Potent Preclinical Impact of Metronomic Low-Dose Oral Topotecan Combined with the Antiangiogenic Drug Pazopanib for the Treatment of Ovarian Cancer

Kae Hashimoto1, Shan Man1, Ping Xu1, William Cruz-Munoz1, Terence Tang1, Rakesh Kumar3, and Robert S. Kerbel1,2

Abstract

Low-dose metronomic chemotherapy has shown promising activity in many preclinical and some phase II clinical studies involving various tumor types. To evaluate further the potential therapeutic impact of metronomic chemotherapy for ovarian cancer, we developed a preclinical model of advanced human ovarian cancer and tested various low-dose metronomic chemotherapy regimens alone or in concurrent combination with an antiangiogenic drug, pazopanib. Clones of the SKOV-3 human ovarian carcinoma cell line expressing a secretable β-subunit of human chorionic gonadotropin (β-hCG) protein and firefly luciferase were generated and evaluated for growth after orthotopic (i.p.) injection into severe combined immunodeficient mice; a highly aggressive clone, SKOV-3-13, was selected for further study. Mice were treated beginning 10 to 14 days after injection of cells when evidence of carcinomatosis-like disease in the peritoneum was established as assessed by imaging analysis. Chemotherapy drugs tested for initial experiments included oral cyclophosphamide, injected irinotecan or paclitaxel alone or in doublet combinations with cyclophosphamide; the results indicated that metronomic cyclophosphamide had no antitumor activity whereas metronomic irinotecan had potent activity. We therefore tested an oral topoisomerase-1 inhibitor, oral topotecan, at optimal biological dose of 1 mg/kg/d. Metronomic oral topotecan showed excellent antitumor activity, the extent of which was significantly enhanced by concurrent pazopanib, which itself had only modest activity, with 100% survival values of the drug combination after six months of continuous therapy. In conclusion, oral topotecan may be an ideal agent to consider for clinical trial assessment of metronomic chemotherapy for ovarian cancer, especially when combined with an antiangiogenic drug targeting the vascular endothelial growth factor pathway, such as pazopanib. Mol Cancer Ther; 9(4); 996–1006. ©2010 AACR.

Introduction

A chemotherapy dosing and scheduling strategy attracting growing interest is low-dose metronomic chemotherapy. It involves the close, regular administration of conventional chemotherapeutic drugs without prolonged drug-free “holidays” over extended periods of time (1–3). In contrast to conventional, pulsatile maximum tolerated dose (MTD) chemotherapy, the main primary target, initially, of metronomic chemotherapy is thought to be the tumor’s neovasculature (1–3), although additional mechanisms are likely involved as well, e.g., stimulation of the immune system through reduction in regulatory T cells (4–6) and possibly direct tumor cell–targeting effects (7). The antiangiogenic effects of low-dose continuous metronomic chemotherapy are thought to be mediated through several possible mechanisms, including direct targeting of activated endothelial cells of angiogenic blood vessel capillaries (1, 2), and circulating bone marrow–derived endothelial progenitor cells (8, 9). Some of the aforementioned cellular antiangiogenic effects may be mediated by systemic induction of angiogenesis inhibitors, e.g., thrombospondin-1 (10, 11). Another recently proposed mechanism is by targeting HIF-1 in the tumor cell population and hence its ability to induce angiogenesis by upregulating factors such as vascular endothelial growth factor (VEGF; ref. 12–14). Concurrent combination of metronomic chemotherapy with targeted biological antiangiogenic agents such as anti-VEGF receptor 2 (VEGFR-2) antibodies or small molecule receptor tyrosine kinase inhibitors can sometimes cause surprisingly potent and sustained antitumor effects in preclinical models, accompanied by an absence of overt host toxicity even after chronic therapy (1, 2, 15).

Given the promising preclinical therapeutic results of a number of metronomic chemotherapy–based treatment studies, and the excellent safety profile of this treatment
strategy, in addition to some early phase II clinical studies that have shown promising results (16), many subsequent metronomic chemotherapy trials have been initiated, a large proportion of which involve concurrent therapy with an antiangiogenic drug such as bevacizumab, sunitinib, or sorafenib, or other types of biological agents, e.g., the hormonal antagonist letrozole (www.clinicaltrials.gov under the heading of “metronomic chemotherapy”). The results of a limited number of such trials have been completed and published, with the most encouraging results thus far reported in patients with metastatic breast cancer (17, 18) and recurrent, advanced, or metastatic ovarian cancer (19–22).

Regarding the various aforementioned ovarian cancer trials reported thus far, all have involved daily low-dose oral cyclophosphamide using a fixed dose of 50 mg, combined with bevacizumab, administered at 10 mg/kg every two weeks. However, because bevacizumab monotherapy is known to be active in advanced ovarian cancer (23–28), it is not clear whether the addition of the metronomic cyclophosphamide contributed meaningful additional activity to the observed clinical benefits in these trials. Even if it did, there may be better chemotherapy drugs for metronomic chemotherapy–based treatments of ovarian cancer. One obvious candidate to consider in this regard is oral topotecan.

Topotecan, a topoisomerase I inhibitor, is an approved drug used for the second-line treatment of ovarian cancer patients whose tumors have become refractory to conventional first-line therapy, e.g., paclitaxel plus platinum-based doublet chemotherapy (29–32). An oral version of topotecan has been approved (33) and thus, in theory, would be ideal for metronomic chemotherapy regimens involving prolonged daily therapy, similar to oral cyclophosphamide. Indeed there is some limited preclinical evidence showing the superiority of daily oral low-dose topotecan compared with intermittent i.v. injected topotecan using a panel of human tumor xenograft models (34). Furthermore, antitumor activity in pediatric xenograft models of topotecan or irinotecan is enhanced by low-dose protracted schedules (see ref. 35). Furthermore, another topoisomerase I inhibitor, irinotecan, when combined with gemcitabine, has been reported to be active when administered in a metronomic fashion in a preclinical model of human colorectal carcinoma xenografts (36) and lung carcinoma xenografts (37), and some preliminary clinical data also indicate metronomic irinotecan may be active in human colorectal carcinoma (38). Finally (as reported in this article), we recently found in preliminary studies that low-dose metronomic irinotecan therapy administered i.p. twice a week was very active in an orthotopic model of human ovarian cancer, and moreover, this was associated with little toxicity, even after long-term treatment.

With the aforementioned information in mind, we decided to test the antitumor activity of oral topotecan alone and in combination with other agents in a new model of advanced orthotopic human ovarian cancer that we developed. The orthotopic model involves luciferase-tagged SKOV-3 ovarian carcinoma cells injected into the peritoneal cavity; treatment is initiated when the disease has been firmly established, as assessed by photon bioluminescence measurements—a methodology that was also used to assess the efficacy of the therapies tested. In addition to oral topotecan, we tested the oral antiangiogenic drug pazopanib, which targets VEGF and platelet-derived growth factor (PDGF) receptors (39–41), and in combination with oral topotecan, which therefore comprises an all-oral combination treatment regimen. We also tested a number of other regimens, including an oral metronomic cyclophosphamide protocol administered through the drinking water known to be highly active in preclinical models of advanced metastatic breast and melanoma that we have previously developed (7, 42) as well as in lymphomas (8). The rationale for testing anticancer treatment strategies, including metronomic chemotherapy, using models of more advanced disease is that the results may have greater relevance (i.e., predictive value) with respect to patients afflicted with the respective malignancies at an advanced stage of disease (7). Some preliminary support exists for this rationale based on a clinical trial evaluating bevacizumab with daily oral metronomic cyclophosphamide and capecitabine (an oral 5-fluorouracil prodrug) in metastatic breast cancer (17); the use of this doublet metronomic chemotherapy regimen was based in part on extremely promising results testing oral metronomic UFT (tegafur plus uracil—another 5-fluorouracil prodrug) plus metronomic cyclophosphamide in a model of established high-volume visceral metastatic breast cancer (7).

Here we report extremely encouraging antitumor results using daily low-dose metronomic oral topotecan, especially when combined with pazopanib. Moreover, the therapy could be maintained for half a year without any obvious toxic side effects.

Materials and Methods

Cells and reagents

The human ovarian cancer cell line SKOV-3 (American Type Culture Collection) was grown in RPMI 1640 (Hyclone) supplemented with 5% fetal bovine serum in a humidified atmosphere at 37°C in 5% CO2. SKOV-3 cells with stable expression of the β subunit of human gonadotropin (β-hCG) and firefly luciferase were generated sequentially, first by transfection of pIRES-hCG plasmid using Lipofectamine (Life Technologies, Inc.) and selection in medium containing puromycin, and subsequently by pcDNA3.1-luciferase transfection also using Lipofectamine and selection of positive clones in medium containing G418. The β-hCG protein is secreted and can be measured in the urine as a surrogate molecular marker of changes in systemic tumor burden (43, 44). Selected β-hCG- and luciferase-positive clones were injected i.p. into severe combined immunodeficient (SCID) mice, and one of the clones (SKOV-3-13) was subsequently chosen for use in all of the experiments. The rationale for selecting the SKOV-3-13 clone...
is that it gave rise to greater levels of peritoneal carcinomatosis than the other clones we analyzed. We also evaluated other human ovarian cancer cell lines, e.g., Caov-3 and OVCAR-3, but almost none of the clones isolated from these cell lines developed a peritoneal carcinomatosis; furthermore, some clones that gave rise to peritoneal tumors were very slow growing, making analysis of therapeutic outcomes impractical.

**Experimental animals**

Six-week-old female CB-17 SCID mice (Charles River Canada) were housed in microisolator cages and vented racks and were manipulated using aseptic techniques. Procedures involving animals and their care were conducted in strict conformity with the animal care guidelines of Sunnybrook Health Science Centre and the Canadian Council of Animal Care. For the advanced orthotopic tumor model, 3 million (5 million for a preliminary experiment) β-hCG- and luciferase-tagged SKOV-3-13 cells were injected i.p. into CB-17 SCID mice. Two weeks later (10 d later for the preliminary experiment) the mice were separated into various groups equalized by assessment of urinary β-hCG levels, and treatment was initiated. For the s.c. transplant model, 3 million SKOV-3-13 cells were injected into the right flank of CB17 SCID mice. Correlation between tumor size and urinary β-hCG levels was evaluated when the tumor volumes reached approximately 100 mm³. Tumor growth was monitored weekly by total body bioluminescence imaging after luciferin administration and was subsequently chosen for use in all of the therapy experiments. A, clones of the SKOV-3 cell with stable expression of luciferase and β-hCG were injected i.p. into CB-17 SCID mice as an advanced orthotopic ovarian cancer model. Tumor growth was monitored by total bioluminescence imaging after luciferin administration. The most aggressive of these clones, SKOV-3-13, develops more peritoneal carcinomatosis and was subsequently chosen for use in all of the therapy experiments. B, correlation between the tumor measurement methods. i, urine β-hCG levels were measured by ELISA and corrected by urine creatinine levels. When the s.c. tumors reached approximately 100 mm³, urinary β-hCG levels (97.3 ± 54.2 mIU/mg) were almost same as the orthotopic model the time of treatment initiation (107.8 ± 41.9 mIU/mg). Relationship between urinary β-hCG levels and bioluminescence (photons/s) in the orthotopic transplant model (ii), or urinary β-hCG levels and tumor volume (mm³) in the s.c. transplant model (iii). Solid line, simple linear regression between the two methods; each dot denotes an individual mouse.

**β-hCG measurements**

Mouse urine was collected by placing mice in empty aerated tip boxes for 2 hours as described previously (43, 44). Collected urine samples were stored at −70°C until analyzed. Urine β-hCG levels were measured using a
free-βhCG ELISA kit (Omega Diagnostics Ltd.), and normalized by concomitant measurement of urine creatinine levels using the QuantiChrom Creatinine assay kit (BioAssay System) following the manufacturer’s instructions.

**Total body bioluminescence imaging**

Mice were administered luciferin (150 mg/kg), and 15 minutes later they were imaged in an IVIS200 Xenogen under isofluorane anesthesia, as previously described (45). Luciferin stock solution (15 mg/mL) was made up in PBS and kept frozen at −70°C until use.

**Analysis of circulating endothelial progenitor cells**

Assessment of circulating endothelial progenitor cells (CEP) used to determine the optimal biological dose (OBD) for metronomic chemotherapy was done as previously described (8, 9). Briefly, using four-color flow cytometry, viable CEPs were defined as CD45−, VEGFR-2+, CD117+, and CD13+. The absolute number of viable CEPs was calculated as the percentage of events collected in CEP enumeration gates multiplied by the total WBC count.

**Drugs and schedules**

Cyclophosphamide (Baxter Oncology GmbH), irinotecan (Mayne Pharma Canada Inc.), paclitaxel (Bristol Mayer Squibb, Canada), cisplatin (Faulding Canada Inc.), and topotecan (GlaxoSmithKline Inc.) were purchased from the institutional pharmacy. Oral topotecan, pazopanib, and the pazopanib vehicle, hydroxypropylmethyl cellulose, were supplied by GlaxoSmithKline. These drugs were reconstituted as per the manufacturer’s instructions.

Metronomic dosing and administration of cyclophosphamide (20 mg/kg/d) was given as described previously (46), i.e., daily through the drinking water, with an initial (upfront) and every 6-week bolus dose (100 mg/kg) i.p. administration of the drug. Low-dose metronomic (LDM) irinotecan (10 mg/kg) and LDM cisplatin (1 mg/kg) were given twice a week by i.p. injection. LDM paclitaxel (1 mg/kg) was given 3 times a week by i.p. injection. These doses were based on CEP analysis, as reported previously (7, 46). In other words, the dose causing the nadir in viable CEP suppression, and showing no toxicity after 1 week of treatment, was used (9). MTD topotecan was given at 1.5 mg/kg 5 days consecutively every 3 weeks through i.p. injection. This MTD was based on the literature (47). For both oral topotecan and pazopanib, we evaluated the putative OBD by CEP analysis (as shown in Fig. 5). Oral topotecan was given at 1 mg/kg daily by gavage, and we used two doses for pazopanib, either 25 mg/kg given twice a day by gavage or 150 mg/kg once a day by gavage.

**Statistical analysis**

Tumor therapy results are reported as mean ± SD. Survival curves were plotted by the method of Kaplan and Meier and were tested for survival differences with the log-rank test. Statistical significance was assessed by Student’s *t* test. The level of significance was set at *P* < 0.05 (**, *P* < 0.01 and *, *P* < 0.05 in figures).

**Results**

**Development of an orthotopic ovarian cancer xenograft model in mice for therapy testing**

We established an “advanced” orthotopic metastatic model of ovarian cancer with which to test various therapeutic regimens. To develop a model comprising a version of more advanced ovarian cancer, we orthotopically implanted SKOV-3 human ovarian cancer cells by i.p. injection because direct i.p. seeding is a common avenue of ovarian cancer metastasis (48–50). Cancer cells detach from the primary tumor and spread throughout the peritoneal cavity, thus generating metastatic tumor deposits...
to be initiated (10 to 14 days after i.p. injection). In addition, to confirm the correlation between tumor size and bioluminescence/urinary β-hCG we analyzed a conventional s.c. transplant model. SKOV-3-13 was implanted s.c. in the right flank, and subsequent tumor growth was monitored by caliper measurements or by urinary β-hCG levels. When the tumor sizes reached about 100 mm³, we evaluated urinary β-hCG levels by ELISA. The level of urinary β-hCG (97.3 ± 54.2 mIU/mg) at this point was similar to the orthotopic model (107.8 ± 41.9 mIU/mg) at the time of treatment initiation (Fig. 1Bi). To confirm the relationship between urinary β-hCG levels and tumor volumes, we plotted tumor volumes and urine β-hCG levels; a linear relationship was found between the two parameters (Fig. 1Bii, r = 0.73). Urinary β-hCG and total body bioluminescence also showed a linear relationship (Fig. 1Bii, r = 0.70).

### Preliminary assessment of combination metronomic chemotherapy regimens

We tested several monotherapy or combination metronomic chemotherapy regimens in the advanced orthotopic ovarian cancer model. We initially chose metronomic cyclophosphamide as the primary “base” treatment and combined it with other chemotherapy drugs (paclitaxel, cisplatin, and irinotecan), all administered in a metronomic dosing fashion. Cyclophosphamide was chosen as the primary partner because of its frequent use in metronomic chemotherapy clinical trials, including ovarian cancer (see Introduction). The other chemotherapy drugs selected—paclitaxel, cisplatin, irinotecan (and oral topotecan)—are all used to treat ovarian cancer patients. SKOV-3-13 cells (5 million cells/mouse) were injected into the peritoneal cavity (n = 5), and 10 days after injection the various treatments were initiated. Treatment with metronomic cyclophosphamide alone and cyclophosphamide plus cisplatin had no obvious antitumor effect. Cyclophosphamide plus paclitaxel caused a tumor growth delay that lasted approximately four weeks after initiation of treatment; at this point tumor growth resumed, resulting in a small survival benefit (Fig. 2A). The most effective combination tested was the cyclophosphamide-plus-irinotecan doublet. Metronomic cyclophosphamide plus irinotecan seems to cause significant tumor growth delays compared with the other drugs tested. Median survival values (P values of survival benefit) were 18 days for control, 18 days (P = 0.87) for single-agent cyclophosphamide, 18 days (P = 0.42) for cyclophosphamide plus cisplatin, 30 days (P = 0.04) for cyclophosphamide plus paclitaxel, and 70 days (P = 0.04) for cyclophosphamide plus irinotecan (Fig. 2B).

### Effect of metronomic cyclophosphamide alone or in combination with irinotecan for the treatment using the orthotopic advanced ovarian cancer xenograft model

Based on our preliminary results, we chose metronomic cyclophosphamide plus metronomic irinotecan chemotherapy to assess treatment efficacy in a comparative manner. We assessed tumor growth and survival in four different therapy groups: vehicle control, LDM
cyclophosphamide, LDM irinotecan, and the doublet combination of LDM cyclophosphamide and irinotecan. In this experiment we modified the orthotopic ovarian cancer xenograft model to create more time before the mice reached the end point, and to ensure a firmly established peritoneal tumor was present at the time therapy was initiated. Thus, we injected 3 million cells, and treatment was initiated two weeks after tumor cell inoculation. As shown in Fig. 3A, single-agent metronomic cyclophosphamide did not have any obvious antitumor effect. Thus, the impact on survival was not significant when comparing the control group versus single-agent metronomic cyclophosphamide. In contrast, single-agent metronomic irinotecan caused a significant tumor growth delay and prolongation of survival. However, there was no difference between single-agent irinotecan and irinotecan plus cyclophosphamide, not only with respect to tumor growth but also to survival. Moreover, the combination treatment group was notable for increase in toxicity. After a second injection of MTD cyclophosphamide, combination treatment mice showed body weight loss and some had to be sacrificed because of excessive body

Figure 4. CEP analysis to determine the OBD of oral topotecan and pazopanib. Normal balb/c mice were treated with oral topotecan or pazopanib. Doses used were 0, 0.25, 0.5, 1.0, and 2.0 mg/kg/d daily gavage for oral topotecan; 0, 10, 25, 50, 100 mg/kg twice a day, by gavage, and 0, 50, 100, 120, 150 mg/kg once a day, by gavage for pazopanib. CEP analysis was done after 7 or 28 d of treatment. *, P < 0.05.
Median survival values were as follows: 36 days for control, 45 days (P = 0.34) for cyclophosphamide, 79 days (P = 0.0026) for irinotecan, and 83 days (P = 0.0026) for cyclophosphamide and irinotecan. Thus, metronomic cyclophosphamide did not seem to have any additive effect on the irinotecan-induced benefit in the orthotopic model (Fig. 3B). In summary, metronomic cyclophosphamide did not have activity when tested in the advanced stage ovarian cancer model we developed.

Impact of metronomic oral topotecan alone or in combination with the oral antiangiogenic agent pazopanib

Given the encouraging results of the low-dose metronomic irinotecan protocol, we decided to evaluate the therapeutic efficacy of an oral topoisomerase inhibitor, oral topotecan, for its efficacy in the advanced ovarian cancer xenograft model we developed. We also tested metronomic oral topotecan in combination with the oral
small molecule antiangiogenic agent pazopanib as a possible all-oral combination treatment. Before the various therapies were tested, we first estimated the OBD for both drugs. In this regard, we have previously reported that levels of bone marrow–derived CEPs can be used as biomarkers to monitor various targeted antiangiogenic drug activity as well as for estimating the OBD; this approach can be used for metronomic chemotherapy as well (7, 9). Using this approach we determined the OBD for oral topotecan administered by gavage on a daily basis. As shown in Fig. 4A, oral topotecan significantly decreased viable CEP levels at 1 mg/kg and 2 mg/kg daily dose after both 7 days and 28 days of continuous treatment. We also evaluated the OBD for pazopanib using daily gavage schedules of twice a day or once a day, based on our observations (Fig. 4B) that showed only a trend in reduction of viable CEP levels, we chose the schedules of 25 mg/kg dose administered twice a day and 150 mg/kg dose once a day. Interestingly, these doses and schedules are not inconsistent with previously published information regarding optimal antitumor activity in several xenograft models based on empirical drug testing in vivo (41). The mice did not show any side effects with either drug at any dose we used, at least for the 28-day schedule we used. Based on these results we estimated the OBD of oral topotecan to be in the 1 mg/kg daily range and pazopanib in the 25 mg/kg range (for the twice-a-day schedule, or bd) and 150 mg/kg (for the once-a-day schedule, or qd).

The treatment groups were as follows: vehicle control, MTD topotecan, 25 mg/kg bd pazopanib, 150 mg/kg qd pazopanib, oral topotecan, oral topotecan plus 25 mg/kg bd pazopanib, and oral topotecan plus 150 mg/kg qd pazopanib. As shown in Fig. 5Ai and Aii, single-agent oral topotecan showed significant tumor growth delay and survival benefit (Fig. 5B) whereas the other single-agent therapies tested did not. The median survival value of mice in the control group was 34 days after start of treatment compared with 73 days ($P = 0.014$) for the MTD topotecan group, 41 days ($P = 0.19$) for the 25 mg/kg pazopanib
group, 41 days \((P = 0.19)\) for the 150 mg/kg pazopanib group, 90 days \((P = 0.0075)\) for the oral topotecan group, and all of the mice in the oral topotecan/pazopanib combination treatment groups were still alive 180 days \((P = 0.0025)\) after initiation of treatment. Pazopanib provided a significant added beneficial effect to oral metronomic topotecan at both schedules of 25 mg/kg twice a day and 150 mg/kg once a day (Fig. 5B), although we noted the gradual, slow emergence of relapsing tumors in the 25 mg/kg twice a day pazopanib plus oral topotecan group after a little over five months of therapy (Fig. 5B). We also evaluated the toxicity of these treatments by body weight loss and WBC counts. Mice showed body weight loss when they became moribund due to tumor growth, but decreases in the body weight were not observed as a result of the treatments (Fig. 5C). Peripheral blood WBC counts were increased by tumor growth, but decreases in the WBC counts lower than non–tumor-bearing mice level were observed only in the MTD topotecan group, after four weeks of treatment (Fig. 5Ci).

Discussion

This study represents the latest in a series of investigations in which models of advanced disease involving human tumor xenografts grown in immune deficient mice are developed for use in the testing of particular anticancer treatment strategies. The cancer treatments we have been studying mainly consist of low-dose metronomic chemotherapy generally in doublet combinations of two different chemotherapy drugs (7, 42) or a single chemotherapy drug combined with a targeted biological agent, usually an antiangiogenic drug (2) or other types of targeted agents such as trastuzumab (44). In this case the focus of our studies has been ovarian cancer. Whereas the other advanced disease models we have developed involve establishment of visceral metastases in multiple organ sites such as the lungs or liver after surgical resection of primary orthotopic transplanted variant tumors previously selected for aggressive spontaneous metastasis, e.g., breast cancer or melanoma (7, 42), here we employed i.p. injection of an established line of human ovarian carcinoma cells (SKOV-3) "tagged" with markers to serially monitor disease burden over time. The rationale for this orthotopic approach was based on ovarian cancer often spreading within the peritoneal cavity, but not necessarily outside this location. Our reasoning is that if a particular therapy induces potent antitumor effect in this more therapeutically demanding and clinically relevant situation, it will likely have a greater probability of showing some kind of meaningful clinical benefit when used to treat patients with advanced disease of the same type of cancer (7, 17). This is similar in approach to that adopted by Landen et al. (51) and Thaker et al. (52) in previous studies.

With the aforementioned rationale in mind, the most compelling results we observed was with daily low-dose metronomic oral topotecan, especially when administered concurrently with daily oral pazopanib, the VEGF and PDGF receptor targeting oral antiangiogenic receptor tyrosine kinase inhibitors. Topotecan is already approved for the second-line treatment of ovarian cancer, but is usually given i.v. at maximum tolerated doses on an intermittent basis, and thus is associated with several toxic side effects such as myelosuppression, fatigue, and diarrhea (29–33). An oral formulation of the drug taken in an outpatient basis at low nontoxic or minimally toxic doses would therefore be a considerable advantage if associated with significant antitumor efficacy. It is important to note that although we only studied one cell line/model, similar therapeutic results utilizing metronomic oral topotecan plus pazopanib in other models of human ovarian cancer xenografts using different cell lines have been obtained concurrently and independently, e.g., as reported in the accompanying paper by Merritt et al. (53). This increases the prospect that this treatment regimen may indeed have promising activity for treating advanced ovarian cancer. In this regard, given the known clinical activity reported for bevacizumab monotherapy in ovarian cancer (24–28), it will be of interest to evaluate low-dose oral metronomic topotecan in combination with this antiangiogenic agent. We would note that bevacizumab has shown antitumor activity in our ovarian cancer model as a single agent, comparable with pazopanib, but combining the oral metronomic cyclophosphamide protocol we used with bevacizumab did not improve the extent of this benefit (data not shown).

An interesting aspect of topotecan as an anticancer drug, especially when administered in a low-dose metronomic manner, is its suppressive effect on expression of tumor cell HIF-1, as first described by Melillo and his colleagues (12). A similar effect has been described by Semenza and colleagues using low-dose doxorubicin (13). There is considerable interest in HIF-1 as a therapeutic target in oncology because of its central role in regulating a broad spectrum of genes involved in tumor angiogenesis, invasion, and metastasis (54). Thus, exposure of tumor cells to topotecan can result in suppressed expression of VEGF likely as a result of HIF-1 downregulation (12). From this perspective metronomic topotecan therapy may be ideal to combine with an effective and chronic antiangiogenic drug (14) therapy that would normally be expected to increase tumor hypoxia and thus possibly act as a potential driving force for both HIF-1–mediated acquired resistance to the antiangiogenic drug by inducing alternate pathways of angiogenesis (55) and/or promoting increased invasion or metastasis (56). The ability of low-dose metronomic oral topotecan to suppress proangiogenic bone marrow derived cells, as reported here, is another way in which it may suppress tumor angiogenesis, and this could conceivably be related to an effect on HIF-1 (13), although this has yet to be determined.

Another interesting aspect of our results is the gradual appearance of tumors in the mice treated with 25 mg/kg...
twice a day of pazopanib plus oral topotecan after over five months of continuous therapy. These relapsing tumors are now being analyzed for resistance to one or both of the drugs to which they were exposed.

Finally we would note that we failed to detect antitumor effects of low-dose metronomic cyclophosphamide in our model of advanced ovarian cancer whether as a monotherapy or when combined with other various agents. Bearing in mind that this is only one model, the results reinforce the possibility that the antitumor efficacy of phase II trials of bevacizumab plus metronomic cyclophosphamide may have been mainly or entirely due to the bevacizumab treatment. Only an appropriate randomized trial would provide a definitive answer to this question. In addition there are other possible factors to consider that are being investigated. For example, it is possible that the levels of active toxic metabolites of cyclophosphamide, such as 4-hydroxycyclophosphamide, attained in the peritoneal environment are not high enough to cause a biological antitumor effect. In this regard we have observed that the metronomic cyclophosphamide protocol we used does in fact have activity against SKOV-3-13 cells when they are grown as a s.c. tumor transplant (Hashimoto and Kerbel, unpublished observations). This also raises the possibility that enzymes involved in cyclophosphamide metabolism such as aldehyde dehydrogenase may be differentially expressed in the different environments in which the tumors are growing.

In summary, based on our results and independently those of Merritt et al. (53), low-dose metronomic oral topotecan chemotherapy may be a promising clinical treatment to consider for testing in advanced ovarian cancer patients, especially when combined with a VEGF pathway–inhibiting drug such as pazopanib or bevacizumab. It will be of interest to evaluate such treatment combinations in preclinical models of recurrent drug resistant (e.g., paclitaxel/platinum resistant) and advanced ovarian cancer xenografts.

Disclosure of Potential Conflicts of Interest

The authors received research support from GlaxoSmithKline. R.S. Kerbel: consultant, GlaxoSmithKline. No other potential conflicts of interest were disclosed.

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Kae Hashimoto, Shan Man, Ping Xu, et al.


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