Fractionated Versus Single-Dose Total Body Irradiation at Low and High Dose Rates to Condition Canine Littermates for DLA-Identical Marrow Grafts


We explored in dogs the immunosuppressive properties of 450 cGy total body irradiation (TBI) delivered from two opposing 60Co sources, as assessed by the criterion of successful engraftment of allogeneic genotypically DLA-identical littermate marrow. Two questions were asked in this study. Firstly, does dose rate affect the immunosuppressive effect of TBI when administered in a single dose? Secondly, does fractionation alter the immunosuppression of TBI when delivered at a very fast dose rate? Dose rates studied included 7 and 70 cGy/min, and fractionation involved four fractions of 112.5 cGy each, with 6-hour minimum interfraction intervals. Six of 7 dogs receiving 450 cGy single-dose TBI at 70 cGy/min showed sustained engraftment of the allogeneic marrow, compared with 1 of 7 dogs receiving single-dose TBI at 7 cGy/min (P = .01). Fractionated TBI at 70 cGy/min resulted in sustained allogeneic engraftment in 3 of 10 dogs, a result that was statistically significantly worse than that with single-dose TBI at 70 cGy/min (P = .03) and not statistically different (P = .24) from that with fractionated TBI delivered at 7 cGy/min (0 of 5 dogs engrafted). A single dose of 450 cGy of TBI delivered at a rate of 70 cGy/min is significantly more immunosuppressive than the same total dose delivered at 7 cGy/min. Fractionated TBI at 70 cGy/min is significantly less immunosuppressive than single-dose TBI at 70 cGy/min and not significantly different from fractionated TBI administered at 7 cGy/min. Results are consistent with the notion that significant DNA repair in lymphoid cells is possible during interfraction intervals at the relatively high dose rate of 70 cGy/min.

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TOTAL BODY IRRADIATION (TBI) has been widely used to condition patients with hematologic malignancy for allogeneic marrow transplantation. The goal of TBI is to deliver the greatest marrow toxic and immunosuppressive effects with acceptable toxicity to nonhematopoietic organs. The effects of TBI are governed by at least three variables: total dose, dose rate, and dose fractionation. Numerous studies have attempted to alter the three variables in such a way that greater antileukemic and immunosuppressive effects with acceptable toxicity to nonhematopoietic organs are achieved. Indeed, previous studies in dogs and mice indicated this fact.

In dogs that received fractionated TBI, the low dose rate of 7 cGy/min spared the cells of the immune system, and a significantly higher proportion of dogs receiving 450, 600, 700, 800, and 920 cGy of fractionated TBI at 7 cGy/min rejected marrow grafts from DLA-identical littermates than of those receiving equivalent total doses of single-dose TBI.

We explored in dogs the immunosuppressive properties of 450 cGy total body irradiation (TBI) delivered from two opposing 60Co sources, as assessed by the criterion of successful engraftment of allogeneic genotypically DLA-identical littermate marrow. Two questions were asked in this study. Firstly, does dose rate affect the immunosuppressive effect of TBI when administered in a single dose? Secondly, does fractionation alter the immunosuppression of TBI when delivered at a very fast dose rate? Dose rates studied included 7 and 70 cGy/min, and fractionation involved four fractions of 112.5 cGy each, with 6-hour minimum interfraction intervals. Six of 7 dogs receiving 450 cGy single-dose TBI at 70 cGy/min showed sustained engraftment of the allogeneic marrow, compared with 1 of 7 dogs receiving single-dose TBI at 7 cGy/min (P = .01). Fractionated TBI at 70 cGy/min resulted in sustained allogeneic engraftment in 3 of 10 dogs, a result that was statistically significantly worse than that with single-dose TBI at 70 cGy/min (P = .03) and not statistically different (P = .24) from that with fractionated TBI delivered at 7 cGy/min (0 of 5 dogs engrafted). A single dose of 450 cGy of TBI delivered at a rate of 70 cGy/min is significantly more immunosuppressive than the same total dose delivered at 7 cGy/min. Fractionated TBI at 70 cGy/min is significantly less immunosuppressive than single-dose TBI at 70 cGy/min and not significantly different from fractionated TBI administered at 7 cGy/min. Results are consistent with the notion that significant DNA repair in lymphoid cells is possible during interfraction intervals at the relatively high dose rate of 70 cGy/min.

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MATERIALS AND METHODS

Litters of beagles, walker hounds, harriers, and pit bull-beagle crossbreeds were either raised at the Fred Hutchinson Cancer Research Center (Seattle, WA) or purchased from commercial kennels in the state of Washington. The dogs weighed from 6.4 to 17.5 (median, 9.8) kg and were between 6 and 20.5 (median, 7) months old. They were watched for disease for at least 2 months before entering the study. All were immunized for distemper, leptospirosis, hepatitis, and parvovirus. Research was performed according to the principles outlined in the Guide for Laboratory Animal Facilities and Care, prepared by the National Academy of Sciences, National Research Council. The research protocol was approved by the Insti-
tutional Animal Care and Use Committee of the Fred Hutchinson Cancer Research Center.

Twenty-nine littermate donor/recipient pairs were chosen on the basis of identity for the serologically detectable canine histocompatibility antigens DLA A and B, and of mutual nonreactivity of their peripheral blood mononuclear cells in mixed leukocyte culture, complemented by restriction fragment-length polymorphism assays for canine major histocompatibility complex class II genes.\textsuperscript{19, 20} Data on 10 of the donor/recipient pairs, marked in Table 1, have been previously reported. They are presented here for purposes of comparison. Donor/recipient pairs were of opposite sex in all cases to permit cytogenetic evaluation of marrow and peripheral blood cells for chimerism after transplantation.

Marrow for transplantation was obtained under general anesthesia by needle aspirations from humeri and femora, as described.\textsuperscript{21} Recipients received TBI from two opposing \textsuperscript{60}Co sources, as described in detail,\textsuperscript{1, 23} with 6-hour minimum interfraction intervals. TBI was administered to unanesthetized dogs housed in a polyurethane cage placed transversely midway between two opposing \textsuperscript{60}Co sources. The cage was narrow with adjustable side walls, assuring that dogs were perpendicular to the beam. Beam intensity over the entire cross-sectional area of the cage was greater than 90% of the central axis intensity. The dose rate in air at the midpoint of the cage was determined with a 0.6-cm\textsuperscript{3} ionization chamber (Keithley Instruments, Inc, Cleveland, OH) and an electrometer system (Keithley Instruments). The midplane tissue-absorbed dose in gray (Gy), as determined by implanted lithium fluoride thermoluminescent dosimeters, was numerically approximately 76% of the exposure in air at the center of the cage measured in roentgens. The midplane dose rates were 7 and 70 cGy/minute, respectively. The thermoluminescent dosimeters contained lithium fluoride phosphor in disks (Teflon), and were read out with a reader (Teledyne Isotopes, Westwood, NJ) calibrated over a range of 1 to 50 Gy. Details on uniformity and standardization of the opposing \textsuperscript{60}Co sources have been previously published.\textsuperscript{24}

Recipients received between 1.1 and 4.4 (median, 3.3) \times 10^8 marrow cells/kg by intravenous (IV) infusion within 4 hours of the last dose of TBI. The day of marrow infusion was designated day 0. Dogs did not receive postgrafting immunosuppression. Postgrafting care has been previously described.\textsuperscript{25} In addition, all dogs received oral antibiotics, neomycin sulfate, and polymyxin B sulfate, three times daily beginning on day -5 through the day on which marrow engraftment was assessed by increases in granulocyte counts, as shown in Fig 1A. Evaluable cytogenetic data showed that the peripheral blood cell findings were consistent with an initial hematopoietic recovery originating from grafted donor marrow cells, which was followed by rejection, and then by recovery of host hematopoietic cells. Only one of the five dogs failed to show a second nadir in counts, and this dog's hematopoiesis was entirely of donor origin (D596).

**Group 1. Dogs receiving single-dose TBI at 7 cGy/min.** Tables 1 and 2 summarize the data. Two of the 7 dogs failed to show recovery of peripheral blood cell counts after the postirradiation nadir and died on day 20 from infection with aplastic marrow. Five dogs showed increasing granulocyte counts along with platelet counts. By day 19, counts began to decline and reached very low levels by day 29. One of the dogs died with pneumonia on day 30 whereas the other four showed complete recovery of their peripheral blood cell counts, as shown in Fig 1A. Evaluative cytogenetic data showed that the peripheral blood cell findings were consistent with an initial hematopoietic recovery originating from grafted donor marrow cells, which was followed by rejection, and then by recovery of host hematopoietic cells. Only one of the five dogs failed to show a second nadir in counts, and this dog's hematopoiesis was entirely of donor origin (D596).

**Group 2. Dogs receiving fractionated TBI at 7 cGy/min.** Tables 1 and 2 summarize the data. Two of the 5 dogs died on days 17 and 18 with pneumonia; their autopsy marrows showed absent cellularity. The allogeneic graft was presumably rejected outright. In one, cytogenetics on day 14 showed host-type cells. The three remaining dogs showed initial evidence of increasing counts, followed by a second nadir, and followed by complete hematopoietic recovery that was entirely of host origin, as evidenced by cytogenetic studies.

**Group 3. Dogs receiving single-dose TBI at 70 cGy/min.** Seven dogs were so treated (Tables 1 and 2). All showed prompt hematopoietic engraftment. In 6 of the 7, donor-type hematopoiesis persisted, as evidenced by cytogenetic studies of marrow and peripheral blood cells, whereas 1 dog (D263) appeared to have rejected the marrow graft, as judged by the pattern of granulocyte changes. This dog developed a pneumonia during the second granulocyte nadir and died on day 42 with a moderately cellular marrow. Granulocyte counts of dogs with engraftment are shown in Fig 1B. One of the dogs with engraftment (D257) had severe acute GVHD. This dog died on day 37 from pneumonia with cellular bone marrow.

**Group 4. Dogs administered fractionated TBI at 70 cGy/min.** Ten dogs were so treated (Tables 1 and 2). All showed initial evidence of increasing peripheral blood white blood cell counts. In three animals, donor-type hematopoiesis persisted without a second granulocyte nadir. In 7 dogs, a second nadir was seen that was similar to the one illustrated in Fig 1A, followed by complete hematopoietic recovery of host type in 4 and by death from infection between days 19 and 21 in 3 dogs.

Comparison of results in the various experimental groups. Table 2 summarizes the results. At the low dose rate of 7 cGy/min, 450 cGy of TBI proved virtually ineffective to condition dogs for DLA-identical marrow grafts, regardless of whether the irradiation was administered as a single dose or in fractions. With a dose rate of 70 cGy/min, 6 of 7 dogs receiving single-dose TBI showed sustained donor-type

cered at 7 or 70 cGy/min. Dogs did not develop diarrhea and maintained adequate oral fluid and food intake without weight loss, so there was no need for parenteral fluid or electrolyte support.

**RESULTS**

Significant nonhematopoietic toxicities were not seen in any of the recipients, regardless of whether TBI was deliv-
Table 1. Marrow Grafts From DLA-Identical Littermates After 450 cGy TBI Delivered at Either 7 or 70 cGy/min as a Single Dose or in Three Fractions

<table>
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<th>Group</th>
<th>Dose Rate (cGy/min)</th>
<th>TBI Schedule</th>
<th>Recipient No.</th>
<th>Increase in WBC Count*</th>
<th>Sustained Allogeneic Graft</th>
<th>Rejection</th>
<th>Autologous Recovery</th>
<th>Survival (ds)</th>
<th>Cause of Death</th>
<th>Marrow Cellularity at Autopsy</th>
<th>BM + PBL Cytogenetics† (days postgrafting)</th>
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Abbreviations: WBC, white blood cell; H, host origin; D, donor origin; D/H, mixed chimerism, donor cells predominate; H/D, mixed chimerism, host cells predominate; BM, bone marrow; PBL, phytohemagglutinin-stimulated peripheral blood lymphocytes; NE, not evaluated; Sod Pent, dog killed with sodium pentobarbital at completion of the study.

* After the postirradiation nadir.
† On the average, 62 metaphases were analyzed per dog; only spreads with 78 chromosomes were analyzed.
‡ Data on these dogs were previously reported.14,15
engraftment, a result that was significantly different \( (P = .01) \) from that of dogs receiving a single dose of TBI at 7 cGy/min. Single-dose TBI at 70 cGy/min also proved to be superior to fractionated TBI administered at 70 cGy/min in conditioning dogs for engraftment \( (P = .03) \). Although the observed engraftment in dogs receiving fractionated TBI at 70 cGy/min was better than that among dogs receiving fractionated TBI at 7 cGy/min (30% v 0%), the difference was not large enough to achieve statistical significance in these small samples \( (P = .24) \).

### DISCUSSION

The current study was conducted with an otherwise lethal TBI regimen of 450 cGy, delivered at a dose rate of 70 cGy/min that was 10-fold higher than the dose rate previously used. The study was prompted by previous observations that, whereas marrow toxicity of single- versus fractionated-dose TBI was equivalent at low dose rates of 7 to 10 cGy/min, fractionated TBI was significantly less immunosuppressive when assessed by the criterion of sustained DLA-identical marrow engraftment. These data suggested a different DNA repair capacity for cells of the lymphoid as compared with the myeloid hematopoietic systems with dose fractionation, at least when delivered at low dose rates. The current study was based on the expectation that TBI delivered at 70 cGy/min would be more toxic than at 7 cGy/min and that, in direct relation to the dose-rate–related increase in toxicity, DNA repair in interfraction intervals would be slowed to a point that fractionated- and single-dose TBI at 70 cGy/min produced equivalent immunosuppression.

These expectations were only met in part. Single-dose TBI at 70 cGy/min was significantly more immunosuppressive than TBI administered at 7 cGy/min, a finding that is consistent with previous data in allografted and xenografted mice. However, even at the high dose rate of 70 cGy/min, current results do not agree with the concept that sublethal repair of lymphoid cells is minimal after fractionated TBI, and they show that the effects on the lymphoid system of single versus fractionated TBI are not equivalent, even when the radiation is delivered at a relatively high dose rate. Our previous studies at the low dose rate of 7 cGy/min showed that only at 920 cGy total dose of fractionated TBI did virtually all dogs engraft.  

Very little data exist in the literature in regard to immunosuppressive effects of fractionated- versus single-dose TBI. In agreement with our data, one group of investigators studying DLA-haploidentical littermate canine marrow grafts described greater efficiency when 1,350 cGy total dose was administered in three fractions over a regimen involving 15 fractions. The dose rate in that study was 4.2 cGy/min. In another study, the dose necessary for consistent engraftment of rat marrow in irradiated mice increased from 800 cGy with a single fraction to 1,500 cGy with five daily fractions. Thus, the available experimental data support the opinion expressed by a minority of clinical investigators that single-dose TBI is more efficient than TBI administered in fractions to condition patients for successful grafts of T-cell–depleted HLA-identical sibling marrow.  

Results in this canine model were obtained with a TBI dose that is almost uniformly lethal in the absence of treatment by either hematopoietic growth factors or infusion of autologous marrow. Thus, results with marrow allografts...
have relevance to the management of radiation accident victims. Present and previous\textsuperscript{17,18} data show that marrow grafts from DLA-identical littermates are useful in extending the survival of dogs exposed to high doses of TBI ranging from 450 to 920 cGy. Sixty-eight percent of dogs in these studies survived (45 of 66 dogs). This included 21 of the 24 dogs (86\%) with successful allografts, and 24 of the 42 dogs (57\%) that survived with autologous hematopoietic recovery after rejection of the allograft. In the latter setting, survival is likely to be due to the extended hematopoietic support provided by the transient allograft. Similar findings have been made by other investigators.\textsuperscript{30,34} The absence of acute or chronic GVHD in most present dogs with sustained allografts may have been related to a transient state of mixed host/donor chimerism, known to facilitate graft-host tolerance in murine studies.\textsuperscript{35} Results imply that HLA-identical marrow grafts should be considered in treatment of victims of potentially fatal radiation accidents. To some extent, the survival of radiation accident victims can be improved by the use of recombinant hematopoietic growth factors; however, transplants are useful over higher exposure ranges than are growth factors. Studies with either canine recombinant granulocyte stimulating factor or c-kit ligand show that "rescue" from marrow death is possible after 400 cGy TBI dose, but less so after 500 cGy, and not at all after 600 cGy.\textsuperscript{36-38}

We conclude that 450 cGy single-dose TBI delivered at a dose rate of 70 cGy/min is significantly more immunosuppressive than the same total dose delivered at 7 cGy/min. In agreement with previous findings made at lower dose rates but at higher total doses,\textsuperscript{39} fractionated TBI delivered at 70 cGy/min is significantly less immunosuppressive than the same dose of single-dose TBI delivered at the same high dose rate. Results are consistent with the notion that significant DNA repair in lymphoid cells is possible during interfraction intervals, even at the high dose rate of 70 cGy/min. In agreement with previous data, the study showed that genotypically DLA-identical marrow grafts improved the dogs’ survival after otherwise lethal TBI, either because of transient allogeneic marrow support, thereby allowing time for autologous recovery to occur, or because of permanent reconstitution of hematopoiesis by allogeneic cells.

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Fractionated versus single-dose total body irradiation at low and high dose rates to condition canine littermates for DLA-identical marrow grafts

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