Systemic prostaglandin E\textsubscript{2} increases cancellous bone formation and mass in aging rats and stimulates their bone marrow osteogenic capacity \textit{in vivo} and \textit{in vitro}

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Abstract

Prostaglandin E\textsubscript{2} (PGE\textsubscript{2}) has been shown to exert a bone anabolic effect in young and adult rats. In this study we tested whether it possesses a similar effect on bone formation and bone mass in aging rats. Fifteen-month-old rats were injected daily with either PGE\textsubscript{2} at 5 mg/kg or vehicle for 14 days. PGE\textsubscript{2} treatment stimulated the rate of cancellous bone formation (a \textasciitilde{} 5.5-fold increase in bone formation rate), measured by the incorporation of calcein into bone-forming surfaces at the tibial proximal metaphysis. This effect resulted in increased cancellous bone area (+54%) at the same site. Since PGE\textsubscript{2} treatment resulted in a much higher proportion of bone surface undergoing bone formation and thus lined with osteoblasts, we tested the hypothesis that PGE\textsubscript{2} stimulates osteoblast differentiation from bone marrow precursor cells both \textit{in vivo} and \textit{in vitro}. We found that \textit{ex vivo} cultures of bone marrow stromal cells from rats injected for 2 weeks with PGE\textsubscript{2} at 5 mg/kg per day yielded more (\textasciitilde{}4-fold) mineralized nodules and exhibited a greater (by 30–40%) alkaline phosphatase activity compared with cultures from vehicle-injected rats, attesting to a stimulation of osteoblastic differentiation by PGE\textsubscript{2}. We also compared the osteogenic capacity of bone marrow from aging (15-month-old) versus young (5-week-old) rats and its regulation by PGE\textsubscript{2} \textit{in vitro}. Bone marrow stromal cell cultures from aging rats exhibited a greatly diminished osteogenic capacity, reflected in reduced nodule formation (\textasciitilde{}6% of young animals) and lower alkaline phosphatase activity (\textasciitilde{}60% of young animals). However, these parameters could be stimulated in both groups of animals by incubation with 10–100 nM PGE\textsubscript{2}. The magnitude of this stimulation was greater in cultures from aging rats (+550% vs +70% in nodule formation of aging compared with young rats).

In conclusion, we demonstrate here that PGE\textsubscript{2} exerts a bone anabolic effect in aging rats, similar to the effect we and others have reported in young, growing rats. The PGE\textsubscript{2}-stimulated bone formation, which augments bone mass, most likely results from recruitment of osteoblasts from their bone marrow stromal precursors.


Introduction

In the last two decades, prostaglandins of the E series (PGEs), especially PGE\textsubscript{2}, have been shown to be potent stimulators of bone formation \textit{in vivo} (reviewed by Norrdin \textit{et al}. 1990 and Jee \& Ma 1997). The anabolic effect of systemically administered PGEs was reported in many species including young (Ueno \textit{et al}. 1985, Jee \textit{et al}. 1987, Suponitzki \& Weinreb 1998) and adult (Ke \textit{et al}. 1991, 1992) rats as well as humans (Ueda \textit{et al}. 1980, Jorgensen \textit{et al}. 1988). Detailed analysis of the effects of PGE\textsubscript{2} in these growing rats showed that it increases bone formation and bone mass mainly by increasing the number of osteoblasts present on bone surfaces and by inducing the production of new bone. However, the anabolic properties of PGE\textsubscript{2} in aging or old animals have been poorly studied so far. Aging in humans is associated with diminished bone mass and consequently higher fracture incidence (Davis \textit{et al}. 1994, Parfitt \textit{et al}. 1995, Heersche \textit{et al}. 1998, Rizzoli \& Bonjour 1999). Bone loss in aging humans is the result of both increased bone resorption and reduced bone formation. The latter is thought to be a consequence of paucity in mature osteoblasts. It is well known that osteoblasts are derived from osteoprogenitor cells (OPC), which are present within the bone marrow stromal compartment (Friedenstein 1990, Simmons 1996). These stromal cells, called CFUs (colony-forming fibroblastic) can be cultured \textit{in vitro} where they differentiate into osteoblast-like cells and produce mineralizing matrix (Friedenstein \textit{et al}. 1968, Maniatopoulos \textit{et al}. 1988, Owen 1988). Therefore, it is not surprising that many studies revealed that the number of CFUs is diminished in...

Therefore, the purpose of this study was twofold: (A) to test whether systemically administered PGE₂ exerts an anabolic effect (i.e. stimulates bone formation and increases bone mass) on cancellous bone of aging rats, and (B) to examine whether the potential of bone marrow stromal cells to differentiate into osteoblasts, which is expected to be diminished in these aging animals, can be stimulated by in vivo or in vitro treatment with PGE₂.

MATERIALS AND METHODS

IN VIVO TESTING

ANIMAL TREATMENT

For each experiment, 15-month-old male Sprague-Dawley rats were divided into two groups (seven or eight rats each). One group received daily subcutaneous injections of PGE₂ (a generous gift of Dr. C. Hall, the Upjohn Company, Kalamazoo, MI, USA) at 5 mg/kg per day in 10% ethanol for 14 days, while the second group received the vehicle alone. In some experiments, both groups were injected with calcein (Sigma, St Louis, MO, USA) at 15 mg/kg, 9 and 2 days prior to sacrifice to measure dynamic parameters of bone formation. At the end of the injections, animals were killed with CO₂, and both hind limbs were removed. Tibiae were fixed in cold 50% ethanol for histomorphometry and femora were used for bone marrow cultures and then for endocortical label measurements (see below).

HISTOMORPHOMETRY

Tibiae and femoral shafts (after the initiation of marrow cultures) were dehydrated in increasing concentrations of ethanol and were embedded in methyl methacrylate (Weinreb et al. 1991, Suponitzki et al. 1997). Ten micrometer thick frontal (tibia) or transverse (femur) sections were cut with a Polycut microtome (Leica, Nussloch, Germany) and were mounted on gelatin-coated slides. Unstained sections were photographed at a ×83 magnification and scanned in a Polaroid Sprintscan Scanner. Bone area in the tibial proximal metaphysis was measured with the Adobe Photoshop software in an area extending 0·5 to 1·75 mm distal to the growth plate. For measurements of dynamic parameters of bone formation, unstained sections were viewed in a fluorescence microscope and an area extending 1–1·9 mm distal to the tibial growth plate was photographed at a final magnification of ×110. The percent bone surface with single (SL) or double (DL) calcein labels was determined as percent of the total bone surface (BS) using a computerized digitizer (Summographics, Fairfield, CT, USA) and the SigmaScan software (Jandel Corporation, San Rafael, CA, USA). The mineralizing surface (MS) was calculated according to the formula MS=(DL+1/2 SL)×100/BS (Parfitt et al. 1987). A similar analysis was performed on the endosteal surface of the distal femoral shaft.

BONE MARROW CULTURES

Femora were defleshed and the epiphyses were removed. Bone marrow was flushed out and a single-cell suspension was achieved by repeated pipetting. Cells were counted with a hemocytometer and were cultured in six-well plates (Nunc, Roskilde, Denmark) at a density of 5–6×10⁶ cells/well in a medium containing α minimal essential medium plus 13% fetal calf serum (all reagents except where noted were from Biological Industries, Beit Haemek, Israel) + 2 mM glutamine + 100 U/ml penicillin + 100 µg/ml streptomycin + 12·5 U/ml Nystatin + 10 mM β-glycerophosphate + 50 µg/ml ascorbic acid (Merck, Darmstadt, Germany) + 10 nM dexamethasone (Sigma). After an attachment period of 24 h, non-adherent cells were removed by rinsing with PBS and cultures were maintained in 7% CO₂ and 37°C for 21 days with twice-a-week medium changes. At the end of the culture period, cultures were rinsed in PBS, fixed in a 1:1:1 solution of 10% formalin–methanol–water for 2 h and stained with the Von Kossa method for mineralized nodules (Keila et al. 1994, Weinreb et al. 1997a). Mineralized nodules (stained black) and non-mineralized nodules (stained yellow) were counted macroscopically with a magnifying glass over transmitted light and the number of each class of nodules per well and the relative proportion of mineralized nodules of the total number of nodules was determined.

In addition to mineralized nodule formation, osteoblastic differentiation was assessed by measuring alkaline phosphatase (AP) activity in culture (Weinreb et al. 1997a, 1999). Femoral cells were cultured as before, and on days 8 and 12 they were washed in PBS and scraped in 10 mM Tris–HCl buffer (pH 7·6) containing 10 mM MgCl₂ and 0·1% Triton X–100. AP activity was determined colorimetrically using a Sigma kit based on p-nitrophenyl phosphate as substrate. The protein content was measured according to Bradford using BSA as standard and a protein assay kit (Bio-Rad Laboratories, Munich, Germany) and enzyme activity was expressed as units/mg protein.

IN VITRO TESTING

BONE MARROW CULTURES

We have previously reported that PGE₂ stimulates in vitro the osteogenic capacity of bone marrow in very young (4-week-old) rats (Weinreb et al. 1997a). In this study we initiated parallel cultures from both young (4 week) and aging (15 months) rats to compare the effect of aging and PGE₂. Femoral bone marrow cells were seeded in six-well plates as described above and PGE₂ (0–1000 nM) in 0·1% ethanol was added upon plating and in each subsequent medium change.
Cells were cultured for either 12 days for determination of AP activity or 21 days for measurement of nodule formation (both performed as indicated above).

All data are presented as means ± S.E.M. Comparison between group means was performed using one-way analysis of variance with post hoc multi-group contrasts.

Results

In vivo testing

The aging rats used in this study gained very little weight throughout the experiment and their epiphyseal growth plates were almost closed.

Systemic administration of PGE2 at 5 mg/kg for 14 days to aging rats increased cancellous bone mass in the tibial secondary spongiosa by ~54% (Fig. 1). The increase in bone mass was associated with increased bone formation, reflected in a much greater fraction of bone surface involved in formation (sL, dL, MS) (Fig. 2). In addition, mineral apposition rate increased by ~36% (Fig. 3). The resulting calculated rate of bone formation increased ~5-5-fold in cancellous bone of PGE2-injected animals (Fig. 3). In addition to stimulation of bone formation on the cancellous envelope, PGE2 treatment stimulated bone formation on the endosteal surface, facing the marrow cavity. As in the case of cancellous bone, PGE2 stimulated both osteoblast recruitment (reflected in the fraction surface involved in formation; Fig. 4) and osteoblastic activity, reflected in mineral apposition rate (MAR) (Fig. 5). Consequently, the calculated endosteal bone formation rate was ~2.5-fold greater in PGE2-injected animals (Fig. 5).

Since these measurements indicated that the extent of bone surface involved in bone formation increased greatly in PGE2-treated animals, a stimulation of osteoblast recruitment from precursor cells present in bone marrow was expected. Indeed, bone marrow from PGE2-treated rats showed increased overall cellularity (Fig. 6) and specifically, an expanded osteoprogenitor pool as evidenced by increased mineralized nodule formation (Fig. 7). Both the number of nodules per well and their relative proportion out of the total number of nodules increased significantly following systemic PGE2 administration. Furthermore, this treatment increased AP activity in ex vivo cultures of bone marrow cells (Fig. 8). As we reported previously (Weinreb et al. 1997a), AP activity increases between 8 and 12 days of culture, parallel with the progressing osteoblastic differentiation of these cells. However, at each of these time points, AP activity in cultures taken from PGE2-treated rats was greater than...
that in cultures taken from vehicle-treated rats. AP activity, expressed as units/mg protein, increased in cultures from PGE2-treated animals in addition to an increase in their protein content (Fig. 9).

These data demonstrated that an anabolic dose of PGE2 increased bone formation and bone mass in aging rats and that this effect can be attributed to stimulation of the osteoprogenitor pool present in bone marrow. Thus bone tissue of aging rats is responsive to the anabolic effect of PGE2, with a mechanism similar to that reported by us in very young (3–4-week-old) rats.

In vitro testing

In addition to the ability of systemically administered PGE2 to exert an anabolic effect, we tested its in vitro stimulatory activity on osteoblastic differentiation in parallel bone marrow cultures from young and aging rats. Despite seeding of a similar number of bone marrow cells, the number of mineralized nodules per well with no PGE2 added was much greater (∼16-fold) in cultures from young compared with aging rats (Fig. 10). These data reflect the great diminution in the proportion of osteoprogenitor cells in aging animals. Addition of PGE2 at 10–100 nM to bone marrow cultures of the two animal groups increased significantly the number of nodules formed while a concentration of 1000 nM was no longer effective (as we previously reported (Weinreb et al. 1999)). However, comparing the magnitude of the stimulation exerted by PGE2 on nodule formation, the effect on cultures from aging rats was more pronounced than that on cultures from young rats (+550% vs +70% respectively).

Figure 4 Systemic PGE2 increases the fraction of endosteal bone surface bearing single- or double-calcein labels or as MS (mineralizing surface). **P<0.01 (PGE2 vs vehicle). Data are presented as means ± S.E.M.s.

Figure 5 Systemic PGE2 increases endosteal mineral apposition rate (MAR) and the calculated bone formation rate (BFR). ***P<0.005 (PGE2 vs vehicle). Data are presented as means ± S.E.M.s.

Figure 6 Systemic administration of PGE2 increases total bone marrow cellularity. **P<0.01 (PGE2 vs vehicle). Data are presented as means ± S.E.M.s.
Similarly, AP activity on day 12 in cultures from aging rats was ~40% lower than that in cultures from young rats (Fig. 11). In both cultures, addition of 100 nM PGE2 increased AP activity significantly. Again, AP activity was stimulated by PGE2 on top of its increase of the protein content of the cultures (Fig. 12).

Cumulatively, the data of this study demonstrate the ability of systemic PGE2 to exert an anabolic effect on bones of aging (15-month-old) rats and strongly suggest that stimulation of osteoblastic differentiation from bone marrow osteogenic precursors is a major mechanism for this effect.

Discussion

We and others have previously shown that PGE2 increases bone formation and mass in intact young, rapidly growing as well as adult rats (Ueno et al. 1985, Jee et al. 1987, Ke...
et al. 1991, 1992, Jee & Ma 1997, Suponitzki & Weinreb 1998). Recently, PGE2 was also shown to increase cortical bone formation rate and red/yellow bone marrow ratio in the tibial shaft of intact old male rats (Yao et al. 1999). Our study shows that PGE2 also increases bone formation rate and consequently bone area of the cancellous bone of the tibial proximal secondary spongiosa of aging rats. Thus, systemic administration of PGE2 into aging or old rats can stimulate bone formation rate in both types of bone tissue. Given the ability of PGE2 to increase cancellous and cortical bone mass, it has previously been used to treat animals with various models of osteopenia such as

![Graph showing the effect of PGE2 on nodule formation](image1)

Figure 10: Incubation of bone marrow cells in vitro with PGE2 at 10–100 nM increases nodule formation in both young (5-week-old) and aging (15-month-old) rats. ** or $, P<0.01$ (vs PGE2=0). Data are presented as means ± S.E.M.s.

![Graph showing the effect of PGE2 on AP activity](image2)

Figure 11: Incubation of bone marrow cells in vitro with PGE2 at 100 nM increases AP activity in both young (5-week-old) and aging (15-month-old) rats. **P<0.01 (PGE2 vs control for both time points). Data are presented as means ± S.E.M.s.
ovariectomy (Mori et al. 1990) or mechanical unloading (Akamine et al. 1992, Jee et al. 1992). Taken together, these studies clearly show that bone tissue of aging rats is responsive to the anabolic action of PGE2.

Our data of increased bone marrow cellularity caused by PGE2 treatment may be relevant to the PGE2-induced changes in bone marrow composition reported in old rats (Yao et al. 1999). In general, osteoblastogenesis and adipogenesis behave in opposite manners in bone tissue (e.g. increase in bone marrow fat content versus the decline in bone formation and osteoblast number with aging (Meunier et al. 1971)). Thus the improvement in red/yellow marrow ratio reported by others or the increased number of cells that can be harvested from the femoral marrow cavity as shown here may reflect a shift away from adipocytic toward osteoblastic commitment, caused by PGE2.

This study documented a significant stimulation of cancellous and endosteal bone formation rate induced by systemic treatment with PGE2. As previously mentioned, osteoblasts differentiating on cancellous and endocortical surfaces originate from marrow osteoprogenitors. Our data clearly show that systemic PGE2 increases the potential of the marrow stromal compartment to produce osteoblasts. The nodule-formation assay used here is based on the observations that these CFUfs are clonogenic (Owen 1988) and that the number of mineralized nodules reflects the number of recruitable osteoprogenitors. These data from the nodule formation assay are corroborated by the PGE2 stimulation of AP activity as shown here, and this effect is compatible with the increase in the number of osteoblasts on bone-forming surfaces measured by the calcein labeling. These stimulatory effects of PGE2 in aging rats was previously reported by us in young, growing rats (Weinreb et al. 1997a). Whether this stimulation of osteoblastogenesis involves effects on proliferation, differentiation or apoptosis is not known. We have shown that a single injection of an anabolic dose of PGE2 induces the expression of various early-response genes in bone marrow cells (Weinreb et al. 1997b), pointing again to the presence of PGE2 target cells within bone marrow.

In this study we found, as others have reported, that aging is associated with a marked reduction in the osteogenic capacity of bone marrow, when compared with that of young rats (Tsuji et al. 1990, Egrise et al. 1992, Kahn et al. 1995, Quarto et al. 1995, Bergman et al. 1996, Inoue et al. 1997). However, this capacity can be stimulated by PGE2 in both young and aging animals, peaking at a concentration of 100 nM (Weinreb et al. 1999). Nevertheless, the fold increase in nodule formation in the aging rats was more pronounced than that in the young rats and the in vitro data strongly point to a direct effect of PGE2 on the stromal cells.

Both the effects of aging (reduction) and PGE treatment (stimulation) on the marrow osteogenic capacity are thus examples of the positive correlation between the rate of bone formation and the number of osteoprogenitors. Our previous report that the osteogenic capacity of bone marrow is greatly diminished in mechanical unloaded rat limbs, in which bone formation is markedly depressed (Keila et al. 1994), is another example of this correlation. The mechanism underlying the aging-associated diminution in osteoprogenitor cells is not known. One possibility is that the abundance of or response to a variety of growth factors is deficient in old animals. A correlation between age-related decline in bone formation and in the

**Figure 12** Incubation of bone marrow cells in vitro with PGE2 at 100 nM increases the protein content of cultures from both young (5-week-old) and aging (15-month-old) rats. **P**<0.01 (PGE2 vs control for each time point). Data are presented as means ± S.E.M.s

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concentration of insulin–like growth factor–I (IGF–I) in bone tissue was suggested (Boonen \textit{et al.} 1997) while others associated aging–related osteopenia with diminished activity and/or availability of transforming growth factor–\( \beta \) (Gazit \textit{et al.} 1998). Whether the stimulation of bone formation and osteoblastic commitment by PGE\(_2\) is mediated via changes in these or other growth factors remains to be determined.

\textbf{Acknowledgements}

This study was supported by the Dr Herman Schauder Memorial Fund of the Sackler School of Medicine, Tel-Aviv University, and was carried out in the Rosenberg Bone Research Laboratory of the Goldschleger School of Dental Medicine. Partially based on a DMD thesis submitted to the Tel–Aviv University Goldschleger School of Dental Medicine by A. K.

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\textit{Journal of Endocrinology} (2001) 168, 131–139

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Received 2 April 2000
Revised manuscript received 1 September 2000
Accepted 27 September 2000