Direct and Bystander Killing of Sarcomas by Novel Cytosine Deaminase Fusion Gene

Margaret Ramnaraine, Weihong Pan, Michael Goblirsch, Christine Lynch, Victor Lewis, Paul Orchard, Patrick Mantyh, and Denis R. Clohisy

ABSTRACT

Soft tissue and bone sarcomas of the extremities can be difficult to eradicate, and standard treatment may require limb amputation. New therapies to decrease tumor size could improve the effectiveness of treatment and decrease the frequency of limb amputation. Cytosine deaminase (CD)-based gene therapy has been shown to be effective in decreasing growth of solid tumors when animals with CD-expressing tumor cells are treated with 5-fluorouracil (5FU), an inert prodrug that is converted to 5-fluorouracil (5FU) by CD. In this investigation, we used a novel CD-containing fusion gene to determine whether CD-based gene therapy affected soft tissue or bone sarcomas. The novel fusion gene (NGFR-CD) encodes for a protein with extracellular and transmembrane domains of human nerve growth factor receptor (NGFR) and cytoplasmic CD. Mice treated with s.c. NGFR-CD tumors affected only soft tissue sarcoma cells but caused significant decrease in the size of 2NGFR-CD tumors (51 ± 60 versus 938 ± 767 mm², treated versus control, P < 0.01). Treatment killed NGFR-CD-transduced sarcoma cells in vitro through direct and bystander effects (P < 0.01). In contrast, 5FU-treated mice with s.c. 2NGFR-CD or 2NGFR-CD tumors affected only 2NGFR-CD tumors. 5FC had no effect on growth of NGFR-CD tumor but caused significant decrease in the size of 2NGFR-CD tumors (60 ± 93 versus 938 ± 767 mm², treated versus control, P < 0.01). Evaluation of bystander killing in vivo revealed significant tumor killing, with a 5-fold reduction in s.c. tumor volume evident in saline versus 5FC-treated mice when tumors were comprised of 90% 2472 cells and 10% 2NGFR-CD selected for fluorescence-activated cell sorting (P < 0.01). Bone sarcomas were eliminated in 9 of 10 2NGFR-CD-treated mice, compared with 11.8 ± 6.0 mm² in saline-treated mice (P < 0.002). In addition, 5FC treatment of bone sarcomas caused a significant reduction in cancer-induced bone destruction (P < 0.002) and resulted in a reduction in the number of osteoclasts. Finally, 5FC treatment had no effect on animal weight or survival, whereas doses of 5FU providing equivalent tumor reduction as 5FC resulted in treatment-associated deaths and significant weight loss (P < 0.001).

INTRODUCTION

Enzyme/prodrug gene therapy can involve transducing tumor cells with a gene encoding nonmammalian enzyme converting a nontoxic prodrug to a cytotoxic agent (1). One enzyme/prodrug therapy uses the prodrug 5FC. 5FC is deaminated by CD into the cytotoxic drug 5FU (2). Designing therapies where CD is expressed in localized areas of cancer is attractive because such treatments could deliver very high local concentrations of 5FU to tumor sites while avoiding toxic systemic levels. CD genes from Escherichia coli and Saccharomyces cerevisiae have been evaluated in experimental animals as enzyme/prodrug therapies. Both the bacterial (b) and yeast (y) enzyme/prodrug systems have been shown to inhibit tumor growth. However, recent work suggests that therapies using yCD are superior because yCD has a 22-fold higher 5FC conversion efficiency than bCD (3, 4).

The CD enzyme/prodrug system has advantages over other enzyme/prodrug systems. One advantage is that 5FU can function as a cytotoxic molecule and as a radiosensitizer (5). This makes the CD system particularly attractive for treating tumors that will receive radiation treatment such as colon cancer. It has been shown in experimental models that CD-based prodrug systems are effective in killing colon cancer cells (2, 3, 6, 7), and recently, a synergistic effect has been reported with combined 5FC treatment and radiation (4, 8). A second advantage of the CD enzyme/prodrug system is 5FU-directed bystander killing (2, 4, 6). Bystander killing occurs when tumor cells not expressing CD are eliminated by passive diffusion of 5FU from adjacent CD-expressing, 5FU-producing cells. An advantage of the bystander effect is making it unnecessary to deliver the gene in all cells to obtain an effect in vivo.

Novel means for reducing the size of extremity sarcomas are needed to improve local treatment of these devastating cancers and to decrease the frequency of limb amputation. In this investigation, a novel fusion gene containing a truncated form of the human NGFR and either the bacterial or yeast CD gene was used to determine whether CD-expressing soft tissue or bone sarcoma cells would respond to 5FC treatment. Both direct and bystander tumor killing were evaluated. In addition, as osteolysis plays a pathological role in bone sarcoma progression, we examined the possibility that 5FC treatment of CD-transduced bone sarcomas decreased tumor-induced osteolysis.

MATERIALS AND METHODS

Cell Culture. 2472 cells, originally derived from a malignant tissue tumor (sarcoma) in a C3H mouse and PA317 amphotrophic packaging cell line, were obtained from the American Type Culture Collection (Manassas, VA). Powdered media was purchased from Sigma-Aldrich Chemical (St. Louis, MO), and sera from Hyclone (Logan, UT). 2472 cells were maintained in NCTC-135 media containing 10% horse serum, and fed twice/week. PA317 cells were maintained in DEMEM containing 10% newborn calf serum and passaged twice weekly. tPBS was used for all washes and reconstituted from 10X stock (Mediatech, Inc., Herndon, VA).

Vector Design. The retrovirus vectors containing the fusion genes were generated using the pCR2.1 vector (Invitrogen Life Technologies, Inc., Carlsbad, CA) and sequenced to confirm its identity. The fusion genes were excised from pCR2.1 and subcloned into the LXSNS vector (10). Clones were screened to confirm the correct orientation. The final constructs, termed LNG/bCDSN and LNG/yCDSN, were transfected into the PA317 packaging line, and 0.4 mg/ml G418 (Life Technologies, Inc.) were used to select positive clones (11). High-titer clones were chosen to generate viral supernatants, which were used to transduce the 2472 tumor line.
Retrovirus Transduction. Tumor cells were plated at 10^7 cells in a 100-mm dish and were transduced with a 2-ml aliquot of viral supernatant containing 20 μg/ml DEAE-Dextran. Cells were cultured for 4 h with rocking before 6 ml media was added. Cells were grown for 48 h before changing to selection media, which contained 0.8 mg/ml G418. Transduced 2472 tumor cells were designated 2NGFR-βCD and 2NGFR-γCD, with 2 indicating 2472 cells. Transduced tumor cells were maintained as the parent lines, except for the addition of 0.8 mg/ml G418.

FACS Analysis. Transduced tumor cells were harvested at passage, and an aliquot of 10^6 cells was used for FACS analysis. Briefly, the cells were pelleted in 12 × 75-mm tubes, resuspended in PBS containing 0.1% BSA, and divided into two 100-μl tubes containing either 100 ng/10^6 cells of the biotinylated monoclonal mouse antihuman NGFR (clone 20.4, provided by Dr. P. Orchard) or an equal amount of a biotinylated isotype control immunoglobulin. Cells were incubated on ice for 30 min, washed once in 10-fold volume of dPBS containing 0.1% BSA, followed by addition of 100 ng/10^6 cells of the secondary antibody conjugated to Streptavidin-PE (BD Biosciences PharMingen, San Diego, CA). Cells were resuspended in 0.5 ml ice-cold lysis buffer [50 mM Tris-HCl (pH 7.6), 150 mM NaCl, 5 mM EDTA, 0.5% Triton X-100, 0.2% SDS, 1 mM NaF, and 1 mM Na_3PO_4] with protease inhibitor mixture tablets (Roche, Indianapolis, IN), then incubated on ice for 20 min and centrifuged 2 min at full speed in a microcentrifuge at 4°C. Supernatant was stored at −80°C. Two hundred μg of cell lysate/lane were separated on a 10% reducing SDS-PAGE and transferred to an nitrocellulose membrane (Schleicher and Schuell, Keene, NH). The membranes were blocked with 5% nonfat milk in PBS containing 0.05% Tween 20 (PBST) for 1 h at room temperature and incubated with primary antibodies overnight at 4°C. Polyclonal antihuman NGFR (p75) antibody (R&D Systems, Inc., Minneapolis, MN) and polyclonal anti-CD (Bio-Trend, Creutzberg, Wiesbaden, CA) were used as a loading control.

In Vitro Cytotoxicity Assay. Cell counts and viability were assessed using a tetrazolium [3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide] dye conversion assay (Promega, Madison, WI). To assess drug cytotoxicity, 5 replicate wells containing 2.5 × 10^4 cells in 0.2 ml were cultured in 96-well plates with various dilutions of 5FU (1–20 μM) or 5FC (0.025–10.0 mM). Cells were semi-depleted at 3 days, a second dose of drug was added and cells returned to incubation for an additional 3 days. Dye was added on day 6 and allowed to react for 2 h at 37°C. Dye conversion was read using an ELISA plate reader at 490 nm against 610 nm. Cytotoxicity was determined by calculation of the number of viable cells as measured against wells containing no drug. Drug cytotoxicity experiments were performed on each transduced and nontransduced cell line in at least three distinct experiments, and average data were used to plot in vitro killing. Bystander killing was assessed, as above, using various ratios of parental and transduced cells.

In Vivo Tumor Killing. A total of 12 C3H/HeJ (National Cancer Institute) or NOD.CB17-PrkdcScid (Jackson Labs, Bar Harbor, ME) mice were used for each tumor or treatment group. The Animal Care and Use Committee of the University of Minnesota approved all experimental protocols. Just before implantation, tumor cells were trypsinized, pelleted, rinsed in dPBS, and resuspended at appropriate concentrations in dPBS containing 1% BSA. Tumor cells were implanted either s.c. or in the left femur intramedullary space. s.c. injection of 5 × 10^5 tumor cells was performed over the left flank in a total volume of 200 μl. To facilitate tumor measurements, a small patch of fur was shaved over the implant site with tumor length and width measured every other day starting at day 6. Tumor volume was calculated using the formula for the volume of an ovoid: volume = 4/3 × π × (length + width)^2 (2). Treatment with 5FC, 400 mg/kg/day (dissolved as 12.5 mg/ml in 0.9% sterile NaCl, injection grade), or 5FU (10, 25, or 50 mg/kg, diluted in 0.9% saline) was started when tumors reached ~100 mm^3. Mice were euthanized 11 days later. At tissue harvest, mice and tumors were weighed, tumors were measured, and s.c. tumors fixed in Z-fix (Anatech, Battle Creek, MI) for histology. Bystander effect was evaluated in s.c. tumors in C3H/HeJ mice, as described above, with a mixture of 90% (4.5 × 10^5) 2472 cells and 10% (0.5 × 10^5) nonsorted or sorted 2NGFR-CD cells.

Intraosseous injections of tumor cells were performed as described previously (12). In brief, injection of 10^3 2NGFR-CD cells in a 20-μl aliquot of dPBS containing 1% BSA was performed through a knee arthroscopy on mice anesthetized with a ketamine/xylazine mixture (100 and 7.5 mg/kg, respectively). Treatment with 5FC commenced 7 days after tumor cell injection, and the animals were sacrificed 9 days later. Radiographs (Faxitron MX-20 cabinet X-ray machine and Kodak Min-R 2000 film) of femora (>5) were performed and bone destruction scores were assessed as follows: 0, no bone loss; 1, intramedullary osteolysis without full thickness cortical osteolysis; 2, intramedullary osteolysis and full thickness cortical erosion through one cortex; and 3, intramedullary osteolysis and full thickness cortical erosion through both cortices (13). Femora were fixed in Z-fix for 24 h, decalcified in neutral 10% EDTA for 10 days, and processed for histology.

Histology, Histomorphometry, and Immunohistochemical Analysis. Tumors from decalcified femora were embedded in paraffin and cut at 5 μm. Routine H&E stain was performed on all specimens, and four replicate sections were used for histomorphometric measurements. Images of whole femora were acquired using a Spot 2 digital charge-coupled device (CCD) on a Nikon E-1000 microscope at ×1 and ImagePro Plus (Media Cybernetics Inc., Silver Spring, MD) used to quantify the area of bone containing tumor.

Immunohistochemistry for NGFR was performed on deparaffinized and hydrated sections of s.c. tumor and femora. Staining was a standard three-step avidin-biotin complex procedure. Briefly, monoclonal mouse antihuman NGFR (clone 20.4, provided by Dr. P. Orchard) was diluted 1:2000 and incubated at 4°C overnight. A biotinylated goat antimouse IgG Fab'(1/2) (Rockland, Gilbertsville, PA) was used as the secondary antibody (1:1000 dilution), and the tertiary reagent was HRP-avidin-biotin complex (HRP-avidin-biotin complex; Vector Labs, Burlingame, CA). 3,3′-Diaminobenzidine (Zymed, San Francisco, CA) was used to develop the staining reactions, and sections were lightly counterstained with Mayer’s hematoxylin, dehydrated, and coverslipped using Permount. Epitope retrieval involved 15-min rinses with first, 0.05% saponin, and second, 0.1% Triton X-100. All antibody incubations were followed by three washes with dPBS. A nonspecific antibody (dPBS containing 10% horse sera), and avidin/biotin blocking steps were performed before addition of the primary antibody. Nonspecific peroxidase activity was blocked by incubation with 3% hydrogen peroxide (10 min) after the secondary antibody.

Statistics. In vitro data are presented as means ± SD and in vivo data as means × SE. Statistical significance was determined by Student’s t test. P of <0.05 was considered statistically significant.

RESULTS

Characterization of NGFR-CD-Transduced 2472 Cells. The NGFR-βCD and NGFR-γCD fusion genes were designed with the extracellular and transmembrane domains of the NGFR protein to facilitate localization of the chimeric protein to the cell surface, with the cytosine deaminase portion of the fusion protein in the cytoplasm. This permits NGFR to be detected on the cell surface, allowing it to function as a positive selection marker and the cytoplasmic CD portion of the protein to function as a negative selectable element (Fig. 1).

2472 cells transduced with 2NGFR-βCD or 2NGFR-γCD expressed...
Cell survival was seen at 0.25 mM 5FC, and observed with both NGFR-CD-transduced cell lines. A decrease in had no effect on the parent 2472 cell line, but tumor cell killing was sarcoma cells transduced with the CD-NGFR genes. 5FC treatment protein levels were higher in 2NGFR-y CD-expressing cells than in apparent molecular weights of

$M_r \approx 95,000$ and NGFR-y CD had two bands with apparent molecular weights of $M_r \approx 67,000$ and $M_r \approx 63,000$. NGFR protein levels were higher in 2NGFR-y CD-expressing cells than in 2NGFR-b CD cells, and NGFR protein levels were higher in 2NGFR-y CD cells selected by FACS for NGFR expression (2NGFR-y CD$^+$) compared with cells selected by neomycin alone (Fig. 2B). Western analysis detected CD protein in 2NGFR-b CD cells (Fig. 1D) and CD in 2NGFR-y CD cells (Fig. 2C). Taken in total, these findings indicate that the NGFR-b CD and NGFR-y CD fusion genes produce intact NGFR-CD proteins of expected size and that cell surface expression of NGFR can be used for positive selection of cells transduced with the NGFR-CD or NGFR-y CD fusion gene.

**Effect of 5FU on Sarcoma Cells in Vitro.** Similar concentrations of 5FU killed the parent sarcoma cell line (2472) and 2NGFR-CD cells. 2NGFR-y CD were cultured in the presence of increasing doses of 5FU. After 5FU treatment, cell viability was assessed and findings indicated that the parent and transduced sarcoma cells were sensitive to 5FU with an estimated ED$_{50}$ of 2 $\mu M$ (Fig. 3A).

**Effect of 5FC on Sarcoma Cells in Vitro.** 5FC treatment killed sarcoma cells transduced with the CD-NGFR genes. 5FC treatment had no effect on the parent 2472 cell line, but tumor cell killing was observed with both NGFR-CD-transduced cell lines. A decrease in cell survival was seen at 0.25 mM 5FC, and <10% of NGFR-CD cells were alive when exposed to 10 mM 5FC after 6 days in culture (Fig. 3B). Comparison of sarcoma cells transduced with NGFR-y CD and 2NGFR-y CD indicated that cells transduced with NGFR-y CD were more sensitive to 5FC treatment. After exposure to 0.75, 1.0, and 1.25 mM 5FC, there were significantly increased numbers of 2NGFR-y CD cells compared with 2NGFR-y CD cells. After treatment with 0.75 mM

5FC, >50% of 2NGFR-y CD cells were alive, compared with 15% of 2NGFR-y CD (Fig. 3B).

**Evaluation of Bystander Killing in Vitro.** 2NGFR-y CD cells killed untransduced 2472 cells through a bystander effect. Bystander killing was examined in vitro by culturing parent 2472 cells with 2NGFR-y CD cells in various concentrations and exposing the cells to increasing doses of 5FC. Bystander killing occurred with as few as 10% 2NGFR-y CD cells (Fig. 3C). ED$_{50}$ increased with decreasing percentages of 2NGFR-y CD cells. Cultures containing 100, 50, and 10% 2NGFR-y CD cells had ED$_{50}$ of 0.01, 0.05, and 0.25 mM 5FC, respectively. Finally, 2.5 mM 5FC eliminated >85% of tumor cells with each mixture of transduced and parent sarcoma cells (Fig. 3C).

**Effect of 5FU on s.c. 2472 Tumors.** 5FU treatment affected growth of s.c. sarcomas. Animals with s.c. 2472 tumors were treated with 10, 25, and 50 mg 5FU/day. Although 10 mg/kg/day 5FU had no effect on tumor volume, doses of 25 and 50 mg/kg/day affected tumor growth. Treatment with 25 mg/kg/day halted tumor growth and treatment with 50 mg/kg/day decreased tumor volume compared with initial values. When compared with saline treatment, significant decreases in tumor volume were present 7 days after 5FU treatment (25 and 50 mg/kg/day). At the end of each experiment, there was a >100% reduction in the tumor volume among mice treated with 25 or 50 mg 5FU/day compared with mice receiving no treatment (Fig. 4A). Corresponding reduction in tumor weights were observed. Final tumor weights for saline, 10, 25, and 50 mg/kg 5FU/day being 0.6 ± 0.4, 0.6 ± 0.1, 0.08 ± 0.06, and 0.04 ± 0.02, respectively (Table 1). When final tumor volumes were compared with tumor volumes before 5FU
treatment, only the highest dose of 5FU (50 mg/kg/day) was effective at decreasing the initial tumor volume (Fig. 4A).

On the basis of body weights and treatment-related deaths, there was substantial morbidity associated with 5FU treatment. Toxicity of 5FU treatment was assessed by animal weights and treatment-associated deaths. Treatment with 10 mg/kg/day 5FU had no effect on weight gained during treatment but treatment with 25 or 50 mg/kg/day caused significant weight loss. At completion of the experiment, saline-treated and mice treated with 10 mg/kg/day 5FU had gained 3.6 ± 1.2 and 3.8 ± 1.4 g, respectively. In contrast, mice treated with 25 and 50 mg/kg 5FU/day had lost 4.0 ± 0.7 and 3.4 ± 1.0 g, respectively (P < 0.001; Table 1). 5FU treatment also caused animal deaths. Although no animals treated with saline, 10, or 25 mg/kg/day 5FU died, all mice treated with 50 mg/kg/day 5FU died before the experiment’s end (17 days).

Effect of 5FC on s.c. 2NGFR-CD Tumors. 5FC treatment decreased growth of s.c. 2NGFR-CD tumors. Mice with 2472, 2NGFR-CD and 2NGFR-CD tumors were monitored. As expected, tumor volumes in saline-treated mice progressively increased over time, whereas tumor volume and weight were measured in animals treated with 5FC, and tumor volume and weight were monitored. As expected, tumor volumes in saline-treated mice progressively increased over time. 5FC treatment had no effect on 2NGFR-CD tumors but resulted in profound effect on 2NGFR-CD tumors. 5FC treatment in animals with 2NGFR-CD tumor reduced tumor volumes below pretreatment size and dramatically decreased tumor volume compared with tumors in saline-treated mice (51 ± 60 versus 938 ± 767 mm³; Fig. 4B). Corresponding reduction in tumor weights was also seen. Tumor weights from 5FC treated mice were significantly smaller than control (0.6 ± 0.4 versus 0.1 ± 0.09 g, P < 0.001) and were indistinguishable from tumor weights in mice treated with 25 or 50 mg/kg 5FU/day (Table 1). In addition, analysis of animal weights and treatment-associated deaths revealed that 5FC treatment had no effect on animal weight and caused no treatment-associated complications (Table 1).

To determine whether decreased tumor volume after 5FC treatment represented immunological killing, similar experiments were performed in NOD/SCID mice. Profound reduction in tumor volume was noted when NOD/SCID mice with 2NGFR-CD tumors were treated with 5FC (n = 9). Eight mice had no detectable tumor, and 1 mouse had a 4-mm³ tumor. In contrast, the mean tumor volume in salinetreated mice was 953 ± 349 mm³. This finding indicates that significant immunological killing was not occurring, and the primary mechanism for tumor killing was a direct cytotoxic effect of prodrug-generated 5FU.

Evaluation of Bystander Killing in s.c. Tumors. 2NGFR-CD cells killed untransduced 2472 s.c. tumors in vivo through a bystander effect. The possibility that sarcoma cells transduced with the NGFR-CD fusion gene could direct bystander killing of nontransduced sarcoma cells was assessed by growing s.c. tumors composed of 10% 2NGFR-CD cells and 90% 2472 cells and treating tumor-bearing mice with saline or 5FC. As expected, tumor volumes in saline-treated mice progressively increased over time. 5FC treatment slowed tumor growth. After ≥7 days of treatment, there was a significant reduction in tumor volumes between saline and 5FC-treated mice (Fig. 4C).
addition, after 10 days of treatment, tumor volumes in saline-treated mice were two times greater than tumor volumes in 5FC-treated mice (Fig. 4C).

Bystander killing mediated by 2NGFR-γCD cells was significant but incomplete, with residual tumor remaining at the completion of each experiment. We next examined the possibilities that increased NGFR-γCD gene expression would enhance the bystander effect. 2NGFR-γCD cells were sorted by FACS and the highest (20%) NGFR-expressing cells were expanded in culture. They showed a 2-fold increase in the level of 2NGFR-γCD expression as determined by FACS analysis. These sorted cells, designated 2NGFR-γCD⁺, were mixed 1:9 with 2472 cells and injected as a s.c. tumor inoculum. Treatment of mice with these tumors revealed increased bystander killing (Fig. 4C). Specifically, after 12 days of treatment, there was a 5-fold reduction in tumor volume between saline and 5FC-treated mice. However, as with the unsorted 1:9 mix tumors, there was tumor growth despite treatment with 5FC.

We hypothesized that if 5FC treatment eliminated NGFR-γCD-expressing cells and therefore limited the bystander effect. Findings indicated that 5FC treatment of mice with 10% 2NGFR-γCD/90% 2472 sarcomas eliminated NGFR-expressing tumor cells. Immunohistochemical evaluation of tumors that grew from 10% 2NGFR-γCD/90% 2472 cells showed different findings in saline-treated and 5FC-treated mice. As expected, tumors from saline-treated mice had NGFR-expressing cells (Fig. 5B). In contrast, NGFR-expressing cells could not be identified in tumors from 5FC-treated mice (Fig. 5A). This finding suggests that 5FC treatment was killing 2NGFR-γCD cells before bystander killing could reduce the tumors below pretreatment size.

**Effect of 5FC on Bone-Residing 2NGFR-γCD Tumors.** 5FC treatment eliminated bone-residing 2NGFR-γCD tumors. The effect of 5FC treatment on bone-residing 2NGFR-γCD tumors was measured by evaluating tumor area in tumor-injected femora. Routine histological examination revealed extensive tumor in the femora of each saline-treated animal (n = 10) but identified tumor in only 1 of the 10 5FC-treated animals. This impression was confirmed by detection of NGFR-expressing tumor cells in femora from saline-treated animals and only minimal positive NGFR staining cells in bones from 5FC-treated animals (Fig. 6, A and B). Bone tumor area in 5FC-treated mice was 1.3 ± 4.1 mm², a significant reduction compared with 11.8 ± 6.0 mm² in saline-treated mice (P < 0.002).

2472 sarcoma tumors are known to cause aggressive bone destruction by stimulating the formation and activation of osteoclasts, the body’s principal bone resorbing cell (12). As experiments with s.c. sarcomas demonstrated 2NGFR-γCD bystander killing of cancer cells, we sought to determine whether 2NGFR-γCD tumors could direct bystander killing of normal host cells (osteoclasts), cells which contribute significantly to the morbidity and progression of bone cancer (14).

Bystander killing of osteoclasts by 2NGFR-γCD bone cancers was profound and prevented cancer-induced bone destruction. Histological sections showed minimal or no bone destruction at sites of osseous tumor injection in mice treated with 5FC. This was a dramatic contrast to effects in bone of saline-treated mice where there was widespread bone destruction (Fig. 6, C and D). Radiographic bone destruction scores were assigned to tumor-injected bones from saline- and 5FC-treated mice. All tumor-injected femora from saline-treated mice had radiographic evidence of bone destruction with a mean bone destruction score of 2.8 ± 0.5. In contrast, only 1 of 10 tumor-injected femora from 5FC-treated mice had radiographic evidence of tumor osteolysis. The mean bone destruction score for femora from 5FC-treated mice was 0.2 ± 0.3 (P < 0.002; Fig. 7). Histological evaluation of bones showed that femora from saline-treated mice had areas of bone resorption with significant numbers of osteoclasts. Femora from 5FC-treated mice had occasional areas of bone resorption but no osteoclasts, indicating that 5FC treatment had eliminated osteoclasts that previously formed at sites of tumor (Fig. 8).

**DISCUSSION**

Our results show that the γCD enzyme/prodrug system has significant cytotoxic effects on soft tissue and bone sarcomas. We show that

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*Table 1*<sup>a</sup>

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Pretreatment weight Mean ± SD (n)</th>
<th>Final weight Mean ± SD (n)</th>
<th>Weight change Mean ± SD (n)</th>
<th>Tumor weight Mean ± SD (n)</th>
</tr>
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<tr>
<td>Saline</td>
<td>22.6 ± 2.0 (30)</td>
<td>27.1 ± 1.9 (30)</td>
<td>4.00 ± 1.25 (30)</td>
<td>0.60 ± 0.42 (30)</td>
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<td>10 mg/kg/d 5FU</td>
<td>22.4 ± 1.6 (8)</td>
<td>27.6 ± 1.1 (8)</td>
<td>4.68 ± 1.59 (8)</td>
<td>0.59 ± 0.13 (8)</td>
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<tr>
<td>25 mg/kg/d 5FU</td>
<td>23.0 ± 1.1 (8)</td>
<td>19.0 ± 1.3 (8)</td>
<td>−4.06 ± 0.75 (8)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.08 ± 0.06 (8)&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>50 mg/kg/d 5FU</td>
<td>21.0 ± 1.8 (12)</td>
<td>17.60 ± 1.7 (12)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>−3.47 ± 1.05 (12)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.04 ± 0.02 (12)&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>400 mg/kg/d 5FC</td>
<td>22.7 ± 2.2 (18)</td>
<td>26.3 ± 2.0 (18)</td>
<td>3.83 ± 1.44 (18)</td>
<td>0.10 ± 0.09 (18)&lt;sup&gt;b&lt;/sup&gt;</td>
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<sup>a</sup> Mice with subcutaneous tumors were treated with saline and increasing doses of 5FU or 5FC. Posttreatment animal weights and tumor weights were determined after 11 days of treatment.

<sup>b</sup> P < 0.001; saline versus drug.
sarcoma cells transduced with NGFR-γCD are sensitive to 5FC treatment in cell culture, in soft tissue, and in bone. s.c. sarcomas transduced with the NGFR-γCD gene regressed after 5FC treatment, and bone sarcomas were eliminated after 5FC treatment in 9 of 10 animals. In contrast, sarcoma cells transduced with NGFR-bCD were killed in vitro by 5FC treatment, but the growth of s.c. sarcomas transduced with NGFR-γCD was not affected by 5FC treatment.

Previous direct comparison of bacterial and yeast CD in animal models report that the γCD systems provide superior tumor killing compared with βCD systems. Kievit et al. (3) studied the effect of βCD and γCD in HT29 human colon cancer cells, reporting that 5FC treatment had no effect on growth of βCD-transduced tumors but caused regression of γCD-transduced tumors. Decreased tumor killing by βCD-transduced HT29 cells was attributed to a 22-fold higher $K_m$ for βCD compared with γCD. Circumstances in this study do not permit direct comparison of NGFR-γCD and NGFR-βCD-transduced cells because CD protein was significantly higher in NGFR-γCD-transduced cells.

Our evaluation of treatment-associated morbidity and mortality indicated that the administration of 5FC in association with CD expression had clear advantages over 5FU treatment. This is an important finding because it provides direct evidence supporting the concept that systemic toxicity is minimal, despite the capacity to eliminate CD-expressing enzyme prodrug system has a tumor killing effect. Furthermore, it shows that catastrophic systemic toxicity (death) results with 5FU doses that achieved the equivalent effect as 5FC.

When nontransduced sarcoma cells were mixed with 2NGFR-γCD cells and treated with 5FC, significant killing occurred in vitro and in vivo. 5FC treatment of a mixture of nontransduced and NGFR-γCD cells in vitro dramatically reduced the number of cancer cells. 5FC treatment of s.c. sarcomas grown from a mixture of 2472 and 2NGFR-γCD cells significantly slowed tumor growth. Similarly, in vivo bystander killing and slowed tumor growth has been observed in an experimental s.c. model of HT29 colon cancer, s.c. WiDr colon tumors, and intrahepatic HT29 colon cancers (2, 8).

The 2472 sarcoma studied in this article has been shown previously to induce significant bone destruction (osteolysis; Ref. 12). The mechanism for this destruction is tumor stimulation of osteoclastic bone resorption caused by stimulation of osteoclast formation and activity. Previous work has defined the benefit of inhibiting tumor-induced osteoclastogenesis and has demonstrated that osteoclast-targeted ther-

Fig. 6. Effect of 5FC on bone-residing sarcomas. Histological sections of tumor-injected bones from mice treated with 400 mg/kg/day 5FC (A and C) or saline (B and D) for 9 days. Serial sections were stained for NGFR (A and B) or H&E (C and D). T = tumor, b = bone; arrow indicates where the tumor has completely eroded bone.

Fig. 7. Effect of 5FC on bone-residing sarcomas. Radiographs of tumor-injected bones from mice treated with 400 mg/kg/day 5FC (A) or saline (B) for 9 days. Arrows indicate area of bone destruction in saline-treated femora.
fig. 8. Bystander killing of osteoclasts by 5FC in bone-residing sarcomas. Histological sections of tumor-injected bones from mice treated for 9 days with 400 mg/kg/day 5FC (A and C) or saline (B and D). Serial sections were stained for H&E (A and B), shown at \( \times 100 \) or telomeric repeat amplification protocol (C and D); outlined area in H&E, shown at \( \times 400 \). Arrowheads identify garnet-stained osteoclasts in bone from saline-treated animal.

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