A Convergent Synthetic Platform for Single-Nanoparticle Combination Cancer Therapy: Ratiometric Loading and Controlled Release of Cisplatin, Doxorubicin, and Camptothecin

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ABSTRACT: The synthesis of polymer therapeutics capable of controlled loading and synchronized release of multiple therapeutic agents remains a formidable challenge in drug delivery and synthetic polymer chemistry. Herein, we report the synthesis of polymer nanoparticles (NPs) that carry precise molar ratios of doxorubicin, camptothecin, and cisplatin. To our knowledge, this work provides the first example of orthogonally triggered release of three drugs from single NPs. The highly convergent synthetic approach opens the door to new NP-based combination therapies for cancer.

Nanoparticle (NP)-based combination cancer therapy has the potential to overcome the toxicity and poorly controlled dosing of traditional systemic combination therapies.1–3 Though NP-based therapeutics for cancer therapy have been the subject of numerous investigations over the past several decades,4–8 ratiometric delivery and synchronized release of multiple drugs from single NP scaffolds remain formidable challenges.9–52 Many of the most studied NP architectures for delivery—e.g., liposomes, micelles, and dendrimers—are not readily amenable to incorporation and release of multiple drugs.

Due to the complex interactions between drugs in living systems, a NP platform for precise tuning and rapid variation of drug loading ratios and release kinetics would enable the discovery of optimal formulations for specific cancer types. We view this challenge as a synthetic problem: multi-drug-loaded NP synthesis would be most efficient if serial particle conjugation and encapsulation reactions were replaced with highly convergent approaches wherein the key elements of a desired NP (e.g., drug molecules) are used to build particles directly.13–17 Herein we present a novel strategy that uses carefully designed drug conjugates as building blocks for the parallel construction of a series of multi-drug-loaded NPs; no extraneous formulation steps are required.

Our NPs carry precise ratios of camptothecin (CPT), doxorubicin (DOX), and/or cisplatin (Pt). These drugs were chosen due to their non-overlapping toxicity profiles.18,19 The most serious dose-limiting side effects from doxorubicin arise from cardiotoxicity,20 while those from cisplatin and camptothecin result from neurotoxicity21 and myelosuppression or hemorrhagic cystitis,22 respectively. Thus, maximum therapeutic index could be achieved, in principle, via simultaneous dosing of each drug at or near its maximum tolerated dose (MTD). We show that three-drug-loaded NPs with ratios matched to multiples of the MTD of each drug outperform analogous one- and two-drug-loaded NPs in in vitro cell viability studies using ovarian cancer (OVCAR3) cells.

Our synthesis relies on the “brush-first” ring-opening metathesis polymerization (ROMP) method,23,24 which enables the preparation of nanoscopic brush-arm star polymers (BASPs). For the purposes of this study, we designed two novel macromonomers (MMs) and a novel cross-linker (Figure 1A). CPT-MM and DOX-MM are branched MMs25 that release unmodified CPT and DOX in response to cell culture media26 and long-wavelength ultraviolet (UV) light,27 respectively. Both MMs feature a 3 kDa poly(ethylene glycol) (PEG) chain that confers water solubility and neutral surface charge to the final NP.28,29 For our cross-linker design, we were drawn to Pt(IV) diester derivatives, which are widely applied as prodrugs for the clinically approved chemotherapeutic cisplatin.30–34 Pt(IV) diesters release cytotoxic Pt(II) species upon glutathione-induced intracellular reduction. We wondered whether a Pt(IV) bis-norbornene complex could serve as a cross-linker during brush-first ROMP. If so, then the resulting BASP core would be connected via labile Pt–O bonds; reduction would lead to particle degradation to yield ~5 nm brush polymers35 and free cisplatin. To explore the feasibility of this approach, we designed and synthesized Pt-XL (Figure 1A, see SI for details).

With this pool of novel monomers in hand, we targeted BASPs with molar ratios of each drug that correspond to 2 times the MTD of CPT,35 2 times the MTD of DOX,36 and 1 times the MTD of cisplatin.37 In the brush-first method, the final BASP size is determined by the MM to cross-linker ratio.23 A series of stoichiometry screens using a non-drug-loaded MM (PEG-MM, Figure 1A) and Pt-XL revealed that the most uniform BASPs formed when the total MM:Pt-XL ratio was...
Thus, this ratio was held constant for all drug-loaded particles; PEG-MM was simply replaced with DOX-MM and/or CPT-MM. For example, a three-drug-loaded particle (3) was prepared as follows: CPT-MM (2.07 equiv), DOX-MM (0.83 equiv), and PEG-MM (4.09 equiv) were exposed to Grubbs third-generation catalyst (cat., 1.00 equiv) for 20 min. Pt-XL (3.00 equiv) was added, and the mixture was stirred for 6 h at room temperature. Analogous one- and two-drug-loaded particles (1, 2a, and 2b) were prepared in parallel following similar procedures. In this system, the mass fraction of drug increases with introduction of new drug (3.4% for 1, 6.1% for 2a, 5.1% for 2b, and 7.8% for 3).

Upon completion of the brush-first ROMP reactions, the crude reaction mixtures were analyzed by gel permeation chromatography (Figure S1). In all cases, the conversion of MM and brush to BASP was >90%. A combination of UV/vis, 1H NMR, and inductively coupled mass spectrometry (ICP-MS) was used to confirm the drug ratios in 3 (Table S1). Dynamic light scattering (DLS, Figure 2B) revealed hydrodynamic diameters ($D_H$) from 122 to 191 nm for this series (Figure 2A). These values are larger than we observed for our previous photocleavable BASPs. Nevertheless, the observed $D_H$ values are suitable for passive tumor targeting via the enhanced permeation and retention (EPR) effect: they are larger than the ca. 6–8 nm renal clearance threshold and smaller than the 200–250 nm splenic clearance cutoff. Transmission electron microscopy (TEM) images of positively (Figure 2C, top) and negatively (Figure 2C, bottom) stained BASPs showed uniform NPs (Figure S2). CryoTEM images of the BASPs in aqueous solution (Figure S3) showed particle diameters that agree well with DLS data.

We next studied the cytotoxicity of these BASPs using OVCAR3 human ovarian cancer cells (Figure 3A). OVCAR3 is an established model cell line derived from a patient with platinum-refractory disease that exhibits genotypic similarity with the high-grade serous subtype. Given the widespread clinical use of anthracyclines and topoisomerase I inhibitors in second-line therapies for recurrent ovarian carcinoma, OVCAR3 is a suitable model for BASP combination chemotherapy. Exposure of OVCAR3 cells to 365 nm UV light for a 10 min irradiation period resulted in a 50% decrease in cell viability (Figure 3B) compared to non-irradiated controls. This effect is due to the release of DOX from the BASP, which is triggered by UV light. The combination of BASPs and UV light synergistically increases the cytotoxicity of these nanoparticles, making them promising candidates for targeted cancer therapy.
10 min (black circles) induced no observable toxicity. A non-drug-loaded BASP displayed toxicity only at very high concentrations (>650 μg/mL) in the presence and absence of UV light (Figure S4). Among the drug-loaded BASPs, 1 (purple curve) had the largest IC50 value: 192 ± 46 μg BASP/mL (23 ± 5 μM drug).

BASP 2a (green curve) showed a much lower IC50: 44 ± 15 μg BASP/mL (9 ± 2 μM drug). BASP 2b had an IC50 of 217 ± 23 μg BASP/mL (32 ± 3 μM drug) in the absence of irradiation (red trace), which is not significantly different from that of 1; exposure to UV for 20 min led to a 2.3 ± 0.3-fold decrease in IC50 to 93 ± 11 μg BASP/mL (14 ± 1 μM drug). No significant decrease in viability was observed following photoexposure of 1 and 2a (P = 0.078 and 0.018, respectively). These results suggest that therapeutically active cisplatin and CPT are released from these BASPs without an external trigger; DOX release is only significant upon irradiation.

When cells were treated with three-drug-loaded BASP 3 without UV irradiation (blue curve), the IC50 was 42 ± 6 μg BASP/mL (9.2 ± 0.8 μM drug). This result can be rationalized via extrapolation of the results for 1, 2a, and 2b: in the absence of light, 3 only released CPT and cisplatin, i.e., it behaved similarly to 2a (P = 0.81). After UV irradiation for 10 min, the IC50 for 3 dropped 2.3 ± 0.4-fold to 18 ± 2 μg BASP/mL (4.0 ± 0.3 μM total drug); the three-drug-loaded NP outperformed the one- and two-drug-loaded systems.

To examine cellular internalization of BASPs, we conducted a series of confocal fluorescence imaging experiments on live cells using the inherent fluorescence of DOX. After 30 min of incubation with 2b in the dark, cells were briefly irradiated with 405 nm laser light once per minute and imaged immediately afterward for 25 min (DOX λex/λem = 561/595 nm). Figure 4 shows images collected at various times (see Figure S5 for full series). Initially, punctate, extranuclear DOX fluorescence was observed to colocalize with acridine orange in the endo/lysosomes (Figure 4, far left); photoinduced DOX release led to rapid redistribution of fluorescence throughout the cytoplasm and nucleus and a 2.7-fold fluorescence intensity increase (Figure S6). To ensure that these results were due to DOX release, an experiment was conducted wherein cells were pulsed with 561 nm light rather than 405 nm. In this case, the particles remained in the endosomes (Figure S7), and no increase in mean fluorescence intensity was observed.

To our knowledge, this work represents the first example of triplex drug delivery tuned precisely to specific ratios of each drug. This novel concept for combination delivery is only made possible using highly convergent NP synthesis. This approach has no fundamental limitation in terms of the number and ratio of molecular species that could be built into particles, as long as the molecules of interest possess addressable functional groups that are compatible with ROMP. Through the combination of alternative MMs, drug linkers, and cross-linkers, libraries of multi-drug-loaded BASPs can be readily synthesized in parallel for efficacy optimization. These studies along with in vivo analysis of the current BASP systems are currently ongoing in our laboratories.

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