Corticosteroid Alteration of Carboplatin-Induced Hematopoietic Toxicity in a Murine Model

By John Rinehart, Lisa Keville, John Measel, A. Michael Spiekerman, and Kimberly Burke

Corticosteroids exhibit extensive hematopoietic effects both in vitro and in vivo. Some of the previously studied effects suggested that corticosteroids may alter hematopoietic toxicity of chemotherapeutic agents. In this study, we examined (1) the optimum dose and schedule of cortisone acetate (CA) to reduce hematopoietic toxicity of carboplatin (CB) and (2) possible mechanisms involved in this protective effect. CA given subcutaneously at 0.5 mg/d per mouse for 7 days before CB reduced CB-induced mortality due to neutropenia from 88% in controls to 14% in CA-treated mice (P < .05). Lower CA doses were not effective. Three days of pretreatment (but not 1 day) was as effective as 7 days. CA given after CB had no effect on mortality. Pharmacokinetic studies of CA at 0.5 mg per mouse demonstrated blood levels of cortisol achievable in patients (peak level, 82 pg/dL). CA treatment markedly reduced spleen cell number and colony-forming units-granulocyte/macrophage (CFU-GM) as well as bone marrow CFU-GM. Bone marrow CFU-GM removed from CA-treated mice demonstrated increased resistance to platinum and increased resistance to high specific activity 3H-thymidine. These findings suggest that treatment of mice with CA induces cellular resistance of hematopoietic precursors to platinum and, thus, reduces CB hematotoxicity. CA or other corticosteroids may be useful in reducing clinical toxicity of CB.

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MATERIALS AND METHODS

Mice. Female C3H/HeJ mice were obtained from the Animal Production Area, National Cancer Institute-Frederick Cancer Research and Development Center (Frederick, MD). Animals were routinely maintained at five to eight mice per cage inside filter bonnets in an isolation room, with food and water provided at will. Mice were quarantined for 1 week before treatment. Experiments were performed using mice at 5 to 8 weeks of age.

Preparation of peripheral blood smears for differential counts. Animals were anesthetized by Forane (isoflurane) inhalant (Anaquest, Madison, WI). Blood samples were then obtained from the postorbital venous plexus using a microcapillary tube coated with 5% EDTA in Hanks’ balanced salt solution (HBSS; Gibco BRL, Gaithersburg, MD). Sixty microliters of the blood was diluted in 120 µL of EDTA solution, and the white blood cell and platelet counts were determined using a model S + IV B Coulter counter (Coulter Electronics, Hialeah, FL). Smears were made of the blood samples and stained with Wright’s stain (Sigma Chemical Co, St Louis, MO). These slides were examined by light microscopy, and the percentages of lymphocytes, granulocytes, and monocytes were determined.

Preparation of spleen mononuclear cell suspensions and leukocyte conditioned media (LCM). Animals were killed by cervical dislocation, and their spleens were removed and placed in cold Iscove’s modified Dulbecco’s Eagle’s medium (IDMEM; Gibco). Spleens were dissociated by pressing through a Celllector tissue sieve (PGC Sciences, Gaithersburg, MD) into 60-mm tissue culture dishes (Falcon 1007; Becton Dickinson Labware, Lincoln Park, NJ) containing IDMEM supplemented with 20% fetal calf serum (FCS). Cells were layered on Ficoll-Paque (Pharmacia Diagnostics, Silver Springs, MD) in 15-mL polypropylene tubes. These were centrifuged at 400g for 25 minutes, and interface cells were harvested. Spleen monoun-
clear cells were washed three times by centrifugation at 200g. Spleen mononuclear cells from treated animals were cultured in a methylcellulose hematopoietic progenitor cell assay for CFU-GM (see below). To produce LCM, washed spleen mononuclear cells from normal, untreated animals were resuspended in IDMEM plus 20% FCS plus 10 μg/mL phytohemagglutinin to a final concentration of 6 x 10^5/mL. The cell suspension was placed in 25-cm² tissue culture flasks and then incubated at 37°C for 5 days. After incubation, the spent media was centrifuged, and the resultant supernatant was passed through a 0.22-μm syringe filter (Gelman Sciences, Ann Arbor, MI) and then stored in 2-ml aliquots at -4°C.

Preparation and culture of bone marrow. Mice were killed by cervical dislocation, and tibias were placed in chilled HBSS (Gibco). Bone marrow cells were obtained by flushing cold HBSS through tibias with a 27-gauge needle. Cells were washed once in cold HBSS and then resuspended at 3 x 10^6/mL in IDMEM supplemented with 20% FCS. Bone marrow mononuclear cells were incubated in methylcellulose at a final concentration of 3 x 10^6/mL supplemented with 20% FCS, 1% antibiotic-antimycotic solution, and 10% LCM (or no LCM for negative controls). The cell cultures were plated in triplicate wells in six-well tissue culture dishes and incubated at 37°C in a fully humidified atmosphere of 5% CO₂ for 5 days. On the fifth day, the number of CFU-GM was determined by examination using an inverted microscope. Cultures that contained 10% LCM developed colonies of 50 to 150 cells at an incidence of 50 to 90%.

Administration of cortisone acetate (CA) and carboplatin (CB). CA (Cortone; Merck Sharp Dohme, West Point, PA) was dissolved in sterile 0.9% NaCl, injections (0.2 mL per mouse) were given subcutaneously. CB (Paraplatin; Bristol Laboratories, Evansville, IN) was dissolved in sterile 0.9% NaCl for injection according to package directions. Individual animals in an experimental group were given an intravenous (IV) injection of CB (0.1 mL) in the lateral or dorsal tail vein.

Staining of bone marrow or spleen for flow cytometry. Bone marrow cells and spleen mononuclear cells were obtained as described above. Cells were washed three times in HBSS and resuspended to 2 x 10^6/mL in HBSS without phenol red containing 1% bovine serum albumin (BSA; Fraction V, Sigma Chemical; staining buffer). Propidium iodide (50 μg/mL in 0.1 Na citrate with 0.1% Triton X100) was added to the cell suspension. After incubating for 20 minutes in an ice bath, the cells were washed by adding 2 mL of staining buffer and pelleting at 300g for 6 minutes at 4°C. Stained cells were resuspended in 400 μL cold staining buffer and held on ice until quantitation. A minimum of 10^5 cell nuclei were counted with a Becton Dickinson (BD) FACScan without electronic gates using list mode analysis. The fluorescence intensity was determined with 1024 channel resolution, and the cell cycle analysis was performed using cell fit analysis supplied by BD. Selected histograms were analyzed on Verity Modfit (Topsham, ME) software to verify the accuracy of the analysis.

3H-thymidine suicide assay. Bone marrow and spleen cells were collected and prepared as previously described, then resuspended to 4 x 10^6/mL in IDMEM containing 20% FCS and 1% antibiotic-antimycotic solution. Cells (4 x 10^6; 100 μL) were transferred to five 15-mL conical tubes with the following additions: (1) control, no additions; (2) 1.2 mg of thymidine (Sigma); (3) 40 μCi 3H-thymidine, 70 to 85 Ci/mmol (Amersham Life Sciences, Arlington Heights, IL) or (4) 1.2 mg thymidine and 40 μCi 3H-thymidine. The cell suspension in each tube was adjusted to 1.0 mL volume with IDMEM containing 20% FCS. Cells were then incubated in a 37°C water bath for 20 minutes. After incubation, cells were washed twice in media containing 20% FCS. Cells were cultured after the methylcellulose hematopoietic progenitor cell assay previously described. Each triplicate culture contained 10% LCM. After 5 days of incubation, the number of CFU-GM was determined. Results were calculated as percent inhibition of the control:

\[
1 - \frac{\text{No. of Colonies With Thymidine}}{\text{No. of Colonies Without Thymidine}} \times 100
\]

Cisplatin inhibition assay. Bone marrow and spleen cells were collected and prepared as previously described, then resuspended to 4 x 10^6/mL in IDMEM containing 20% FCS and 1% antibiotic-antimycotic solution. Cells (16 x 10^6/mL; 400 μL) were transferred to five 15-mL conical tubes, and 100 μL of IDMEM either containing cisplatin (Platinol; Bristol Meyers) or no cisplatin (in case of control) was added to achieve final cisplatin concentrations of (1) 0 μg/mL (control), (2) 0.62 μg/mL, (3) 1.2 μg/mL, (4) 2.5 μg/mL, or (5) 5.0 μg/mL. The cell suspension in each tube was adjusted to a 4-mL volume with IDMEM containing 20% FCS. Cells were then incubated in a 37°C water bath for 30 minutes. After incubation, cells were washed twice with IDMEM and resuspended at 3 x 10^6/mL in IDMEM containing 20% FCS. Cells were cultured using the methylcellulose hematopoietic progenitor cell assay previously described. Each triplicate culture contained 10% LCM. After 5 days of incubation, the number of CFU-GM was determined. Results were calculated as percent inhibition of the control:

\[
1 - \frac{\text{No. of Colonies With Cisplatin}}{\text{No. of Colonies In Control}} \times 100
\]

Plasma cortisol levels. Cortisol plasma levels were determined using the Abbott TDx (Arlington, TX), which uses a fluorescence polarization immunoassay; 50 μL of each sample was run in duplicate, simultaneously with cortisol controls. Plasma samples exceeding 60 μg/dL of cortisol were diluted until levels were within the range of the system.
We examined blood levels of cortisol (the principal active hepatic metabolite of the biologically inactive CA) induced by administration of 0.5 mg SC CA (Fig 2); peak levels of 82 μg/dL were observed at 1 hour, and blood levels remained above baseline at 24 hours (4.5 ± 1.1 μg/dL v 8.2 ± 1.2 μg/dL, P < .057). Blood cortisol levels were also examined in mice that had received six daily injections of CA 0.5 mg SC: at 24 hours after the sixth CA dose, cortisol levels were 5 μg/dL, and at 3, 6, and 12 hours after the seventh CA dose, cortisol levels were 31, 22, and 15 μg/dL.

We examined the schedule dependency of the activity of CA (at 0.5 mg per mouse per dose) in reducing the mortality induced by high-dose CB (Fig 3): pretreatment of mice daily with CA for 3 days was as effective as pretreatment for 7 days. Single doses of CA at 3 or 24 hours before CB did not statistically improve survival, although some delay and reduction in mortality is suggested by inspection of the sur-
vival curves (Fig 3A). Administration of CA post-CB was ineffective (Fig 3B).

We examined the effect of treatment of mice with CA at 0.5 mg SC for 7 days (days −7 to −1) on peripheral blood cell counts before and after CB 450 mg/m² (day 0, Fig 4A through C). A lower dose of CB was used in these experiments so that peripheral blood cell counts could be observed through recovery in control as well as CA-pretreated mice. Treatment with CA induced, as expected, a granulocytosis and lymphopenia (day 0, pre-CB counts, Fig 4A and B). Mice pretreated with CA demonstrated less severe granulocyte and platelet nadirs and more rapid recovery times. Interestingly, CA-treated mice remained relatively lymphopenic for 20 days post-administration of CB (Fig 4B). Treatment of mice for 7 days with CA 0.5 mg markedly reduced the number of CFU-GM in both bone marrow and spleen, as well as the total cell number of spleen cells (Tables 1 and

<table>
<thead>
<tr>
<th>Table 1. Effect of CA on Hematopoietic Parameters in C3H/HeJ Mouse Bone Marrow</th>
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<tbody>
<tr>
<td>Dose (mg/mouse/d × 7 days)*</td>
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<tr>
<td>0 (control)</td>
</tr>
<tr>
<td>CA 0.5 mg</td>
</tr>
<tr>
<td># Leukocytes/bone marrow</td>
</tr>
<tr>
<td>CFU-GM</td>
</tr>
<tr>
<td>% Bone marrow leukocytes in S phase</td>
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</tbody>
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Data are presented as mean ± SE of two separate experiments (n = 10).

* Mice were killed on day 8 after 7 days of subcutaneous CA at dose indicated.
† P < .001, statistical analysis by one-way ANOVA.
CORTICOSTEROID ALTERATION OF HEMATOPOIESIS

Table 2. Effect of CA on Hematopoietic Parameters in C3H/HeJ Mouse Spleen Leukocytes

<table>
<thead>
<tr>
<th>Dose (mg/mouse/d × 7 days)*</th>
<th>0 (control)</th>
<th>CA 0.5 mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spleen weight (mg)</td>
<td>134.0 ± 6.0</td>
<td>61.0 ± 4.01</td>
</tr>
<tr>
<td>No. of leukocytes/spleen</td>
<td>20.4 × 10^6 ± 1.2 × 10^4</td>
<td>2.3 × 10^6 ± 0.3 × 10^4</td>
</tr>
<tr>
<td>CFU-GM</td>
<td>526.3 ± 70.3</td>
<td>122.8 ± 42.61</td>
</tr>
<tr>
<td>% Spleen leukocytes in S phase</td>
<td>1.6 ± 0.1</td>
<td>1.6 ± 0.2</td>
</tr>
</tbody>
</table>

Data are presented as mean ± SE of two separate experiments (n = 10).
* Mice were killed on day 8 after 7 days of subcutaneous CA at dose indicated.
† P < .001, statistical analysis by one-way ANOVA.

2). The fraction of cells in S-phase in total bone marrow and spleen as estimated by flow cytometry was unchanged by treatment with CA (Tables 1 and 2).

To determine if treatment of mice with CA induced resistance of CFU-GM to CB on cellular level, bone marrow and spleen cells were harvested from mice after treatment with CA or carrier for 7 days (Fig 5A and B). Whole cell populations were incubated with no cisplatin or four concentrations of cisplatin for 30 minutes, washed, and assayed for CFU-GM. Bone marrow (Fig 5A) but not spleen (Fig 5B) CFU-GM from mice treated with CA exhibited significant resistance to platinum. To determine if this resistance was related to alteration in the number of CFU-GM in S-phase, 3H-thymidine suicide assays were undertaken in identically treated mice (Fig 6). Bone marrow and splenic CFU-GM from mice treated with CA exhibited marked reduction in sensitivity to high specific activity 3H-thymidine, suggesting a decreased fraction of CFU-GM from CA-treated mice were in S-phase.

DISCUSSION

Previous investigators have demonstrated that corticosteroids given to mice before sublethal doses of hematotoxic chemotherapeutic agents increased the number of residual, postchemotherapy hematopoietic precursors in bone marrow. We have expanded these studies to (1) determine if, at optimal dose and schedule of corticosteroids, the hematopoietic effects were clinically relevant in reducing hematopoietic toxicity of carboplatin, and (2) examine relevant biologic effects of corticosteroids that may explain induction of resistance to CB.

Pretreatment of mice for 3 or 7 days with CA significantly reduced mortality (from 88% to 14%) induced by 600 mg/m² CB. In patients, the maximum tolerated dose of CB is 400 mg/m² without supportive measures, and hematotoxicity is dose-limiting; our findings in mice are similar. CA in this schedule (3 or 7 days pre-CB) ameliorated CB-induced granulocyte and platelet nadirs and enhanced recovery times. The dose of CA used induced high (82 μg/dL) levels of cortisol, the active metabolite of CA. However, these levels are routinely achieved in clinical practice using similar corticosteroids. Thus, at a clinically achievable dose and practical schedule, CA markedly reduced hematotoxicity of carboplatin administered at a dose similarly toxic in humans.

The mechanisms by which CA reduces CB hematotoxicity are very likely much different from cytokines such as IL-1. Pretreatment of mice with IL-1 reduces CB hematotoxicity as effectively as does CA. However, IL-1 increases splenic cellularity, CFU-GM, and the number of spleen cells in S-phase. In contrast, CA reduced splenic cellularity and CFU-GM in spleen and bone marrow. Thus, IL-1 may act by increasing the number of hematopoietic precursors at risk for damage by CB; i.e., given a similar fraction of hematopoietic precursors killed by a given CB dose, IL-1-pretreated mice exhibit higher postchemotherapy residual hematopoietic precursor (eg, CFU-GM) levels and more rapid hematopoietic

![Fig 5. Effect of treatment of mice (in vivo) with CA versus carrier-treated controls on in vitro resistance to platinum of bone marrow hematopoietic precursors (CFU-GM). Mice were treated with CA 0.5 mg per mouse or carrier (six separate experiments) for 7 days. Mice were killed on day 9, and bone marrow (A) and spleen (B) cells were removed as described in Materials and Methods. Bone marrow (A) or spleen (B) cells were incubated with cisplatin for 30 minutes and then cultured for assay of CFU-GM. Data are presented as percent inhibition of CFU-GM in bone marrow or spleen cells not exposed to cisplatin. Bone marrow cells from mice treated with CA were more resistant to cisplatin than controls at cisplatin concentrations of 0.62 and 1.2 μg/ml (P < .06). Data are presented as means ± SE.](image-url)
controls (no exposure to thymidine in vitro). The percent inhibition of fraction of CFU-GM in S-phase. CFU-GM from mice treated with CA to cold thymidine, $^3$H-thymidine, both, or no thymidine (control) before assay for CFU-GM (see Materials and Methods). Data are expressed as a percentage of the number of CFU-GM observed in control (no exposure to thymidine in vitro). The percent inhibition of CFU-GM in the presence of $^3$H-thymidine alone is a measure of the fraction of CFU-GM in S-phase. CFU-GM from mice treated with CA exhibited a significant decrease in the fraction of cells in S-phase ($n = 7$ experiments; $P < .05$). Data are presented as means ± SE.

Two general mechanisms may be involved in CA reduction in CB hematoxocity: alteration in pharmacokinetics and induction of CB resistance on a cellular level. We examined this latter possibility and found that, paradoxically, bone marrow but not splenic CFU-GM from CA-treated mice compared with control mice demonstrated greater resistance to in vitro concentrations of platinum obtained with standard doses of CB in patients. The mechanism of this resistance was not elucidated by our studies, but as reviewed by Los and Muggia, possible mechanisms include (1) decreased protein kinase-C, (2) decreased cyclic adenosine monophosphate (AMP), (3) increased glutathione and metallothionein, and (4) enhancement of DNA repair mechanisms. Corticosteroids are known to alter cyclic AMP in some cells. Decreased levels of protein kinase-C are associated with decreased proliferative rate. The decreased number of CFU-GM in CA-treated mice and the resistance of CFU-GM to high specific activity $^3$H-thymidine suggest but do not prove that during CA treatment, CFU-GM have a lower proliferative rate and that fewer CFU-GM are in S-phase. However, reduction in the fraction of CFU-GM in S-phase was not sufficient alone for induction of cellular resistance to cisplatin, because in CA-treated mice, both bone marrow and spleen CFU-GM demonstrated increased in vitro resistance to high specific activity $^3$H-thymidine, but only bone marrow CFU-GM were resistant to platinum in vitro. Therefore, of the mechanisms of platinum resistance discussed, increased glutathione or metallothionein levels and increased capacity for DNA repair may be more likely to explain CA induction of relative platinum resistance. Evaluation of the mechanisms of CA-increased platinum resistance will be difficult in vivo, and therefore, we are attempting to reproduce the phenomenon in vitro using expanded populations of purified normal hematopoietic cells. We have not explained the difference in response to CA treatment of bone marrow and spleen in regard to cellularity and induction of resistance to platinum in vitro. However, these differences were consistently present through multiple experiments. Although we only examined in vitro resistance of CFU-GM from CA-treated and normal mice to platinum and high-dose $^3$H-thymidine, other hematopoietic precursors may be similarly affected, as CA-treated mice demonstrated protection from CB-induced thrombocytopenia as well as neutropenia.

The data presented here suggest that at a clinically achievable dose and schedule, corticosteroids reduce the hematotoxicity of moderate to high-dose CB. The extent of reduction in hematotoxicity is similar to that observed with the use of hematopoietic growth factors in clinical situations and experimental models. One mechanism of CA reduction in hematotoxicity may be induction of resistance to platinum at the cellular level. These findings raise the possibility that corticosteroids may be useful in reducing hematopoietic toxicity of CB in patients.

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9. Joyce RA, Chervenick PA: Corticosteroid effect on granulo-

![Diagram](image-url)


Corticosteroid alteration of carboplatin-induced hematopoietic toxicity in a murine model

J Rinehart, L Keville, J Measel, AM Spiekerman and K Burke