Fibrinogen-Coated Droplets of Olive Oil for Delivery of Docetaxel to a Fibrin(ogen)-Rich Ascites Form of a Murine Mammary Tumor

Charity M. Einhaus,1 Andrew C. Retzinger,1 Andre O. Perrotta,1 Michael D. Dentler,1 Abhijeet S. Jakate,2 Pankaj B. Desai,2 and Gregory S. Retzinger1

1Department of Pathology and Laboratory Medicine and the 2College of Pharmacy, the University of Cincinnati, Cincinnati, Ohio

ABSTRACT

Micronized droplets of olive oil loaded with docetaxel and coated with functional fibrinogen were administered intraperitoneally to mice bearing the fibrin(ogen)-rich ascites form of the TA3/St mammary tumor. When compared with docetaxel administered intraperitoneally as its commercial formulation (i.e., Taxotere), docetaxel-loaded oil droplets coated with murine fibrinogen prolonged the median survival time of tumor-bearing mice from 14.5 to 29.5 days. Drug-free oil droplets provided no therapeutic benefit. Significantly more docetaxel was associated with tumor cells 24 and 48 hours after administration of the drug in fibrinogen-coated oil droplets than after its administration as Taxotere. Consistent with a role for thrombin in the retention of fibrinogen-coated oil droplets within the tumor microenvironment, hirudin significantly reduced the association of tumor cells with docetaxel delivered in fibrinogen-coated oil droplets and, at the same time, reduced the therapeutic efficacy of the droplets to that of Taxotere. Importantly, fibrinogen-coated oil droplets formed rosettes with tumor cells in vivo, a process prevented by hirudin. Although mice treated with oil droplets developed antifibrinogen antibodies, those antibodies seemed to be inconsequential. Taken together, our results and observations indicate fibrinogen-coated oil droplets markedly improve the therapeutic efficacy of docetaxel for the treatment of a mammary tumor grown in ascites form, a consequence of thrombin-mediated retention of the drug-loaded droplets within the tumor microenvironment.

INTRODUCTION

Fibrinogen, of all of the plasma proteins, binds avidly to hydrophobic surfaces (including those of hydrophobic liquids) in contact with blood (1, 2). The bound protein can remain functional in the classic sense of fibrin gelation. Earlier, we exploited the affinity of fibrinogen for hydrophobic liquids to develop fibrinogen-coated olive oil droplets as vehicles with which to deliver lipophilic drugs to sites of fibrin(ogen) deposition in vivo (3). Subsequently, we showed that fibrinogen-coated droplets of olive oil administered intravenously accumulated at an imposed fibrin(ogen)-rich inflammatory site. As a consequence of that demonstration, we proposed such droplets might be used advantageously to deliver oil-soluble drugs to any site of fibrin(ogen) deposition, including malignant tumors (4, 5). In support of our proposal, we showed that fibrinogen-coated droplets of olive oil loaded with docetaxel, a lipophilic taxane, significantly prolong the survival of mice bearing a solid tumor, the B16F10 melanoma (6).

The effectiveness of fibrinogen-coated, docetaxel-loaded oil droplets against a solid tumor like the melanoma prompted us to consider whether the droplets might also be effective against less consolidated tumors (e.g., ascites tumors) that are especially prone to fibrinogen deposition (7). An example is the TA3/St ascites tumor, which derived from a spontaneous mammary carcinoma in a mouse of the A/HeHa strain (8, 9). Because its microenvironment is so fibrin(ogen)-rich, we felt the TA3/St tumor might be ideally suited to treatment with fibrinogen-coated olive oil droplets loaded with docetaxel, an agent particularly effective against mammary carcinomas (10, 11).

In this report, we describe studies in which the TA3/St mammary tumor grown in ascites form was used to compare the anticancer activity of docetaxel delivered in fibrinogen-coated olive oil droplets to that of docetaxel administered as its standard formulation, Taxotere. Because the therapeutic benefit conferred by the fibrinogen-coated oil droplets was substantial, additional studies were done to elucidate the role of thrombin activity/fibrin formation in the operation of the droplets, and to determine whether the droplets elicit antifibrinogen antibodies that are of obvious clinical consequence.

MATERIALS AND METHODS

Reagents and Chemicals. Docetaxel and Taxotere were obtained from Aventis Pharmaceuticals (Bridgewater, NJ). Murine fibrinogen was purchased from Sigma Chemical Co. (St. Louis, MO). Unless specified otherwise, it was used as received. Human fibrinogen was obtained from Enzyme Research Laboratories (Indianapolis, IN). The buffer composition of the human fibrinogen was changed by gel permeation chromatography.
using Sephadex G-25 as matrix material and 0.02 mol/L Tris-HCl (pH 7.40) as eluent. The human fibrinogen was then ali-quoted and stored frozen at −20°C until use. Fibrinogen concentration was determined with 5.12 × 10⁵ M⁻¹ cm⁻¹ as the molar absorptivity of the protein at 280 nm. Docetaxel was tritium custom-labeled by Amersham Biosciences (Piscataway, NJ). Labeling of the drug was limited to its aryl rings, yielding a final product of specific activity 259 GBq · mmol⁻¹. Fatty acid-free BSA was purchased from ICN (Irvine, CA). Pluronic F68 (F68) was obtained from BASF Corporation (Mt. Olive, NJ). Olive oil, casein, murine thrombin (>1,000 NIH units · mg⁻¹), and hirudin (3,000 units · mg⁻¹) were obtained from Sigma. Refludan was purchased from Aventis Pharma (Frankfurt, Germany). Rabbit antihuman fibrinogen IgG was purchased from American Diagnostica (Greenwich, CT). Rabbit antihuman thrombin IgG that cross-reacts with murine thrombin was obtained from American Diagnostica (Greenwich, CT). Rabbit antihuman fibrinogen IgG was purchased from American Diagnostica (Greenwich, CT). Rabbit antihuman thrombin IgG that cross-reacts with murine thrombin was also obtained from American Diagnostica. Horse radish peroxidase-conjugated goat antimouse IgG, and alkaline phosphatase (AP)-conjugated goat antirabbit IgG were purchased from Promega (Madison, WI). Polystyrene-divinylbenzene beads of diameter 6.4 ± 1.9 µm, and polystyrene-divinylbenzene beads of diameter 0.945 ± 0.0064 µm were obtained from Seradyn (Indianapolis, IN). Before use, beads were washed and lyophilized as described elsewhere (12). Freund’s incomplete adjuvant was obtained from Difco Laboratories (Detroit, MI). All other reagents and chemicals were of the highest quality available commercially.

**Mice.** Eight- to 10-week-old female A/Jax mice weighing between 17 and 20 g were from The Jackson Laboratory (Bar Harbor, ME). Before use, mice were acclimated to the local environment for a period of 1 week. The animal protocol was reviewed and approved by the Institutional Animal Care and Use Committee of the University of Cincinnati.

**Tumor Cells.** TA3/St ascites tumor cells were from Drs. Janice Nagy and Harold Dvorak (Boston, MA). Tumor cells were propagated as stock cultures within the abdominal cavities of A/Jax mice. Tumor cells intended for administration to test animals were collected from the abdominal cavities of three mice that had carried tumor cells for 5 days. Tumor cells from the three animals were pooled, and then washed once using 20 mL of normal saline (NS) and centrifugation at 1,500 × g for 3 minutes. Before inoculating them into naive mice, tumor cells were dispersed in NS to a final concentration of 1 × 10⁶ cells · mL⁻¹. The volume of a tumor cell inoculum was always 1 mL.

**Preparation of Emulsions.** When included in an olive oil preparation, docetaxel was first dissolved in the oil phase to a final concentration of 1 mg · mL⁻¹ with an ultrasonic water bath and intermittent sonication over the course of 1 hour. As determined by using high performance liquid chromatography, such sonication does not result in any discernible deterioration of docetaxel (6).

Both drug-free and drug-loaded olive oil were emulsified with the method of high pressure extrusion (3, 6). Two mL of drug-free or drug-loaded olive oil and 3 mL of NS containing F68 at a concentration of 1 mg · mL⁻¹ added to a clean, 12 × 75-mm glass tube. The oil/water mixture was gently agitated and was then extruded 5 times under high pressure, 103.5 MPa, through the aperture of a homogenizer (EmulsiFlex-20,000-B3; Avestin, Ottawa, Canada). To the resulting oil-in-water emulsion was immediately added either 2 mL of NS or 2 mL of NS containing murine fibrinogen, human fibrinogen or BSA. Because murine fibrinogen from commercial source is exceedingly expensive, we reduced the concentration of all proteins used to coat droplets from 4 mg · mL⁻¹ (6) to 2 mg · mL⁻¹. After sonication the emulsion for 10 to 15 seconds with an ultrasonic water bath, centrifugation at 1,500 × g for 15 minutes was used to float the oil droplets. The resulting infranatant was removed, and an ultrasonic water bath was used to disperse the residual cream layer in 3 mL of NS. The volume of emulsion used for an injection was 1 mL, of which 40% was olive oil. Oil droplets prepared in this fashion are polydisperse in size, ranging in diameter from ~1 to ~100 µm, with a mean diameter of ~12 µm (6).

Unless specified otherwise, NS as diluent was used to prepare Taxotere for injection to a final concentration of 0.40 mg · mL⁻¹.

**Tumor Model and Treatments and Toxicity Assessment.** To begin an experiment, mice received an injection intraperitoneally with tumor cells. Three days later, a single inoculum of test or control material was then administered intraperitoneally to the animals. Whether in oil droplets or as Taxotere, the amount of docetaxel administered per test inocu-lum was always 0.40 mg (i.e., ~20 mg/kg animal body mass). Regardless of material/vehicle, the total volume per injection was always 1 mL.

For some experiments, Refludan was administered to tumor-bearing mice. The first dose was administered intraperitoneally ~2 hours before treating animals with test or control materials. Thereafter, tumor-bearing mice received a similar bolus at 24 hour intervals on all subsequent days. Before injection, the Refludan was diluted with NS. The amount of Refludan administered each time was 40 µg in 0.2 mL.

To assess toxicity, a separate experiment was done in which healthy, tumor-free mice of known weights were treated in groups of five, each with a single intraperitoneal injection of one of several preparations. Using a top-loading balance, we measured the weights of the animals every day for 15 days. Statistical significances of differences between mean weights of mice from the various treatment groups were determined by using Student’s t test. We took as significant P ≤ 0.05.

**Analysis of Antitumor Efficacy Data.** The number of mice surviving in an experimental group was monitored as a function of time after tumor cell inoculation. Results of survival studies were plotted as the percentage of animals remaining alive in a group versus day after tumor cell inoculation. For purposes of inter-group comparisons, the percentage of increase in life span (%ILS) because of a treatment was defined as [median days of survival of treated group − median days of survival of NS-treated group]/median days of survival of NS-treated group] × 100%. Statistical significances of differences between mean survival times of various treatment groups were determined by using Student’s t test. Again, we took as significant P ≤ 0.05.

**Abdominal Cavity Lavage and Recovery and Evaluation of Ascites/Lavage Fluid.** Mice that had been treated variously were euthanized and, immediately thereafter, each was given an intraperitoneal inoculum of 2 mL NS. Three-milliliter plastic syringes equipped with 18 gauge needles were...
then used to collect as much of the lavage fluids and their accompanying materials as possible from the abdominal cavities of the animals. Lavage fluid recovered from an animal was used in various ways. Sometimes it was immediately spread onto glass microscope slides and either covered with a coverslip for viewing or prepared as a smear. For one set of experiments, centrifugation at 1,500 \( \times g \) for 10 minutes was used to clear lavage fluids of cells, and a turbidimetric method (14) was used to assess the thrombin activities in 20–50 \( \mu \)L aliquots of the resulting cell-free fluids. In brief, the turbidimetric method involves adding a test sample to a stirred dispersion of fibrinogen-coated, microscopic latex beads. Such beads agglutinate in the presence of thrombin, a consequence of interbead fibrin formation. A platelet aggregometer or other photometric device can be used to monitor agglutination. The rate of change of light-scattering of the stirred bead dispersion is proportional to the thrombin activity in the sample. Thrombin-inducible agglutination of fibrinogen-coated beads is inhibited in stoichiometric fashion by hirudin, a thrombin specific inhibitor (14).

**Monitoring the Association of Docetaxel with Tumor Cells.** \(^{[1]}\)H/docetaxel was added to both oil droplets and Taxotere. When included in oil droplets, \(^{[1]}\)H/docetaxel was added along with unlabeled docetaxel to the oil just before emulsification of that phase. When included in Taxotere, \(^{[1]}\)H/docetaxel was added to the ethanolic polysorbate 80 of the commercial preparation just before dilution of that material with NS.

Three days after administering tumor cells to mice, tumor-bearing animals were each given an intraperitoneal injection of the radioactively spiked version of either Taxotere or docetaxel-loaded oil droplets. Some oil droplet-treated mice were also treated with Refludan as described above. Twenty-four or 48 hours later, all of the animals of a group were sacrificed, their abdominal cavities were lavaged, and the lavage fluids and accompanying materials were collected as described above. After determining the number of cells in a lavage sample, centrifugation at 1,500 \( \times g \) for 2 minutes was used to sediment the cells in the sample. The radioactivity associated with tumor cells was then measured after diluting them with liquid scintillation medium. Results were recorded as nanograms of docetaxel per 1,000 recovered tumor cells.

**Immunodetection of Proteins.** Immunoblotting was used to detect thrombin in fluids recovered from the abdominal cavities of tumor-bearing mice. Mice that had received injection with tumor cells were euthanized after various lengths of time. Immediately after euthanizing an animal, its abdominal cavity was inflated with 2 mL of NS. The lavage and accompanying ascites fluid were then collected by using a 3-\( \mu \)L plastic syringe equipped with an 18 gauge needle. Centrifugation at 1,500 \( \times g \) for 15 minutes was used to sediment tumor cells, and the cell-free fluid was aspirated and saved. Ten microliters of the aspirate were blotted alongside control materials onto a polyvinylidene difluoride membrane. NS was used to rinse washed oil droplets from a filter. Ten microliters of the resulting dispersion of oil droplets were blotted alongside positive and negative control materials onto a polyvinylidene difluoride membrane. NS was used to rinse washed oil droplets from a filter. Ten microliters of the resulting dispersion of oil droplets were blotted alongside positive and negative control materials onto a polyvinylidene difluoride membrane.

**Elicitation and Assessment of Antifibrinogen Antibodies.** Mice in groups of 3 to 6 received injection intraperitoneally at time 0 and after 7, 14, and 21 days with one of several preparations. The preparations included (a) NS, 1 mL; (b) emulsion containing docetaxel-free, fibrinogen-free oil droplets, 1 mL; (c) emulsion containing docetaxel-free oil droplets coated with murine fibrinogen, 1 mL; (d) emulsion containing docetaxel-free oil droplets coated with human fibrinogen, 1 mL; (e) Freund’s incomplete adjuvant, 0.4 mL, containing 1 mg of murine fibrinogen in NS; and (f) Freund’s incomplete adjuvant, 0.4 mL, containing 1 mg of human fibrinogen in NS. After 38 days, blood was also collected in similar fashion from age-matched untreated mice. After centrifugation of the blood samples at 1,500 \( \times g \) for 12 minutes, ELISA was used to assess the plasma from each for antifibrinogen antibodies.

For the ELISA, 96-well flat-bottomed microtiter plates (PRO-BIND, Becton Dickinson, Franklin Lakes, NJ) were prepared and used as follows. Into each well of a plate was added 150 \( \mu \)L of 0.05 mol/L carbonate buffer (pH 9.60), containing 100 \( \mu \)g \( \cdot \)mL\(^{-1} \) of fibrinogen. Depending on the experiment, either human or murine fibrinogen was used. Before using the murine fibrinogen, we removed the IgG that contaminated the protein by using a 1 mL Protein G Sepharose column (HiTrap Protein G HP, Amersham Biosciences) according to the col-
uum’s manufacturer. The solution containing the appropriate species-specific fibrinogen was incubated in the wells of a plate for 2 hours at room temperature. After that time, the fibrinogen-containing solution was forcibly ejected from the wells. “Blocking” medium, 250 μL, containing 0.01 mol/L phosphate buffer (pH 7.40), 0.15 mol/L NaCl, 0.1% (v/v) Tween 20, 10 mg · mL⁻¹ of casein and 20 mg · mL⁻¹ of BSA was next added to each well of the plate, which was then left undisturbed for 60 minutes. After forcibly ejecting the blocking medium and rinsing the wells four times with phosphate-buffered saline containing 0.1% (v/v) Tween 20, the plate was ready for the addition of plasma samples. Plasma samples to be assessed for antifibrinogen antibody content were prediluted 1:5, v/v, with 0.1 mol/L HEPES buffer (pH 7.40) containing 0.10 mol/L NaCl, 10 mg · mL⁻¹ BSA, and 0.1% (v/v) Tween 20. A 250 μL aliquot of such a dilution was added to the first well of a row of wells on a fibrinogen-coated plate. To each of the remaining wells of a row was added 125 μL of the HEPES-buffered diluent. Two-fold serial dilution of the content of the first well was then done, out to a maximum of 24 wells. The dilutions of plasma were incubated in the wells for 1 hour at room temperature, after which the dilutions were forcibly ejected, and the wells were rinsed 4 times with a buffer containing 0.1% (v/v) Tween 20. One hundred and fifty microliters of a 1:2,500 dilution of horse radish peroxidase-conjugated goat antimouse IgG was next added to the wells, and the plates were rinsed 4 times with buffer containing 0.1% (v/v) Tween 20 before adding o-phenylenediamine (Sigma) as colorimetric substrate for horse radish peroxidase. The end point titer of the antifibrinogen antibodies was determined from visual inspection of the intensity of color in the wells after 20 minutes.

Assessment of the Coagulability of Citrated Plasma Samples. Blood samples from the retro-orbital plexuses of mice were collected by using plain Caraway blood collecting tubes. Within 3 seconds of the start of the experiment, citrated plasma was collected within a tube was pressed on a fibrinogen-coated plate. To each of the remaining wells of a row was added 125 μL of the HEPES-buffered diluent. Two-fold serial dilution of the content of the first well was then done, out to a maximum of 24 wells. The dilutions of plasma were incubated in the wells for 1 hour at room temperature, after which the dilutions were forcibly ejected, and the wells were rinsed 4 times with a buffer containing 0.1% (v/v) Tween 20. One hundred and fifty microliters of a 1:2,500 dilution of horse radish peroxidase-conjugated goat antimouse IgG was next added to the wells, and the plates were rinsed 4 times with buffer containing 0.1% (v/v) Tween 20 before adding o-phenylenediamine (Sigma) as colorimetric substrate for horse radish peroxidase. The end point titer of the antifibrinogen antibodies was determined from visual inspection of the intensity of color in the wells after 20 minutes.

RESULTS

Antitumor Efficacy of Docetaxel Formulations and Preliminary Assessment of Toxicity. Earlier, we showed that docetaxel delivered within fibrinogen-coated droplets of olive oil significantly prolongs the survival of mice bearing a solid, intra-abdominal form of the B16F10 melanoma (6). With respect to docetaxel delivered as Taxotere, docetaxel delivered within oil droplets coated with human fibrinogen increased the median survival time of melanoma-bearing mice by 330%. We set out to determine whether docetaxel delivered within fibrinogen-coated oil droplets would, with respect to Taxotere, provide a survival benefit to mice bearing a fibrinogen-rich ascites tumor. In the past, we used only human fibrinogen to coat oil droplets because the human protein is much less expensive than murine fibrinogen. Now, however, and despite its much greater cost, we wanted to use murine fibrinogen for at least some of our experiments to show the operational equivalence of the murine protein. Additionally, we anticipated murine fibrinogen would a priori be less likely than human fibrinogen to elicit an immune response in oil droplet-treated mice (see below).

After first demonstrating that the survival benefit conferred to TA3/St tumor-bearing mice by docetaxel-loaded oil droplets coated with either murine or human fibrinogen was the same (P = 0.40, data not shown), we then compared that survival benefit to those conferred by other preparations, including NS, docetaxel-free oil droplets coated with either BSA or murine fibrinogen, Taxotere, docetaxel-loaded oil droplets coated with BSA, or docetaxel-loaded oil droplets that had not been coated with any protein. As shown in Fig. 1, the survival plots related to NS and docetaxel-free droplets of olive oil were virtually superimposable, the differences in mean survival times not being statistically significant (P ≥ 0.80). For mice in those groups, the median time to death (MTTD) was 9.5 days. Taxotere-treated mice lived significantly longer than vehicle-treated mice (P = 0.0002), their MTTD being 14.5 days (%ILS = 53). Mice treated with BSA-coated droplets of docetaxel-loaded olive oil lived significantly longer (P = 0.035, MTTD = 20 days, %ILS = 111) than Taxotere-treated mice, but not as long as mice treated with either uncoated droplets of docetaxel-loaded olive oil (P = 0.007, MTTD = 25 days, %ILS = 163) or docetaxel-loaded oil droplets coated with murine fibrinogen (P = 0.0001, MTTD = 29.5 days, %ILS = 211). Although the MTTD’s of the last 2 groups were different and their survival profiles overlapped only slightly, the mean times to death of
animals in the 2 groups (i.e., 24.8 ± 2.8 days for mice treated with uncoated droplets and 28.4 ± 4.7 days for mice treated with fibrinogen-coated droplets) were not significantly different, \( P = 0.082 \). This last finding was not unexpected (6), and is addressed below. We conclude that droplets of olive oil, particularly ones precoated with fibrinogen, are better vehicles for the intraperitoneal delivery of docetaxel to the ascites form of the TA3/St mammary tumor than ethanolic polysorbate 80, the medium within which docetaxel is formulated commercially.

Unless indicated otherwise, the fibrinogen we used for all subsequent experiments was of human origin. As a preliminary assessment of toxicity, we monitored for 15 days the weights of healthy, tumor-free mice treated with either NS, Taxotere, or fibrinogen-coated droplets of docetaxel-loaded olive oil. At each daily weighing, there were no statistically significant differences between the average weights of animals of any of the treatment groups. With respect solely to recipient weight, we conclude that a single intraperitoneal injection of fibrinogen-coated droplets of docetaxel-loaded olive oil is no more harmful to mice in the short term than is a single intraperitoneal injection of NS.

**Thrombin Activity in Ascites Fluid from Tumor-Bearing Mice.** Fibrinogen-coated droplets of olive oil were developed by us as vehicles with which to deliver oil-soluble drugs to sites of fibrin formation. We expected thrombin activity existing at such sites would facilitate incorporation there of the droplets into nascent fibrin clots. Because fibrin accumulates within the abdominal cavities of A/Jax mice bearing the ascites form of the TA3/St mammary tumor (7), we anticipated thrombin would be present in ascites fluids of tumor-bearing animals. Indeed, thrombin was present both antigenically (data not shown) and functionally, Fig. 2, in cell-free ascites/lavage fluids recovered from tumor-bearing mice. On average \( n = 3 \), the thrombin activity recovered from a tumor-bearing mouse after 3 days was 0.019 ± 0.009 units/mL of recovered fluid. After 5 days, the thrombin activity had increased significantly \( (P \leq 0.05) \) to 0.053 ± 0.015 units/mL of recovered fluid. No thrombin activity was detected in lavage fluids recovered from healthy, tumor-free mice \( (n = 3) \).

**Measures that Reduce the Therapeutic Efficacy of Droplets of Docetaxel-Loaded Olive Oil.** If thrombin-catalyzed fibrin formation of droplet-bound fibrinogen contributes to therapeutic efficacy, then measures that prevent/limit that formation should prevent/limit therapeutic efficacy. Two such measures include inhibiting thrombin activity by using, for example, hirudin and precoating droplets with a protein other than fibrinogen (e.g., BSA). In fact, both measures prevented/limited the therapeutic efficacy of docetaxel-loaded oil droplets, Figs. 1 and 3. Because the half-life of hirudin in vivo is short, \( t_{1/2} = 1.3 \) hours (15) and because we found the thrombin activity in the abdominal cavities of tumor-bearing mice to be high, we administered a rather large dose of hirudin (Refludan), 40 μg, each day to each test animal. On the basis of drug mass per unit recipient mass, that amount of hirudin corresponds to approximately 4 times the usual loading dose of the drug when it is used in humans (15). As shown in the figure, whereas the daily administration of hirudin by itself had no statistically significant effect \( (P = 0.25) \) on the survival of tumor-bearing mice, it did reduce the survival benefit of mice treated with any of the docetaxel-loaded oil droplets to that of mice treated with Taxotere \( (P \geq 0.80) \). Taken together, these results suggest fibrin formation at the surface of the oil droplets contributes to the survival benefit conferred by docetaxel-loaded droplets of olive oil, whether the droplets are precoated with fibrinogen or not.

**Association of Docetaxel with Tumor Cells In vivo.** Previously, we presented preliminary evidence that the association of docetaxel with intra-abdominal solid tumor tissue is significantly greater when the drug is delivered intraperitoneally in fibrinogen-coated oil droplets than when the drug is delivered intraperitoneally as Taxotere (6). The availability of \( [\text{3}^H] \)docetaxel as well as the ease with which ascites tumor cells can be collected from the abdominal cavities of mice prompted us to determine more directly the relationship between delivery vehicle and the association of docetaxel with tumor cells. Mice inoculated 3 days earlier with TA3/St tumor cells were given \( [\text{3}^H] \)docetaxel either as Taxotere or in fibrinogen-coated oil droplets. Some droplet-treated mice were also given hirudin as described above. Twenty-four or 48 hours after treating them with \( [\text{3}^H] \)docetaxel, animals of a group were sacrificed, and their tumor cells were harvested and washed to remove any unbound materials. Subsequently, radioactivities associated with the cells were measured. We then determined for each group the mean (± SD) mass, in nanograms, of docetaxel per

![Fig. 2](image)

**Fig. 2** Five units of hirudin (A) inhibits the decrease in apparent absorbance that otherwise (B) accompanies the addition of ascites fluid to a stirred dispersion of fibrinogen-coated microscopic beads. The decreasing apparent absorbance is attributable to bead aggregation, a thrombin-dependent phenomenon. Arrows indicate the addition of cell-free ascites fluid to reaction cuvettes containing beads in aqueous dispersion. See text and reference 14 for details.
Fibrinogen-Coated Oil Droplets, Docetaxel, and Tumors

Coated droplets of docetaxel-loaded olive oil plus hirudin (0.062, NS alone (n = 8); ○, NS and hirudin (n = 6); ▲, Taxotere alone (n = 5); ●, BSA-coated droplets of docetaxel-loaded olive oil plus hirudin (n = 4); ○, human fibrinogen-coated droplets of docetaxel-loaded olive oil plus hirudin (n = 4); □, uncoated droplets of docetaxel-loaded oil droplets plus hirudin (n = 4); and (◆), human fibrinogen-coated droplets of docetaxel-loaded olive oil minus hirudin (n = 4). Whereas the three distinct groups of profiles are all significantly different from each other (P ≤ 0.03), none of the individual profiles of a group is significantly different from the other profiles of that group (P ≥ 0.80). See text for details.

1,000 tumor cells per animal. After 24 hours, the value was 0.062 ± 0.043 for mice (n = 5) treated with Taxotere and 0.446 ± 0.116 for mice (n = 5) treated in the absence of hirudin with docetaxel-loaded oil droplets coated with fibrinogen. After 48 hours, the value was 0.010 ± 0.001 for mice (n = 5) treated with Taxotere, 0.149 ± 0.046 for mice (n = 5) treated in the absence of hirudin with docetaxel-loaded oil droplets coated with fibrinogen, and 0.047 ± 0.050 for mice (n = 4) treated with both hirudin and docetaxel-loaded oil droplets coated with fibrinogen. We conclude that, at least during the first 2 days after treatment and in the absence of hirudin, about an order of magnitude more docetaxel is associated with tumor cells if the drug is administered in fibrinogen-coated oil droplets than if it is administered as Taxotere (P ≤ 0.001). Furthermore, and consistent with the results of the survival studies, if hirudin is coadministered with fibrinogen-coated droplets of docetaxel-loaded olive oil, the association after 2 days of the drug with tumor cells is reduced significantly (P ≤ 0.02) from that observed in the absence of the thrombin inhibitor.

Association of Oil Droplets with Tumor Cells In vivo. If fibrin does mediate the binding of drug-loaded oil droplets to tumor cells, then one might expect to see oil droplets adhered to tumor cells recovered from oil droplet-treated mice. Furthermore, hirudin should prevent such adherence. As shown in Fig. 4, rosettes consisting of oil droplets and tumor cells were abundant in ascites removed from tumor-bearing mice shortly after having administered to the animals either fibrinogen-coated droplets or uncoated droplets. Coadministration of hirudin with either of those droplets prevented rosette formation. Although the association of BSA-coated droplets with tumor cells was much less obvious than that seen when using either fibrinogen-coated droplets or uncoated droplets, such association was still present and sensitive to hirudin. We conclude that fibrin does indeed mediate the binding of oil droplets to tumor cells.

Endogenous Fibrin(ogen) Both on Oil Droplets and on Tumor Cells In vivo. One of us showed earlier that BSA molecules coated onto a hydrophobic particle that is subsequently implanted into a mouse are digested and replaced with endogenous protein, most notably fibrinogen (16). Thus, whereas BSA molecules preadsorbed to oil droplets can, in the short term, block the binding of endogenous fibrinogen, the latter protein ultimately coats the droplets in vivo yielding, in effect, fibrinogen-coated particles. It came as no surprise to us, then, that not only uncoated oil droplets but also BSA-coated droplets of docetaxel-loaded oil or BSA-coated docetaxel-loaded oil adhere to tumor cells recovered from oil droplet-treated, tumor-bearing mice. Tumor cells were washed extensively before plating them onto a slide for photomicroscopy. In A and D, oil droplets are stained with oil red O. B, C, E, and F are photos taken with phase-contrast microscopy of unstained oil droplets and/or cells. A, B, D, and E are photos taken of material recovered from tumor-bearing mice treated with only fibrinogen-coated, docetaxel-loaded oil droplets. As shown, tumor cells and fibrinogen-coated droplets from such animals adhere to each other, forming rosettes. Similar results are obtained even if docetaxel-loaded droplets are not precoated with fibrinogen before their administration. C and F are photos of material recovered from tumor-bearing mice treated with both hirudin and fibrinogen-coated, docetaxel-loaded oil droplets. The last dose of hirudin was given ~2 hours before the collection of ascites/lavage fluid. As shown, hirudin prevents the association of fibrinogen-coated oil droplets with the cells. See text for details.
droplets of docetaxel-loaded olive oil elicited a significant improvement over Taxotere (see Fig. 1). Using an immunoblotting technique, we found, as expected, that both uncoated droplets and BSA-coated droplets acquire in vivo a layer of endogenous fibrin(ogen), Fig. 5A. Importantly, not only the droplets, but also the ascites tumor cells are coated with fibrinogen, Fig. 5B. Because fibrin molecules on juxtaposed microparticles can interact to cause the mutual adhesion of the particles (2, 14), our results suggest oil droplets are tethered to tumor cells by fibrin polymers that are themselves anchored to the two surfaces.

**Production of Antifibrinogen Antibodies in Mice Treated with Olive Oil Droplets.** Many proteins become immunogenic when they are bound to oil droplets or other hydrophobic particles (16, 17). For this reason, we looked for antifibrinogen antibodies in plasmas from healthy, tumor-free mice that had been treated with 4 weekly doses of olive oil droplets. One group of mice was treated with droplets that had been coated with human fibrinogen, another was treated with droplets that had been coated with murine fibrinogen, and another was treated with uncoated oil droplets. Untreated mice served as negative controls, and mice treated with Freund’s incomplete adjuvant containing either human fibrinogen or murine fibrinogen served as positive controls. Whereas none of the mice in the untreated control group (n = 6) had demonstrable antibodies directed against fibrinogen of either murine or human origin, all of the mice in the positive control groups and all of the mice in the groups treated with fibrinogen-coated oil droplets had substantial amounts of antifibrinogen antibodies (Table 1). Although significantly higher titers of antifibrinogen antibodies were achieved when human fibrinogen was used as coating than when murine fibrinogen was used as coating (P ≤ 0.001), the levels of antifibrinogen antibodies in both cases were appreciable. Perhaps not surprisingly, two of five mice treated with uncoated oil droplets had demonstrable, albeit low, levels of antibodies directed against murine fibrinogen. These findings prompted investigation of the biological consequences of antifibrinogen antibodies in mice treated with fibrinogen-coated oil droplets.

**Effect of Droplet-Induced Antifibrinogen Antibodies on Survival of Tumor-Bearing Mice Treated with Taxotere.** Because docetaxel administered in oil droplets conferred a significant benefit to survival in comparison to docetaxel delivered as Taxotere, we considered the possibility that antifibrinogen antibodies might somehow contribute to the therapeutic efficacy of docetaxel when the drug is administered in oil droplets. If so, then Taxotere administered to tumor-bearing mice with high titers of droplet-induced antifibrinogen antibodies might be expected to survive longer than tumor-bearing mice treated with Taxotere alone. To test this, Taxotere was administered both to tumor-bearing mice that had no demonstrable antifibrinogen antibodies and to age-matched, tumor-bearing mice in which high titers of antihuman fibrinogen antibodies had been elicited by the time of tumor cell inoculation. As shown in Fig. 6, the presence of even very high levels of droplet-induced antifibrinogen antibodies did not prolong the survival of tumor-bearing animals beyond that yielded by Taxotere alone (P = 0.26). Such a result suggests antifibrinogen antibodies play no role in the therapeutic efficacy of docetaxel when the drug is delivered within fibrinogen-coated droplets of olive oil.

**Coagulability of Plasma from Mice Treated with Fibrinogen-Coated Droplets of Olive Oil.** Antibodies directed against fibrinogen, a protein critical to coagulation, might be expected to interfere with blood clotting in vivo and/or in vitro. In cancer patients, such interference would be undesirable. Although tumor-bearing mice treated with fibrinogen-coated oil droplets did not seem to be any more predisposed to hemorrhage than tumor-bearing mice treated otherwise, we could not, by direct observation alone, exclude the possibility of a more subtle coagulation defect in droplet-treated mice. In a preliminary attempt to determine what effect, if any, antifibrinogen antibodies elicited by fibrinogen-coated oil droplets have on coagulation, the aPTT’s of healthy tumor-free droplet-treated mice (n = 7) were compared with those of healthy tumor-free untreated mice (n = 6). To ensure the presence of very high titers of antifibrinogen antibodies, the oil droplets used for the experiment were coated with human fibrinogen. Citrated plasmas were used to determine both antifibrinogen antibody titers and aPTT’s. Whereas none of the plasmas from untreated mice had demonstrable antihuman fibrinogen antibodies, all of the plasmas from droplet-treated mice were positive for such antibodies.

---

**Fig. 5** A, immunoblot of fibrinogen bound to docetaxel-loaded oil droplets. Tumor-bearing mice were treated intraperitoneally with either murine fibrinogen-coated (FC), uncoated (UC), or BSA-coated (AC) droplets of docetaxel-loaded olive oil. One hour later, the droplets were recovered, washed extensively, and then immunostained for fibrinogen. Materials in the top two rows were exposed to both the 1° antibody and the AP-conjugated 2° antibody. Those materials included authentic murine fibrinogen (MF), FC oil droplets, UC oil droplets, AC oil droplets (first row); and the last washes of the oil droplets (second row). The materials in the third row (i.e., MF, FC oil droplets, UC oil droplets, and AC oil droplets) were exposed to only the 2° antibody (as negative controls). See text for details. B, immunoblot of fibrinogen bound to TA/St ascites tumor cells. Both 1° and AP-conjugated 2° antibodies were used to visualize murine fibrinogen in samples of a, authentic murine fibrinogen; b, intact ascites fluid; c, washed ascites tumor cells; and d, the last wash of the ascites tumor cells. In e, washed ascites tumor cells were exposed to only the AP-conjugated 2° antibody (as a negative control). See text for details.
Fibrinogen-Coated Oil Droplets, Docetaxel, and Tumors

mice by oil droplets coated with that protein do not interfere with the normal antihuman fibrinogen antibodies elicited in mice was 24.3-fold. The efficacy of docetaxel-loaded oil droplets is not affected by the presence of uncoated fibrinogen, because in the former cases extraneous proteins limit the packing density of endogenous fibrinogen. We conclude that microscopic droplets of olive oil, particularly ones precoated with fibrinogen, are a more effective means by which to deliver docetaxel to the ascites form of the TA3/St mammary tumor than Taxotere. It seems the conversion of droplet-bound fibrinogen to fibrin by thrombin acting locally facilitates the specific adherence of drug-loaded droplets to tumors and, perhaps, the general retention of droplets within the tumor microenvironment. We speculate that measurement of thrombin activity existing within malignant tissue may prove a useful means by which to identify tumors that might be most responsive to the new therapy.

Whether droplets are precoated with fibrinogen of human origin or of murine origin, they elicit in recipient mice a significant antibody response against the protein. Indeed, two of five mice treated with uncoated oil droplets developed measurable titers of antifibrinogen antibodies. Our observations and preliminary studies suggest such antibodies are of no obvious short-term consequence in A/Jax mice bearing the ascites form of the TA3/St tumor; neither do they contribute to, nor do they detract from, the therapeutic benefit that derives from a single injection of docetaxel. But because even droplet-treated tumor-bearing A/Jax mice all succumb to tumor by 35 days, we are unable to make any claim regarding the long-term effects of the antibodies in those animals. It is conceivable such antibodies might limit the effectiveness of subsequent oil droplet treatments. Whereas that consideration was not apropos to the single treatment model used here by us (i.e., antibodies or not, droplets of docetaxel-loaded olive oil provided a benefit to survival significantly conferred by Taxotere, because endogenous fibrinogen coats those droplets, rendering them equivalent operationally to droplets precoated with fibrinogen.

Table 1: Antifibrinogen antibodies elicited by various oil preparations

<table>
<thead>
<tr>
<th>Last positive well (v/v)</th>
<th>Anti-MF</th>
<th>Anti-HF</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIA/MF</td>
<td>3,3,3,3</td>
<td>NM</td>
</tr>
<tr>
<td>Oil droplets/MF</td>
<td>2,5,6,7,11</td>
<td>NM</td>
</tr>
<tr>
<td>FIA/HF</td>
<td>NM</td>
<td>21,21,22</td>
</tr>
<tr>
<td>Oil droplets/HF</td>
<td>≥24,≥24,≥24,≥24</td>
<td>NM</td>
</tr>
<tr>
<td>Oil droplets/uncoated</td>
<td>&lt;1,1,1,2,2</td>
<td>NM</td>
</tr>
</tbody>
</table>

NOTE. Mice in groups of three to six were treated intraperitoneally with one of the oil preparations listed in the left column. Depending upon the species from which the fibrinogen used in the formulation was derived, the plasmas were assessed for antibodies directed against either human fibrinogen (MF) or human fibrinogen (HF). Mice treated with uncoated (i.e., fibrinogen-free) oil droplets were assessed for antibodies directed against MF. See text for details. For a given plasma, 2-fold serial dilutions were made, with the first well of a series being a 1:5, v/v, dilution. The numbers in the table refer to the last obviously positive wells of the plasmas of the mice in a group.

Abbreviations: FIA, Freund’s incomplete adjuvant; NM, not measured; MF, murine fibrinogen; HF, human fibrinogen.

out to a dilution of one part in $8 \times 10^7$. Consistent with published data (18), the mean ± SD of the aPTT of untreated mice was 24.3 ± 3.9 seconds. The mean ± SD of the aPTT of droplet-treated mice was not significantly different, 21.2 ± 2 seconds ($P = 0.09$). Taken together, these results and our gross observations suggest antihuman fibrinogen antibodies elicited in mice by oil droplets coated with that protein do not interfere overtly with coagulation in vitro or in vivo.

DISCUSSION

In a previous paper, we described the preparation, characterization and anticancer activity of fibrinogen-coated droplets of docetaxel-loaded olive oil (6). We proposed there that the fibrinogen coating facilitated the retention of the particles within the fibrin(ogen)-rich tumor microenvironment, thereby increasing the therapeutic efficacy of the docetaxel with respect to that of Taxotere, the existing commercial formulation of the drug. In the present report, we used a fibrin(ogen)-rich, ascites tumor model to (a) extend our earlier studies on the therapeutic efficacy of the droplets, (b) show, by various means, the role of fibrin formation in that efficacy, and (c) document and explore immunologic consequences of the new therapy. We address these three items next.

If left untreated, mice bearing the ascites form of the TA3/St mammary tumor all die by 10 days. Whereas Taxotere prolongs the median survival of tumor-bearing mice by 53%, docetaxel delivered in microscopic droplets of olive oil prolongs median survival by as much as 211% (i.e., a 4-fold improvement over Taxotere). Several experiments indicate droplet-bound fibrinogen and its conversion to fibrin are responsible for the efficacy of docetaxel-loaded oil droplets. Briefly, maximal survival benefit is achieved when droplets are precoated with fibrinogen, and a measure that inhibits thrombin activity (i.e., a measure that inhibits fibrinogen-to-fibrin conversion) reduces the survival benefit of docetaxel-loaded oil droplets to that of an equivalent dose of docetaxel administered as Taxotere. It is not surprising that even uncoated or BSA-coated droplets confer a hirudin-sensitive benefit to survival that is greater than that shown, by various means, the role of fibrin formation in that efficacy, and (c) document and explore immunologic consequences of the new therapy.

Whether droplets are precoated with fibrinogen of human origin or of murine origin, they elicit in recipient mice a significant antibody response against the protein. Indeed, two of five mice treated with uncoated oil droplets developed measurable titers of antifibrinogen antibodies. Our observations and preliminary studies suggest such antibodies are of no obvious short-term consequence in A/Jax mice bearing the ascites form of the TA3/St tumor; neither do they contribute to, nor do they detract from, the therapeutic benefit that derives from a single injection of docetaxel. But because even droplet-treated tumor-bearing A/Jax mice all succumb to tumor by 35 days, we are unable to make any claim regarding the long-term effects of the antibodies in those animals. It is conceivable such antibodies might limit the effectiveness of subsequent oil droplet treatments. Whereas that consideration was not apropos to the single treatment model used here by us (i.e., antibodies or not, droplets of docetaxel-loaded olive oil provided a benefit to survival significantly conferred by Taxotere, because endogenous fibrinogen coats those droplets, rendering them equivalent operationally to droplets precoated with fibrinogen. The survival benefits conferred by uncoated droplets and BSA-coated droplets are somewhat less than that conferred by droplets precoated with fibrinogen because in the former cases extraneous proteins limit the packing density of endogenous fibrinogen. We conclude that microscopic droplets of olive oil, particularly ones precoated with fibrinogen, are a more effective means by which to deliver docetaxel to the ascites form of the TA3/St mammary tumor than Taxotere. It seems the conversion of droplet-bound fibrinogen to fibrin by thrombin acting locally facilitates the specific adherence of drug-loaded droplets to tumors and, perhaps, the general retention of droplets within the tumor microenvironment. We speculate that measurement of thrombin activity existing within malignant tissue may prove a useful means by which to identify tumors that might be most responsive to the new therapy.

Whether droplets are precoated with fibrinogen of human origin or of murine origin, they elicit in recipient mice a significant antibody response against the protein. Indeed, two of five mice treated with uncoated oil droplets developed measurable titers of antifibrinogen antibodies. Our observations and preliminary studies suggest such antibodies are of no obvious short-term consequence in A/Jax mice bearing the ascites form of the TA3/St tumor; neither do they contribute to, nor do they detract from, the therapeutic benefit that derives from a single injection of docetaxel. But because even droplet-treated tumor-bearing A/Jax mice all succumb to tumor by 35 days, we are unable to make any claim regarding the long-term effects of the antibodies in those animals. It is conceivable such antibodies might limit the effectiveness of subsequent oil droplet treatments. Whereas that consideration was not apropos to the single treatment model used here by us (i.e., antibodies or not, droplets of docetaxel-loaded olive oil provided a benefit to survival significantly

Fig. 6 Survival profiles of TA3/St tumor-bearing A/Jax mice treated with NS (A) or with Taxotere (B and C). The mice in groups A (n = 4) and C (n = 4) had no antifibrinogen antibodies preexisting in their plasma before treatment. Each mouse in group B (n = 6), however, had an exceedingly high titer (i.e., positive past a plasma dilution of $1.8 \times 10^7$, v/v) of antihuman fibrinogen antibodies at the time of treatment. B and C are statistically different from A ($P \leq 0.001$) but not from each other ($P = 0.26$). See text for details.

Downloaded from clinicancreas.aacrjournals.org on April 13, 2017. © 2004 American Association for Cancer Research.
greater that that provided by Taxotere), it would be relevant to treatment regimens in which multiple doses of drug-loaded oil droplets were administered over time. We note anecdotally that the antifibrinogen antibody response of droplet-treated C57BL/6 mice is essentially the same as that of droplet-treated A/Jax mice. Importantly, two of nine C57BL/6 mice “cured” of an intraperitoneal form of B16F10 melanoma by treatment with fibrinogen-coated droplets of docetaxel-loaded olive oil (6) had no demonstrable antifibrinogen antibodies 1 year after treatment.

To be sure, much still needs to be done to delineate both the benefits and limitations of the new docetaxel formulation, in particular, and of the delivery vehicle, in general. To date, we have used fibrinogen-coated droplets of docetaxel-loaded olive oil to treat only tumors that are, by intention, confined to the abdominal cavity. Whereas we suspect tumors confined to other closed spaces (e.g., the pleural cavity, pericardial sac, or brain case) will benefit similarly from treatment with the droplets, we have not yet tested that suspicion. Neither have we tested the efficacy of docetaxel-loaded droplets against tumors that either are located within a specific organ or are widely metastatic. We do know that, after their intravenous administration, fibrinogen-coated oil droplets are retained in organs of the reticuloendothelial system (3). Thus, intravenous administration might be especially good for the delivery of droplets to tumors in organs that typically harbor metastatic disease. Regardless, we are now developing smaller versions of fibrinogen-coated oil droplets that might better circulate and percolate through tissues. We are also testing the suitability of fibrinogen-coated oil droplets for the delivery of a number of other lipophilic anticancer agents, both individually and in combination. Eventually, we hope to develop a single formulation that delivers several mechanistically dissimilar agents.

For many reasons, cancer patients are predisposed to thrombosis (19), and thus they occasionally need to be treated with an anticoagulant or even a fibrinolytic agent. Our results suggest concurrent administration of such agents with fibrinogen-coated droplets of docetaxel-loaded olive oil might reduce the therapeutic efficacy of the droplets. On the other hand, if anticoagulants and fibrinolytics reduce the therapeutic efficacy of the droplets, then perhaps pro-coagulants and antifibrinolytics might improve efficacy. Clearly, before the full potential of fibrinogen-coated oil droplets as delivery vehicles for lipophilic anticancer agents can be realized, much more needs to be done to delineate the influence of coagulation-related medicinals on the new modality.

The use of docetaxel in its current clinical formulation is attended by several adverse side effects attributable to either the drug itself (e.g., fluid retention, neurotoxicity, musculoskeletal toxicity and neutropenia; ref. 20), or to the solvent system used in the drug’s commercial preparation (e.g., hypersensitivity; ref. 21). One would hope any new formulation of docetaxel would not only better target the drug to malignant tissue but would also be attended by fewer or less severe side effects. Although we addressed some toxicity issues in the studies presented here, we focused more on the anticancer efficacy of the new formulation and on understanding the basis of that efficacy than on adverse side effects. We hope in the near future to compare specific indices of toxicity (e.g., neutrophil count) after treatment of mice with docetaxel-loaded oil droplets to those same indices after treatment with Taxotere.

Aside from their ability to target tumors as sites of fibrin formation, fibrinogen-coated oil droplets (or other fibrinogen-coated microparticles) might be ideally suited to delivering anticancer agents to malignancies for yet another reason. Work in one of our laboratories supports the hypothesis that macrophages transport particulate materials and even tumor cells in fibrinogen-dependent extracellular fashion (22), and one of us has proposed that metastasis is, at least in part, a manifestation of extracellular trafficking of tumor cells by macrophages (22, 23). If the macrophage-directed “traffic patterns” of particulate materials and metastatic tumor cells are the same, then it is not unreasonable to suppose anticancer agents delivered as/within fibrinogen-coated particulate materials might be exploited to target metastatic disease.

ACKNOWLEDGMENTS

G. Retzinger thanks Ruth Mary Retzinger for inspiration.

REFERENCES


---

8 G. Retzinger, unpublished data.

9 C. Einhaus and A. Perrotta, unpublished data.


15. BERLEX Laboratories, Refludan prescribing information, 02-419-0069/October, 2002.


Fibrinogen-Coated Droplets of Olive Oil for Delivery of Docetaxel to a Fibrin(ogen)-Rich Ascites Form of a Murine Mammary Tumor

Charity M. Einhaus, Andrew C. Retzinger, Andre O. Perrotta, et al.


Updated version
Access the most recent version of this article at:
http://clincancerres.aacrjournals.org/content/10/20/7001

Cited articles
This article cites 18 articles, 5 of which you can access for free at:
http://clincancerres.aacrjournals.org/content/10/20/7001.full.html#ref-list-1

E-mail alerts
Sign up to receive free email-alerts related to this article or journal.

Reprints and Subscriptions
To order reprints of this article or to subscribe to the journal, contact the AACR Publications Department at pubs@aacr.org.

Permissions
To request permission to re-use all or part of this article, contact the AACR Publications Department at permissions@aacr.org.