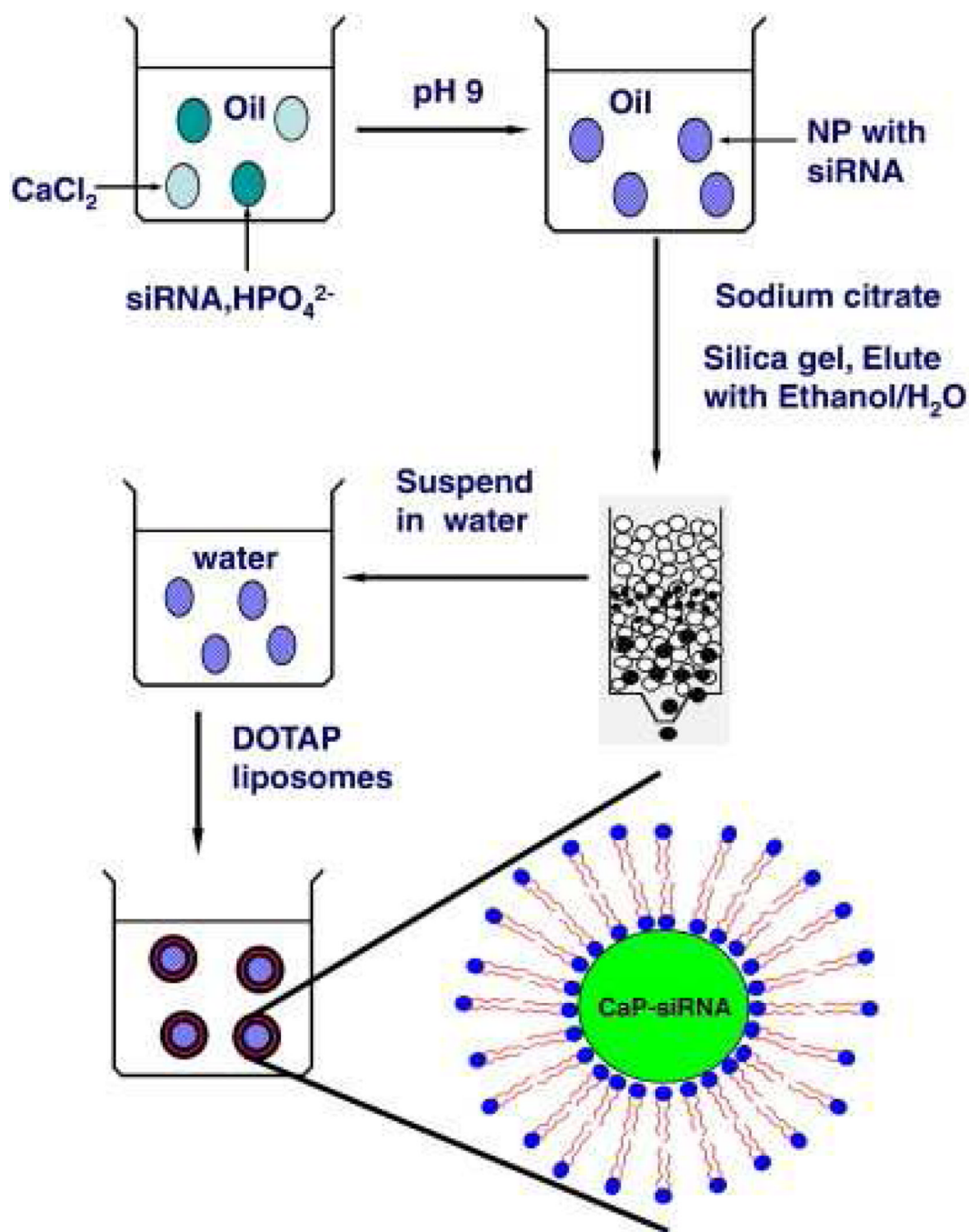


Figure 6. The formation process of liposome/calcium/phosphate (LCP) nanoparticles. Figure is reproduced from reference [38] with permission.

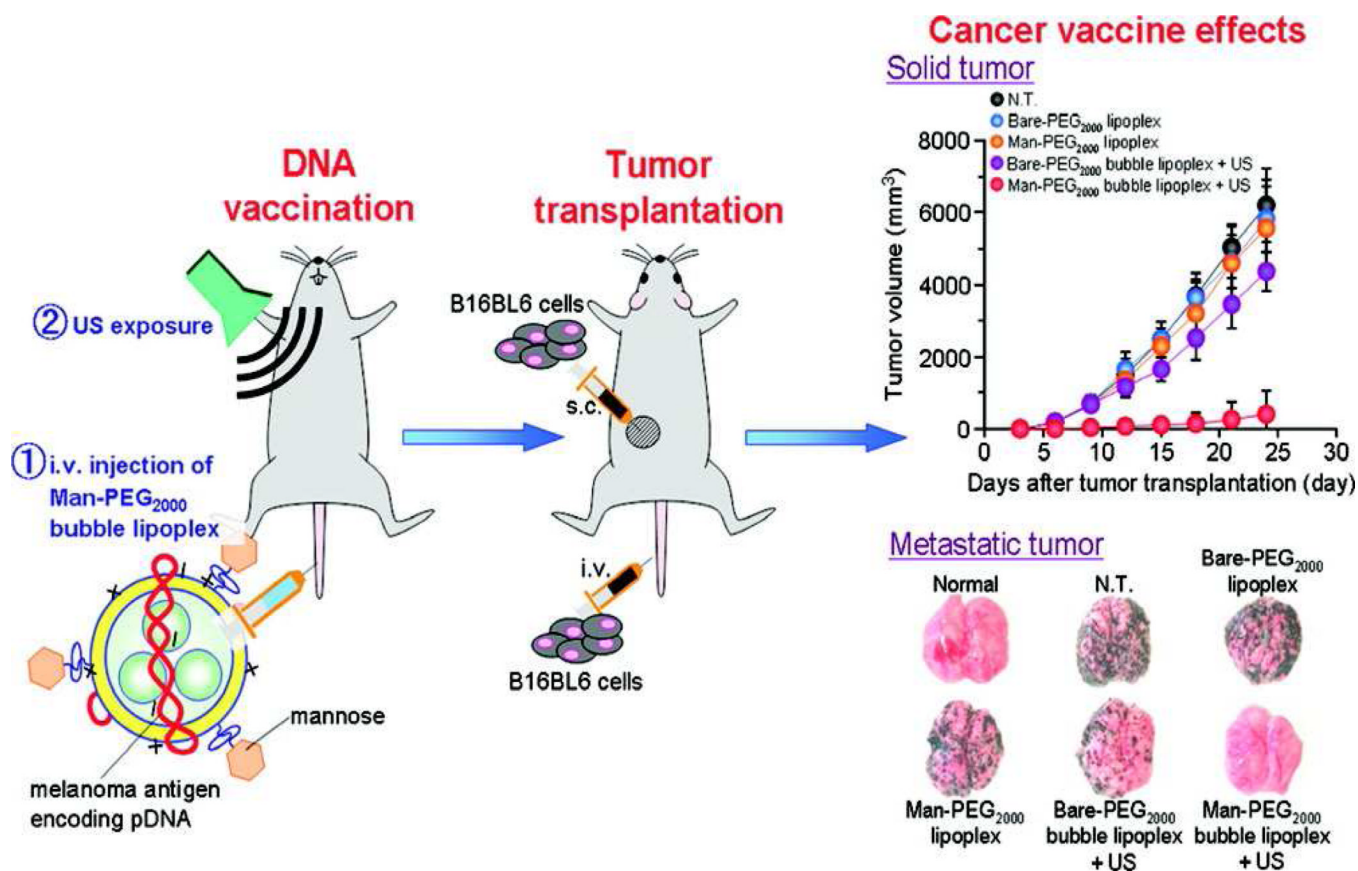


Figure 7. Cancer vaccine effects against solid tumors by DNA vaccination using Man-PEG₂₀₀₀ bubble lipoplexes and US exposure. Figure is reproduced from reference [55] with permission.