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13. ABSTRACT ***(Maximum 200 Words)***

In this proposal, we will first test the ability of poly(L-glutamic acid)-paclitaxel (PG-TXL) to overcome certain types of Taxol-resistance controlled by P-gp 170 and HER-2/neu. We will also create and evaluate another novel generation of these polymeric formulations, HA-TXL, designed to selectively target and kill ovarian cancer cells that have high levels of CD44, a receptor for hyaluronic acid (HA). This should facilitate efficient and specific receptor-mediated uptake of HA-TXL via its HA backbone.

Our results to date indicate that PGA-TXL at a single-dose of 180 mg/kg (paclitaxel equivalents) injected i.p. was able to induce marked tumor growth delay and even apparent cures in two orthotopic human ovarian adenocarcinoma xenograft models, HEY and NMP-1, whether administered two or seven days after tumor implantation. In contrast, a multiple-dose MTD (10 mg/kg) regimen of Taxol was without efficacy in either model when administered at seven days post-implanation; some increase in lifespan was observed in the HEY model when the Taxol regimen was initiated two days after tumor implanatation. Limited studies demonstrated similar trends with i.v. administration, as well as with multiple-dose i.p. schedules of PGA-TXL. These studies will be extended to CD44(+) tumor models and the HA-TXL formulations.

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INTRODUCTION

Although Taxol has proven to be a most worthy addition to the chemotherapeutic regimens which can be offered to ovarian cancer patients, as with other drugs, evidence for resistance to Taxol has emerged. Among these resistance mechanisms are the P-gp 170 membrane-associated drug-efflux pump and over-expression of the oncogene, HER-2/neu. Strategies to address Taxol-resistance include its combination with other chemotherapeutic agents and dose-intensification. However, in recent randomized clinical trials, the latter has proven to be a case of diminishing returns, with little meaningful clinical benefit at the price of severe toxicities. Further, recent evidence suggests that Taxol and cis-platin may be antagonistic in certain circumstances, an argument against their therapeutic combination. Therefore, in light of the above considerations, new agents and strategies are urgently needed to address Taxol-resistant ovarian cancer.

One approach to overcoming drug resistance is the use of drug copolymers. These high molecular weight conjugates can be actively transported to the endosome, wherein they are cleaved to release free drug at this organelle. High molecular weight drug copolymers may, on the one hand, 1) restrict diffusion-controlled uptake by normal tissues which occurs with free drug, thereby reducing toxicity; on the other hand, they may 2) enhance extravasation across the abnormal tumor endothelium, thereby increasing tumor localization compared to free drug. The first paclitaxel copolymer to be employed in the proposed studies has shown both reduced toxicity and greater tumor localization in animal models, thereby fulfilling two expectations of copolymer behavior. Further, in our laboratory, it has shown efficacy and even curative ability in two human ovarian carcinoma/nude mouse xenograft models that are extremely resistant to Taxol itself. This formulation is likely endocytosed via non-specific pinocytosis. In this proposal, we will first establish the anti-tumor efficacy of this paclitaxel copolymer in human ovarian carcinoma models with high vs. low HER-2/neu and/or P-gp 170 expression.

Recent evidence indicates that patients whose ovarian cancer cells have high levels of the adhesion molecule, CD44, have more aggressive disease and poorer survival. CD44 is likely involved in ovarian carcinoma invasion outside of the ovarian capsule and implantation on the peritoneal mesothelium; it binds to a sugar polymer, hyaluronic acid, which is found widely in the peritoneum. Thus, targeting paclitaxel to cells that have high CD44 levels and aggressiveness may more selectively kill this dangerous population of cells and improve patient survival.

In this proposal, we will first test the new polymeric formulation of Taxol that has shown promise in other systems at overcoming certain types of Taxol-resistance. Determination of the ability of this formulation to circumvent the drug resistance controlled by P-gp 170 and the oncogene, HER-2/neu, is a major goal of this proposal. These studies will be carried out in models of drug-resistant human ovarian tumors growing in the peritoneal cavities of immunodeficient mice. This site is clinically relevant to the progression of ovarian cancer in the majority of patients. We will also create and similarly evaluate another novel generation of these polymeric formulations designed to selectively target and kill ovarian cancer cells that have high levels of CD44 via a hyaluronic acid backbone. This should facilitate efficient and specific receptor-mediated uptake of the copolymer.

BODY

Task 1 Synthesis and characterization of hyaluronic acid-paclitaxel (HA-TXL) conjugates with ester or acid-labile linkages
(Months 1-12)

This key Task, upon which the other three Tasks depend, has been regretably delayed until very recently due to unforeseen difficulties in securing an adequate supply of hyaluronic acid (HA) preparations to serve as backbones in the synthesis of hyaluronic acid-paclitaxel (HA-TXL) conjugates. After significant effort, we were able to arrange for their synthesis through k3corp, in Great Falls, VA, which has a business relationship with a company actually doing the synthesis, the latter located in Prague, Czech Republic. After the initial e-mail agreement early this year, we had to negotiate past their policy of pre-payment and other issues. Nevertheless, the first preparations have been recently shipped and have just arrived this week.

We requested three preparations of HA: ~50 kDa, 500 kDa, and 1.6 Mda. The former size was selected to allow comparisons to PGA as a backbone for copolymers with a similar molecular weight; most of the PGA-formulations had been 30-40 kDa. Since we are planning to emphasize i.p. injections, we further reasoned that evaluation of larger HA backbones might reveal retardation in copolymer clearance from the peritoneum and thereby greater efficacy against i.p. ovarian tumors. We were able to order standard prepartions of the two large sizes from k3corp; however, the smaller size, evidently derived by hyaluronidase treatment of a much larger precursor, required special ordering and caused delay. We have also been notified by them that the preparations are estimated to be ~42 kDa, but they do not consider this to be determined by a validated assay.

We will now proceed with our previously proposed syntheses; two types of conjugates had been proposed, either with ester-linkages or with acid-labile linkages. At about the same time as our submission of the original grant proposal, and unknown to us at that time, a report appeared ("Synthesis and selective cytotoxicity of a hyaluronic acid-antitumor bioconjugate", Y. Luo and G.D. Prestwich, *Bioconjugate Chem.*: 10, 755-763, 1999) describing an approach to the coupling of paclitaxel to HA. This is similar to one of our proposed approaches, namely the one resulting in an ester linkage. It involves reaction of the free carboxyl group of the dissacharide moiety of HA with adipic dihydrazide. This dihydrazido-functionalized HA is then coupled to a paclitaxel-NHS ester. The NHS ester was prepared via sequential succinic anhydride modification of the 2' hydroxyl of paclitaxel, followed by coupling of the paclitaxel-hemisuccinate to N-hydroxysuccinimido diphenyl phosphate.

Their final HA-TXL formulation has a 14 atom linker between the carboxyl of HA and the 2' hydroxyl of paclitaxel. Furthermore, they have employed a low molecular weight HA, averaging about 28 disaccharide units per HA molecule, or ~10-11 kDa. In contrast, our HA-TXL formulations, because they are synthesized using pre-blocking of the more reactive 2' hydroxyl group, will have the coupling to HA through the 7' hydroxyl group, and linkers of either 3 or 6 atoms. As noted, our intent was to evaluate HA backbones of comparable (~30-50 kDa) in size to the PGA in PGA-TXL, and also larger HA backbones (~0.5 and 1.6 MDa) to determine whether these might lead to a greater depo effect following i.p. administration. We are considering synthesis according to their schemes, as well, although they have not reported any *in vivo* evaluation to date.

Task 2 Mechanistic Studies: Effects on Cell Cycle Distribution/Apoptosis and RAF-1 Kinase Activation (Months 7-18)

A Conduct cell-cycle (PI staining) and apoptosis assays (TUNEL and hypodiploidy) on human ovarian carcinoma cell lines (SKOV-3 and OVCAR-3/NMP-1 models of high and low HER-2/neu and CD44 expression, respectively) to be used in Task 4 to establish responses to Taxol, PGA-TXL and HA-TXL in vivo

B Using these cell lines and the drug doses established as relevant to previous endpoints, determine the role of Raf-1 kinase pathway in these responses

Studies related to this task have not yet been initiated.

Task 3 Pharmacokinetics: Cellular and IP Administration
(Months 13-24)

A Establish parameters of cellular uptake and fate of paclitaxel, PGA-TXL and HA-TXL; determine extent and site of PGA-TXL and HA-TXL cleavage to paclitaxel

B Establish pharmacokinetic parameters for peritoneal clearance of paclitaxel, PGA-TXL and HA-TXL following i.p. administration; determine extent and site of PGA-TXL and HA-TXL cleavage to paclitaxel

Studies related to this task have not yet been initiated.

Task 4 Efficacy Studies: Her-2/neu- and CD44- high and low expression models
(Months 19-36)

A Compare tumor responses and effects on survival of Taxol or PGA-TXL administered i.p. at single- or multiple-dose MTDs to nude mouse i.p. models of HER-2/neu high (SKOV-3) and basal (NMP-1) expressing human ovarian carcinomas

B Compare tumor responses and effects on survival of PGA-TXL (non-targeted) vs. HA-TXL (CD44-targeted) paclitaxel prodrugs administered i.p. in SKOV-3, high CD44-expressing and NMP-1, low CD44-expressing human ovarian carcinoma models

C Conduct histopathology and *in situ* TUNEL assays on tumors from Taxol, PGA-TXL and HA-TXL treatment groups

Studies related to this task have not yet been initiated.

KEY RESEARCH ACCOMPLISHMENTS

- Demonstrated and reported reduced toxicity and high anti-tumor efficacy of PGA-TXL in Taxol-resistant NMP-1 human ovarian tumor/nude mouse xenograft model
- Demonstrated and reported reduced toxicity and high anti-tumor efficacy of PGA-TXL in Taxol-resistant HEY human ovarian tumor/nude mouse xenograft model

REPORTABLE OUTCOMES

An abstract entitled "Paclitaxel Copolymers to Address Taxol Resistance" by J. Klostergaard, E. Auzenne, C. Li, N.J. Donato, D. Farquhar, M. Khodadaian, and Y. Zou was submitted and accepted to the 6th US-Japan Symposium on Drug Delivery Systems to be held in December, 2001 in Maui. It was presented as a poster as well as being presented in a workshop.

A publication entitled "Superior therapeutic profile of poly-L-glutamic acid-paclitaxel copolymer compared to Taxol in xenogeneic compartmental models of human ovarian carcinoma" by Auzenne, E., Donato, N..J.,Li, C., Leroux, E., Price, R.E., Farquhar, D. and Klostergaard, J. was published in Clinical Cancer Research, 8: 573-581, 2002.

CONCLUSIONS

PGA-TXL, administered i.p. at a single-dose near MTD of 180 mg/kg (paclitaxel equivalents), was able to induce marked tumor growth delay and even apparent cures in two orthotopic human ovarian adenocarcinoma xenograft models (HEY and NMP-1), whether administered two or seven days after tumor implantation. In contrast, a multiple–dose MTD (10 mg/kg) regimen of Taxol was without efficacy in either model when administered at seven days post-implantation; some increase in lifespan was observed in the HEY model when the Taxol regimen was initiated two days after tumor implantation. Limited studies demonstrated similar trends with i.v. administration as well as with multiple-dose i.p. schedules of PGA-TXL. These studies will be extended to CD44(+) tumor models and the HA-TXL formulations.

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APPENDICES

PACLITAXEL COPOLYMER TO ADDRESS TAXOL RESISTANCE

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We have evaluated a paclitaxel-poly(L-Glu) copolymer in human tumor/nude mouse orthotopic xenograft models which either reflect resistance to Taxol (HEY/ovarian) or over-express HER-2/neu (MDA-361/breast). Early treatment (Day 2 HEY) with MTD Taxol achieved some improvement in survival, but was not curative. However, treatment with copolymer markedly improved survival and some apparent cures were observed. The higher tumor burden at Day 7 rendered this model resistant to MTD Taxol, but still responsive to copolymer. Similarly, early treatment (Day 7) of the 361 breast model with paclitaxel copolymer resulted in substantial tumor growth delay, regression, or even apparent cure. When administered later, the copolymer still caused tumor growth delay, but no cures were observed. We conclude that formulation of paclitaxel with this poly(L-Glu) backbone substantially enhanced its potency, and rendered it active in two highly drug-resistant models. Supported in part by DOD grants BC980420, BC991113 and OC000036 (JK).

Superior Therapeutic Profile of Poly-L-Glutamic Acid-Paclitaxel Copolymer Compared with Taxol in Xenogeneic Compartmental Models of Human Ovarian Carcinoma[1]

Edmond Auzenne, Nicholas J. Donato, Chun Li, Elena Leroux, Roger E. Price, David Farquhar, and Jim Klostergaard[2]

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ABSTRACT

Previous preclinical studies with ectopic tumor models have demonstrated remarkable improvements in the therapeutic profile of paclitaxel, formulated as a copolymer with poly-L-glutamic acid, compared with paclitaxel in the clinical formulation, Taxol. In this study, we evaluated these formulations in two human ovarian carcinoma xenograft models, NMP-1 and HEY, in nude mice. i.p. implantation in female nude mice of either cell line gave rise to progressive disease within the peritoneum, in the parenchyma of visceral organs, and eventually at extraperitoneal sites; the resultant, increasing morbidity then required host sacrifice. i.p. administration of multiple-dose Taxol at its maximum tolerated dose 1 week after tumor implantation afforded minimal or no increased survival compared with controls in either model. Consistent with the predictions of drug copolymer behavior, paclitaxel, as the poly-L-glutamic acid-paclitaxel copolymer, displayed much less toxicity than Taxol in these hosts. When evaluated for antitumor efficacy in both the Taxol-resistant NMP-1 and HEY models, significant improvement in survival, and even some cures, were observed after a single i.p. treatment with this copolymer. The observed antitumor response correlated with histopathological analysis of peritoneal and extraperitoneal tumor burden in comparing control HEY mice sacrificed near the onset of morbidity with mice receiving paclitaxel copolymer. We conclude that both the i.p. NMP-1 and HEY models have significant value in establishing the efficacy of candidate agents, which might address Taxol-resistant human ovarian carcinoma. Furthermore, the poly-L-glutamic acid-paclitaxel copolymer has a superior therapeutic profile in these Taxol-resistant compartmental models.

INTRODUCTION

Ovarian cancer is the second most common and the most lethal gynecologic malignancy (1). Peritoneal implantation is a crucial and common aspect of this disease, because it predictably leads to a familiar clinical course attributable to progressive encasement of intra-abdominal organs followed by many morbid sequelae. Carcinomatous involvement of the peritoneum is present in ~80% of patients with stage III–IV ovarian carcinoma (2). Recent clinical results support the value of an i.p. route of drug administration in this setting. Patients with minimal residual disease after cytoreductive surgery were randomized to i.v. CDDP[3] (II) + cyclophosphamide or i.p. CDDP + i.v. cyclophosphamide arms; greater survival and reduced toxicities were seen in the latter group (3).

Treatment of ovarian carcinoma with platinum-containing regimens is widely considered standard therapy for stage III–IV disease (reviewed in Ref. 4). This treatment results in high initial response rates, but the vast majority of patients eventually represent with chemotherapy-resistant disease (4–6). This resistance is multifactorial and, because of treatment toxicities, cannot be readily circumvented by dose-intensification. Given the diverse mechanisms leading to CDDP resistance and treatment toxicities (7–15), new agents with distinct mechanisms of action and nonoverlapping toxicities are greatly needed.

One such agent, Taxol, the clinical formulation of paclitaxel, has already demonstrated activity in ovarian carcinomas (16). Paclitaxel increases tubulin polymerization, stabilizes microtubules, and prevents tubulin depolymerization, resulting in tubulin bundling (17–19). The mechanisms linking these effects to mitotic and G_2/M arrest are complex and are concentration-dependent (20, 21). Taxol resistance has been linked to: (*a*) alterations in tubulin (22–25); (*b*) expression of the P-gp 170 drug-efflux pump (26, 27); (*c*) high Raf-1 kinase activity (28); and (*d*) overexpression of HER-2/*neu* (29–32). A number of recent observations suggest that dose-intensification with Taxol

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[3] The abbreviations used are: CDDP, *cis*-diamminedichloroplatinum; PGA, poly(L-glutamic acid); TXL, paclitaxel; PAA, poly(L-aspartic acid); EPR, enhanced permeability and retention.

to overcome resistance may be a situation of diminishing returns (reviewed in Ref. 33; Refs. 34, 35). This plateau effect has been attributed to saturation of the paclitaxel binding sites on β-tubulin (35) or to antagonistic effects of the Cremophor vehicle (36, 37). Furthermore, recent evidence suggests Taxol may interact negatively with 5-fluorouracil (38) and with CDDP (39), a caution against use of these drug combinations (40, 41). Thus, other approaches to Taxol-resistant disease strongly merit exploration.

Macromolecular drug delivery systems have been developed as one approach to overcome drug resistance and to improve the therapeutic index. Examples include polymeric conjugates of chemotherapeutic agents; these are internalized by endocytosis, resulting in their accumulation in perinuclear lysosomes, thereby rendering drug released from polymer both closer to nuclear targets and less accessible to membrane-linked drug efflux mechanisms than the free drug originally incorporated by diffusion (42). Drug copolymers may also have pharmacokinetic advantages over free drugs. The latter may readily extravasate to normal tissues, whereas the size of the former may restrict such distribution, potentially reducing toxicity. Despite this restriction, the leaky, irregular vasculature of solid tumors may still be readily traversed by these macromolecules, which, when combined with their greater retention in the tumor interstitium, results in superior tumor localization and less toxicity compared with free drug (43, 44).

Some copolymer formulations of paclitaxel have already been characterized; these include cyclodextrins; copolymers of D, L-lactide, and polyethylene glycol (45–47); and PGA-TXL (48). PGA-TXL has already demonstrated key advantages over free paclitaxel (as Taxol): (*a*) greatly reduced toxicity; (*b*) greater localization to tumor implants; and (*c*) greater antitumor efficacy and even curative ability in several rodent models.

To date, PGA-TXL has been evaluated using systemic administration, in syngeneic murine and xenogeneic human tumor models, and in tumor models using both ectopic and orthotopic implantation (48–50). In the current studies, we have evaluated PGA-TXL in two human tumor xenograft models using i.p. implantation of tumor in nude mice. This route was used to facilitate characterization of the response of nascent disease invading i.p. from the ovarian capsule, or more realistically given the typically late detection of ovarian cancer, residual peritoneal tumor burden after surgical and chemotherapeutic debulking of advanced disease. In this report, we first demonstrate that these models, NMP-1 and HEY, are highly resistant to multiple-dose MTD Taxol, administered i.p. beginning 1 week after tumor implantation. Secondly, we demonstrate that a single i.p. administration of PGA-TXL administered at the same time as the first Taxol dose results in significant improvement in survival and even in some long-term cures in both models.

MATERIALS AND METHODS

Cell Lines

The human ovarian adenocarcinoma cell line OVCAR-3 was obtained from American Type Culture Collection (Rockville, MD). It was originally established from malignant ascites and is reported to be resistant to several drugs *in vitro* (51). After subsequent selection procedures, OVCAR-3 has been characterized as an i.p. tumor xenograft model in nude mice demonstrating progressive metastatic spread akin to the human disease (52). However, successful implantation i.p. required a high number of inoculated cells ($\geq 10^7$).

A cisplatin (CDDP; Bristol-Myers Squibb)-resistant cell line, C-1, was developed from parental OVCAR-3 cells by *in vitro* incubation of OVCAR-3 cells with increasing concentrations of CDDP (53). Cells surviving several rounds of selection in CDDP-containing medium (1 μg/ml) were cloned by limiting dilution, expanded, and retested for CDDP sensitivity. C-1 cells demonstrated durable resistance to drug even after 3 months of passage in the absence of CDDP. NMP-1 cells were derived from ascites of nude mice into which C-1 cells had been implanted i.p. These NMP-1 cells retained *in vitro* CDDP-resistance levels identical to the original C-1 population.

The human ovarian carcinoma cell line HEY was originally established from a peritoneal deposit of a moderately differentiated papillary ovarian cystadenocarcinoma, and it has been reported to be moderately resistant to CDDP in a clonogenic assay (IC_{90} ~1 μg/ml; Refs. 54, 55).

PGA-TXL

PGA-TXL was prepared by carbodiimide-mediated, ester coupling of hydroxyl groups of paclitaxel and γ-carboxyl groups of glutamic acid (as PGA), as described previously (48). Copolymers composed of 13% and 37% paclitaxel (w/w) were used in these studies. The molecular mass of the PGA backbone was M_r 30,000–40,000 daltons. PGA-TXL was dissolved in warmed (37°C) physiological saline before injection.

In Vitro Cytotoxicity Assays

NMP-1 and HEY cells were cultured overnight in 96-well plates in 100 μl of medium (DMEM/F12; Life Technologies, Inc.) supplemented with 5% FCS/well before treatment. Based on preliminary experiments, cell numbers were adjusted to 1×10^4 cells/well in order to achieve subconfluent control cell monolayers at the end of the assay. The cytotoxic effects of Taxol (paclitaxel in Cremophor EL; Mead Johnson/Bristol-Myers Squibb) were established using a dose range of drug up to 4 μg/ml. Remaining viable cells were stained with neutral red after 96 hr, and the percentage of control survival as measured by optical density of incorporated dye was determined. The results from two to four experiments of each type are shown.

In Vivo Efficacy Assays

NMP-1. On Day 0, 1×10^7 viable NMP-1 cells were injected into the peritoneal cavities of groups of 6–9-week-old female nude mice (Harlan). Five to 25 mice/experimental group were used as the basis for statistical analyses. i.p. therapy was initiated 1 week later (day 7). Histopathological examination of mice in parallel studies indicated that by this time frame, abdominal tumors were already present (data not shown). Taxol was administered on a q7d × 3 or q4d × 3 schedule, at ≤20 mg/kg. Since it was important to evaluate PGA-TXL in a relevant preclinical setting, the clinical formulation of paclitaxel (Taxol) was used as a comparison rather than alternative formulations of paclitaxel with reduced or zero Cremophor content.

PGA-TXL was dissolved in PBS and administered at ≤200 mg/kg (paclitaxel equivalents) as a single i.p. injection on day 7, or at 180 mg/kg on a q7d × 3 schedule beginning on day 7, or as a single i.v. injection.

Since mice implanted i.p. with NMP-1 tumor cells develop marked, debilitating ascites as one of the earliest clinical signs of peritoneal tumor and substantially before other aspects of tumor progression, ascites fluid was repeatedly removed at intervals from mice, beginning after the fourth week. As the peritoneal tumor burden continued to increase as detected by direct visualization of tumor through the distended abdominal wall, relief from ascites removal became less effective. Cachexia, spine prominence, and other morbid symptoms became more severe, and these animals were humanely sacrificed by carbon dioxide asphyxiation.

HEY. On day 0, 3 × 10^5 viable HEY cells were injected into the peritoneal cavities of 6–9-week-old female nude mice. i.p. therapy was initiated on either day 2 or day 7. No macroscopic or histopathologic evidence of a tumor was observed in control mice that were sacrificed either 2 or 7 days after i.p. inoculation of HEY cells, reflecting the very low tumor burden at the times of treatment. Taxol was administered on a q7d × 3 schedule at ≤10 mg/kg, because toxicity had been observed with 20 mg/kg in the NMP-1 studies.

PGA-TXL was dissolved in PBS and administered at ≤180 mg/kg (paclitaxel equivalents), the most effective dose in the NMP-1 studies, as a single i.p. injection on day 2 or day 7, or at 180 mg/kg on a q7d × 3 schedule beginning on day 7.

For mice implanted with HEY tumors, the first sign of tumor growth was in the needle track in the muscle of the abdominal wall, and eventually palpable i.p. tumor was evident. As the latter progressed, cachexia became more significant. These morbid symptoms eventually required humane sacrifice. They did not display prominent abdominal distention from ascites as observed with the NMP-1 model.

On occasion, mice bearing either tumor succumbed between daily observations and before the opportunity to sacrifice them. In this case, the day of death was considered to be the day before the date they were discovered. The day of humane sacrifice/death was recorded for each mouse, and these values were compared among control and treatment groups by paired or unpaired Student's *t* tests.

In addition to the survival end points described above, to provide objective, blinded data, mice were implanted with HEY tumor and randomized into three groups of four to six animals. These groups included: (*a*) controls to which saline was administered; (*b*) mice treated on day 2 with 180 mg/kg PGA-TXL; and (*c*) mice treated on day 7 with 180 mg/kg PGA-TXL. On day 31, before any deaths in the controls, mice were sacrificed and subjected to macroscopic and histopathologic analysis (see below) in a blinded fashion.

Histopathology

The mice were killed by exposure to CO_2. The skin was removed from the torso of each mouse, and 1 cc of 10% neutral phosphate-buffered formalin was injected into both the pleural and peritoneal cavities before the complete body of each animal being immersed in 10% neutral phosphate-buffered formalin for tissue fixation. The intracavitary infusion of formalin was added to improve fixation of abdominal and thoracic viscera. After the animals had fixed for ≥2 days, the bodies of the mice were immersed in 10% formic acid for 2–3 days to decalcify the osseous tissues. After fixation and decalcification, axial sections of the head, thorax, and two levels of the abdomen were routinely processed, and 4–6 μm paraffin sections, which were stained with H&E, were prepared for histopathologic examination. In addition to descriptions of the extent of tumor involvement in each tissue examined, the overall tumor burden in each animal was subjectively classified as no tumor present or modest (1+), moderate (2+), marked (3+), or severe (4+) levels of tumor burden within the abdominal wall and abdominal cavity. Tumor burden was classified based on the percentage of the area of the abdominal cavity and wall that the tumors composed, with modest = <25%, moderate = 25–50%, marked = 51–75%, and severe = >75% involvement.

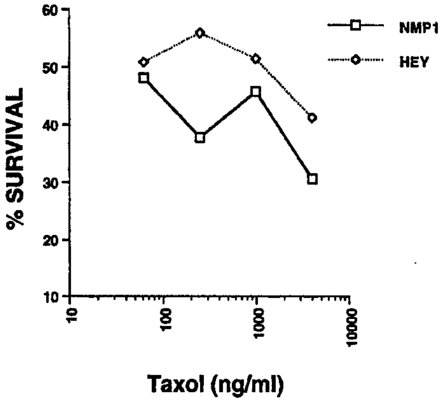

Fig. 1 Survival of NMP-1 and HEY cells after 96-hr treatment with Taxol *in vitro.*

RESULTS

Taxol Response of NMP-1 and HEY *in Vitro*. NMP-1 and HEY cells were treated with a concentration range of Taxol for 96 hr. Both cell lines demonstrated a loss of survival in response to Taxol, with NMP-1 cells being slightly more sensitive (Fig. 1). The concentration-response curves were shallow, with an effect evident at the lowest concentration but even the highest concentration being incapable of achieving 100% cell death in this time frame.

NMP-1 Resistance to i.p. Multiple-Dose MTD Taxol *in Vivo*. NMP-1 cells were implanted i.p. in nude mice on day 0. Beginning on day 7, q7d × 3 regimens were initiated using Taxol at 10 or 20 mg/kg/injection. The survival of treated animals and of control mice that received saline alone is shown in Fig. 2 and Table 1. Control animal survival was 43.4 ± 1.1 days (mean ± SE). Taxol administered at 10 mg/kg failed to improve survival (41.7 ± 0.5 days; $P = 0.32$). When a dose of 20 mg/kg was used, drug toxicity became evident, and host survival was reduced significantly on either a q7d × 3 (13.8 ± 4.1 days) or q4d × 3 (26.2 ± 3.3 days) regimen compared to controls ($P < 0.0001$). Therefore, this ovarian model, with treatment beginning 1 week after implantation of tumor, ap-

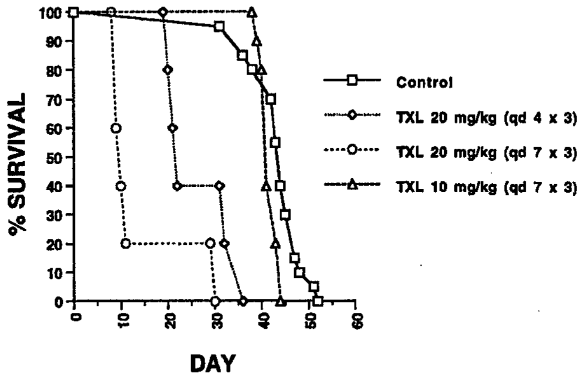

Fig. 2 Effects of multiple-dose i.p. Taxol on survival of mice bearing 7-day i.p. implants of NMP-1 tumors. Groups of five or more female nude mice were given i.p. saline (*Control*) or Taxol at 10 or 20 mg/kg on q4d × 3 or q7d × 3 regimens beginning 7 days after implantation of NMP-1 cells. The day of death/sacrifice is noted.

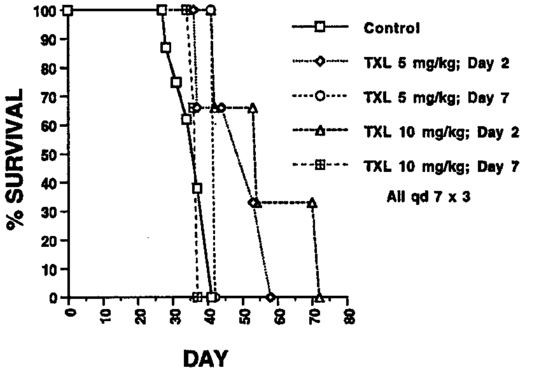

Fig. 3 Effects of multiple-dose i.p. Taxol on survival of mice bearing 2-day or 7-day i.p. implants of HEY tumors. Groups of three to six female nude mice were given i.p. saline (*Control*) or Taxol at 5 or 10 mg/kg on q7d × 3 regimens, beginning either 2 or 7 days after implantation of HEY cells. The day of death/sacrifice is noted.

Table 1 Responses of NMP-1 tumors to i.p. multiple-dose MTD Taxol

Group/treatment	Mean day of sacrifice/death	P^a
Controls	43.4 ± 1.1	
Taxol, 10 mg/kg q7d × 3^b	41.7 ± 0.5	0.318
Taxol, 20 mg/kg q7d × 3^b	13.8 ± 4.1	<0.0001
Taxol, 20 mg/kg q4d × 3^b	26.2 ± 3.3	<0.0001

[a] Compared with controls.
[b] Initiated on day 7.

Table 2 Responses of HEY tumors to i.p. multiple-dose MTD Taxol

Group/treatment	Mean day of sacrifice/death	P^a
Controls	36.3 ± 1.7	
Taxol, 5 mg/kg q7d × 3, beginning day 2	46.7 ± 6.1	0.045
Taxol, 5 mg/kg q7d × 3, beginning day 7	42.0 ± 0.0	0.082
Taxol, 10 mg/kg q7d × 3, beginning day 2	56.0 ± 8.7	0.007
Taxol, 10 mg/kg q7d × 3, beginning day 7	36.7 ± 0.3	0.891

[a] Compared with controls.

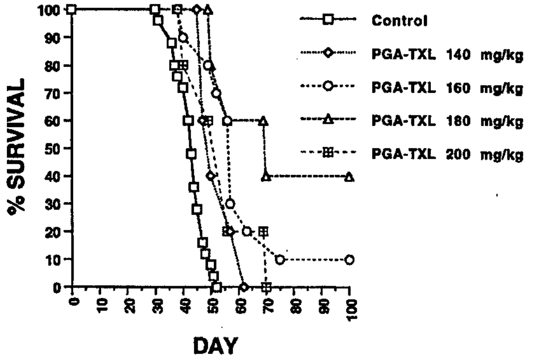

Fig. 4 Effects of single-dose i.p. PGA-TXL at different dose levels on survival of mice bearing 7-day i.p. implants of NMP-1 tumors. Groups of five or more female nude mice were given i.p. saline (*Control*) or a single i.p. injection of PGA-TXL at 140 to 200 mg/kg 7 days after implantation of NMP-1 cells. The day of death/sacrifice is noted.

peared to be highly Taxol-resistant using this multiple-dose MTD regimen.

HEY Response to i.p. Multiple-Dose MTD Taxol *in Vivo*. HEY cells were implanted i.p. on day 0. Beginning either on day 2 or on day 7, q7d × 3 regimens were initiated using Taxol at 5 and 10 mg/kg, administered i.p.; in light of the toxicity observed in the NMP-1 model with the 20 mg/kg Taxol regimen, this higher dose level was not evaluated in this model. The survival of treated animals and of control mice that received saline alone is shown in Fig. 3 and Table 2. Control animal survival was 36.3 ± 1.7 days. The effect of Taxol was both dose-dependent and tumor burden-dependent. When the q7d × 3 regimen was begun with the lower tumor burden present on day 2, 5 mg/kg Taxol increased survival nominally to 46.7 ± 6.1 days ($P = 0.045$; Table 2). However, a dose level of 10 mg/kg resulted in a substantial increase in mean survival to 56.0 ± 8.7 days ($P < 0.007$), reflecting sensitivity to the higher Taxol dose in animals with lower tumor burden. In contrast, when treatments were begun with the higher tumor present on day 7, even the 10 mg/kg dose level of Taxol could not improve survival (36.7 ± 0.3 days; $P = 0.89$). Comparing the NMP-1 and HEY models using initiation of intervention on day 7 for both, these models appear particularly resistant to multiple-dose MTD Taxol.

NMP-1 Response to Single-Dose i.p. PGA-TXL *in Vivo*. NMP-1 cells were implanted on day 0, and on day 7, a single i.p. injection of PGA-TXL was administered at 140, 160, 180, or 200 mg/kg (paclitaxel equivalents). Effects of these treatments on host survival are shown in Fig. 4 and Table 3. All four of the treatment arms demonstrated improved survival compared to controls ($P \leq 0.042$). Whereas control survival in this experiment was 43.0 ± 1.3 days, two of five mice in the 180 mg/kg group were alive at >380 days at the termination of the experiment. Interestingly, the highest dose level used, 200 mg/kg, did not achieve the longest survival. These results, nevertheless,

Table 3 Responses of NMP-1 tumors to i.p. single-dose PGA-TXL

Group/treatment	Mean day of sacrifice/death	P^a
Controls	43.0 ± 1.3	
PGA-TXL[b]		
140 mg/kg	52.6 ± 3.0	0.0034
160 mg/kg	65.6 ± 9.8	0.0103
180 mg/kg	119.2 ± 43.8[c]	0.0419
200 mg/kg	54.4 ± 4.9	0.0047

[a] Compared with controls.
[b] Administered on day 7.
[c] Survival of two of five mice censored at day 381.

Table 4 Responses of NMP-1 tumors to i.v. single-dose or i.p. single-dose or multiple-dose PGA-TXL

Group/treatment	Mean day of sacrifice/death	P
Controls	42.6 ± 3.1	
PGA-TXL (180 mg/kg/dose)		
i.p., single dose[a]	50.8 ± 5.4	0.861[b] 0.073[c]
i.v., single dose[a]	50.2 ± 2.4	
i.p., triple dosing q7d × 3, beginning day 7	58.6 ± 2.4	0.0004[b]

[a] Administered on day 7.
[b] Compared with i.v.
[c] Compared with triple dosing.

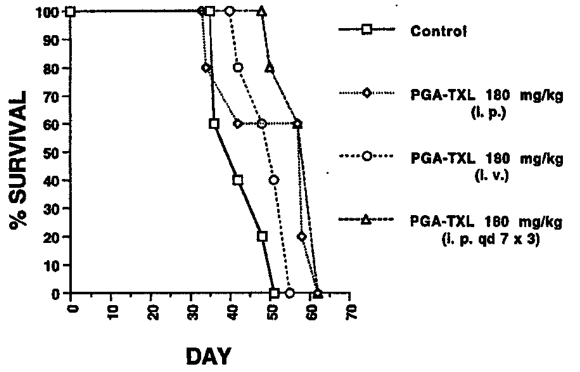

Fig. 5 Effects of single-dose i.p., or i.v. PGA-TXL, or multiple-dose i.p. PGA-TXL on survival of mice bearing 7-day i.p. implants of NMP-1 tumors. Groups of five or more female nude mice were given i.p. saline (*Control*), a single i.p. or i.v. injection of PGA-TXL at 180 mg/kg, or three i.p. injections of PGA-TXL at 180 mg/kg each on a q7d × 3 regimen, 7 days after implantation of NMP-1 cells. The day of death/sacrifice is noted.

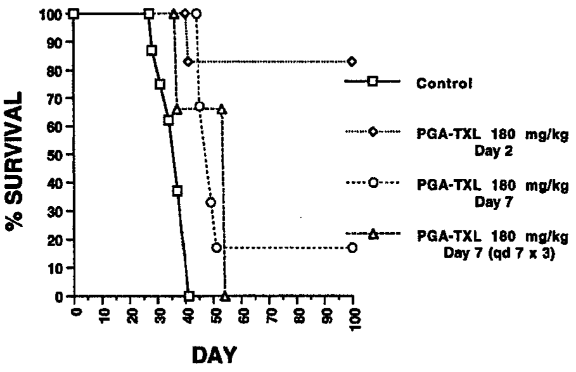

Fig. 6 Effects of single-dose i.p. PGA-TXL on survival of mice bearing 2-day or 7-day i.p. implants of HEY tumors. Groups of six female nude mice were given either i.p. saline (*Control*) or a single i.p. injection of PGA-TXL at 180 mg/kg, either 2 or 7 days after implantation of HEY cells. The day of death/sacrifice is noted.

demonstrate striking efficacy of single-dose PGA-TXL in this Taxol-resistant model.

NMP-1 Response to i.v. Single-, i.p. Single-, or Multiple-Dose PGA-TXL *in Vivo*. The effects on host survival of a single i.v. injection, a single i.p. injection, or of multiple i.p. injections (q7d × 3) of PGA-TXL (180 mg/kg/injection paclitaxel equivalents) administered after implantation of NMP-1 cells on day 0 are shown in Fig. 5 and Table 4. Single-dose administration on day 7 by the i.v. or i.p. routes resulted in similar improvements in survival (50.2 ± 2.4 and 50.8 ± 4.8 days; $P = 0.86$ for i.v. *versus* i.p.). In a subsequent experiment with five additional mice, some possible toxicity was evident using the i.v. route, because one of the mice expired within 11 days of drug administration. Combining the two experiments using i.v. administration, the nine surviving mice demonstrated improved survival compared to controls (52.8 ± 2.8 days; $P < 0.038$). The multiple-dose i.p. regimen additionally improved survival but only slightly to 58.6 ± 2.4 days ($P < 0.0001$ *versus* control; $P = 0.073$ *versus* single dose in this experiment).

There was more modest improvement in survival (treated *versus* control = 118 for single i.p. injection and 146 for triple i.p. injection) and no long-term survivors in this experiment using a 37% paclitaxel formulation of PGA-TXL compared with the more compelling improvements in survival and even cures observed with a single injection of the same dose (180 mg/kg) of the 13% paclitaxel formulation in the previous experiment (Table 3). This suggests that the extent of paclitaxel substitution may be an important variable in optimizing the efficacy of PGA-TXL.

HEY Response to i.p. Single- or Multiple-Dose PGA-TXL *in Vivo*. HEY cells were implanted i.p. on day 0. On either day 2 or day 7, a single i.p. injection of 180 mg/kg (paclitaxel equivalents) PGA-TXL was administered to several groups of mice. The resultant effects of treatment on survival are shown in Fig. 6 and Table 5. There was clear benefit to survival whether PGA-TXL was administered with low tumor burden (day 2; survival = 226.7 ± 42.5 days with four of six mice alive at ≥222 days; $P = 0.0002$ *versus* control) or high tumor burden (day 7; survival = 76.8 ± 29.0 days with one of six mice alive at 222 days; $P = 0.13$ *versus* controls; $P < 0.016$ *versus* intervention on day 2). Earlier intervention clearly favored long-term survival. Curiously, multiple-dose administration (q7d × 3) beginning on day 7 did not improve survival (48.3 ± 5.7 days; $P = 0.02$ *versus* controls) compared with single-dose administration ($P = 0.526$).

To verify that the survival data reflected the consequences

Table 5 Responses of HEY tumors to i.p. single- or multiple-dose PGA-TXL

Group/treatment	Mean day of sacrifice/death	P^a
Controls	36.3 ± 1.7	
PGA-TXL (180 mg/kg/dose)		
Single dose, day 2	226.7 ± 42.5[b]	0.0002
Single dose, day 7	76.8 ± 29.1	0.129
Triple dosing q7d × 3, beginning day 7	48.3 ± 5.7	0.020

[a] Compared with controls.

[b] Survival of four of six mice censored at days 222 (1) and 304 (3).

of progressive tumor burden, mice were implanted i.p. with HEY tumor cells, and four to six animals per group were treated either with saline (controls) or a single i.p. injection of 180 mg/kg PGA-TXL on either day 2 or day 7 after tumor implantation. All of the mice were sacrificed on day 31 and prepared for blinded histopathological examination. The results are shown in Fig. 7.

All four of the control mice presented with single discrete 5–12 mm diameter tumors in the abdominal wall and s.c. adipose tissues (Fig. 7, *A*). These tumors were typically located along the ventral midline close to the area where the i.p. injections were performed. One of the control animals also had several other small 1–4 mm diameter tumors that were present in the muscle of the lateral abdominal wall adjacent to the larger midline tumor mass. At this time point, no evidence of tumor was present within the abdominal cavity or the abdominal wall of any of the four mice administered PGA-TXL on day 2 (Fig. 7, *B*). This observation correlates well with survival for mice on this protocol being ~227 days *versus* ~36 days for the controls (Table 5). Similarly, five of six mice administered PGA-TXL on day 7 did not have any histopathological evidence of tumor at day 31. Only one of these mice had a single, small (~2 mm) diameter tumor observed between the spleen and pancreas (Fig. 7, *C*). This also correlates with improved survival with this group (~77 days; Table 5) but with fewer cures achieved than with day 2 treatment.

DISCUSSION

Drug copolymers may have key advantages over free drugs, including reduced toxicity (56); high plasma Cmax values (57), and rapid extravasation, which contribute to toxicity of free drugs and should be largely abrogated with copolymer prodrugs, of which the diffusion rates are limited because of their size (58). However, the so-called EPR effect (59–61) should still allow copolymer accumulation and retention within the tumor interstitium followed by endocytic uptake by tumor and stromal cells, activation of the prodrug, drug access to intracellular targets, and cell death.

Some copolymer formulations of paclitaxel have already been characterized, including PGA-TXL (48–50). The latter has already demonstrated key advantages over free paclitaxel (as Taxol) as monotherapy or when combined with radiotherapy: (*a*) greatly reduced toxicity; (*b*) greater localization to tumor implants; and (*c*) greater antitumor efficacy. As seen in the current studies, the latter includes achieving some apparent cures in highly Taxol-resistant human ovarian carcinoma xenograft models. The strong *in vivo* resistance to Taxol was unexpected, given the sensitivity of both NMP-1 and HEY tumor cells to Taxol *in vitro* (Fig. 1). Based on a favorable preclinical profile, clinical trials of PGA-TXL are now underway.

There would appear to be two quite different mechanisms for PGA-TXL processing, which could be proposed. The first is that after fluid phase pinocytosis, subsequent activation involves two distinct steps: first, an endosomal protease of the appropriate specificity cleaves the amide bonds linking the PGA backbone, thereby liberating free glutamic acid and a glutamic acid ester linked via its γ-carboxyl group to one of the hydroxyl groups of paclitaxel. Endosomes degrade PGA but not PAA nor their D-isoforms, as shown by the ability of all of the latter but not the first to protect against gentamycin-induced nephrotoxicity (62–64). Thus, only with PGA backbone will the amino acid/paclitaxel ester product be generated. Next, this ester is expected to be inherently chemically labile and to undergo spontaneous release of paclitaxel by an autocatalytic hydrolysis involving nucleophilic attack by the α-carboxylate group on the γ-ester linkage (Fig. 8). Therefore, only PGA-TXL will be internalized by endocytosis and then also successfully proteolyzed, ultimately rendering paclitaxel available intracellularly. A similar autocatalytic hydrolysis mechanism would not be expected to occur with PAA because of the lack of initial and requisite endosomal proteolysis of the backbone. This hypothesis is consistent with the observation that PAA-TXL does not share the potency of PGA-TXL (48).

An alternative to this two-step, proteolytic/autoesterolytic mechanism could involve exogenous esterase-dependent release of the paclitaxel from the copolymer and does not depend on endosomal processing. The EPR effect alone would afford a superior response to that observed with Taxol. However, this is unlikely to be an efficient mechanism for paclitaxel release, since negatively charged molecules are poor substrates for carboxylate esterases (65). However, it should be noted that substituents such as hydroxylamine on PGA have been reported to increase the degradation by lysosomal proteases (reviewed in Ref. 66). On the other hand, conjugation of PGA to adriamycin resulted in an inactive prodrug (67) possibly because of the stability of the amide linkage between the backbone and the 3-amino group of the sugar. Whether substitution of PAA or PGA, for example with paclitaxel, would similarly increase catalysis by esterases is not established; if it is increased, this could contribute to the "leakiness" of the prodrug before tumor localization. Furthermore, a gradual and pH-dependent release of paclitaxel from PGA-TXL in PBS has been observed.[4] A direct comparison of solvolysis rates for PGA-TXL with those for PAA-TXL would help to establish the relative importance of these prodrug processing mechanisms *in vivo*.

Although not extensively studied, there appeared to be some effect of varying the extent of paclitaxel substitution on antitumor efficacy of PGA-TXL in the NMP-1 model (compare Tables 3 and 4); in this case, lower substitution (13%) appeared to be more efficacious and gave more long-term survival benefit

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[4] C. Li, unpublished observations.

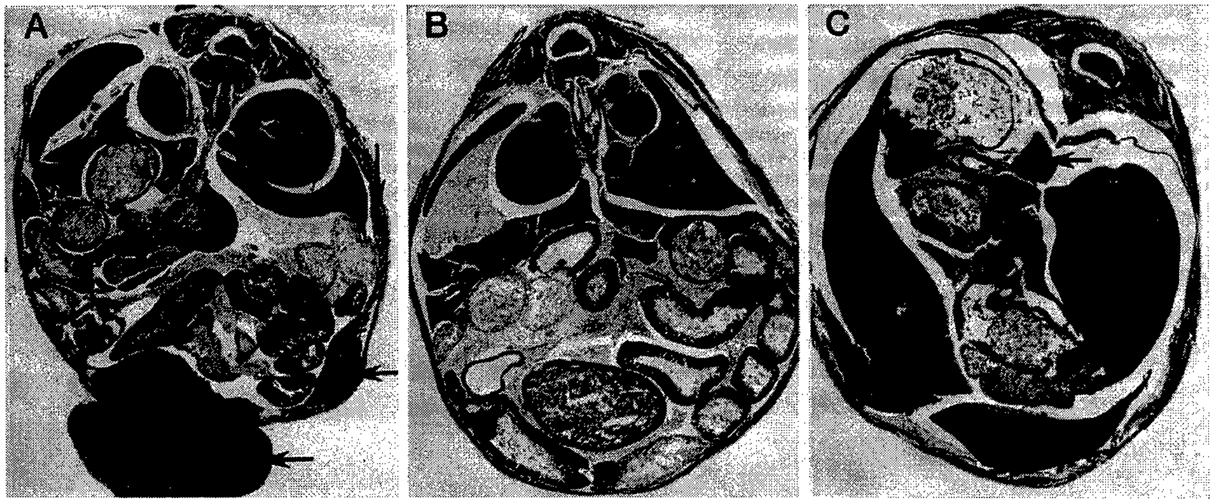

Fig. 7 Sections of abdomens of mice bearing i.p. HEY tumors sacrificed on day 31. Mice had been given saline (controls; *A*), 180 mg/kg PGA-TXL on day 2 (*B*), or 180 mg/kg PGA-TXL on day 7 (*C*). Histopathologically defined tumors are shown by *arrows*. *A*, all four controls demonstrated marked tumor burden, typical of that shown here. *B*, none of four mice treated on day 2 had macroscopic or histopathologically detectable tumor. *C*, only one of six mice treated on day 7 had macroscopic or histopathologically detectable tumor, as shown here.

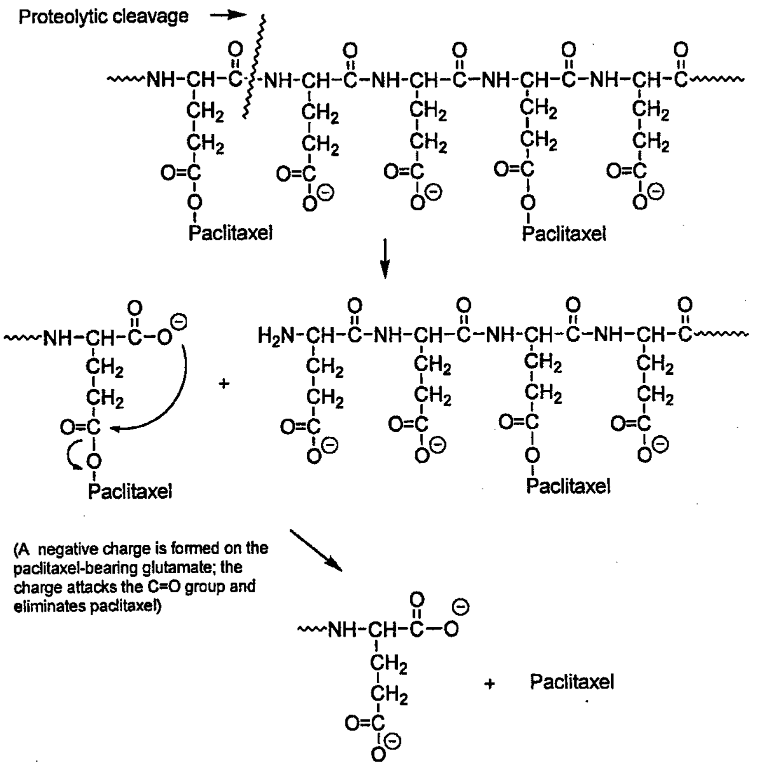

Fig. 8 Proposed two-step, proteolytic/autoesterolytic pathway for endosomal degradation of PGA-TXL. The first step involves cleavage of PGA backbone amide linkages by an endosomal protease(s) of restricted specificity. The second involves an autocatalytic ester cleavage in the paclitaxel/glutamic acid heterodimer, liberating paclitaxel.

than with the 37% formulation. Perhaps as a result of differences in substitution and accessibility to proteases or esterases, these formulations differed in their processing by either the two-step or one-step mechanisms cited above. The extent of substitution should be considered a variable to be optimized in formulation based on mechanisms of prodrug processing.

In neither of the ovarian tumor models employed in our studies should the EPR effect be profound, given the low tumor burden and minimal tumor angiogenesis expected, particularly in the day 2 or day 7 HEY model. Nevertheless, copolymer delivery of paclitaxel may contribute to its slower peritoneal clearance and ability to maintain effective drug doses over longer periods of time. This might particularly be the case when the much higher-tolerated doses of PGA-TXL compared with Taxol are considered.

Previous studies, both in experimental tumor models (68) and in the clinic (69), have suggested that i.p. administration of Taxol drugs may be beneficial for targeting ovarian carcinomas confined to the peritoneum. The present study supports the adequacy of this approach and has shown that the i.p. administration of this copolymer formulation of paclitaxel is much more effective and better tolerated than conventional Taxol in these two Taxol-resistant tumor models. In this light, it will also be important to establish the relative benefits of i.p. *versus* i.v. delivery on copolymer uptake by i.p.-implanted tumors.

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