The adaptive response of bone to mechanical loading in female transgenic mice is deficient in the absence of oestrogen receptor-α and -β

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Abstract

Postmenopausal osteoporosis represents a failure of the response by which bone cells adapt bone mass and architecture to be sufficiently strong to withstand loading without fracture. To address why this failure should be associated with oestrogen withdrawal, we investigated the ulna’s adaptive response to mechanical loading in adult female mice lacking oestrogen receptor-α (ERα−/−), those lacking oestrogen receptor-β (ERβ−/−) and their wild-type littermates. In wild-type mice, short periods of physiologic cyclic compressive loading of the ulna in vivo over a 2-week period stimulates new bone formation. In ERα−/− and ERβ−/− mice this osteogenic response was respectively threefold and twofold less (P<0.05). In vitro, primary cultures of osteoblast-like cells derived from these mice were subjected to a single short period of mechanical strain. Twenty-four hours after strain the number of wild-type cells was 61 ± 25% higher than in unstrained controls (P<0.05), whereas in ERα−/− cells there was no strain-related increase in cell number. However, the strain-related response of ERα−/− cells could be partially rescued by transfection with functional human ERα (P<0.05). ERβ−/− cells showed a 125 ± 40% increase in cell number following strain. This was significantly greater than in wild types (P<0.05).

These data support previous findings that functional ERα is required for the full osteogenic response to mechanical loading and particularly the stage of this response, which involves an increase in osteoblast number. ERβ appears to depress the ERα-mediated strain-related increase in osteoblast number in vitro, but in female transgenic mice in vivo the constitutive absence of either ERα or ERβ appears to diminish the osteogenic response to loading.


Introduction

Postmenopausal osteoporosis represents a failure of the normal homeostatic mechanisms by which functional load bearing establishes and maintains a sufficiently robust bone structure to withstand the forces of everyday activities without fracture (Lanyon & Skerry 2001). We hypothesise that this failure is due to a reduction in oestrogen receptor (ER) number and/or function in bone cells resulting from oestrogen deficiency.

It is currently believed that most of the functions of oestrogen in bone are mediated by ERα (Riggs et al. 2002). These include the regulation of osteoblast proliferation and differentiation, the synthesis of bone matrix proteins, the promotion of osteocyte survival, the suppression of bone resorption and the promotion of osteoclast apoptosis (Riggs et al. 2002). In vitro evidence suggests that ERα in bone cells is also involved in mediating responses to mechanical stimulation. The strain-related increase in cell number of monolayer cultures of rat and human osteoblast-like cells can be blocked with ER antagonists and enhanced by transfection with additional ERα (Damien et al. 1998, 2000, Zaman et al. 2000, Cheng et al. 2002). Moreover, mechanical strain stimulates ERα phosphorylation and oestrogen response element (ERE) activation via a pathway which is dependent on three well-established mediators of the in vivo osteogenic response of whole bones to mechanical loading: movement of calcium ions and the production of nitric oxide and prostaglandins (Zaman et al. 2000, Jessop et al. 2001, 2002).

Support for a reduction in ER number and function in bone cells in oestrogen-deficient states has been published by other workers. Bone biopsies from oestrogen-deficient women have fewer ERα-positive osteocytes than those from oestrogen-replete women (Hoyland et al. 1999) and osteoblasts cultured from postmenopausal women are less responsive to oestrogen compared with osteoblasts from younger women in terms of oestrogen-induced collagen synthesis and ERE activation (Ankrom et al. 1998). In addition, reduced levels of ERα mRNA have been detected in trabecular bone following ovariectomy in rats (Lim et al. 1999).
The inference that adaptive bone (re)modelling would be dependent upon functional ER\(\alpha\) was supported by data from a pilot experiment \textit{in vivo} (Lee et al. 2003), which showed that the loading response of ER\(\alpha\) knockout (ER\(\alpha^{-/-}\)) mice was threefold less than that in wild-type littermates. However, unravelling the effects of ER in bone cells is complicated by the presence of two ERs: ER\(\alpha\) and ER\(\beta\). Both are present in osteoblasts but the action of ER\(\beta\) in particular is currently uncertain (Riggs et al. 2002). Studies of ER\(\beta\) knockout (ER\(\beta^{-/-}\)) mice suggest that ER\(\beta\) is not required for the protective effect of oestrogen on bone mass. The responses of the bones of young adult ER\(\beta\) knockout (ER\(\beta^{-/-}\)) female mice to ovariectomy and oestrogen-replacement therapy have been shown to be the same as those in wild types (Sims et al. 2002). However, 1-year-old female ER\(\beta^{-/-}\) mice have a low bone turnover and a high bone mineral density compared with wild types. This phenotype has been associated with higher ER\(\alpha\) mRNA levels in the bones of ER\(\beta^{-/-}\) mice compared with wild types (Windahl et al. 2001). Therefore ER\(\beta\) may have a repressive effect on ER\(\alpha\) expression in bone and thus an inhibitory effect on the maintenance of an appropriate bone mass by oestrogen and mechanical loading.

The primary aim of the study reported here was to investigate the role of both ER\(\alpha\) and ER\(\beta\) in bone’s adaptive response to mechanical loading. \textit{In vivo} we did this by studying the osteogenic response of the ulna of ER\(\alpha^{-/-}\), ER\(\beta^{-/-}\) and wild-type mice to mechanical loading. We then cultured ER\(\alpha^{-/-}\), ER\(\beta^{-/-}\) and wild-type osteoblast-like cells from these mice and assessed \textit{in vitro} changes in cell number following a period of mechanical strain. In addition, we assessed the effect of transfection of human ER\(\alpha\) on the strain responsiveness of ER\(\alpha^{-/-}\) cells.

Materials and Methods

Mice

ER\(\alpha\) knockout (ER\(\alpha^{-/-}\)) and ER\(\beta\) knockout (ER\(\beta^{-/-}\)) mice were bred from two distinct breeding colonies. ER\(\alpha^{-/-}\) mice were homozygous for an insertional mutation in the first coding exon, exon 2, of the mouse ER\(\alpha\) gene (Lubahn et al. 1993). ER\(\beta^{-/-}\) mice were homozygous for an insertional mutation in exon 3 of the mouse ER\(\beta\) gene (Krege et al. 1998). The background strain of both colonies was C57Bl/6j. Knockout and wild-type littermates were bred from heterozygous breeding pairs. Hereafter ER\(\alpha^{-/-}\) and ER\(\beta^{-/-}\) mice represent the wild-type littermates of ER\(\alpha^{-/-}\) and ER\(\beta^{-/-}\) mice respectively.

Mice were genotyped by PCR analysis. Primers used for detection of the intact and disrupted ER\(\beta\) genes were 5’-AACCTGCGCGGCTGCACTTTAACC-3’ (ER\(\alpha\) exon 2), 5’-CAGGGTGTGCAAGGCAACGC-3’ (ER\(\alpha\) exon 2) (Vidal et al. 2000), 5’-GTGTTCCGGCTGTGACGGCCA-3’ (neomycin cassette) and 5’-GTCCTGCAGGCGTCCGGC-3’ (neomycin cassette) (K S Korach, personal communication). Primers used for detection of the intact and disrupted ER\(\beta\) genes were 5’-AGAATTTGACTGCCCGCTGCTGC-3’ (ER\(\beta\) intron 2), 5’-GGAGTAGAAGCAATCCAGAC-3’ (ER\(\beta\) intron 3) and 5’-GCAGACGTCTGGATTCCACATACACTTC-3’ (neomycin cassette) (Windahl et al. 1999).

Breeding colonies were maintained under standardized conditions, in a specific pathogen-free environment, with free access to water and a standard breeding or maintenance rodent diet as appropriate. All animal procedures complied with the Animals (Scientific Procedures) Act 1986 and institutional guidelines.

Calibration of the in vivo mechanical loading apparatus

The technique for applying cyclic axial compression to the mouse ulna \textit{in vivo} through the flexed elbow and flexed carpus has been published previously (Fig. 1) (Lee et al. 2002).
The forces required to produce the peak strains and strain rates previously recorded from the ulna during locomotion (Lee et al. 2002) were determined ex vivo, using four forelimbs from 20- to 24-week-old female mice from each of the following four groups: ER$\alpha^{-/-}$ mice and their ER$\alpha^{+/+}$ littersmates; ER$\beta^{-/-}$ mice and their ER$\beta^{+/+}$ littersmates. Strain gauges (EA-06-015 LA-120; Measurements Group UK Ltd, Basingstoke, Hamps, UK) were bonded to the lateral midshaft of each ulna and the forelimb positioned in the loading apparatus as shown in Fig. 1. The relationship between force and strain under axial compression loading was determined using linear regression analysis and slopes and intercepts were compared between genotypes using the Mann–Whitney test.

In vivo loading

The left ulnae of eight 20- to 24-week-old female ER$\alpha^{-/-}$ mice and seven of their ER$\alpha^{+/+}$ littersmates were loaded by cyclic axial compression for 10 min on 3 alternate days each week for 2 weeks. In a separate experiment, the left ulnae of four 20- to 24-week-old female ER$\beta^{-/-}$ mice and four of their ER$\beta^{+/+}$ littersmates were loaded using the same regimen. The right ulnae of these mice served as non-loaded paired controls. Loading sessions comprised 40 cycles of a trapezoidal waveform with a peak load of $\pm$ 3·4 Newtons (N), which engendered peak strains of 2800 microstrain at a maximum strain rate of 0·1/s at the lateral ulna midshaft. Following each load cycle there was a rest period of 14·9 s.

On day 21, cells were washed in PBS and released with 0·05% trypsin and 0·02% EDTA for subculture. Only first passage cells were used for the following experiments. Sample cells were reserved at each extraction to confirm an osteoblastic phenotype. These cells expressed alkaline phosphatase, synthesised osteocalcin and formed mineralised nodules in long-term culture in the presence of 50 µg/ml ascorbic acid and 10 mM $\beta$-glycerophosphate (Sigma) (Zaman et al. 1997).

Transfection and mechanical straining of osteoblast cultures

Four sets of primary osteoblast-like cell cultures were prepared for mechanical straining: ER$\alpha^{-/-}$ cells,
ERβ<sup>−/−</sup> cells, wild-type cells and ERα<sup>−/−</sup> cells transfected with a functional human wild-type ERα expression vector, pRST7-ER (Tzukerman et al. 1994). All cells were seeded in monolayers onto sterile, tissue culture-treated, plastic strips (Nunc, Dossel, Germany) at a density of 80 000 cells per strip and incubated in DMEM containing 10% charcoal dextran–stripped FCS. The only exception was the ERα<sup>−/−</sup> cells for transfection, which were seeded at a density of 50 000 cells per strip.

ERα<sup>−/−</sup> cells were transiently transfected with pRST7-ER using Effectene (Qiagen) according to the manufacturer’s instructions. One µg pRST7-ER vector was used per strip and the incubation period was 3 h. To determine transfection efficiency, cells were simultaneously transfected with a lac z expression plasmid, at a concentration of 1 µg DNA per strip. β-Galactosidase activity was detected in fixed cells by histochemical staining (lac z staining kit; Promega) and the percentage of positive cells was calculated using phase contrast microscopy at a magnification of × 200.

Monolayer cell cultures were cyclically loaded by four-point bending for 10 min at a frequency of 1 Hz to peak strains of 3400 microstrain, using a custom designed loading apparatus as described previously (Zaman et al. 1997). Following loading, cultures were retained in the same culture medium and incubated for a further 24 h. The cells were then washed in PBS, fixed for 15 min in neutral-buffered formalin (BDH, Poole, Dorset, UK), washed twice in PBS and stored at 4 °C pending analysis. Control cultures were treated in the same way as strained cultures including being subjected to the same fluid perturbations, except they were not exposed to cyclic mechanical strain. Each experiment consisted of three strained and three control strips. Experiments were repeated three to five times.

**Assessment of the proliferative response of osteoblasts to mechanical strain**

The *in vitro* response of osteoblasts to mechanical strain was measured in terms of cell proliferation, by comparing the numbers of cells in strained cultures to those in non-strained control cultures by manual cell counting. To facilitate cell counting the nuclei of the fixed cells were stained with a fluorochrome, Hoechst 33258 (Sigma), using a modification of a previously described method (Rago et al. 1990). Briefly, fixed cells were washed with distilled water and incubated in 1 mg/ml Hoechst 33258 in TNE buffer (10 mM Tris, 1 mM EDTA and 2 M NaCl, pH 7·4) in the dark for 30 min. Cells were then blotted dry and mounted in glycerol. Cells were counted in 16 randomly chosen frames per strip using an ultraviolet microscope at × 4 magnification and the KS300 image analysis software (Imaging Associates Ltd). The mean number of cells per frame per strip was calculated. Cell number on strained and non-strained controls were compared using the paired *t*-test. Responses to mechanical strain were then expressed as the percentage difference in cell number between strained cultures and non-strained controls.

All statistical tests were carried out using SPSS10 (SPSS Inc., Chicago, IL, USA) and a 5% significance level. Data are presented as means ± S.E. unless otherwise stated.

**Results**

**Absence of ERα or ERβ has no effect on stiffness under axial compression**

ERα<sup>−/−</sup> ulnae (13·2 ± 0·02 mm, *n* = 4) were 4% shorter (*P* < 0·01) and straighter than ERα<sup>+</sup>/+ ulnae (13·8 ± 0·01 mm, *n* = 4). The length (and shape) of ERβ<sup>−/−</sup> ulnae (13·6 ± 0·17 mm, *n* = 4) was not significantly different from ERβ<sup>+</sup>/+ ulnae (13·7 ± 0·03 mm, *n* = 4). *Ex vivo*, cyclic axial compression loading of each of these ulnae revealed a strong linear correlation (*R*<sup>2</sup> = 0·96, *P* < 0·001) between peak compressive force and peak tension strain at the lateral ulna surface between 1·0 N and 4·0 N. No significant differences in the structural stiffness of the mouse ulna under cyclic axial compression loading were found between ERα<sup>−/−</sup> and ERα<sup>+</sup>/+ mice and between ERβ<sup>−/−</sup> and ERβ<sup>+</sup>/+ mice. Therefore data from knockout mice and their wild-type littermates were collated to predict the strain engendered at the lateral ulna midshaft under axial compression loading (Fig. 2). For ERα<sup>−/−</sup> and ERα<sup>+</sup>/+ ulnae: peak lateral strain = (−804·88 × peak compressive force) + 104·56; *R*<sup>2</sup> = 0·86; *P* < 0·001. For ERβ<sup>−/−</sup> and ERβ<sup>+</sup>/+ ulnae: peak lateral strain = (−730·25 × peak compressive force) + 365·21; *R*<sup>2</sup> = 0·69; *P* < 0·001. Therefore for both
knockouts and their wild-type littermates a peak compressive force of ~3·4 N resulted in a peak lateral strain of 2800 microstrain.

**Histomorphometric analysis of the non-loaded control ulnae**

Histomorphometric analysis of the non-loaded control ulnae demonstrated small but significant differences between the baseline adult skeletal phenotype of ER$^+/+$ and ER$^+/−$ mice. There were no significant differences between the baseline adult skeletal phenotype of ER$^−/−$ and ER$^+/+$/mice.

Non-loaded control ER$^+/−$ ulnae had a 12% greater cortical area and a 6% greater periosteal perimeter than non-loaded control ER$^+/+$ ulnae, but there were no significant differences in marrow cavity area or endosteal perimeter between genotypes (Table 1). Periosteal modelling activity was barely detectable in all non-loaded control ulnae, as expected for adult mice with a mature skeleton (Sheng et al. 1999) (Fig. 3). Likewise, endosteal bone turnover was consistent with skeletal maturity in all non-loaded control ulnae, but endosteal mineralising surface and bone formation rate were significantly lower in ER$^+/−$ ulnae compared with ER$^+/+$ ulnae ($P<0.050$) (Fig. 4).

The osteogenic adaptive response to mechanical loading is threefold lower in ER$^+/−$ mice compared with ER$^+/+$ mice

Short periods of mechanical loading to peak strains of 2800 microstrain on 3 alternate days each week for 2 weeks stimulated periosteal and endosteal bone formation in the ulnae of both adult female ER$^+/−$ and ER$^+/+$ mice. In ER$^+/+$ ulnae this resulted in an $8±0.8\%$ ($P<0.001$) increase in cortical area. However, in ER$^+/−$ ulnae the loading-induced increase in cortical area was threefold less ($P<0.001$) than in ER$^+/+$ ulnae resulting in only a $2.4±0.8\%$ ($P<0.001$) increase in cortical area (Fig. 5). In both ER$^+/+$ and ER$^+/−$ ulnae, 80% of the loading-induced increase in cortical area was due to periosteal expansion and the remainder was due to endosteal new bone formation (Table 2). Both loading-induced periosteal and endosteal bone formation rates were 60% lower in ER$^+/−$ ulnae compared with ER$^+/+$ ulnae ($P<0.001$) (Figs 3 and 4). At the periosteum this was due to a 40% lower loading-induced increase in periosteal mineralising surface in ER$^+/−$ ulnae compared with

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**Table 1** Ulna cortical areas and perimeters

<table>
<thead>
<tr>
<th></th>
<th>ER$^+/+$ (n=7)</th>
<th>ER$^+/−$ (n=8)</th>
<th>ER$^+/+$ (n=4)</th>
<th>ER$^+/−$ (n=4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical bone area (mm$^2$)</td>
<td>$0.206±0.005$</td>
<td>$0.231±0.007$</td>
<td>$0.181±0.006$</td>
<td>$0.180±0.007$</td>
</tr>
<tr>
<td>Marrow cavity area (mm$^2$)</td>
<td>$0.024±0.003$</td>
<td>$0.022±0.002$</td>
<td>$0.017±0.003$</td>
<td>$0.022±0.005$</td>
</tr>
<tr>
<td>Periosteal perimeter (mm)</td>
<td>$1.884±0.032$</td>
<td>$1.987±0.032$</td>
<td>$1.882±0.028$</td>
<td>$1.812±0.044$</td>
</tr>
<tr>
<td>Endosteal perimeter (mm)</td>
<td>$0.615±0.034$</td>
<td>$0.598±0.021$</td>
<td>$0.529±0.053$</td>
<td>$0.587±0.063$</td>
</tr>
</tbody>
</table>

Cortical areas and perimeters were measured 3·5 mm distal to the ulna midshaft in the non-loaded control ulnae. $P$ values represent comparisons between knockouts (ER$^+/−$ and ER$^+/−$) and their wild-type littermates (ER$^+/+$ and ER$^+/+$), n.s., $P>0.05$. 

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**Figure 3** Histomorphometric analysis of the periosteal osteogenic response to mechanical loading in ER$^+/+$ (a+/+), ER$^+/−$ (a+/−), ER$^+/+$ (β+/+), ER$^+/−$ (β+/−), ER$^+/+$ (β−/−), and ER$^+/−$ (β−/−) ulnae. Periosteal mineralising surface (MSP), periosteal mineral apposition rate (MARp), and pereiosteal bone formation rate (BFRp) in loaded (L) and control (C) ulnae. a, $P<0.001$; b, $P<0.010$; c, $P<0.050$ for comparisons between control and loaded ulnae of the same genotype. Values are means ± s.e.
stimulated periosteal (but not endosteal) bone formation in the ulnae of both adult female ERβ<sup>−/−</sup> and ERβ<sup>+/+</sup> mice. In ERβ<sup>−/−</sup> ulnae, this resulted in a 6 ± 1·0% (P=0·007) increase in cortical area. However, in ERβ<sup>−/−</sup> ulnae, the loading-induced increase in cortical area was twofold less (P=0·035) than in ERβ<sup>+/+</sup> ulnae resulting in only a 3·1 ± 0·7% (P=0·017) increase in cortical area (Fig. 5). This was associated with a 50% lower loading-induced increase in periosteal mineral apposition rate in ERβ<sup>−/−</sup> ulnae compared with ERβ<sup>+/+</sup> ulnae (P=0·049, Table 2).

There was no evidence of gross fractures, microfractures, bone resorption or intracortical remodelling in any of the loaded ulnae. The loading-induced osteogenic responses were therefore representative of physiological adaptation to an altered mechanical environment as demonstrated previously using the CD1 mouse (Lee et al. 2002).

The in vitro proliferative response to mechanical strain of osteoblast-like cells is absent in ERα<sup>−/−</sup> cells, but enhanced in ERβ<sup>−/−</sup> cells compared with wild-type cells

A 10-min period of mechanical strain resulted in a 61 ± 25% increase in cell number in osteoblast-like cells derived from ERα<sup>−/−</sup> mice (P=0·05) over the following 24 h. The same treatment resulted in a 125 ± 40% increase in cell number in osteoblast-like cells derived from ERβ<sup>−/−</sup> mice (P=0·02). Conversely, osteoblast-like cells derived from ERα<sup>−/−</sup> mice showed no such increase in proliferation in response to mechanical strain, but rather experienced a 24 ± 9% decrease in cell number (P=0·01). However transfection of osteoblast-like cells derived from ERα<sup>−/−</sup> mice with a functional wild-type ERα vector restored the proliferative response to mechanical strain, resulting in a mechanical strain-induced 48 ± 8% increase in cell number (P=0·02). This restoration was associated with a transfection efficiency of 20 ± 2%.

Discussion

In vivo, the ulna of female mice lacking fully functional ERα but possessing functional ERβ have a threefold lower osteogenic response to mechanical loading than their wild-type littermates. This finding in ERα<sup>−/−</sup> mice is consistent with the demonstration in vitro that ERα<sup>−/−</sup> osteoblast-like cells fail to increase their number in response to mechanical strain, but that this response can be restored by transfection with functional human ERα. These findings support the concept that ERα is required for at least those components of bone’s early adaptive response to mechanical loading, which involves increase in the number of osteoblasts and the formation of new bone.

![Figure 4](https://www.endocrinology.org)

Figure 4 Histomorphometric analysis of the endosteal osteogenic response to mechanical loading in ERα<sup>+/+</sup> (α+/+), ERα<sup>−/−</sup> (α−/−), ERβ<sup>+/+</sup> (β+/+) and ERβ<sup>−/−</sup> (β−/−) ulnae. Endosteal mineralising surface (MSe), endosteal mineral apposition rate (MARes) and endosteal bone formation rate (BFRes) in loaded (L) and control (C) ulnae. a, P<0·001; b, P<0·01; c, P<0·05 for comparisons between control and loaded ulnae of the same genotype. Values are means ± s.e.

![Figure 5](https://www.endocrinology.org)

Figure 5 The loading-induced percentage increase in cortical area in ERα<sup>+/+</sup> (α+/+), ERα<sup>−/−</sup> (α−/−), ERβ<sup>+/+</sup> (β+/+) and ERβ<sup>−/−</sup> (β−/−) ulnae. C, control ulnae; L, loaded ulnae. a, P<0·001; b, P<0·01 for comparisons between knockout and wild-type littermates. Values are means ± s.e.
The 55 kDa protein has not been detected in wild-type in vivo (Couse et al. 1998). It has been shown to be capable of estrogen-dependent ERE activation in vitro (Pendaries 2002). It has been isolated from human primary osteoblasts and has been isolated from human primary osteoblasts (Pendaries 2002). The exact function of this isoform contains all the regions of the classical full-length ERα protein in vivo (Couse et al. 1995, Pendaries et al. 2002). The 56 kDa ERα isoform contains all the regions of the classical full-length ERα protein apart from the A/B domain (Pendaries et al. 2002). It has been shown to be capable of oestrogen-dependent ERE activation in vitro and in vivo and has been isolated from human primary osteoblasts (Metzger et al. 1995, Denger et al. 2001, Pendaries et al. 2002, Shughrue et al. 2002). The exact function of this protein in normal physiology has yet to be determined. Nonetheless, its possible presence does not detract from the findings of this study since it was clearly unable to fully compensate for the absence of the full-length ERα protein in this model of bone adaptation.

If ERα is required for bone’s adaptive response to mechanical loading, then the simple absence of functional ERα should lead to a disuse bone phenotype. In this study, the ulnae of adult female ERα−/− mice were observed to be straighter than their wild-type counterparts. This is significant because mechanical loading is required for the development of a normal bone curvature (Chalmers & Ray 1962, Lanyon 1980, Rodriguez et al. 1988). The absence of a normal ulnar curvature in ERα−/− mice is therefore consistent with an abnormal response to natural mechanical loading during growth. However, in other respects the structure of the ERα−/− ulnae does not suggest a disuse phenotype: these bones are shorter in length, with a greater cortical thickness and similar structural stiffness to wild-type ulnae (Vidal et al. 1999, 2000, Lindberg et al. 2001).

The absence of an uncomplicated disuse phenotype and the presence of a small in vivo osteogenic response to mechanical loading in ERα−/− mice may be due to a number of influences including high circulating oestrogen and testosterone concentrations (Couse & Korach 1999, Kousteni et al. 2001, Lindberg et al. 2002, Sims et al. 2002), low insulin-like growth factor concentrations (Lindberg et al. 2001) and possible compensatory effects of unopposed ERβ (Sims et al. 2002).

The in vivo and in vitro data from the ERβ−/− mice appear inconsistent with one another. In vivo, the ulna of female mice lacking fully functional ERβ but possessing functional ERα have a twofold lower osteogenic response to mechanical loading than their wild-type littermates. Conversely, in vitro ERβ−/− osteoblast-like cells show a greater increase in cell number in response to mechanical strain compared with wild-type cells. The data presented in this study do not permit us to explain this apparent discrepancy.

The in vitro data suggested that ERβ decreases while ERα enhances the strain-related increase in cell number in response to mechanical strain. This suggested that ERβ

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**Table 2** The effect of mechanical loading on cortical bone formation

<table>
<thead>
<tr>
<th>Loading-induced changes</th>
<th>ERα+/+ (n=7)</th>
<th>ERα−/− (n=8)</th>
<th>ERβ+/+ (n=4)</th>
<th>ERβ−/− (n=4)</th>
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<tbody>
<tr>
<td>Periosteal</td>
<td></td>
<td></td>
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<tr>
<td>New bone area (% of cortical bone area)</td>
<td>6.4 ± 0.7</td>
<td>2.0 ± 0.4</td>
<td>6.0 ± 1.0</td>
<td>3.0 ± 0.7</td>
</tr>
<tr>
<td>Mineralising surface (%)</td>
<td>61.5 ± 3.5</td>
<td>38.3 ± 3.7</td>
<td>31.3 ± 3.9</td>
<td>29.7 ± 5.0</td>
</tr>
<tr>
<td>Mineral apposition rate (µm/day)</td>
<td>1.34 ± 0.14</td>
<td>0.97 ± 0.17</td>
<td>1.40 ± 0.18</td>
<td>0.72 ± 0.26</td>
</tr>
<tr>
<td>Bone formation rate (µm²/µm per day)</td>
<td>0.90 ± 0.09</td>
<td>0.37 ± 0.06</td>
<td>0.49 ± 0.11</td>
<td>0.30 ± 0.08</td>
</tr>
</tbody>
</table>

All parameters represent the loading-induced effect on bone formation 3-5 mm distal to the ulna midshaft and were calculated by subtracting the value for each control ulna from that of its paired loaded ulna. P values represent comparisons between knockouts (ERα−/− and ERβ−/−) and their wild-type littermates (ERα+/+ and ERβ+/+). n.s., P>0.05.
either opposes the effects of ERα or suppresses the effects of ERα with respect to the ERα-mediated strain-related increase in osteoblast cell number. Such antagonism between ERα and ERβ has been described in previous in vitro studies. One such study using a mouse osteoblast cell line found that an increase in ERβ expression resulted in a suppression of oestrogen-dependent ERα-mediated activation of the API transcriptional factor, c-fos (Ishibashi et al. 2001). Another study found that ERα and ERβ have opposite effects on API transcription sites in breast cancer and uterine cell lines (Paech et al. 1997). However, the in vivo data suggested that the presence of ERβ as well as ERα enhances bone’s osteogenic response to mechanical loading.

In our present study it may be that ERβ acts differently in the absence of ERα than in its presence (Sims et al. 2002). For example, their dual presence may result in the formation of heterodimers, which may have distinct actions compared with those of homodimers (Petterson et al. 1997). However, this would not explain the difference in response between the in vitro and in vivo experiments presented, since the cells in the in vitro study were derived from the same population of mice as that used in the in vivo study. The ERβ−/− mouse used in this study is believed to be a true knockout and has not been shown to contain any mutant or non-mutant ERβ gene transcripts (Krege et al. 1998). Therefore the presence of such transcripts should not be involved in this response. However, secondary consequences of the absence of functional ERβ protein in other tissues may affect the in vivo responses of bone to mechanical loading, but may not be evident in pure cultures of osteoblast-like cells. In addition, the formation of new bone during a 2-week period of loading in vivo is likely to be a more complex process compared with the increase in number of osteoblast-like cells in the 24 h after strain in vitro.

We can conclude from the results of this study that functional ERα number is an important determinant of the capacity of bone to adapt to mechanical loading in vivo. Changes in functional ERα number may help to explain the aetiology of the structurally inappropriate bone loss, which occurs at and after the menopause in women and is associated with low available oestrogen levels in men. Our data are somewhat equivocal on the role of ERβ. The level of strain-related change in cell number in vitro suggested that ERβ opposes the effect of ERα. However, there was no evidence of any such inhibition being removed in vivo where the constitutive absence of either ERα or ERβ is associated with a smaller osteogenic response to loading than if both receptors were present.

Acknowledgements

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