

siRNA Delivery Using Dithiocarbamate-Anchored Oligonucleotides on Gold Nanorods

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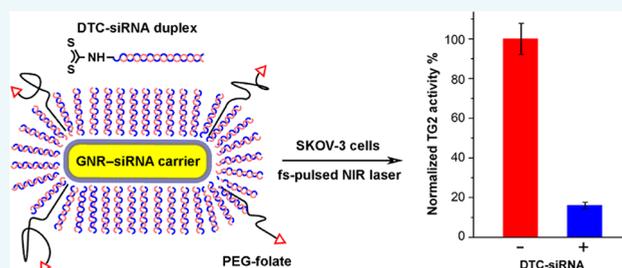
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Supporting Information

ABSTRACT: We present a robust method for loading small interfering RNA (siRNA) duplexes onto the surfaces of gold nanorods (GNRs) at high density, using near-infrared laser irradiation to trigger their intracellular release with subsequent knockdown activity. Citrate-stabilized GNRs were first coated with oleylsulfobetaine, a zwitterionic amphiphile with low cytotoxicity, which produced stable dispersions at high ionic strength. Amine-modified siRNA duplexes were converted into dithiocarbamate (DTC) ligands and adsorbed onto GNR surfaces in a single incubation step at 0.5 M NaCl, simplifying the charge screening process. The DTC anchors were effective at minimizing premature siRNA desorption and release, a common but often overlooked problem in the use of gold nanoparticles as oligonucleotide carriers. The activity of GNR-siRNA complexes was evaluated systematically against an eGFP-producing ovarian cancer cell line (SKOV-3) using folate receptor-mediated uptake. Efficient knockdown was achieved by using a femtosecond-pulsed laser source to release DTC-anchored siRNA, with essentially no contributions from spontaneous (dark) RNA desorption. GNRs coated with thiol-anchored siRNA duplexes were less effective and also permitted low levels of knockdown activity without photothermal activation. Optimized siRNA delivery conditions were applied toward the targeted knockdown of transglutaminase 2, whose expression is associated with the progression of recurrent ovarian cancer, with a reduction in activity of >80% achieved after a single pulsed laser treatment.



INTRODUCTION

Small-interfering RNA (siRNA) oligonucleotide duplexes offer the capacity to suppress production of virtually any gene product. The mechanism of siRNA inhibition was elucidated nearly 20 years ago,¹ sparking a global effort to harness siRNA's therapeutic potential for the selective inhibition of proteins and signaling pathways, many previously considered to be "undruggable".² The design of robust platforms that enable the precise delivery and release of siRNA duplexes for efficient knockdown within target cells remains a primary challenge. Many promising contenders are nanoparticulate by design, several of which have entered clinical trials with the goal of transforming siRNA delivery into a true therapy.^{3–5}

Gold nanoparticles (GNPs) were introduced as carriers for nucleic acid delivery more than a decade ago, initially via electrostatic adsorption with polyethylenimine,^{6,7} followed by chemisorption with thiol-terminated siRNA.^{8,9} An appealing

reason for using GNPs as siRNA carriers is their capacity to produce a strong photothermal response at visible or near-infrared (NIR) wavelengths. The plasmonic excitation of GNPs can trigger the release of bound surface molecules^{10,11} while enabling their escape from endocytic vesicles¹² and can provide spatiotemporal control over siRNA release for "on-demand" knockdown therapies.¹³ NIR-absorbing GNPs are especially appealing as photothermal carriers because NIR light can penetrate into biological tissues with relatively low attenuation.¹⁴

Special Issue: Delivery of Proteins and Nucleic Acids: Achievements and Challenges

Received: October 9, 2018

Revised: November 2, 2018

Published: November 5, 2018

Concerning the mechanism of siRNA knockdown, the RNA duplex (20–25 bp) serves as the substrate for the cytoplasmic RNA-induced silencing complex (RISC), which catalyzes the removal of one strand (passenger) and the hybridization of the remaining antisense strand (guide) with the target mRNA sequence, effectively tagging it for degradation.¹⁵ This means that the photothermal trigger should be designed to release intact RNA duplexes from GNP surfaces rather than single-stranded antisense RNA for maximum interference. In this respect, the use of a femtosecond (fs)-pulsed NIR laser is more effective than continuous-wave (CW) laser irradiation for siRNA duplex release. The absorption of ultrashort laser pulses by GNPs generates localized photoacoustic effects that favor the ejection of siRNA duplexes from the surface while rupturing the encapsulating liposome.^{10–12} By comparison, photothermal effects from CW laser irradiation are less intense and produce more conventional forms of heat that promote denaturation and the release of single-stranded RNA.^{13,16}

With regard to *in vivo* delivery, siRNA duplexes are capable of activating the innate immune response soon after cell uptake,¹⁷ especially for systems that rely on electrostatic adsorption to cationic lipids or polymers.¹⁵ GNPs loaded with dense monolayers of axially oriented RNA duplexes have proven to be an excellent alternative to cationic lipoplexes for siRNA delivery, as this architecture shields siRNA from nucleases and Toll-like receptors. Studies by Mirkin and coworkers have shown that “spherical nucleic acids” (dense monolayers of thiolated oligonucleotides on 13 nm GNP cores) are stable in physiological environments and resist enzymatic degradation,^{8,18} and can produce *in vivo* knockdown effects without generating a collateral immune response.^{19,20}

These observations have motivated us to design siRNA carriers in which duplexes are covalently anchored onto cores of gold nanorods (GNRs), whose strong NIR absorptions have proven valuable in a variety of nanomedicine applications.^{21,22} The siRNA monolayer can be further shielded from protein-mediated degradation by installing PEG chains on the GNR surface,²³ decorated with targeting ligands to encourage cell-specific uptake (Figure 1).²⁴ Previous studies of GNPs as

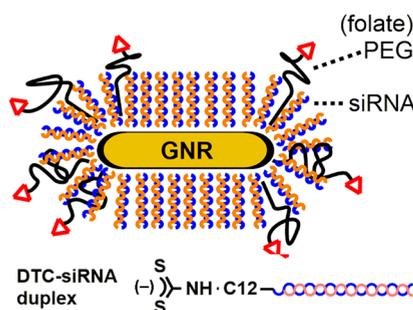


Figure 1. Gold nanorod (GNR)–siRNA carrier, consisting of a monolayer of oriented siRNA duplexes anchored by dithiocarbamate (DTC) units, with thiolated polyethylene glycol–folate (HS-PEG–folate) as a coadsorbate.

siRNA carriers have relied on cationic polyelectrolytes for electrostatic adsorption,^{25–36} but to our knowledge there have been no reports of GNPs supporting chemisorbed layers of siRNA duplexes, thus lagging behind other NIR-active carriers such as nanoshells^{12,37–41} and nanostars.^{42,43}

Two major technical hurdles must be addressed to produce effective GNR–siRNA platforms. The first is the efficient

chemisorption of oriented siRNA duplexes: siRNA loading must overcome electrostatic repulsion while maintaining dispersion stability during surface adsorption. Thiolated oligonucleotides are typically adsorbed onto GNPs at high density using the charge screening or “salt-aging” process by gradually increasing the ionic strength of the solution (up to 1 M).^{44–46} This practice is less straightforward for GNPs due to their structural anisotropy and the challenges posed by cetyltrimethylammonium bromide (CTAB), a cationic surfactant used in GNP synthesis²² whose efficient removal requires considerable attention to detail.^{47–49} Several methods for exchanging CTAB with thiolated DNA have been described^{50–52} but have not been applied toward the loading of siRNA duplexes on GNPs.

A second, more vexing problem associated with thiolated oligonucleotides is their appreciable rate of surface desorption under physiological conditions. This compromises the efficacy of a timed photothermal release and can also introduce off-target effects, as has been observed with siRNA delivery based on electrostatic adsorption.^{25,27–30,34} The chemisorptive stability of thiols on Au depends on the chemical environment: In the extracellular milieu, electrolytes can accelerate ligand oxidation and displacement,⁵³ whereas high levels of intracellular glutathione can displace ligands prematurely by mass action.⁵⁴ The issue of nonspecific desorption can be addressed by replacing thiols with dithiocarbamates (DTCs) as the surface anchor for siRNA duplexes (Figure 1). Complex molecules with terminal amines are readily converted into DTCs by *in situ* treatment with CS₂,^{55,56} enabling their robust adsorption onto Au surfaces including GNPs.^{23,24,49,57} Liu and coworkers demonstrated that DTC–DNA could be anchored onto GNPs at similar loading densities as thiolated DNA but with much greater resistance to displacement by dithiothreitol.⁵⁸

In this paper, we present a method for loading siRNA duplexes onto GNPs using DTC chemistry and demonstrate their receptor-mediated uptake by SKOV-3 cells, a drug-resistant ovarian cancer cell line, with light-triggered siRNA release and efficient knockdown of two target gene products. siRNA loading is performed in a single step by using oleylsulfobetaine (OSB),⁵⁹ a novel zwitterionic surfactant, to maintain colloidal stability at high ionic strength. The stability and release profiles of DTC–siRNA are compared against those of iminothiolate–siRNA using pulsed or CW laser irradiation for photothermal activation. Importantly, no background effects are observed when using DTC–siRNA in the absence of light irradiation. The GNR–siRNA delivery system has been vetted against the knockdown of enhanced green fluorescent protein (eGFP) in transfected SKOV-3 cells and against tissue transglutaminase 2 (TG2), a cross-linking enzyme whose expression is increased in recurrent and metastatic ovarian cancer,⁶⁰ with a knockdown of >80% in the latter case.

RESULTS AND DISCUSSION

Stabilizing Gold Nanorods at High Ionic Strength with Zwitterionic Surfactants. It is widely known that the surface chemistry and behavior of ligand-modified GNPs are easily compromised by the incomplete removal of CTAB, a cationic surfactant commonly used in GNP synthesis.^{22,47} To address this, we previously established a scalable protocol for the exhaustive removal of CTAB from GNP suspensions, followed by surface exchange with citrate ions.^{48,49} These

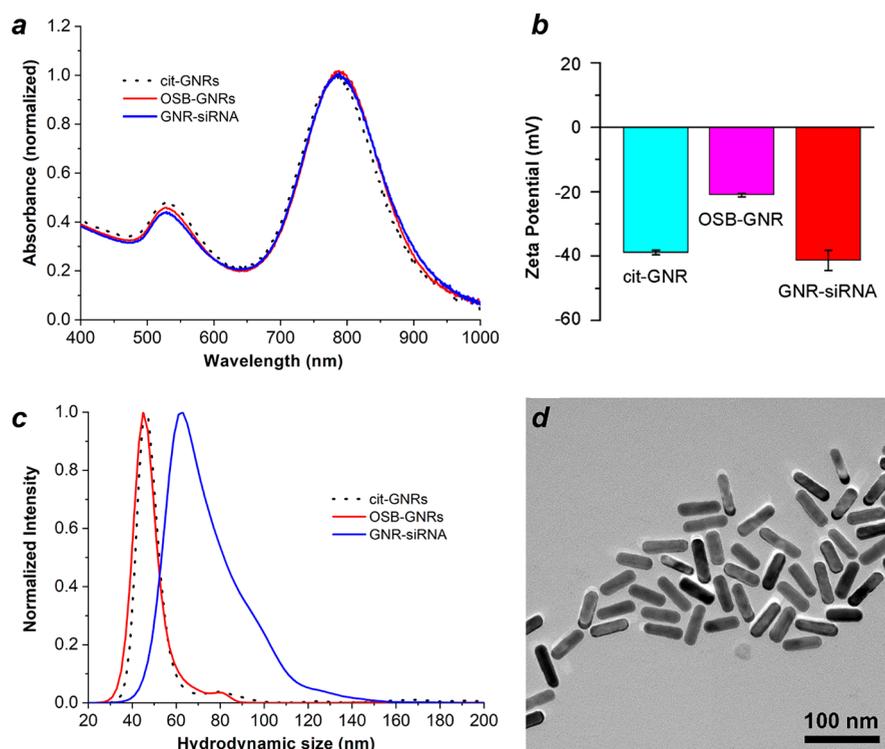


Figure 2. Characterization of surface-modified GNRs. (a) Visible–NIR absorption spectra, (b) zeta potentials, (c) hydrodynamic size (NTA), and (d) TEM image of GNR–siRNA carriers, prepared using DTC–siRNA duplexes encoded for eGFP knockdown plus HS-PEG-folate. Cit-GNRs were dispersed in 5 mM citrate; OSB–GNRs and GNR–siRNA carriers were dispersed in 0.1 M NaCl.

anchored passenger strand, which is resistant to surface displacement (see below).^{55,58} Dehybridization was achieved by heating the GNR–siRNA carriers to 100 °C in the presence of excess free passenger RNA, which inhibited rehybridization of the Dy547-labeled strand with GNR-bound RNA upon cooling.

Initial attempts at siRNA loading using iminothiolate-modified siRNA duplexes produced a low loading density after GNR recovery, suggesting poor surface attachment. We considered that chemisorption might be compromised by residual Ag species on GNR surfaces, as identified in previous X-ray photoelectron spectroscopy (XPS) and imaging studies.^{48,64} This problem was effectively solved by treating CTAB-GNR suspensions with 5 μ M H₂AuCl₄ and ascorbic acid for the galvanic displacement of surface Ag prior to surfactant exchange, which had a negligible effect on GNR plasmon resonance.⁶⁵

Several charge-screening conditions were then evaluated for optimized siRNA loading with coadsorption of HS-PEG-folate. Remarkably, we found that a gradual “salt-aging” process was unnecessary; indeed, irreversible GNR aggregation was often observed when solution ionic strength was increased in stages up to 1 M. Instead, OSB–GNRs could be treated with DTC–siRNA duplex and HS-PEG-folate in a single step using 0.5 M NaCl, incubated overnight (<12 h) at room temperature with minimum loss of dispersion stability.⁵² On the basis of the thermal dehybridization of Dy547-labeled guide strands from GNR–siRNA carriers, we determined that the one-step siRNA loading in 0.5 M NaCl yielded a surface density of >230 duplexes per GNR, equal to a molecular footprint of 10 nm² or 10⁵ duplexes/ μ m² (Figure S5). The siRNA density is similar to or higher than that reported for ssDNA-coated GNRs using other charge-screening methods,^{50–52} although differences in

ligand-to-GNR ratios and ligand type preclude a systematic comparison.

The high siRNA density is even more remarkable when taking into account that the loading was performed with coadsorption of HS-PEG-folate, which is considered to adopt a mushroom-like conformation upon surface attachment.⁴⁹ DTC ligands are generally more aggressive than thiols, and the disordered conformation of individual PEG chains is poorly matched with the dense packing of oriented siRNA duplexes. We postulate that the chemisorption of thiolated PEG is limited to the GNR termini, where the radius of curvature is small and the adsorption of bulky ligands is facile.^{66,67} We thus consider HS-PEG-folate to be a minor component in GNR–siRNA carriers despite its relative abundance in solution, based on this argument and other supporting data below.

The conversion of citrate-stabilized GNRs into GNR–siRNA complexes was characterized by absorption spectroscopy, zeta potential, changes in hydrodynamic size (d_h) by nanoparticle tracking analysis (NTA), and TEM analysis (Figure 2). Previous studies have correlated increases in d_h with changes in GNR length as a function of surface coating, with a resolution of 5 nm or less.⁴⁹ A significant shift in NTA mode peak was observed upon exchanging OSB to DTC–siRNA, from a d_h value of 45 nm for OSB–GNRs to 63 nm for GNR–siRNA carriers, with no apparent changes in the size of the GNR core. The 18 nm increase in d_h agrees well with the model of radially oriented siRNA duplexes presented in Figure 1, using an estimated length of 9.2 nm for a 27 bp duplex based on B-DNA geometry. Any contributions by HS-PEG-folate to hydrodynamic size are eclipsed by the monolayer of oriented siRNA duplexes, whose persistence length ensures their radial extension from the GNR surface.

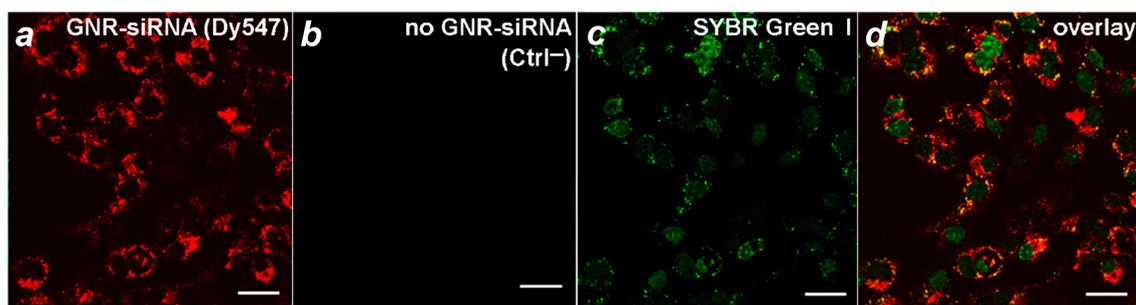


Figure 3. Confocal microscopy of GNR–siRNA carriers with coadsorbed HS-PEG-folate internalized by SKOV-3 cells. siRNA duplexes are DTC-anchored and labeled with a fluorescent dye (Dy547). (a,b) SKOV-3 cells after 24 h of incubation with GNR–(Dy547)siRNA (85 pM) plus control (Ctrl[−]). (c) SYBR Green I counterstain of nuclear dsDNA and cytoplasmic RNA. (d) Overlay of panels a and c showing the cytoplasmic localization of GNR–siRNA. Bar = 30 μm .

siRNA Uptake, Retention, and Release in SKOV-3 Cells. Cell uptake studies were performed with GNRs loaded with DTC-anchored siRNA duplex (see Table 2 for siRNA sequence details), labeled with HS-PEG-folate and Dy547-modified guide strands for fluorescence imaging. SKOV-3 cells were incubated for 24 h with GNR–siRNA carriers at 85 pM (equivalent to 20 nM siRNA), then examined by confocal fluorescence microscopy for the confirmation of cell uptake (Figure 3). The siRNA carriers did not penetrate the nucleus in accord with previous observations of folate-mediated GNR uptake,²⁴ although some SYBR Green I staining was observed in the cytoplasm suggesting colocalization with extranuclear DNA or RNA.⁶⁸ A control experiment of GNR–siRNA carriers with coadsorbed HS-mPEG (without folate) showed much less internalization by SKOV-3 cells after 24 h, confirming the supporting role of folate receptor-mediated uptake (Figure S6). The cytotoxic response of SKOV-3 cells to GNR–siRNA carriers was low, following a 24 h exposure at the highest level tested (Figure S7).

The effect of chemisorption stability (iminothiolate vs DTC) on siRNA retention and release was quantified by flow cytometry based on the knockdown in eGFP production by transfected SKOV-3 cells. Cells were irradiated for 15 min with a CW-NIR laser irradiation 24 h after treatment with 340 pM GNR–siRNA with coadsorbed HS-PEG-folate. Solution temperatures were monitored by thermal imaging and maintained below 42 °C by using a neutral density filter to avoid unintended hyperthermic effects, with a final CW laser power density of 1.33 W/cm². For iminothiolate-anchored siRNA, a knockdown efficiency of over 40% was achieved 3 days after laser-triggered release (4 days post-transfection); however, >20% knockdown was also observed without laser irradiation (Figure 4a). This indicates that uncontrolled RNA release is significant when using the thiolated linker, albeit below the level needed to produce an efficient knockdown response. In contrast, GNRs conjugated with DTC–siRNA were able to resist nonspecific desorption within SKOV-3 cells, with essentially no knockdown effect 4 days after incubation at 37 °C in the dark. Indeed, the stability of the DTC-anchored siRNA on GNRs was such that CW laser irradiation was unable to trigger any knockdown effect.

Importantly, short-term cell viability was unaffected by laser treatment after a 24 h exposure to folate-labeled GNR–siRNA carriers (Figure S8). This implies that changes in cell population dynamics over time, if any, can be attributed to the consequences of RNA interference. We previously established that GNRs are capable of inducing cell death at

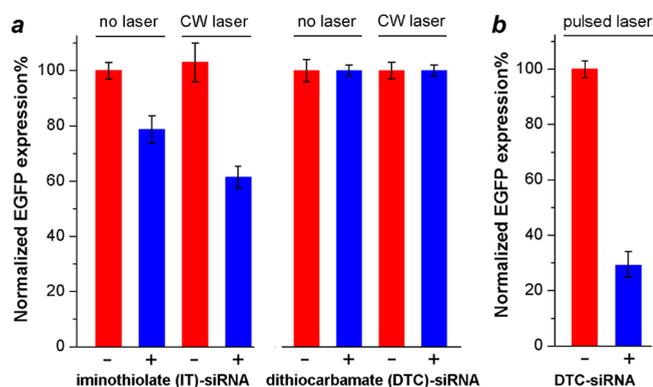


Figure 4. (a) Retention and release profiles of iminothiolate (IT)-anchored siRNA versus dithiocarbamate (DTC)-anchored siRNA on GNRs labeled with HS-PEG-folate (340 pM; blue) versus controls without siRNA (red) in transfected SKOV-3 cells using CW laser irradiation (1.33 W/cm², 15 min). eGFP knockdown experiments performed using 340 nM GNR–siRNA; efficiencies quantified by flow cytometry 3 days after laser treatment. (b) eGFP knockdown using DTC-anchored GNR–siRNA carriers (85 pM; blue) versus controls without siRNA (red) 4 days after pulsed laser treatment (0.6 W/cm², 3 min). All measurements were performed in triplicate.

low laser power by compromising membrane integrity if irradiated within a few hours of cell uptake.^{21,24} Photothermalolysis is greatly reduced for longer periods of incubation as the GNRs are internalized and stored in endosomes, which imparts greater control over cell fate by using NIR laser pulses for siRNA delivery and release.

Having established the robust chemisorption of DTC-anchored siRNA duplexes on GNRs, we relied on pulsed laser irradiation to trigger their photothermal release. SKOV-3 cells were incubated for 1 day with 85 pM GNR–siRNA carrier, then irradiated for 3 min with a stationary fs-pulsed laser at 1.2 W/cm² (Figure S9) or with a scanning fs-pulsed laser at a mean power density of 0.6 W/cm² (1.5 nJ/pulse; Figure 4b). In the former case, eGFP production was evaluated by flow cytometry using various incubation periods post-irradiation. We observed knockdown effects to be most pronounced after a 4-day incubation period, in agreement with previous observations.^{8,13}

GNR–siRNA treatment followed 24 h later by scanning fs-pulsed laser irradiation and a 4 day incubation period yielded a knockdown efficiency of 70%, whereas the control groups produced no effect (Figure 4b). This effect was stronger than that produced by stationary pulsed laser treatment (45%

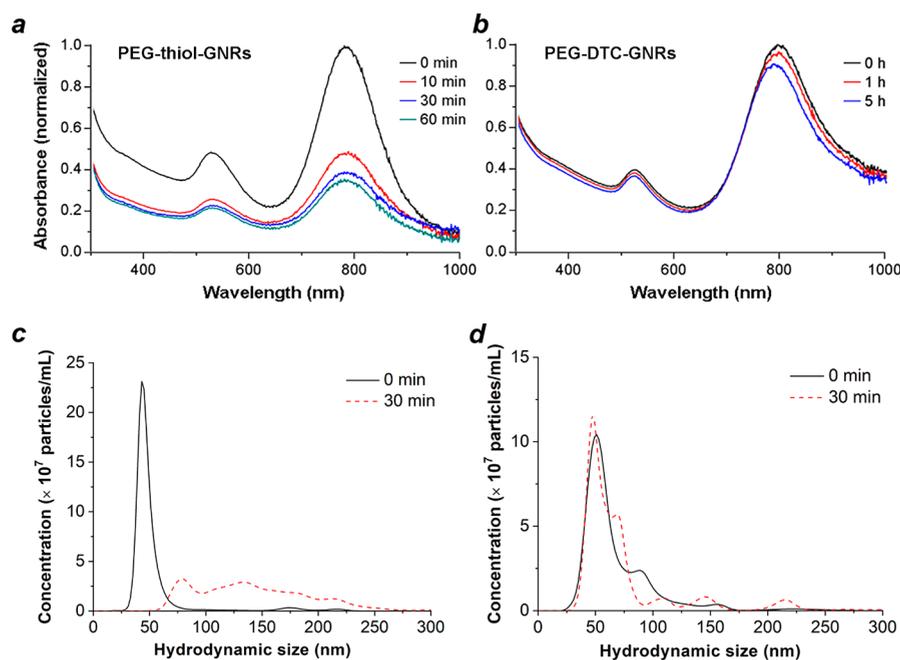


Figure 5. Dispersion stability of mPEG-coated GNRs versus exposure to 20 mM mercaptoethanol based on absorption spectroscopy ((a,b) incubation at 25 °C) and NTA ((c,d) incubation at 37 °C). (a,c) GNRs coated with thiolated mPEG (5 kDa); (b,d) GNRs coated with DTC-mPEG.

knockdown), despite the lower mean power density. The greater knockdown effect under scanning conditions was achieved by focusing the laser pulses into a 5 μm spot, intensifying the local energy density by as much as 5×10^5 times relative to the unfocused beam. It is also worth noting that knockdown by the laser-triggered release of siRNA from GNR carriers at 85 μM is higher than that obtained by the delivery of 20 nM siRNA using a cationic transfection agent (Lipofectamine RNAiMAX), consistent with previous studies using nanoshell carriers^{12,38} (Figure S9).

We attribute the absence of “dark” knockdown from GNR–siRNA carriers to the thermal stability of DTC chemisorption, including in the presence of competing adsorbates.^{55,58} Further support for this argument was obtained by evaluating the dispersion stabilities of coated GNRs in the presence of β -mercaptoethanol, a reagent used to displace chemisorbed thiols from GNRs.⁶⁹ GNRs coated with thiolated 5 kDa mPEG were treated with 20 mM mercaptoethanol, then monitored by absorption spectroscopy and NTA (Figure 5a,c). These were observed to aggregate within minutes, ostensibly due to ligand exchange and degradation of the supporting monolayer. In comparison, GNRs coated with DTC-anchored mPEG (Figure S10) were far more resistant to mercaptoethanol-induced aggregation, with a dispersion half life well over 24 h (Figure 5b,d). We note that DTC-anchored ligands can also stabilize GNRs without Au overgrowth, suggesting their robust adsorption onto Ag surfaces or adatoms (Figure S11).

To demonstrate triggered RNA interference on a gene product of biomedical importance, we applied the GNR–siRNA system toward the knockdown of tissue TG2, a critical target in preventing the metastasis of recurrent ovarian cancers.⁷⁰ TG2 promotes the epithelial-to-mesenchymal transition in SKOV-3 cells and facilitates their dislodgement from the primary tumor and invasion into the peritoneal matrix, leading to metastatic implants.^{60,71} In vivo studies using orthotopic tumor mouse models have shown that TG2

knockdown in ovarian cancer cells inhibits peritoneal metastasis,^{71,72} which motivated us to develop GNR-based carriers for the efficient delivery of TG2 siRNA to ovarian cancer cells with spatiotemporal control over siRNA release.

TG2-specific siRNA duplexes were modified by in situ DTC formation (see Table 2 for sequence details), then combined with HS-PEG-folate and added to OSB-stabilized GNRs using the ratios and optimized conditions described previously to yield the corresponding GNR–siRNA platforms. These were incubated with SKOV-3 cells for 24 h, then exposed to scanning pulsed laser irradiation for 3 min and incubated for an additional 4 days. TG2 knockdown was quantified by using a colorimetric assay to measure specific enzyme activity (Figure S12), with comparison against a positive control ($N = 3$; Figure 6). On the basis of this assay, the mean knockdown in TG2 activity was determined to be >80%, 4 days after a 3 min exposure to scanning fs-pulsed laser irradiation.

CONCLUSIONS

siRNA duplexes are securely anchored onto gold nanorod surfaces at high loading densities by using in situ DTC formation. This can be achieved with the assistance of zwitterionic surfactants such as OSB to support GNR dispersions at high ionic strength, allowing DTC-mediated chemisorption to be performed at 0.5 M NaCl in a single, efficient step. The siRNA duplexes are densely packed on GNRs with a mean footprint of 10 nm², corresponding to over 230 duplexes per nanorod. The carriers are compact in size ($d_h < 65$ nm) and form stable dispersions under physiological conditions. The DTC-anchored siRNA are highly resistant to nonspecific desorption and are released specifically by ultrafast laser pulses tuned to the GNR plasmon resonance. The enhanced control of siRNA retention and release is important for avoiding siRNA overdose and reducing the risk of nonspecific or off-target effects.⁷³ The uptake of GNR–siRNA carriers by ovarian cancer cells is greatly increased by

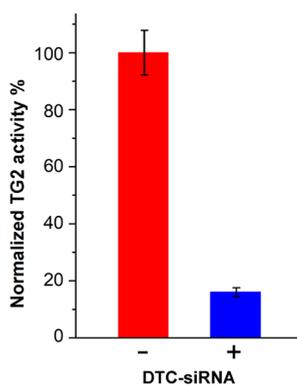


Figure 6. TG2 knockdown in SKOV-3 cells using GNR–siRNA carriers (85 pM) prepared with DTC-anchored siRNA and labeled with HS-PEG-folate, 4 days after scanning fs-pulsed laser irradiation ($N = 3$). Knockdown efficiency was estimated using a TG2-specific activity assay, which indicated >80% reduction relative to untreated cells (Figure S11).

the coadsorption of folate-PEG, enabling the targeted knockdown of cancer-relevant gene products by 80%. The use of DTC chemistry for nucleic acid chemisorption and triggered release has substantial advantages over the use of thiols and can be applied toward other siRNA delivery systems based on GNP carriers.

METHODS

All materials were obtained from Sigma-Aldrich unless otherwise noted. Polyethylene glycol (PEG) derivatives were obtained from Nanocs, RNA oligonucleotides from GE Dharmacon, Lipofectamine RNAiMAX transfection reagent from Invitrogen, 3-(*N,N*-dimethylpalmitoyl-aminopropyl)-ammonio)sulfopropyl betaine and 3-(*N,N*-dimethylmyristoyl-aminopropyl)-ammonio)sulfopropyl betaine (ASB-14 and ASB-16) from G-Biosciences, and 3-(*N,N*-dimethyloctadecylammonio)sulfopropyl betaine (C18-SB) from Be Pharm. Oleyl sulfobetaine (OSB) was synthesized as recently described.⁵⁹

Absorbance spectra and optical densities (ODs) were measured with a Cary Bio50 spectrophotometer (Varian). TEM images were obtained using a CM-100 microscope (Philips) with an accelerating voltage of 100 kV. Confocal fluorescence images were obtained using a FV1000 laser scanning microscope (Olympus) with 488 and 543 nm laser lines and emission filters set at 505–525 and 560–660 nm, respectively. Zeta potential analysis was performed with a ZetaSizer Nano (Malvern Instruments) using 633 nm laser illumination.

Nanoparticle tracking analysis (NTA) was performed with a Nanosight LM-10 microscope (Malvern Instruments) using 405 nm laser illumination; data analysis was supported by NTA v3.0. In a typical NTA study, surfactant-stabilized GNRs were diluted to OD 0.01 to 0.05 using particle-free distilled water stored in polyethylene containers, just prior to analysis. Three tracking videos were collected per sample; 50 μ L of fresh solution was injected in between each run to prevent particles from settling, followed by a 60 s recording at a camera level of 12. Optimized parameters for video analysis (advanced mode) included a detection threshold of 8, a 9×9 blur setting, and automated settings for track length. GNR concentrations were also estimated by NTA and calibrated against standardized 100 nm polystyrene particles. OSB–GNRs were

analyzed at two concentrations to establish the relationship between OD and particle concentration (Figure S4).

Preparation of OSB–GNRs. CTAB–GNRs were prepared on a gram scale using the method described by Khanal and Zubarev,⁷⁴ followed by an overgrowth process based on a protocol described by Mirkin and coworkers.⁶⁵ In brief, an aqueous suspension of GNRs (100–200 pM) in 0.01 M CTAB was treated with a final concentration of 1 mM ascorbic acid and 5 μ M HAuCl₄ for 1 h. Citrate-stabilized GNRs were prepared by subjecting CTAB–GNRs to three rounds of centrifugation and redispersion (C/R) in 1 wt % Na-PSS (M_w 70 kDa) and two rounds of C/R in 5 mM sodium citrate based on a previously established protocol.⁴⁸ Citrate–GNRs were subjected to two rounds of C/R in 0.1 M NaCl containing 1 mM OSB, resulting in OSB–GNRs.

Preparation of Iminothiolate–siRNA and DTC–siRNA. 5'-Dodecylamino-modified passenger RNA in borate buffer (pH 8.5) containing 5 mM EDTA was treated with a 20-fold excess of 2-iminothiolane (2-IT) for 3 h at 25 °C, then purified with a Zeba spin column (7 kDa MWCO) to remove excess 2-IT. The IT-modified passenger RNA was treated with one molar equivalent of antisense (guide) RNA in 100 mM NaCl for 10 min at 25 °C to form the iminothiolate–siRNA duplex.

To prepare DTC–siRNA, a saturated aqueous solution of CS₂ was freshly prepared in RNase-free water (28 mM). Dodecylamino-modified passenger RNA in borate buffer (pH 9.5) was then treated with a 100-fold excess of CS₂ solution, with a final RNA concentration above 50 μ M. The reaction mixture was allowed to sit for 8–10 h at 25 °C for in situ DTC formation, then neutralized with mildly acidic PBS (pH 6) to a final pH of 7.4. The DTC-modified passenger RNA was treated with one molar equivalent of antisense RNA in 100 mM NaCl for 10 min at 25 °C to form the DTC–siRNA duplex, which was confirmed by native PAGE (data not shown).

Preparation and Quantitative Analysis of GNR–siRNA Carriers. A suspension of OSB–GNR in 0.1 M NaCl (OD 2, ca. 170 pM) was treated with excess DTC–siRNA or IT–siRNA duplex and HS-PEG-folate, both in a 20 000:1 ratio with OSB–GNRs, and allowed to incubate in 0.5 M NaCl (adjusted concentration) for up to 12 h at 25 °C. The resulting GNR–siRNA carriers were subjected to three rounds of C/R in PBS buffer at pH 7.4. To quantify the loading density, siRNA duplexes were prepared by first converting dodecylamino-modified passenger RNA into iminothiolate– or DTC–siRNA, followed by hybridization with Dy547-labeled antisense (guide) RNA and loading the corresponding siRNA duplexes onto GNRs, as described above. For antisense strand release, a 64 pM solution of GNR–siRNA carrier (1 mL) was split into two portions. One portion was mixed with a 100 nM solution of free passenger RNA, then incubated for 10 min on a heating block at 100 °C for thermal dehybridization;⁶³ the other portion was kept at room temperature. GNRs from each portion were removed by centrifugation for 10 min at 15 000 g. Fluorescence intensities of the resulting supernatant were recorded using a Cary Eclipse spectrophotometer (Varian; $\lambda_{ex}/\lambda_{em}$ 548/564 nm) and used to quantify the concentration of released Dy547-labeled antisense RNA after background subtraction. The molarity of Dy547-labeled RNA was calibrated against a standard linear curve (Figure S5), which yielded a concentration of 14.7 nM. All measurements were performed in triplicate.

Cell Culture. All cells were cultured at 37 °C in a humidified atmosphere with 5% CO₂. SKOV-3 cells (human ovarian cancer cell line, HTB-77, American Type Culture Collection (ATCC)), MDCK cells (canine kidney epithelial cell line, CCL-34, ATCC), HepaRG cells (human hepatoma cell line), and LLC-PK1 cells (pig kidney proximal tubule epithelial cell, CL-101, ATCC) were cultivated in T-75 flasks using a RPMI 1640 culture medium (Corning Cellgro) supplemented with 10% fetal bovine serum (FBS Premium; Atlanta Biologicals), 1% glutamine, and 1% penicillin–streptomycin (Invitrogen/Thermo Fisher). SKOV-3 cells were cultured in RPMI 1640 without folic acid (Gibco/Thermo Fisher), supplemented with 10% FBS and 1% penicillin–streptomycin. Folate receptor expression was confirmed by the controlled uptake of a dye-labeled conjugate, as characterized by flow cytometry (see Figure S13). eGFP-expressing SKOV-3 cells were prepared by transfection with the corresponding DNA plasmid (pEGFP-N1, ClonTech) using linear 25 kDa polyethylenimine as the transfection agent and G418 sulfate as a selection antibiotic.⁷⁵ Fluorescence-based cell sorting was used for additional selection and repeated every tenth passage to maintain a high level of expression for gene-knockdown experiments.

Cell Viability Assays. Cell survival was quantified by the mitochondrial oxidation of methyl thiazolyl tetrazolium bromide (MTT) or by the exclusion of Trypan Blue. All experiments were performed in triplicate; reported concentration values are based on final volumes. In a typical MTT assay, SKOV-3 cells were harvested after passage and plated at a density of 5000 cells/100 μL in 96-well microtiter plates, then incubated at 37 °C under a 5% CO₂ atmosphere for 24 h. Cells were treated with 100 μL aliquots of test agent (sulfobetaine surfactant or GNR–siRNA carrier), prepared as serial dilutions with culture medium. Wells were incubated at 37 °C for 24 h, exchanged with fresh medium (90 μL) plus freshly prepared 0.5% MTT (10 μL), incubated for another 4 h, then exchanged with dimethyl sulfoxide (200 μL) and incubated at 25 °C in the dark for 16 h. The production of purple formazan was quantified by an automated plate reader (TECAN Spectrafluor Plus) at 590 nm. Cell viability was normalized relative to control cells treated with media alone prior to the MTT assay. In a typical Trypan Blue exclusion assay, SKOV-3 cells were suspended and mixed with one equal volume of 0.4% w/v Trypan Blue and allowed to stand for 3 min. Cell viability was quantified by loading a 10 μL sample onto a hemocytometer (Neubauer-improved) and determining the ratio of unstained cells versus total cell count.

Knockdown Studies. SKOV-3 cells were cultured in 96-well microtiter plates at 37 °C for 24 h, then treated with GNR–siRNA carrier (85 or 340 pM) and incubated for another 24 h prior to exposure to laser irradiation. CW irradiation was produced from a diode laser with a collimating lens and a long-pass filter (808 nm, 1.33 W/cm²). Pulsed irradiation was produced from a tunable solid-state laser (Insight DS+, Spectral Physics) with a pulse duration of 120 fs and a repetition rate of 80 MHz. Cells were washed thrice with PBS prior to laser treatment, except in the case of scanning pulse laser irradiation.

For experiments involving CW irradiation, individual wells were exposed to a 8 mm laser beam for 15 min, with solution surface temperatures monitored using a thermal camera and maintained at or below 42 °C by using neutral density filters. For experiments with stationary fs-pulsed irradiation, individ-

ual wells were exposed for 3 min to an 8 mm laser beam having a mean power density of 1.2 W/cm². For experiments with scanning fs-pulsed irradiation, the laser was focused to a 5 μm spot using a 4× objective (NA 0.1) and rastered across each well for a 3 min period (1.2 s per scan repetition) with a mean power density of 0.6 W/cm². Incident laser powers were measured with a thermopile meter (Newport). After laser irradiation, cells were incubated in the dark at 37 °C for up to 5 days, with medium replaced every other day.

Knockdown efficiencies were quantified by fluorescence-based cytometry (eGFP) or by a colorimetric enzyme activity assay (TG2). Flow cytometry (FACSCalibur, Becton-Dickinson) was performed 3 or 4 days after laser-triggered siRNA release (for representative data, see Figure S14). eGFP-transfected SKOV-3 cells in 96-well plates were washed with PBS and harvested by trypsinization, then resuspended in PBS and subjected to analysis. The distribution of eGFP fluorescence intensities was collected from a population of 10 000 cells using 488 nm laser excitation and a 530/30 nm emission filter. Mean intensity values were used to calculate knockdown efficiency; experiments were performed in triplicate.

TG2 activity was quantified by a colorimetric assay (TG2-CovTest, Novus Biologicals) and performed according to the manufacturer's instructions. Absorbance readings were calibrated by performing the assay using different SKOV-3 cell counts (serial two-fold dilution from 3.2 × 10⁴ cells; Figure S11). Treated cells were lysed at 0 °C for 10 min in a buffer composed of 150 mM NaCl, 50 mM Tris-Cl (pH 8.0), 1% Triton X-100, and 1% phenylmethylsulfonyl fluoride (PMSF), then subjected to centrifugation at 12 000g for 10 min. The cell lysates were used to establish a standard curve for the colorimetric assay. The experimental samples and untreated controls (Ctrl⁺) were both assayed in triplicate, and the relative knockdown in TG2 activity was estimated by using the linear fit from the standard curve.

■ ASSOCIATED CONTENT

📄 Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.bioconjchem.8b00723.

Characterization and quantification of surface-modified GNRs; cytotoxicity studies of GNR–siRNA and SB surfactants; standard curves for RNA density and TG2 activity; optimization of RNA knockdown conditions; flow cytometry of eGFP knockdown and folate expression (PDF)

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We gratefully acknowledge support from the Purdue University Center for Cancer Research (P30 CA023168), the Walther Cancer Institute, The U.S. Department of Veterans Affairs (I01 BX000792-06), and Mr. Dundas I. Flaherty. P.L. was supported by a Stephen R. Ash Fellowship at Purdue. We also thank Chi Zhang for assistance with fs-pulsed laser excitation, Ourania Andrisani for HepaRG cells, and Philip Low for folate-AF647.

ABBREVIATIONS

ASB, amidosulfobetaine; Cit, citrate; CTAB, cetyltrimethylammonium bromide; CW, continuous wave; DTC, dithiocarbamate; EDTA, ethylenediaminetetraacetic acid; eGFP, enhanced green fluorescent protein; FBS, fetal bovine serum; fs, femtosecond; GNP, gold nanoparticle; GNR, gold nanorod; LLC-PK1, Lilly laboratory cells, porcine kidney 1; MDCK, Madin-Darby canine kidney; mPEG, methyl(polyethylene) glycol; mRNA, messenger RNA; MTT, methyl thiazolyl tetrazolium; NIR, near-infrared; NTA, nanoparticle tracking analysis; OSB, oleylsulfobetaine; PBS, phosphate-buffered saline; RISC, RNA-induced silencing complex; siRNA, small-interfering ribonucleic acid; ssDNA, single-stranded DNA; TEM, transmission electron microscopy; TG2, transglutaminase 2; XPS, X-ray photoelectron spectroscopy

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