Dual Metronomic Chemotherapy with Nab-Paclitaxel and Topotecan Has Potent Antiangiogenic Activity in Ovarian Cancer


Abstract

There is growing recognition of the important role of metronomic chemotherapy in cancer treatment. On the basis of their unique antiangiogenic effects, we tested the efficacy of nab-paclitaxel, which stimulates thrombospondin-1, and topotecan, which inhibits hypoxia-inducible factor 1-α, at metronomic dosing for the treatment of ovarian carcinoma. In vitro and in vivo SKOV3ip1, HeyA8, and HeyA8-MDR (taxane-resistant) orthotopic models were used to examine the effects of metronomic nab-paclitaxel and metronomic topotecan. We examined cell proliferation (Ki-67), apoptosis (cleaved caspase-3), and angiogenesis (microvessel density, MVD) in tumors obtained at necropsy. In vivo therapy experiments demonstrated treatment with metronomic nab-paclitaxel alone and in combination with metronomic topotecan resulted in significant reductions in tumor weight (62% in the SKOV3ip1 model, \( P < 0.01 \) and 96% in the HeyA8 model, \( P < 0.03 \)) compared with vehicle (\( P < 0.01 \)). In the HeyA8-MDR model, metronomic monotherapy with either cytotoxic agent had modest effects on tumor growth, but combination therapy decreased tumor burden by 61% compared with vehicle (\( P < 0.03 \)). The greatest reduction in MVD (\( P < 0.05 \)) and proliferation was seen in combination metronomic therapy groups. Combination metronomic therapy resulted in prolonged overall survival in vivo compared with other groups (\( P < 0.001 \)). Tube formation was significantly inhibited in RF-24 endothelial cells exposed to media conditioned with metronomic nab-paclitaxel alone and media conditioned with combination metronomic nab-paclitaxel and metronomic topotecan. The combination of metronomic nab-paclitaxel and metronomic topotecan offers a novel, highly effective therapeutic approach for ovarian carcinoma that merits further clinical development.

Introduction

Metronomic dosing is defined as the frequent administration of a chemotherapeutic agent at low, minimally toxic doses. Metronomic chemotherapy is believed to inhibit tumor growth primarily by targeting proliferating endothelial cells (1), with an expectation of reduced side effects. Preclinical and clinical data have strengthened the rationale for the use of metronomic chemotherapy in many malignancies, including ovarian cancer (2–6). Angiogenic pathways and the tumor microvasculature are attractive targets for cancer treatment, as supported by the robust number of ongoing clinical trials in this arena (6, 7–13) in a variety of solid malignancies, including breast, prostate, neuroendocrine, hepatocellular, colorectal, and ovarian cancer. The use of metronomic chemotherapy as a means of inhibiting angiogenesis is generating clinical interest (2, 5).

Paclitaxel plays a critical role in frontline adjuvant therapy for ovarian cancer and has been shown to result in increased thrombospondin-1 (TSP-1) in the tumor microenvironment (14). However, the cremophor diluent in paclitaxel may interfere with angiogenesis inhibition at metronomic doses (15, 16). Nab-paclitaxel is a cremophor-free compound that uses 130-nanometer albumin-bound (nab) technology to circumvent the need for solvents. Nab-paclitaxel achieves a larger volume of distribution and greater suppression of tumor growth at metronomic doses than cremophor paclitaxel in many preclinical tumor models (15, 17, 18). Nab-paclitaxel has demonstrated promising activity in patients with recurrent ovarian, fallopian tube, and primary peritoneal cancers (19).

Camptothecins such as topotecan, which are known to inhibit topoisomerase I, also have antiangiogenic properties (20–24). One known mechanism of action of topotecan is its ability to suppress expression of hypoxia-inducible factor (HIF)-1α, a key hypoxia-induced transcription factor that regulates the expression...
of several proangiogenic genes such as VEGF (25, 26). Metronomic topotecan has been found effective in multiple preclinical and clinical models (27–29), including ovarian cancer (20, 23, 30–34). We have previously shown that metronomic doses of topotecan decrease cell proliferation and angiogenesis while simultaneously increasing apoptosis in murine ovarian cancer models, effects likely attributable to reductions in VEGF and HIF1α (20, 21).

Several preclinical studies in solid malignancies such as breast cancer and melanoma have previously evaluated the use of doublet combination metronomic therapy using metronomically dosed cyclophosphamide and uracil-tegafur (a fluorouracil oral prodrug; ref. 35), metronomic low-dose metronomic vinblastine and low-dose metronomic oral cyclophosphamide (36), and low-dose metronomic vinblastine and low-dose metronomic cyclophosphamide (37). The effectiveness of dual metronomic therapy preclinically has prompted evaluation of combination metronomic chemotherapy in clinical trials (38–42).

Given the unique and nonoverlapping mechanisms of action of nab-paclitaxel and topotecan (i.e., increasing secretion of TSP-1 and inhibiting HIF1α), we investigated the effects of these agents combined at metronomic doses in preclinical models of ovarian carcinoma.

**Materials and Methods**

**Ovarian cancer cell lines**

Experiments were conducted using taxane-sensitive (HeyA8 and SKOV3ip1) and taxane-resistant (HeyA8-MDR) epithelial ovarian cancer cell lines. Descriptions of the derivation and maintenance of these cell lines have been reported previously (43–45). In brief, HeyA8 and SKOV3ip1 cells were maintained in RPMI-1640/15% FBS with 0.1% gentamicin sulfate (Gemini Bioproducts). HeyA8-MDR cells were grown in the same media supplemented with 300 μg/mL paclitaxel. All experiments were performed with cells at 70% to 80% confluence. The tissue-specific microvascular endothelial cell line MOEC (murine ovarian endothelial cells) and immortalized human vascular endothelial cells (RF-24) were used for the in vitro experiments; their derivation and characterization have been previously reported (46, 47). Cells were maintained in DMEM supplemented with pyruvate, amino acids, and penicillin/streptomycin. Cell lines were obtained from the ATCC and routinely tested for absence of Mycoplasma using MycoAlert (Cambrex Bio Science) according to the manufacturer’s instructions.

**Nab-paclitaxel and topotecan reconstitution**

Nab-paclitaxel was obtained from Abraxis (Costa Mesa; ref. 48). The nab-paclitaxel dosage was determined by the paclitaxel content of the albumin-bound formulation (48). According to the manufacturer’s instructions, nab-paclitaxel was reconstituted in normal saline to a concentration of 5 mg/mL paclitaxel, prepared fresh each day, and administered within an hour of mixing. Topotecan was obtained from GlaxoSmithKline (23). According to the manufacturer’s instructions, the lyophilized powder was reconstituted to 10 mmol/L in Tri-HCl (pH 4.0), then diluted in sterile water for oral therapy before use.

**Western blot analyses**

HeyA8 cells were treated with nab-paclitaxel, metronomic topotecan or vehicle (normal saline) for 24 to 96 hours. Whole-cell lysates were prepared from both treated and untreated cells at 24-hour time points up to 96 hours using modified RIPA buffer. Forty micrograms of protein lysate was boiled for 5 minutes and then loaded onto a 8% polyacrylamide/SDS gel, transferred to nitrocellulose, and incubated with anti-human TSP-1 antibody overnight (1:100 dilution; Abcam) and carbonic anhydrase IX (1:500; Novus Biologicals). Each Western blot analysis was performed in triplicate. Equal loading was verified using vinculin (1:3,000 dilution; Sigma-Aldrich).

**Immunohistochemistry**

Immunostaining for Ki-67, cleaved caspase-3, CD31, and TSP-1 was performed on paraffin-embedded slides of ovarian cancer tumors from HeyA8 and HeyA8-MDR orthotopic models to determine the proliferative index of the cells (i.e., to determine the effects of treatment on tumor cell proliferation). Considering the proposed role of angiogenesis inhibition in the treatment of ovarian cancer, we also determined the microvessel density (MVD).

Slides were deparaffinized sequentially in xylene and declining grades of ethanol before rehydration. Antigen retrieval before Ki-67 and cleaved caspase-3 staining was performed by heating slides in a steam cooker for 10 minutes in 0.2 mol/L Tris buffer, pH 9.0, while antigen retrieval for CD31 and TSP-1 immunohistochemical analysis was accomplished using proteinase K (DakoCytomation) at room temperature. Endogenous peroxidases were blocked with 3% H2O2 in methanol (Ki-67, cleaved caspase-3, and TSP-1) or PBS (CD31). Nonspecific epitopes were blocked using 5% normal horse serum and 1% normal goat serum at room temperature. Slides were then incubated with primary antibody to Ki-67 (1:200, DakoCytomation); cleaved caspase-3 rabbit polyclonal anti-human, mouse, or rat (1:200; Biocare Medical); TSP-1 (1:100; Abcam); or CD31 (1:800; PharMingen) at 4°C overnight. After washing the slides with PBS, we added the appropriate horseradish peroxidase–conjugated secondary antibody in blocking solution for one hour at room temperature. Slides were developed with 3,3′-diaminobenzidine chromogen (Invitrogen) and counterstained with Gill No. 3 hematoxylin (Sigma-Aldrich).

The proliferative index was calculated by dividing the number of Ki-67–positive (brown) nuclei by the total number of cells for each of 5 randomly selected ×200 high-power fields per tumor specimen for each treatment group. MVD was calculated by viewing 10 representative ×200 fields per slide in each treatment group and counting the number of microvessels per field. A microvessel was defined as an open lumen with at least one CD31-positive cell immediately adjacent to it (49, 50). The apoptotic index for each treatment group was quantified as the number of apoptotic tumor cells in 10 randomly selected ×200 high-power fields per slide, excluding areas of necrosis. TSP-1 expression was quantified using ImageJ software.

Hypoxic areas on tumor samples were then evaluated using immunohistochemical staining for pimonidazole protein adducts. Hypoxic areas were determined using the Hypoxprobe staining kit (NPI, Inc.). Paraffin sections were used, and antigen retrieval was performed using a citrate solution in a microwave processor. Sections were probed with Hypoxprobe Mab-1 (1:500) overnight at 4°C; after washing, slides were incubated with secondary antibody (1:500) for 1 hour at room temperature. The hypoxic area was measured using ImageJ software.
We injected SKOV3ip1 tumor cells i.p. (1 × 10^6 cells) into female athymic mice. Fourteen days after tumor cell injection, mice were randomized into one of five treatment groups (n = 5/group): vehicle alone, MTD paclitaxel (30 mg/kg daily for 5 consecutive days in a 28-day cycle), 2.5, 5, or 10 mg/kg metronomic (daily) nab-paclitaxel. Nab-paclitaxel was administered by i.p. injection. All mice were collectively sacrificed and tumors were harvested when the control group became moribund. Blood samples were collected by intracardiac withdrawal before necropsy for hematologic assessment. Mice were monitored daily for signs of toxic effects and intolerance to therapy. Tumor weights and nodule formation were recorded and analyzed. An additional dose-finding experiment was then performed to ascertain whether greater distinction could be drawn between metronomic treatment groups. We conducted an additional dose-finding experiment using metronomic dosing of nab-paclitaxel at 2.5, 5, and 10 mg/kg every other day using HeyA8 cells (n = 5/group).

To evaluate whether therapeutic effects could be augmented while maintaining treatment tolerability, we administered metronomic topotecan by oral gavage daily at dose levels previously reported by our group (i.e., 0.5 mg/kg daily; ref. 20). Nab-paclitaxel was administered i.p. at metronomic doses every other day as determined by our dose-finding experiments. All treatments were started 7 days after tumor cell injection.

Figure 1. Tumor growth inhibition with metronomic nab-paclitaxel alone and in combination with metronomic topotecan. Nab-paclitaxel dose-finding experiment in SKOV3ip1 (A) and HeyA8 (B) tumor models of ovarian carcinoma in athymic mice. SKOV3ip1 or HeyA8 tumor-bearing mice were given nab-paclitaxel at MTD or metronomic (MET) doses of 2.5, 5, or 10 mg/kg. MET doses were administered daily for SKOV3ip1 and on alternating days for HeyA8. Mean tumor weights (±SE; n = 5 per group) are shown; *, P < 0.05 compared with vehicle. C, SKOV3ip1, HeyA8, and HeyA8-MDR tumor-bearing mice were randomly allocated to four groups and treated with either: vehicle (control), metronomic nab-paclitaxel alone (2.5 mg/kg i.p. every other day), metronomic topotecan alone (0.5 mg/kg orally every day), or metronomic nab-paclitaxel plus metronomic topotecan. Mean tumor weights (±SEM) are shown; *, P < 0.01; **, P < 0.005; ***, P < 0.005 compared with vehicle. D, survival of mice treated with vehicle (control), metronomic nab-paclitaxel, or metronomic topotecan alone and combination metronomic nab-paclitaxel plus metronomic topotecan. Nude mice (n = 10 per group) were injected with HeyA8 cells and subsequently randomized into the different treatment regimens. Treatment was continued until mice were individually moribund, and the days of life were recorded. E, mean (±SE) temporal complete blood count parameters in the SKOV3ip1 model from the therapy experiments at baseline (solid bars) and after 3 weeks of treatment (white bars). WBC, white blood count; Hgb, hemoglobin.
Figure 2.
Biologic effects of metronomic nab-paclitaxel and metronomic topotecan. A, representative images of HeyA8 tumor samples immunohistochemically stained for CD31, cleaved caspase-3, and Ki-67 from mice treated with vehicle, metronomic nab-paclitaxel (2.5 mg/kg i.p. every other day), metronomic topotecan (0.5 mg/kg orally every day), or a combination of metronomic nab-paclitaxel and metronomic topotecan. Error bars, SEM; *, P < 0.05 compared with vehicle; **, P < 0.01 compared with vehicle. hpf, high-power field. (Continued on the following page.)
inoculation, and mice were randomized into one of four treatment groups \( n = 10 \). Mice were monitored daily for adverse effects and drug tolerance. All animals were sacrificed and tumors were harvested at necropsy when the control mice began to appear moribund, approximately 3 to 4 weeks after the initiation of therapy, depending on the cell line used \( (45) \). Mouse weight, tumor weight, tumor distribution, and ascites volume were recorded.

**Animals and orthotopic model of ovarian cancer**

*In vivo* studies used female athymic mice \( (NCr-nu) \) purchased from the National Cancer Institute-Frederick Cancer Research and Development Center \( (Frederick, MD) \). Housing and care in specific pathogen-free conditions were provided as stipulated by guidelines from the American Association for Accreditation of Laboratory Animal Care, the U.S. Public Health Service Policy on Human Care and Use of Laboratory Animals, and the National Institutes of Health. All studies were approved and monitored by The University of Texas MD Anderson Cancer Center Institutional Animal Care and Use Committee.

The development of the orthotopic murine model of advanced ovarian cancer has been extensively reported by our laboratory \((51)\). In brief, SKOV3ip1, HeyA8, and HeyA8-MDR cells were collected from 70% to 80% confluent cultures using either 0.25% Trypsin-EDTA \( (GIBCO) \) or 0.1% EDTA, depending on the cell line. Cells lifted with trypsin underwent trypsin-neutralization with FBS-containing medium before being centrifuged and resuspended in the appropriate volume of serum-free Hank’s balanced salt solution \( (HBSS; Invitrogen) \) for animal inoculation. Cell lines lifted with EDTA alone were directly centrifuged at 1,000 rotations per minute for 7 minutes at 4°C, washed with PBS, and then resuspended in serum-free HBSS at the appropriate concentrations for intraperitoneal inoculation: A total of \( 2.5 \times 10^5 \) cells/200 µL HBSS for HeyA8 cells or \( 1 \times 10^5 \) cells/200 µL HBSS for SKOV3ip1 and HeyA8-MDR cells.

Therapy experiments were performed using all three cell lines. Mice were collectively sacrificed when mice in any group appeared near moribund, approximately 4 weeks after initiation of therapy, depending on the cell line. Tumors and ascites were harvested at the time of necropsy from the peritoneal cavities of mice. The number of tumor nodules were quantified, and total tumor weights were determined. Additional tumor tissue for the hematoxylin and eosin staining and immunohistochemistry (see above) was fixed in formalin at the time of tumor collection and then embedded in paraffin. Paraffin sections were uniformly cut to 5 µm.

**Endothelial cell tube formation assay**

HeyA8 cells were seeded at a density of 100,000 per well in a 6-well plate and allowed to attach overnight. The culture medium was then aspirated and replaced with fresh culture medium containing 40 nmol/L MTD nab-paclitaxel, 25 nmol/L MTD topotecan, 20 nmol/L metronomic nab-paclitaxel, 25 nmol/L metronomic topotecan, or a combination of metronomic nab-paclitaxel and metronomic topotecan. In the control, MTD nab-paclitaxel, and MTD topotecan wells, the culture medium was aspirated every 24 hours and replaced with fresh culture medium containing no drug. In the metronomic nab-paclitaxel, metronomic topotecan, and metronomic combination wells, the culture medium was aspirated every 24 hours and replaced with a fresh preparation of medium containing treatment at the concentrations listed above. After 72 hours, the culture medium from each well was collected.

RF-24 cells were maintained in DMEM supplemented with pyruvate, amino acids, and penicillin/streptomycin at 37°C. A 96-well plate was coated with 50 µL of Matrigel, which was allowed to solidify at 37°C for 10 minutes. Next, 20,000 cells per well were seeded on the Matrigel and cultured with conditioned media from wells treated with control \((n = 1)\), MTD nab-paclitaxel, MTD topotecan, metronomic nab-paclitaxel, metronomic topotecan, or a combination of metronomic nab-paclitaxel and metronomic topotecan. The cells were incubated at 37°C for 16 hours. To assess tube formation, we counted and photographed complete tubules from randomly chosen fields using an Olympus inverted microscope connected to a digital camera.

**Statistical analysis**

*In vivo* therapy experiments were powered to detect a 50% difference in tumor weight \( (β \text{ error} = 0.2) \). The Mann–Whitney rank-sum test was used to analyze nonparametric and non-normally distributed datasets. Survival experiments were analyzed by the Kaplan–Meier method. Statistical analyses were performed using SPSS 12.0 for Windows \( (SPSS \text{ Inc.}) \), and significance was set at \( P < 0.05 \) (two-tailed).

**Results**

**Metronomic dosing of nab-paclitaxel**

To determine the optimal dose and frequency of dosing to effectively inhibit tumor growth, we conducted a dose-finding experiment with nab-paclitaxel. Female nude mice \( (n = 5 / \text{group}) \) were injected with SKOV3ip1 cells i.p. and were treated with vehicle, a single dose of MTD nab-paclitaxel \((30 \text{ mg/kg i.p. daily for 5 consecutive days in a 28-day cycle}) \) or metronomic nab-paclitaxel at daily doses of 2.5, 5, or 10 mg/kg. All daily metronomic dosing levels of nab-paclitaxel produced profound inhibition of tumor growth \((\text{Fig. 1A})\).

These findings led us to perform additional dose-finding experiments using an alternating day dosing frequency in the HeyA8 tumor model. This dosing schedule resulted in less tumor inhibition \((\text{Fig. 1B})\). Moreover, pancytopenia was observed in mice that were treated with nab-paclitaxel doses of 5 and 10 mg/kg after 2 weeks, but not with the 2.5 mg/kg dose \((\text{Supplementary Fig. S1})\). Therefore, we selected 2.5 mg/kg nab-paclitaxel i.p. every other day as the optimal dose for subsequent combination experiments. MTD dosing and metronomic nab-paclitaxel at 10 mg/kg would abrogate tumor growth.
growth and prevent assessment of dual metronomic therapy. We had previously selected the dosing schedule for metronomic topotecan (20).

**In vivo effects of metronomic nab-paclitaxel and topotecan on ovarian carcinoma**

The next experiment had 4 treatment groups: (i) vehicle, (ii) metronomic nab-paclitaxel (2.5 mg/kg i.p. every other day), (iii) metronomic topotecan (0.5 mg/kg daily via oral gavage), and (iv) metronomic nab-paclitaxel every other day plus metronomic topotecan daily. Compared with vehicle, treatment with metronomic nab-paclitaxel alone resulted in a 62% reduction in tumor weight (P < 0.01), and treatment with the combination of metronomic nab-paclitaxel and metronomic topotecan resulted in a 96% reduction in tumor weight (P < 0.01) in the SKOV3ip1 tumor model (Fig. 1C). Similar results were obtained in the HeyA8 tumor model: Metronomic nab-paclitaxel alone and metronomic nab-paclitaxel combined with metronomic topotecan elicited >90% reductions in tumor weight (P < 0.03) compared with vehicle (Fig. 1C).

Recognizing the high prevalence of taxane resistance in recurrent ovarian cancer, we also tested the therapeutic potential of metronomically dosed nab-paclitaxel and topotecan in the taxane-resistant HeyA8-MDR tumor model. Although metronomic monotherapy with either cytotoxic agent alone did not overcome taxane resistance, the combination of metronomic nab-paclitaxel and metronomic topotecan decreased tumor burden by 60% (P < 0.05) compared with vehicle, thereby supporting the use of a combination of two metronomic cytotoxic agents to augment the observed therapeutic effect (Fig. 1C).

On the basis of these results with regard to inhibition of in vivo tumor growth using metronomic regimens, we next examined the effects of these regimens on survival using the HeyA8 model. Treatment with metronomic nab-paclitaxel or metronomic topotecan prolonged survival; the most significant effect on survival time was in the combination arm with metronomic nab-paclitaxel and metronomic topotecan, where survival was significantly increased (P < 0.001; Fig. 1D).

No differences in body weight were identified among treatment groups in any of the models. To assess hematologic tolerance of the combination therapy, complete blood counts were performed using blood drawn via tail vein phlebotomy just before initiating treatment and again after 3 weeks of treatment. In the complete blood count analysis, white blood cell and platelet counts did not differ over the course of treatment in animals treated with metronomic nab-paclitaxel alone or in those treated with metronomic nab-paclitaxel combined with metronomic topotecan (Fig. 1E). Direct observation of the animals’ eating habits and daily veterinary care of other physical characteristics revealed no obvious deviation from typical bowel or feeding habits, posture, or mobility among the four treatment groups in any of the three models.

**Biologic effects of metronomic nab-paclitaxel and metronomic topotecan on proliferation, angiogenesis, and apoptosis**

Given the proposed role of nab-paclitaxel on angiogenesis inhibition, we calculated the MVD of tumors harvested at the end of treatment experiments. HeyA8 tumors from animals treated with metronomic nab-paclitaxel or topotecan alone had a significant increase in apoptotic cells (2.3- and 2.68-fold, respectively; P < 0.01). Meanwhile, the combination treatment had the most profound effect on apoptosis (4.5-fold; P < 0.01; Fig. 2A). Furthermore, HeyA8-MDR tumors from mice treated with metronomic nab-paclitaxel or topotecan alone resulted in a 1.98- and 2.14-fold increase in apoptotic cells, whereas the combination therapy induced a 4.96-fold increase (Fig. 2B; P < 0.01).

We examined treatment effects on tumor cell proliferation by calculating the proliferative index after immunohistochemical staining for cleaved caspase-3 in tumors harvested after the therapy experiments. HeyA8 tumors from animals treated with metronomic nab-paclitaxel or topotecan resulted in a 64% reduction of MVD (P < 0.01) compared with vehicle (Fig. 2A). In the HeyA8-MDR model, treatment with metronomic nab-paclitaxel or topotecan had no effect on MVD; however, treatment with the combination of metronomic nab-paclitaxel and metronomic topotecan resulted in a nearly 60% reduction of MVD compared with vehicle (P < 0.01; Fig. 2B).

To determine whether apoptosis contributed to the antitumor effects observed with metronomic nab-paclitaxel and metronomic topotecan, we conducted immunohistochemical staining for cleaved caspase-3 in tumors harvested after the therapy experiments. HeyA8 tumors from animals treated with metronomic nab-paclitaxel or topotecan alone had a significant increase in apoptotic cells (2.3- and 2.68-fold, respectively; P < 0.01). Meanwhile, the combination treatment had the most profound effect on apoptosis (4.5-fold; P < 0.01; Fig. 2A). Furthermore, HeyA8-MDR tumors from mice treated with metronomic nab-paclitaxel or topotecan alone resulted in a 1.98- and 2.14-fold increase in apoptotic cells, whereas the combination therapy induced a 4.96-fold increase (Fig. 2B; P < 0.01).

To further evaluate the contribution of metronomic therapy on angiogenesis inhibition and hypoxia, we treated 3 mice from each treatment arm in the SKOV3ip1 tumor model with a hypoxia marker, pimonidazole, before sacrificing them and staining the harvested tumor tissue for pimonidazole protein adducts, which represent areas of hypoxia within the solid tumor. Immunohistochemical staining with pimonidazole showed that treatment with metronomic nab-paclitaxel alone and metronomic topotecan alone resulted in hypoxic areas in approximately 10% of the tumor tissue, compared with only 5% after treatment with vehicle (Fig. 2C). Treatment with the combination of metronomic nab-paclitaxel and metronomic topotecan resulted in nearly double the percentage of tissue showing hypoxia (19%, P = 0.04; Fig. 2C), further supporting the observation that metronomic nab-paclitaxel and metronomic topotecan exert antiangiogenic effects directly on tumors. Treatment with metronomic topotecan, nab-paclitaxel, or combination therapy led to an increase in carbonic anhydrase IX expression tumors from mice inoculated with HeyA8 cells (Fig. 2D).

**In vitro effects of metronomic nab-paclitaxel compared with MTD nab-paclitaxel**

One possible mechanism underlying the antitumor effects of metronomic chemotherapy is increased tumor cell expression of antiangiogenic factors such as TSP-1 in response to treatment. To test whether metronomic nab-paclitaxel induces TSP-1 expression in ovarian cancer cells, we treated HeyA8 cells with a sub-IC50 dose of nab-paclitaxel (0.5 nmol/L) for
up to 96 hours. In Western blot analysis, we found that protracted exposure of HeyA8 tumor cells to nab-paclitaxel resulted in a substantial and time-dependent induction of TSP-1 protein expression (Fig. 3A). TSP-1 expression was maximally induced after 72 hours of treatment, corresponding to a 2.5 times increase in TSP-1 expression compared with vehicle. To determine whether metronomic topotecan and MTD nab-paclitaxel could induce TSP-1, we treated HeyA8 cells with nab-paclitaxel at the beginning of the experiment and daily topotecan for 72 hours. Western blot analysis shows that both treatments induced TSP-1 expression (Fig. 3B) treatment with daily topotecan, MTD nab-paclitaxel and combination treatments.

Figure 3.
Effect of metronomic nab-paclitaxel and topotecan on TSP-1 expression. A, Western blot images depicting the effect of control (normal saline) and metronomic nab-paclitaxel on TSP-1 protein expression. HeyA8 cells were continuously treated with either vehicle or 0.5 nmol/L nab-paclitaxel for up to 96 hours and cell lysates were collected at 24-hour time points. The graph shows the band intensity of TSP-1 normalized to the loading control, vinculin. B, Western blot analysis depicting the effect of control (normal saline), metronomic topotecan (25 nmol/L daily), and the maximally tolerated dose (MTD) of nab-paclitaxel (20 nmol/L once) on TSP-1 expression. Cell lysates were collected after 72 hours. C, tube formation of RF-24 cells after treatment with conditioned media of each treatment group, representative images shown. (original magnification ×100; scale bar, 100 µm). D, representative images of HeyA8 tumor samples immunohistochemically stained and quantified for TSP-1 (original magnification ×100; scale bar, 100 µm). Error bars, SEM; *, P < 0.05 compared with vehicle; **, P < 0.01 compared with vehicle.
Next, we performed tube formation assays using RF-24 cells exposed to conditioned media from HeyA8 cells that were exposed to nab-paclitaxel or topotecan. Tube formation was inhibited in RF-24 endothelial cells exposed to conditioned media from HeyA8 cells exposed to metronomic nab-paclitaxel and topotecan whereas the combination treatment had the most robust effect (Fig. 3C).

To investigate whether metronomic dosing increased TSP-1 expression in vitro, we performed immunohistochemistry analyses on HeyA8 tumor samples. Our data show that metronomic nab-paclitaxel and topotecan increased TSP-1 expression whereas this effect was exacerbated in the combination group (Fig. 3D).

**Discussion**

In this study, we demonstrated marked antitumor activity in ovarian carcinoma models using combination metronomic chemotherapy. These effects were mediated, in part, through a significant reduction in tumor cell proliferation and increased apoptosis. We also demonstrated that metronomic administration of nab-paclitaxel increased levels of TSP-1, thereby disrupting angiogenesis and providing a mechanism by which this compound elicits its therapeutic effects. These antitumor and anti-angiogenic effects were validated in both taxane-sensitive and taxane-resistant tumor models.

Our results suggest that, although apoptosis plays a role in eliciting the observed antitumor effects of treatment with metronomic topotecan, the reduction in tumor growth seen with metronomic nab-paclitaxel appears to be more attributable to the inhibition of angiogenic factors, resulting in large areas of hypoxia within the tumor. In addition, a resultant increase in the inhibition of endothelial tube formation by conditioned media from cells treated with metronomic nab-paclitaxel alone and in combination with metronomic topotecan supports existing evidence that metronomic dosing not only has direct cytotoxic effects on endothelial cells, but also indirectly inhibits angiogenesis through the release of mediators from the cancer cell into the tumor microenvironment (52).

Angiogenic pathways and the tumor microvasculature are attractive targets for cancer treatment, as supported by the robust number of ongoing clinical trials in this arena (6). Nevertheless, both intrinsic and acquired resistance to angiogenic drugs are emerging as clinically relevant issues (53, 54). Mounting data suggest that administering traditional cytotoxic agents at metronomic doses exerts antiangiogenic effects (6, 52, 55, 56). Metronomic paclitaxel has stronger antitumor activity in terms of antitumor efficacy, and novel combination regimens of metronomic chemotherapy are needed.

Our study provides evidence of potent antitumor activity in both taxane-sensitive and taxane-resistant orthotopic models of metastatic ovarian carcinoma after treatment with metronomic nab-paclitaxel alone and in combination with metronomic topotecan. With potent antitumor effects in the absence of overt toxic effects that occur with traditional chemotherapy, metronomic nab-paclitaxel alone or in combination with topotecan is a strategy worthy of further clinical investigation.

**Disclosure of Potential Conflicts of Interest**

No potential conflicts of interest were disclosed.

**Authors' Contributions**

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Dual Metronomic Chemotherapy with Nab-Paclitaxel and Topotecan Has Potent Antiangiogenic Activity in Ovarian Cancer

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