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"This research was originally published in THE JOURNAL OF BIOLOGICAL CHEMISTRY. Author (Gabriel L. Galea, Lee B. Meakin, Toshihiro Sugiyama, Noureddine Zebda, Andrew Sunters, Hanna Taipaleenmaki, Gary S. Stein, Andre J. van Wijnen, Lance E. Lanyon and Joanna S. Price). Title. Estrogen Receptor Mediates Proliferation of Osteoblastic Cells Stimulated by Estrogen and Mechanical Strain, but Their Acute Down-regulation of the Wnt Antagonist Sost Is Mediated by Estrogen Receptor β Journal Name (THE JOURNAL OF BIOLOGICAL CHEMISTRY). Year. 2013 Vol:288, 9035-9048. © the American Society for Biochemistry and Molecular Biology"

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Estrogen Receptor α Mediates Proliferation of Osteoblastic Cells Stimulated by Estrogen and Mechanical Strain, but Their Acute Down-regulation of the Wnt Antagonist Sost Is Mediated by Estrogen Receptor β

Received for publication, August 14, 2012, and in revised form, January 13, 2013 Published, JBC Papers in Press, January 29, 2013, DOI 10.1074/jbc.M112.405456

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Mechanical strain and estrogens both stimulate osteoblast proliferation through estrogen receptor (ER)-mediated effects, and both down-regulate the Wnt antagonist Sost/sclerostin. Here, we investigate the differential effects of ERs and -β in these processes in mouse long bone-derived osteoblastic cells and human Saos-2 cells. Recruitment to the cell cycle following strain or ERβ-estradiol occurs within 30 min, as determined by Ki-67 staining, and is prevented by the ERα antagonist 1,3-bis(4-hydroxyphenyl)-4-methyl-5-[4-(2-piperidinylethoxy)phenol]-1H-pyrazole dihydrochloride. ERβ inhibition with 4-[2-phenyl-5,7-bis(trifluoromethyl)pyrazolo[1,5-β]pyrimidin-3-yl] phenol (PTHPP) increases basal proliferation similarly to strain or estradiol. Both strain and estradiol down-regulate Sost expression, as does in vitro inhibition or in vivo deletion of ERα. The ERβ agonist 2,3-bis(4-hydroxyphenyl)-propionitrile and ERB041 also down-regulated Sost expression in vitro, whereas the ERα agonist 4-A4'4"-[4-propyl-(1H)-pyrazol-1,3,5-triyl]tris-phenol or the ERβ antagonist PTHPP has no effect. Tamoxifen, a nongenomic ER antagonist, down-regulates Sost expression in vitro and in bones in vivo. Inhibition of both ERs with fulvestrant or selective antagonism of ERβ, but not ERα, prevents Sost down-regulation by strain or estradiol. Sost down-regulation by strain or ERβ activation is prevented by MEK/ERK blockade. Exogenous sclerostin has no effect on estradiol-induced proliferation but prevents that following strain. Thus, in osteoblastic cells the acute proliferative effects of both estradiol and strain are ERα-mediated. Basal Sost down-regulation follows decreased activity of ERs and increased activity of ERβ. Sost down-regulation by strain or increased estrogens is mediated by ERβ, not ERα. ER-targeting therapy may facilitate structurally appropriate bone formation by enhancing the distinct ligand-independent, strain-related contributions to proliferation of both ERα and ERβ.

Bone architecture is adjusted to be functionally appropriate for load-bearing through processes in which the strains engendered by loading initiate cascades of responses in resident bone cells that in turn influence the activity of cells responsible for bone formation and resorption. The activity of these cells is also influenced by estrogens. Loss of estrogens following menopause is associated with the development of osteoporosis, a widespread condition of skeletal inadequacy that has been hypothesized to reflect a failure of the homeostatic mechanisms by which bone adapts to its functional load-bearing environment, commonly referred to as the mechanostat (1). The cellular mechanisms of the mechanostat are locally influenced by the estrogen receptors ERα7 and ERβ acting ligand-indepen-

* This work was supported by the Wellcome Trust. This work was also supported in part by National Institutes of Health Grant R01AR049069 (to A. v. W.).
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7 The abbreviations used are: ER, estrogen receptor; MPP, 1,3-bis(4-hydroxyphenyl)-4-methyl-5-[4-(2-piperidinylethoxy)phenol]-1H-pyrazole dihydrochloride; PTHPP, 4-[2-phenyl-5,7-bis(trifluoromethyl)pyrazol[1,5-β]pyrimidin-3-yl] phenol; PPT, 4,4'4"-[4-propyl-(1H)-pyrazol-1,3,5-triyl]tris-phenol; DPN, 2,3-bis(4-hydroxyphenyl)-propionitrile; E2, 17β-estradiol; β2-MG, β2-microglobulin; LRP, low density lipoprotein receptor-related protein; CLBObs, cortical long bone osteoblastic cells; rSOST, recombinant human sclerostin.
ER-mediated Regulation of Osteoblast Proliferation and Sost

dently (2–4). This implies that compounds that target the ERs should be able to enhance the sensitivity of the mechanostat and so provide effective, mechanically appropriate, treatment for osteoporosis. The action of the selective estrogen receptor modulator tamoxifen illustrates this; it reduces fracture risk in human patients (5), and in mice it synergistically enhances the effects of loading on bone gain (6).

Loading-induced increases in bone formation involve osteoblastic cell proliferation (7, 8) and down-regulation of Sost/sclerostin (9–11), a glycoprotein secreted primarily by osteocytes. Although a direct effect of sclerostin on strain-induced osteoblast proliferation has never been shown, sclerostin is presumed to exert its potent anti-osteogenic effect through inhibition of the Wnt pathway in neighboring osteoblasts by antagonizing Wnts binding to their low density lipoprotein receptor-related (LRP)-5 and -6 co-receptors (12). Neutralizing antibodies against sclerostin appear to have substantial and sustained osteogenic effects in humans and are now in advanced stages of clinical trials for the treatment of osteoporosis (13). A reduction in sclerostin production is also achieved by treatment with estrogens (14, 15), which also increase osteoblast proliferation (16). However, the mechanisms by which estrogens and loading converge to achieve similar outcomes remain largely unknown.

To investigate the potential mechanisms involved, we have established a model in which human female osteoblastic Saos-2 cells are subjected to mechanical strain by four-point bending of their substrate in vitro (17). These cells have been reported by ourselves and others to express Sost and sclerostin protein (17, 18). In this model, exposure to strain causes down-regulation of Sost expression over a time course consistent with that observed following loading of rodent bones in vivo (19, 20), through mechanisms requiring extracellular signal-regulated kinase (ERK) signaling (17). ERK is activated in bones subjected to loading in vivo (21) and in osteoblastic cells subjected to strain in vitro (22–24). This involves ERα and ERβ acting ligand-independently (24).

Other effects of strain on ligand-independent ER activity include activation of genomic estrogen-response elements (25), ERα-mediated nongenomic activation of Wnt/β-catenin (26, 27), and AKT (27) signaling. Osteoblastic cells from wild type (WT) mice proliferate in response to strain in the absence of estrogenic ligands, whereas similarly derived cells from Eraf⁻/⁻ mice do not (28, 29). Consistent with this observation, cells overexpressing ERα are more proliferative in response to strain than cells only expressing endogenous ERα (25). The role of ERα in bones’ local adaptive responses to loading has also been demonstrated in vivo in a number of studies, each of which show a diminished response to loading in female mice when ERα activity is reduced (2, 30–32).

In contrast, the role of ERβ in regulating bones’ adaptation to loading remains controversial. The first in vivo study of ER’s involvement in loading-related adaptation in bone reported a lower osteogenic response to axial loading of the ulna in female ERβ⁻/⁻ mice compared with WT littermates (32). However, later studies using knock-outs regarded as being more “complete,” showed enhanced responses to axial loading (2, 33).

ERβ has been suggested to be the dominant regulator of estrogen receptor signaling, in part due to its ability to form heterodimers with ERα (34). However, the outcomes of ERβ signaling depend on the cellular context in which it operates; whereas ERβ largely inhibits transcriptomic changes caused by estrogen treatment when ERα is present, it promotes expression of a subset of genes when ERα is deleted (35). In osteoblastic cells, ERα activation increases ERβ expression (36) and has been shown to directly bind the ERβ promoter in other cell types (37). In contrast, ERβ can repress ERα expression (38), and mice lacking ERβ have increased ERα in their bones (39). The outcomes of ERα and ERβ signaling are therefore closely linked in what has been described as a “ying yang” relationship determined by a subtle balance between them (35, 40). Compensation for the absence of ERα activity by ERβ, and vice versa, is demonstrated by the mild effect of loss of either receptor alone compared with deletion of both ERs in bone and other tissues (41–43).

Having originally reported the involvement of the ERs in bones’ adaptive response to loading (30, 32), and more recently ERK’s involvement in Sost down-regulation by mechanical strain in vitro (17), we hypothesized that these commonalities between estrogen and strain signaling meant that ERα and ERβ could both contribute to the ligand-independent mechanisms by which loading down-regulates Sost expression and in turn regulates proliferation of osteoblasts in response to strain. The studies reported here used subtype-selective receptor agonists and antagonists against the ERs to establish the contributions of ERα and ERβ to the regulation of Sost and proliferation by both estradiol and strain in osteoblasts.

MATERIALS AND METHODS

Reagents and Cell Culture—17β-Estradiol (E2) was from Sigma and dissolved in molecular grade ethanol (EOH). Selective estrogen receptor modulators used were the ERα-selective agonist 4,4’-4-propyl-(1H)-pyrazol-1,3,5-triy[tris-phenol (PPT, 0.1 μM) (44)] or antagonist 1,3-bis(4-hydroxyphenyl)-4-methyl-5-[4-(2-piperidinylethoxy)phenol]-1H-pyrazole dihydrochloride (MPP, 0.1 μM) (45), the ERβ agonist 2,3-bis(4-hydroxyphenyl)-propionitrile (DPN, 0.1 μM) (46) or antagonist 4-[2-phenyl-5,7-bis(trifluoromethyl)pyrazolo[1,5-β][pyrimidin-3-yl]phenol (PTHPP, 0.1 μM) (47), the context-dependent agonist/antagonist tamoxifen (0.1 μM), and the nonselective ERα/ERβ antagonist fulvestrant (0.1 μM, ICI 182780). The mitogen-activated protein kinase (MAPK)/ERK inhibitor PD98059 was used at a final concentration of 10 μM. All were from Tocris Bioscience (Bristol, UK). Fulvestrant was dissolved in EOH, and all other compounds were dissolved in dimethyl sulfoxide (DMSO). Cells were pretreated with the selective antagonists MPP, PTHPP, and PD98059 30 min before strain or E2 treatment, whereas fulvestrant was added 16 h before as described previously (27).

Wnt3a and recombinant human sclerostin were from R&D Systems (Abingdon, UK). Sclerostin was dissolved in phosphate-buffered saline (PBS) and added 1 h before strain or E2 treatment. The diluents never reached concentrations greater than 0.1% in the culture medium.
Cell Culture—All cells were maintained in phenol red-free DMEM containing 10% heat-inactivated FCS (PAA, Somerset, UK), 2 mM l-glutamine, 100 IU/ml penicillin, and 100 IU/ml streptomycin (Invitrogen) (complete medium) in a 37 °C incubator at 5% CO₂, 95% humidity as described previously (17).

Saos-2 cells were a kind gift of Dr. S. Allen (Royal Veterinary College, London, UK). Mouse cortical long bone osteoblastic cells (cLBs) were derived from explants of young adult female C57BL/6 mice as described previously (26, 28, 30). In brief, cLBs were explanted by harvesting the diaphyses of long bones under sterile conditions in PBS containing 1× solution of antibiotic/antimycotic (PAA, Somerset, UK). All surface tissues were removed, and marrow contamination was eliminated by repeated flushing with PBS. The bones were subsequently chopped into fragments and cultured in complete medium until cell outgrowth was observed. Like similarly derived cells from rat bone (48), mouse cLBs express markers of osteoblastic differentiation (Runx2, collagen 1 A1, and osteocalcin) (4) and form mineralized nodules (supplemental Fig. 1 supplemental Methods), however, they do not express Sost under the conditions required for in vitro strain experiments (4).

Cell Culture for Proliferation Studies—Cells were seeded at an initial density of 5000 cells/cm² (Saos-2) or 10,000 cells/cm² (cLBs) on sterile custom-made plastic strips and allowed to adhere and grow for 24 h. Cells were then serum-depleted overnight in 2% charcoal/dextran-stripped serum to reduce the presence of steroids and their basal proliferation, before being subjected to strain or other treatments the next morning (i.e. cells were cultured for 2 full days before treatment). Cells were cultured in the same medium they were strained in until they were harvested at the appropriate time point for quantitative RT-PCR studies.

Cell Culture for Studies of Sost Regulation—Markers of osteoblastic differentiation, including Sost, increase in Saos-2 cells with time in culture (18, 49). Therefore, for studies of Sost regulation, we used over-confluent cultures that express Sost at a significantly higher level than subconfluent, proliferative cultures (supplemental Fig. 2). Sclerostin protein is readily detectable in confluent Saos-2 cells by Western blotting, and sclerostin levels in the cell culture supernatant are comparable with previously reported levels in human serum (supplemental Fig. 3).

Using a previously described protocol (17), cells were seeded at an initial density of 40,000 cells/cm², allowed to grow for 72 h before being serum-depleted in 2% charcoal/dextran serum overnight, and then subjected to strain or other treatment(s) (4 full days in culture before treatment). As was the case for proliferation studies, cells were always cultured in the same medium they were strained in until they were harvested at the appropriate time point for quantitative RT-PCR studies.

Straining Cells in Vitro—Strain was applied to the plastic strips on which cells were adherent using a well established protocol (17, 26, 27). This involves a brief period (~17 min) of 600 cycles of four-point bending engendering a peak strain on the surface of the strip of 3400 micro-strain (unless otherwise stated). A testing machine was used (Zwick Testing Machines Ltd., Leominster, UK) to achieve peak strain rates on and off of ~24,000 micro-strain/s, dwell times on and off of 0.7 s, and a frequency of 0.6 Hz.

Ki-67 Staining to Assess Proliferation—Anti-Ki-67 antibodies were from Santa Cruz Biotechnology (mouse anti-human, sc-23900; goat anti-mouse, sc-7846). Ki-67 staining in human Saos-2 cells was performed essentially as described previously (50). However, for anti-mouse Ki-67 staining, the antigen was retrieved by heating in PBS with 0.5% v/v Triton™ X-100 (Sigma), blocked in 1% BSA solution for 30 min, 10% rabbit serum for 1 h and then 10% horse serum for 1 h at room temperature. In both cases the primary antibody was used at a 1:100 dilution overnight at 4 °C. NorthernLight™, conjugated donkey secondary antibodies were from R&D Systems (Abingdon, UK) and used at a concentration of 1:100. Slides were mounted in Fluoroshield™ containing DAPI counter-stain (Sigma) and imaged on a Leica DMRB microscope. All slides in each experiment were imaged under identical conditions.

To assess proliferation by Ki-67 staining, the percentage of cells stained positive was analyzed under ×20 magnification in four randomly chosen fields per slide. In each case, representative proliferation results are shown as the proportion of all cells in each field stained positive for Ki-67.

The nuclear distribution of Ki-67 antigen is cell cycle stage-specific, as documented previously (50–53). Cell cycle stages were analyzed under ×40 magnification using the pattern of Ki-67 nuclear distribution in individual cells. In each case, the proportion of actively replicating (Ki-67 positive) cells in G₁, G₂/S, S, G₂, or M phase are shown. For this, 213 ± 12 Ki-67-positive nuclei were analyzed in 10 randomly chosen high power fields per slide. Key results were independently confirmed by the author G. L. Galea and L. B. Meakin.

Quantitative RT-PCR—RNeasy™ Plus mini kits (Qiagen, Sussex, UK) were used to eliminate DNA and extract RNA. First strand cDNA synthesis was performed using SuperScriptII™ (Invitrogen). Product copy numbers quantified against standard curves were normalized relative to β₂-microglobulin (β₂-MG). PCR primers were designed using Primer3 Plus (54). Human Sost and β₂-MG primers were as described previously (17). ERβ primers were also described previously (55). Other primers were as follows: mouse Sost sense TGCCGGAGGCTGCACATACAC and antisense CACCACTTACGCGCCC-GAT; mouse β₂-MG sense ATGGCTCGCTCGGTGACCCT and antisense TTCTCCGGTGGGTGCGTGA; mouse OPG sense TGTTGTGTCCCTTGCCCTGACCA and antisense ACACGCTTGGTGGTGCGTGA; mouse POG sense TGTGTTGTCCTTTGCGCCCATC and antisense GCAC-TCAGACCTCAGGATC.

Quantitative RT-PCR data are presented as pooled results from two to four independent experiments with n = 4–6 in each experiment. In each case, the control group was set at 100%.

In Vivo Studies—Adult female mice (7 months) were bred from a previously described ERα−/− colony (26, 42). Mice were housed up to five per cage and provided standard mouse chow and water ad libitum throughout the study. For RNA extraction, bones were dissected, the epiphyses were removed, and the marrow was flushed with sterile PBS. Bones were pulverized in QIAzol™ using a TissueLyser LT™
RNA was extracted, and genomic DNA was eliminated using RNeasy™ Plus Universal kits (Qiagen, Sussex, UK). To evaluate the effect of tamoxifen (2 mg/kg/day), mice were treated using a regimen that we have previously shown synergistically enhanced loading-related bone gain (6). At 16 weeks of age (day 1), virgin female C57BL/6 mice were sham-ovariectomized (Sham, n = 110058) or ovariectomized (n = 1100516). Ten days after the operation (day 11), the ovariectomized mice were randomly subdivided into two groups (n = 8) and received either vehicle (peanut oil, 5 ml/kg; Sigma) or tamoxifen citrate (Tocris Cookson Inc., Ellisville, MO) by s.c. injection on days 11, 13, 15, 18, and 21 and were then sacrificed on day 25. All procedures were in accordance with the Institutional Animal Care and Home Office, UK, guidelines and approved by the ethics committee of the University of Bristol or of the Royal Veterinary College, London, UK.

**Statistical Analysis**—Statistical analysis was carried out on SPSS version 17 for Windows. Comparisons of two groups were by independent sample t tests, and more than two groups were compared by analysis of variance with Bonferroni or Games Howell post hoc adjustments. Data are presented as the mean ± S.E. p < 0.05 was considered significant.

**RESULTS**

Both Estrogens and Strain Rapidly Stimulate Osteoblastic Proliferation—Exposure to 1 μM E2, or a short period of mechanical strain, increased the proportion of cLBObs staining...
positive for the proliferating cell marker Ki-67 24 h later (Fig. 1A). No significant differences were detected between the proportions of Ki-67-positive cells in different stages of the cell cycle following either treatment (Fig. 1B). A similar proliferative response to both E2 and strain was observed in Saos-2 cells (Fig. 1D), with no change observed in the proportion of replicating cells in different stages of the cell cycle 24 h following treatment (Fig. 1E). This indicates that both estradiol and strain recruit otherwise Ki-67-negative quiescent cells to the cell cycle. Pretreatment with E2 for 30 min before exposure to strain did not significantly change the proportion of cells staining positive in these asynchronous cultures relative to treatment with strain or E2 alone (Fig. 1F). Thus, strain and estradiol similarly recruit a cohort of Ki-67-negative cLBObs or Saos-2 cells to the cell cycle without altering their progression through it.

Because it is not currently known when osteoblast-like cells are first stimulated to proliferate following a brief episode of strain, a time course of proliferation was undertaken. This showed a significant increase in the proportion of Saos-2 cells staining positive for Ki-67 within 30 min following strain (Fig. 1G). A similarly rapid response was observed in cLBObs (Fig. 1H). E2 also initiated Saos-2 proliferation within 30 min (Fig. 1I). This increase in Ki-67-positive cells was associated with a transient increase in the proportion of cells in the G1/S phase of the cell cycle (Fig. 1J). Taken together, these data show that strain and estradiol both recruit a cohort of osteoblast-like cells to the cell cycle within 30 min of stimulation.

Strain and E2-induced Proliferation Requires ERα—Osteoblast proliferation following strain (28) or estradiol treatment (56, 57) has previously been reported to involve ERα. Blockade of ERα with methyl-piperidino-pyrazole (MPP) prevented the increase in Ki-67-positive cells 8 h following either strain (Fig. 2A) or 1 μM E2 (Fig. 2B) and was associated with a significant reduction in basal proliferation after 24 h (49 ± 4% decrease, p < 0.01 versus vehicle-treated controls). In contrast, blockade of ERβ with PTHPP was associated with a significant increase in basal proliferation with no significant further increase observed following strain or E2 treatment (Fig. 2, C and D). The increase in basal proliferation following ERβ blockade was prevented by pretreatment with the ERα antagonist (Fig. 2E). Thus, strain and estradiol involve ERα to stimulate proliferation of osteoblast-like cells, although basal proliferation of these cells is inhibited by ERβ.

Proliferation Following Strain and Wnt3a, but not E2, Is Inhibited by Exogenous Sclerostin—Osteocyte-derived sclerostin is presumed to exert its potent anti-osteogetic effect through inhibition of the Wnt pathway in neighboring osteoblasts (12). Consistent with this, pretreatment with 10 ng/ml recombinant human sclerostin (rhSOST), while not significantly changing the proportion of Saos-2 cells stained positive for Ki-67, prevented the increase in proliferation observed following treatment with 10 ng/ml Wnt3a (Fig. 3A). Similarly, pretreatment with rhSOST prevented the increase in Ki-67-positive cells 8 h following strain (Fig. 3B). However, rhSOST pretreatment did not prevent the increase in Ki-67-positive cells 8 h following treatment with 1 μM E2 (Fig. 3C). Thus, although both strain and estradiol stimulate rapid proliferation in osteoblastic cells, they do so by different mechanisms. Only proliferation caused by strain is prevented by the inhibitor of Wnt signaling, sclerostin.

Down-regulation of Sost Expression by E2, Activation of ERβ, and Inhibition of ERα—Both strain and estradiol trigger ER-dependent regulation of transcription in osteoblastic cells (25) and both down-regulate Sost. E2, at doses equal to or greater than 10 nM, down-regulated Sost expression within 8 h (Fig. 4A). Selective activation of ERα with 0.1 μM propyl pyrazole triol (PPT) had no effect on Sost expression after 8 h (Fig. 4B), whereas activation of ERβ with the agonists diarylpropionitrile...
Having established that ER signaling regulates basal Sost expression, we next investigated whether this is relevant to the regulation of Sost by strain. As reported previously (17), Sost expression was down-regulated in Saos-2 cells within 8 h following exposure to strains equal to or greater than 2000 micro-strain (Fig. 5A). Nonselective blockade of both ERα and ERβ with fulvestrant had no effect on basal expression of Sost, but prevented its down-regulation 8 h following strain (Fig. 5B) or estradiol (supplemental Fig. 5). Blockade of ERα with the selective antagonist MPP did not prevent significant Sost down-regulation by strain (Fig. 5C) or E2 (Fig. 5D), irrespective of its reduction in basal levels. In contrast, selective blockade of ERβ with PTHPP prevented Sost down-regulation following exposure to strain (Fig. 5E) or E2 (Fig. 5F).

ERK Mediates Sost Down-regulation by Strain or E2—Both ERα and ERβ mediate rapid activation of ERK signaling in osteoblastic cells subjected to strain (24). In Saos-2 cells ERK activation is required for Sost down-regulation by strain (17). Treatment of Saos-2 cells for 24 h with 10 μM of the ERK inhibitor PD98059 did not significantly change cell number or viability (supplemental Fig. 6, a and b), but significantly reduced ERK phosphorylation (supplemental Fig. 6, c and d). Inhibition of ERK activation also prevented Sost down-regulation by strain.
ER-mediated Regulation of Osteoblast Proliferation and Sost

The ability of a bone to withstand loading without fracture critically depends upon the ongoing (re)modeling within its constituent tissue. The amount of bone formed as a result of the various stimuli responsible for (re)modeling is dependent upon the strength of the stimuli themselves and the responsiveness of the cells they influence. Two major regulators of bone (re)modeling are mechanical strain and estrogens. The experiments reported here demonstrate that exposure to either estradiol or a short period of dynamic strain stimulate proliferation, as indicated by an increased proportion of Ki-67-positive cells, in osteoblast-like cells derived from the weight-bearing cortical bones of female mice, and in the female human osteoblastic Saos-2 cell line. Increases in both estradiol and strain initiate this effect within 30 min, far earlier than we had assumed. Other early strain-related events in osteoblastic cells include; increased ligand-independent ERα phosphorylation within 5 min (23), ERK activation, also within 5 min (23), and an increase in β-catenin translocation to the nucleus within 30 min (26).

One potential pathway by which both strain and estrogen could exert their effects on osteoblast proliferation, and thus bone formation, is via the Wnt pathway. There are now numerous in vivo studies demonstrating a role for the Wnt pathway in mediating bones’ response to mechanical loading (63–65). Deletion of the LRP-5 co-receptor reduces the osteogenic effects of loading (63). Conversely, mice harboring mutations in LRP-5, which make it insensitive to the antagonistic effects of sclerostin (66), show enhanced osteogenic responses to mechanical loading (64, 65). We have previously shown that Wnt activation in osteoblastic cells subjected to strain is facilitated by ERα and that activation of β-catenin and its translocation to the nucleus in response to mechanical strain is abrogated in osteoblastic cells lacking ERα (26, 27).

The finding that exogenous sclerostin prevents proliferation of osteoblastic cells stimulated by strain suggests that, in the natural situation, sclerostin down-regulation following mechanical loading relieves its inhibition of proliferation stimulated by Wnt proteins present in the local microenvironment. The parallel finding that exogenous sclerostin has no effect on estrogen-related proliferation suggests that the pathway from estrogen to osteoblast proliferation is by a different route in which Sost down-regulation is either not a rate-limiting step or is not involved at all. Possible Sost-independent mechanisms by which estrogens have their effect include ER-mediated effects on AP-1 transcription (67) or the physical association of ERα with TCF-4 independently of β-catenin (68). We have no evidence from this study to suggest a specific role for Sost down-regulation in the multiple responses of bone cells to estrogens, except that lower levels of extracellular sclerostin would be expected to increase the sensitivity to Wnt of any cells sharing this extracellular environment, given that sclerostin also inhibits proliferation following Wnt3a. The observation that down-regulation of Sost can be associated with different biological outcomes is not novel; both intermittent and continuous PTH down-regulate Sost in vivo, however one is anabolic and the other is catabolic (69, 70).

DISCUSSION

FIGURE 5. Blockade of ERβ prevents Sost down-regulation by strain or estradiol. Saos-2 cells were subjected to the indicated peak strain magnitudes and harvested 8 h later (A). Cells were subjected to strain with or without 16 h of pretreatment with 1 μM ICI 182,780 (ICI) (fulvestrant) and harvested 8 h later (B). Cells were subjected to strain with the indicated concentrations of MPP (C) or treated with E2 with or without pretreatment with 0.1 μM MPP and harvested 24 h later (D). Cells were subjected to strain with the indicated concentrations of PTHPP (E) or treated with E2 with or without pretreatment with 0.1 μM PTHPP (F). Sost levels were quantified relative to β2-MG. Bars represent the mean ± S.E. ns means not significant; *, p < 0.05; **, p < 0.01 versus the relevant control; #, p < 0.05; ##, p < 0.01 versus strained or E2-treated vehicle controls.

(Fig. 6A), E2 (Fig. 6B), and the ERβ agonist DPN (which has previously been reported to activate the nongenomic ERK pathway (Fig. 6C) (58)).

Tamoxifen used clinically as an ERα inhibitor in the treatment of breast cancer, also acts as a nongenomic ERβ agonist (59, 60), and in Saos 2 cells it also down-regulated Sost expression through a mechanism dependent on ERK activation (Fig. 6D).

Tamoxifen Down-regulates Sost in Vivo—We next sought to substantiate the in vitro finding that tamoxifen down-regulates Sost, using an in vivo approach in mice in which we had previously reported that tamoxifen synergistically enhances bones’ adaptive response to mechanical loading (6). Down-regulation of Sost by tamoxifen was confirmed in bones in vivo (Fig. 7A) and was associated with increased expression of cyclin D1 (CCND1, Fig. 7B) and osteoprotegerin (OPG, Fig. 7C), known Wnt target genes (61, 62).
The finding that the increase in proliferation stimulated by strain and estradiol is mediated by ERα/H9251, is consistent with a previous report that nonselective ER blockade with fulvestrant (ICI 182780) prevents proliferation in rat osteoblasts in response to the same stimuli (71). In contrast, selective inhibition of ERα/H9252 increases proliferation, an increase that can be prevented by selectively blocking ERα. Thus, ERα and ERβ have opposite effects on basal osteoblastic cell proliferation, a situation that is well established in various other cell models (72–75).

The two ER subtypes also have different effects on Sost/sclerostin expression. Sclerostin is naturally produced primarily by osteocytes, and ideally, we would have wished to investigate its regulation in primary osteocyte cultures, but obtaining cultures of sufficient purity for large scale in vitro loading experiments is not currently possible. Unfortunately, the well established MLO-Y4 and MLO-Y5 osteocyte-like cell lines have been found to express very low to undetectable levels of Sost (76, 77). The recently reported IDG-SW3 cell line that replicates osteoblast to osteocyte differentiation does synthesize Sost, however, this requires at least 14 days of treatment with osteogenic differentiation medium that promotes mineralization (77) and mineralized cultures cannot be used for experiments involving strain. We therefore used the human osteoblastic Saos-2 cell line for our experiments because these cells secrete sclerostin when highly confluent (16, 17), and in this model exposure to strain causes down-regulation of Sost expression over a time course consistent with that observed in vivo (18).

The finding that the increase in proliferation stimulated by strain and estradiol is mediated by ERα, is consistent with a previous report that nonselective ER blockade with fulvestrant (ICI 182780) prevents proliferation in rat osteoblasts in response to the same stimuli (71). In contrast, selective inhibition of ERβ increases proliferation, an increase that can be prevented by selectively blocking ERα. Thus, ERα and ERβ have opposite effects on basal osteoblastic cell proliferation, a situation that is well established in various other cell models (72–75).

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In cultures of these cells, both estradiol and strain down-regulate Sost/sclerostin expression through either ERα and/or ERβ as evidenced by its blockade with fulvestrant. However, whereas the ERα agonist PPT has no effect on basal Sost levels, the ERα antagonist MPP causes down-regulation. Thus, although increased ERα activity does not increase basal levels of Sost, decreased ERα activity causes Sost down-regulation. Consistent with this, loss of ERα also results in lower Sost levels in bones from female ERα−/− mice compared with WT controls.
ER-mediated Regulation of Osteoblast Proliferation and Sost

In contrast, the ERβ agonist DPN and the partial ERβ agonist tamoxifen both cause down-regulation of Sost, whereas the ERβ antagonist PTHPP has no effect. This shows that although increased ERβ activity down-regulates basal Sost, the decreased ERβ activity does not increase it. Selective antagonism of ERβ rather than ERα also prevents the down-regulation of Sost by acute increases in either estradiol or strain.

The differences we report on the effects of ERα and ERβ on Sost expression were unexpected; we had anticipated that ERα would mediate strain-related down-regulation of Sost because the absence of ERα in female (but not male) mice has been repeatedly associated with a lower adaptive response to applied loading than in their WT background (30–32). This has been assumed to be the result of ERα’s ligand-independent involvement in a number of the early stages of bones’ osteogenic/anti-resorptive response to loading. ERα’s strain-related functions include its association with ERK in the signalosome (24), with the IGF receptor’s response to IGF (27), and its role in the translocation of β-catenin from cytoplasm to nucleus (26). Instead, these findings notwithstanding, our present data suggest that, in human female osteoblastic cells at least, the effects of acute changes in strain or estradiol are mediated primarily by ERβ. This inference is based on a number of elements in our present study as follows. (i) Selective activation of ERβ imitates the ERK-mediated down-regulation of Sost by strain or estradiol. (ii) Tamoxifen, which acts as a nongenomic ERβ agonist while, at least in other cell types, antagonizing ERα (59, 60), also imitates Sost down-regulation by strain or estradiol. (iii) Prevention of Sost down-regulation by strain or estradiol. (iii) Prevention of Sost down-regulation by strain or estradiol. (iii) Prevention of Sost down-regulation by strain or estradiol.

The finding that MAPK/ERK blockade prevents ERβ-mediated Sost down-regulation is consistent with the report that ERβ, like ERα, is involved in the rapid strain-related activation of ERK signaling in osteoblastic cells (24). The potential involvement of ERK signaling suggests a nongenomic mode of action of ERβ, at least in the context of strain, although the involvement of this signaling pathway in a wide range of cellular processes limits interpretation of this result. Nongenomic activation of ERK signaling by either ERβ or ERα in a variety of cell types is increasingly being associated with diverse biological outcomes (78, 79). That ERβ activation may regulate Sost expression and activate ERK signaling has recently been suggested by the report that feeding rats soy isoflavones, which act as potent and relatively selective ERβ agonists (80, 81), increases ERK phosphorylation in bone and down-regulates Sost/sclerostin levels similarly to E2 treatment in vivo (15). The potential use of soy isoflavones for the treatment of osteoporosis is currently being investigated (82). We also demonstrate that tamoxifen reduces Sost expression in vivo, a finding consistent with an effect through ERβ. The potential for ERβ to mediate the therapeutic effects of tamoxifen treatment has been proposed elsewhere in the context of breast cancer (60), and tamoxifen administration has a profound osteogenic effect in cancellous regions of mouse bones, where ERβ is intensely expressed in osteocytes (83). A role for ERβ in mediating bone’s response to loading is consistent with tamoxifen synergistically enhancing bone gain in the tibiae of female mice subjected to mechanical loading (6). In this regard, the effects of tamoxifen are similar to those of parathyroid hormone and EP4 targeting compounds, both of which have been reported to down-regulate Sost (17, 76) and synergistically enhance bone gain following loading (84–86).

The inference that Sost regulation by strain is mediated by ERβ is also consistent with the original report by Lee et al. (32) that mice with incomplete ablation of ERβ activity show an impaired increase in cortical bone formation following loading of the ulna. However, subsequent reports in mice with more complete ERβ ablation (32) have shown a greater cortical osteogenic response to loading (2, 33). It is only possible to speculate on the inconsistencies between these studies because of potentially compensatory up-regulation of ERα (39) and opposite global transcriptomic influences of ERβ with or without ERα (35). What is clear is that the role of ERβ in the bone’s adaptation to loading remains controversial and, compared with ERα, under-studied. It is also becoming increasingly apparent that the functions of ERα and ERβ in determining the osteoregulatory effects of loading are dependent not only on the systemic biochemical/hormonal systemic context but also on the region of the bone involved (2).

Although this study investigates the role of the ERs in differentiated osteoblasts, ERs also play an active role during osteoblast lineage progression. Both ERα and ERβ are expressed in stromal pre-osteoblasts (83, 87, 88), which either proliferate to maintain the progenitor pool or differentiate into osteoblasts (as schematically represented in Fig. 8). Mechanical loading and E2 both increase osteoblast differentiation (89–91), and the mechanism by which strain promotes osteoblast differentiation involves LRP-independent activation of β-catenin (89, 92, 93). However, the role of the ERs in these processes is not clearly understood. Both ERs may mediate osteoblast differentiation following E2 treatment (94), although ERα inhibits mineralization (95) and bone morphogenetic protein-induced differentiation (96). Marrow stromal cells from individuals with a hypomorphic ERα have lower estradiol responsiveness but enhanced intrinsic differentiation (97). ERα also inhibits the transcriptional activity of the master regulator of the osteoblast lineage, Runx2 (98).

Loading and estrogen both promote proliferation of pre-osteoblasts (99–102), more differentiated osteoblastic cells (as used in the present study), and bone-lining cells (7, 8, 16). The proliferative effects of strain on osteoblastic cells have repeatedly been found to require ligand-independent activation of ERα (28, 29, 71). Similarly, estrogen promotes proliferation through a nongenomic function of ERα (56). In this study, ERα promotes proliferation following strain or estradiol treatment, whereas ERβ suppresses basal proliferation. Intriguingly, in MG63 cells, estrogen acting through ERβ has also been reported to suppress proliferation (103).

In mature osteoblasts in vivo, the osteogenic effects of estradiol require a fully functional ERα (104), whereas the osteogenic effects of loading do not require the ligand-binding AF2 domain of this receptor (4). Ligand-independent functions of ERα activated in osteoblastic cells by strain include its potentiation of the IGF receptor (27) and the translocation of...
β-catenin to the nucleus (26). Although roles for ERβ in the responses of these cells to strain are largely unknown, in MG63 cells ERβ is required for estradiol to up-regulate expression of matrix components (103). ERβ also selectively regulates the expression of genes related to migration (105), a process that is likely to be involved in matrix secretion.

Following secretion of matrix, osteoblasts become quiescent, terminally differentiate into osteocytes, or become apoptotic. Loading and estrogen both reduce apoptosis (24, 106–109), and estradiol has been shown to contribute to anti-apoptotic processes by activation of either ERα or ERβ through nongenomic mechanisms in a variety of cell models (55, 107, 110). In osteocytic MLO-Y4 cells, mechanical strain exerts anti-apoptotic effects through ERK activation that requires nongenomic mechanisms in a variety of cell models (55, 107, 110). Both receptors regulate Sost expression, as described here; ERβ mediates its acute down-regulation by strain and estradiol, and ERα maintains its basal expression. However, understanding the physiological context in which this complex interaction operates requires further investigation.

In conclusion, ERα and ERβ differentially regulate the responses of osteoblastic cells to acute changes in their ligand (estrogens) and to mechanical strain, thus influencing the context in which these proliferative stimuli act (schematically represented in Fig. 8). Exposure of osteoblastic cells in vitro to either a short period of mechanical strain or to an acute increase in the estradiol concentration in their environment stimulates proliferation mediated at least in part through ERα. Such exposure to changes in estradiol concentration and to short exposure to dynamic strain also down-regulates the expression of the Wnt antagonist Sost/sclerostin. Whereas ERα maintains basal expression of Sost, ERβ activity inhibits basal proliferation. However, it is ERβ and not ERα that mediates acute reduction in Sost in response to either changes in estrogens or strain. The (re)modeling response of bone to either strain or estrogens involves control of targeted formation and resorption. The extent of this osteogenic/anti-resorptive response will depend inter alia upon both the “proliferative context” in which it operates and the strength/duration of the stimulus to which the responsive cells are subjected. The data presented here suggest that the contribution of ERα is primarily to the proliferative context, although the contribution of ERβ is to the acute response of the resident bone cells to their mechanical and hormonal environment. In the case of exposure to
strain, this response involves reduced expression of the Wnt antagonist Sost.

Acknowledgments—We are grateful to Dr. P. Babij and Dr. A. Yu (Amgen) for measuring sclerostin protein in Saos-2 cell lysates and cell culture supernatants.

REFERENCES

The adaptive response of bone to mechanical loading in female transgenic mice is deficient in the absence of oestrogen receptor-α and -β. J. Endocrinol. 182, 193–201


Zhao, L., and Brinton, R. D. (2007) Estrogen receptor α and β differentially regulate intracellular Ca2+ dynamics leading to ERK phosphorylation and estrogen neuroprotection in hippocampal neurons. Brain Res. 1172, 48–59


ER-mediated Regulation of Osteoblast Proliferation and Sost

89. Cao, L., Bu, R., Oakley, J. I., Kalla, S. E., and Blair, H. C. (2003) Estrogen receptor-β modulates synthesis of bone matrix proteins in human osteo-

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Signal Transduction:
Estrogen Receptor α Mediates Proliferation of Osteoblastic Cells Stimulated by Estrogen and Mechanical Strain, but Their Acute Down-regulation of the Wnt Antagonist Sost Is Mediated by Estrogen Receptor β

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doi: 10.1074/jbc.M112.405456 originally published online January 29, 2013

Access the most updated version of this article at doi: 10.1074/jbc.M112.405456

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