The development of bone changes induced in rats by recombinant human granulocyte colony-stimulating factor is suppressed by bisphosphonate

M. Suzuki¹,², K. Adachi², T. Sugimoto², H. Nakayama¹ and K. Doi¹

¹Department of Veterinary Pathology, Faculty of Agriculture, The University of Tokyo, Bunkyo-ku, Tokyo, Japan and ²Toxicology Laboratory, Chugai Pharmaceutical Co., Ltd., Gotemba-shi, Shizuoka, Japan

Summary. We have previously demonstrated that high doses of recombinant human granulocyte colony-stimulating factor (rhG-CSF) induce bone changes characterized by osteoclastic bone resorption and osteogenesis due to intramembranous ossification in rats. In this communication we examined the effects of a pretreatment with 3-amino-1-hydroxypropy lidene-1,1-bisphosphonate (AHPrBP), which is a powerful inhibitor of osteoclastic bone resorption, on bone changes induced by rhG-CSF in order to investigate the relation between osteoclastic bone resorption and osteogenesis. AHPrBP (5 mg/kg/day) was subcutaneously given to 6-week-old rats for 2 days. From the following day of the final injection of AHPrBP, rats received a subcutaneous injection of rhG-CSF (1,000 μg/kg/day) for 14 days, and the femur and tibia were evaluated histopathologically. By the analysis of peripheral blood leukocyte counts, spleen weights and bone marrow findings, the pretreatment with AHPrBP had no effect on the activation of hematopoiesis related to the major pharmacological activity of rhG-CSF. In the rats treated with rhG-CSF alone, accelerated osteoclastic bone resorption and osteogenesis due to intramembranous ossification were observed in the trabeculae of metaphyseal spongiosa. The accelerated osteoclastic bone resorption induced by rhG-CSF was suppressed by the pharmacological activity of AHPrBP. Furthermore, the osteogenesis induced by rhG-CSF was also suppressed by AHPrBP. These results suggest that the osteogenesis induced by rhG-CSF is a sequential reaction of accelerated osteoclastic bone resorption, and moreover that the main action of rhG-CSF on bone is an acceleration of osteoclastic bone resorption.

Key words: Granulocyte colony-stimulating factor, Osteoclastic bone resorption, Osteogenesis, Intramembranous ossification, Bisphosphonate

Introduction

A large number of studies have suggested that colony-stimulating factors (CSFs) regulate the proliferation and differentiation of hematopoietic progenitor cells and that granulocyte CSF (G-CSF) acts on the granulocyte lineage and enhances some functions of mature granulocytes (Demetri and Griffin, 1991).

Recently, accelerated osteoclastic bone resorption and/or increased in number of osteoclasts have been reported in rats (Keller and Smalling, 1993; Soshi et al., 1996; Suzuki et al., 1997a-c) and mice (Lee et al., 1991) exogenously administered with recombinant human G-CSF (rhG-CSF), and in human G-CSF-transgenic mice (Takahashi et al., 1996). These observations suggest that G-CSF plays a role in the process not only of hematopoiesis but also of bone modulation. Furthermore, Keller and Smalling (1993) and the authors (Suzuki et al., 1997a-c) have demonstrated that osteogenesis due to intramembranous ossification was also observed in rats exogenously administered with rhG-CSF. In addition, we reported previously that bone resorption was observed in almost all lesions, and some of which accompanied osteogenesis. Lesions showing osteogenesis alone were observed in only a few areas (Suzuki et al., 1997b,c). This result suggests that the osteogenesis due to intramembranous ossification might be a coupling phenomenon after bone resorption. However, the relation between bone resorption and osteogenesis in bone changes induced by rhG-CSF is still obscure, and the role of G-CSF in bone modulation is poorly understood.

The present experiment was therefore undertaken to determine whether the rhG-CSF-induced osteogenesis is dependent upon bone resorption by testing the effects of bisphosphonate, which has a high affinity for hydroxyapatite crystals and is a powerful inhibitor of osteoclastic bone resorption (Boonekamp et al., 1986; Fleisch, 1987; Lowik et al., 1988; Flanagan and Chambers, 1989), on the rhG-CSF-induced bone changes.
Materials and methods

Animals

Twenty male Sprague-Dawley rats were purchased from Japan SLC Inc. (Shizuoka, Japan) and subjected to the experiments at the age of 6 weeks. The animals were housed in cages (5/cage) in an animal room maintained at a temperature of 23±2 °C, a relative humidity of 55±10% and a 14-hour light and 10-hour dark cycle, and they were fed pelleted chow (MF; Oriental Yeast Co., Ltd., Tokyo) and tap water ad libitum.

Injection of rhG-CSF and bisphosphonate

Recombinant human G-CSF (250 µg/ml) produced by Chugai Pharmaceutical Co., Ltd. (Tokyo, Japan) was used for this study. Bisphosphonate (3-amino-1-hydroxypropyliidine-1,1-bisphosphonate, AHPrBP) was purchased from Ciba-Geigy Pharmaceutical Co. (Basel, Switzerland), and was dissolved in saline to a final concentration of 1.25 mg/ml.

AHPrBP was subcutaneously injected into rats (over the upper back) at the dose level of 5 mg/kg once a day for 2 days. From the following day of the final injection of AHPrBP, rats received subcutaneous injection of rhG-CSF at the dose level of 1,000 µg/kg once a day for 14 days.

Study design

The rats were divided into 4 groups of 5 animals each, receiving: 1) saline for 16 days (totally negative control), 2) rhG-CSF after 2-days saline treatment (rhG-CSF-treated group), 3) saline for 14 days after AHPrBP treatment (AHPrBP-treated group), and 4) rhG-CSF after AHPrBP treatment (rhG-CSF+AHPrBP-treated group). All animals were weighed on days 0 (first dosing day), 2, 5, 9, 12 and 16, and the doses of rhG-CSF and AHPrBP were weight-adjusted. During the injection period, clinical signs of all animals were observed every day. On the day following the final injection, all animals were sacrificed by exsanguination under ether anesthesia. Before necropsy, peripheral blood leukocyte (white blood cell (WBC)) counts were measured in blood samples obtained from the abdominal aorta using a multiparameter auto-cell counter (electrical resistance detection, CC-780; Toa Medical Electronic Co. Ltd., Hyogo, Japan). Furthermore, serum samples were obtained from the abdominal aorta, and calcium (Ca) and inorganic phosphorus (IP) were measured using the o-cresolphthalein complexon and modified Taussky method, respectively.

Bone histopathology

At necropsy, the femur (distal metaphysis), tibia (proximal metaphysis), and spleen were removed from each animal, and the spleen was weighed. The bones were fixed in 10% neutral-buffered formalin and embedded in paraffin after ethylenediaminetetraacetic acid (EDTA) decalcification. Longitudinal thin sections were made and stained with hematoxylin and eosin (HE).

For enzyme histochemical study, the tibia (proximal metaphysis) was fixed in periodate-lysine-paraformaldehyde fixative (containing 4% paraformaldehyde) (McLean and Nakane, 1974) overnight at 4 °C. The specimens were decalcified in EDTA-glycerol solution (Mori et al., 1988) for 5 weeks at -5 °C, and embedded in paraffin by Amex methods (Sato et al., 1986). Sections of the specimens were deparaffinized in xylene and acetone, and enzyme histochemically stained. The tartrate-resistant acid phosphatase (TRAP) activity was detected according to the procedure using naphthol AS-BI phosphate (Sigma Chemical Co., St. Louis, MO) as substrate and hexazotized pararosaniline (Sigma Chemical Co.) as coupler, and the substrate solution was completed by adding 100 mM L(+)-tartratic acid (Barka and Anderson, 1962).

Statistical analysis

Group mean values and standard deviations were calculated for body weight, WBC counts, serum Ca, serum IP and spleen weight. These data were analyzed for statistical significance of any differences between the control group and each drug-treated group, using Student’s or Welch’s t-test at levels of 1 and 5%.

Results

Clinical signs and body weights

No abnormal clinical signs were observed in any group. Figure 1 illustrates the body weights. The body weights of the rhG-CSF- and the AHPrBP-treated groups were judged not to be different from those of the control group. The body weight at day 16 was significantly lower in the rhG-CSF+AHPrBP-treated group than in the control group.

WBC counts, spleen weights and bone marrow findings

Marked increase in WBC counts and prominent splenomegaly were observed in the rhG-CSF- and the rhG-CSF+AHPrBP-treated groups (Table 1). In addition, no significant difference was observed in the WBC counts and spleen weight between the rhG-CSF-treated and the rhG-CSF+AHPrBP-treated groups. In the bone marrow, an increase of granulopoietic cells was observed in the rhG-CSF- and the rhG-CSF+AHPrBP-treated groups, and marrow cavities were fully occupied by hematopoietic cells.

Serum Ca and IP values

No significant changes in serum Ca and IP levels were observed in the rhG-CSF+AHPrBP-treated group as compared with the control group.
Bone changes induced in rats by rhG-CSF

Histopathological nature of bone changes

The histopathological nature of bone changes is summarized in Table 2.

In the rhG-CSF-treated group, bone changes characterized by accelerated osteoclastic bone resorption and osteogenesis due to intramembranous ossification were observed in the metaphyseal spongiosa of femur and tibia (Figs. 2b, 3-5). The changes were distributed in the area from the secondary spongiosa to the interface of primary spongiosa and secondary spongiosa. In the spongy trabeculae, a large number of osteoclasts and bone resorption bays (Howship's lacunae) were observed on the bone surface (Fig. 3). The medullary cavity primary spongiosa and secondary spongiosa. In the were observed in all groups (Table 1).

*: Significantly different from the control (p<0.05).

Histopathological findings of bone were the same as those of the AHPrBP-treated group (Fig. 2d, 6b, 7b). Namely, trabeculae with spicules of calcified cartilage were more numerous in the metaphysis, and extended further towards the diaphyseal region. On the trabecular bone surfaces, a large number of osteoclasts without ruffled border were observed, and bone resorption bays were not found.

Discussion

Recently, we have demonstrated that bone changes characterized by accelerated osteoclastic bone resorption and osteogenesis due to intramembranous ossification were observed in rats administered with 100 and 1,000 

<table>
<thead>
<tr>
<th>GROUP</th>
<th>WBC (x10^3/μl)</th>
<th>CA (mg/dl)</th>
<th>IP (mg/dl)</th>
<th>SPLEEN (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>6.7±0.8</td>
<td>10.49±0.13</td>
<td>9.67±0.52</td>
<td>694±114</td>
</tr>
<tr>
<td>rhG-CSF</td>
<td>49.4±8.7*</td>
<td>10.29±0.37</td>
<td>9.32±1.00</td>
<td>2,121±184*</td>
</tr>
<tr>
<td>AHPrBP</td>
<td>6.9±1.2</td>
<td>10.44±0.49</td>
<td>8.58±0.72</td>
<td>605±51</td>
</tr>
<tr>
<td>rhG-CSF + AHPrBP</td>
<td>60.9±14.9*</td>
<td>10.16±0.34</td>
<td>8.94±0.70</td>
<td>2,236±297*</td>
</tr>
</tbody>
</table>

Each value represents the mean±SD (n=5).*: significantly different from the control (p<0.01).
Bone changes induced in rats by rhG-CSF

In the present study, rhG-CSF was given to rats for 14 days at dose level of 1,000 μg/kg. Marked increase in number of WBC counts, prominent splenomegaly with extensive extramedullary hematopoiesis (Keller and Smalling, 1993) and granulocytic hypercellularity of bone marrow, which are related to the major pharmacological activity of rhG-CSF (Demetri and Griffin, 1991; Keller and Smalling, 1993), were observed in the rhG-CSF- and rhG-CSF+AHPrBP-treated group. There were no differences in the aforementioned findings between the rhG-CSF-treated group and the rhG-CSF+AHPrBP-treated one. These results indicated that the pretreatment

Table 2. Histopathological findings of bone in rats injected with rhG-CSF and AHPrBP

<table>
<thead>
<tr>
<th>FINDINGS</th>
<th>CONTROL</th>
<th>rhG-CSF</th>
<th>AHPrBP</th>
<th>rhG-CSF + AHPrBP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Femur</td>
<td>Tibia</td>
<td>Femur</td>
<td>Tibia</td>
</tr>
<tr>
<td>rhG-CSF-related changes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accelerated osteoclastic bone resorption</td>
<td>0*</td>
<td>0</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Osteogenesis due to intramembranous ossification</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>AHPrBP-related change</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Increase in metaphyseal spongy trabeculae</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Each group is composed of 5 rats. *: number of rats with changes.

Fig. 2. Femur sections of rats injected with saline (a; control), 1,000 μg/kg of rhG-CSF (b), 5 mg/kg of AHPrBP (c), and both 1,000 μg/kg of rhG-CSF and 5 mg/kg of AHPrBP (d). b. Bone changes involving the replacement of medullary cavity by mesenchymal tissues are observed in the metaphysis. c and d. The amount of trabecular in the metaphysis is greatly increased. HE, x 40.
Bone changes induced in rats by rhG-CSF

with AHPPrBP did not affect the major pharmacological activity of rhG-CSF.

In the AHPPrBP-treated group, the amount of trabeculae in the metaphysis was greatly increased. The fact that spicules of calcified cartilage were observed in the trabeculae indicated that the trabeculae occupying the metaphysis were cartilage bone due to enchondral ossification from growth plate. On the bone surfaces, an increase in number of osteoclasts was observed, whereas ruffled border of osteoclasts and bone resorption bays on bone surface were not found. These findings suggested that osteoclastic bone resorption was suppressed, and then, unresorbed enchondral bone (also called cartilage bone) trabeculae occupied the metaphysis. Therefore, it was confirmed that AHPPrBP exhibited its effect of resorption-suppression in this study.

In the rhG-CSF-treated group, bone changes characterized by accelerated osteoclastic bone resorption and osteogenesis due to intramembranous ossification were observed. The histopathological nature of bone changes was similar to that in our previous studies (Suzuki et al., 1997b,c). In the rhG-CSF-AHPPrBP-treated group, histopathological findings of bone were the same as those in the AHPPrBP-treated group. The increase in number of osteoclasts was observed in the rhG-CSF- and rhG-CSF-AHPPrBP-treated groups. It is known that, in growing rats treated with AHPPrBP, the increase in number of osteoclasts is a secondary reaction occurring after the increase in amount of bone tissues due to suppressed osteoclastic bone resorption (Miller and Jee, 1975, 1977, 1979; Reitsma et al., 1980; Flanagan and Chambers, 1989). It is considered that the increase in number of osteoclasts in the rhG-CSF-AHPPrBP-treated group involved both the effect of rhG-CSF and the secondary reaction of AHPPrBP-treatment.

In the rhG-CSF-AHPPrBP-treated group, the accelerated osteoclastic bone resorption induced by rhG-CSF was suppressed by the pharmacological activity of AHPPrBP. Furthermore, the osteogenesis due to intramembranous ossification induced by rhG-CSF was also suppressed by pretreatment with AHPPrBP. These results suggest that the osteogenesis induced by rhG-CSF is dependent on the presence of a coupling mechanism, and moreover that the osteogenesis is a sequential reaction of accelerated osteoclastic bone resorption induced by rhG-CSF. The main action of rhG-CSF on bone, therefore, seems to be the acceleration of osteoclastic bone resorption.

It has been established that osteoclasts are derived from hematopoietic stem cell population and that the CSFs, especially macrophage CSF, regulate the

![Fig. 3. Femur section of a rat injected with rhG-CSF. In the trabeculae, a large number of osteoclasts and resorptive bays (Howship's lacunae) are observed. HE, x 160](image)

![Fig. 4. Tibia section of a rat injected with rhG-CSF. TRAP-positive osteoclasts and mononuclear cells are observed on the bone surface and in the mesenchymal tissues. x 125](image)

![Fig. 5. Femur section of a rat injected with rhG-CSF. Irregular-shaped woven bones are seen near the area replaced by mesenchymal tissues. The bones are filled with osteoid osteocytes, and their surfaces are covered with formative osteoblasts. HE, x 125](image)
Bone changes induced in rats by rhG-CSF

Fig. 6. Femur sections of rats in-infected with AHPrBP and rhG-CSF. Large amount of trabecular with spicules of calcified cartilage are observed in rats injected with AHPrBP alone (a), and both rhG-CSF and AHPrBP (b). HE, x 160

Fig. 7. Tibia sections of rats injected with AHPrBP and rhG-CSF. A large number of TRAP-positive osteoclasts are observed in rats injected with AHPrBP alone (a), and both rhG-CSF and AHPrBP (b). X 100

proliferation and differentiation of osteoclast progenitors (Kodama et al., 1993; Hofstetter et al., 1996; Suda et al., 1996; Odgren et al., 1997). At present, the role of G-CSF in osteoclastogenesis is poorly understood. However, it has been reported that G-CSF weakly stimulated growth of osteoclast progenitors in vitro (Takahashi et al., 1991). In addition, we have previously reported that the development of bone changes induced by rhG-CSF is closely related to the bone marrow hematopoietic activity and that the changes take place in the bone with active hematopoietic marrow (Suzuki et al., 1997a). Therefore, it is conceivable that high levels of rhG-CSF might result in stimulation of the proliferation and differentiation of osteoclast progenitors as well as hematopoietic progenitors.

In addition, it has been shown that G-CSF affects not only hematopoietic cells but also stromal cells (Bussolino et al., 1989, 1994; Fukushima et al., 1992, 1994). These cells, which are components of marrow microenvironment, play an important role in modulating the hematopoiesis and the development of osteoclasts (Kukita et al., 1993; Shevde et al., 1994; Takahashi et al., 1995; Suda et al., 1996). It is possible that high levels of rhG-CSF may affect marrow microenvironment and bring about not only hematopoiesis but also osteoclast development. Now, further study on the mechanisms of rhG-CSF-induced bone changes is in progress.

Acknowledgments. We thank Ms. Masako Un-no, Ms. Yukiko Tabata, Ms. Yayoi Karasawa, Ms. Kyouko Aruga and Ms. Fusami Akahane at Chugai Pharmaceutical Co. for their skillful technical assistance.

References


Flanagan A.M. and Chambers T.J. (1989). Dichloromethylene-
bisphosphonate (Cl2MBP) inhibits bone resorption through injury to osteoclasts that resorb Cl2MBP-coated bone. Bone Miner. 6, 33-43.


Overexpression of the granulocyte colony-stimulating factor gene leads to osteoporosis in mice. Lab. Invest. 74, 827-834.

Bone changes induced in rats by rhG-CSF


Accepted October 28, 1996