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The Gene for Aromatase, a Rate-Limiting Enzyme for Local Estrogen Biosynthesis, Is a Downstream Target Gene of Runx2 in Skeletal Tissues

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The essential osteoblast-related transcription factor Runx2 and the female steroid hormone estrogen are known to play pivotal roles in bone homeostasis; however, the functional interaction between Runx2- and estrogen-mediated signaling in skeletal tissues is minimally understood. Here we provide evidence that aromatase (CYP19), a rate-limiting enzyme responsible for estrogen biosynthesis in mammals, is transcriptionally regulated by Runx2. Consistent with the presence of multiple Runx2 binding sites, the binding of Runx2 to the aromatase promoter was demonstrated in vitro and confirmed in vivo by chromatin immunoprecipitation assays. The bone-specific aromatase promoter is activated by Runx2, and endogenous aromatase gene expression is upregulated by Runx2 overexpression, establishing the aromatase gene as a target of Runx2. The biological significance of the Runx2 transcriptional control of the aromatase gene is reflected by the enhanced estrogen biosynthesis in response to Runx2 in cultured cells. Reduced in vivo expression of skeletal aromatase gene and low bone mineral density are evident in Runx2 mutant mice. Collectively, these findings uncover a novel link between Runx2-mediated osteoblastogenic processes and the osteoblast-mediated biosynthesis of estrogen as an osteoprotective steroid hormone.

Runx2 is an essential transcription factor in bone formation during embryogenesis (40). The ablation or C-terminal truncation of Runx2 prevents bone formation (3, 16), and a heterozygous mutation of Runx2 results in cleidocranial dysplasia in both mice and humans (15, 17). Mechanistically, Runx2 positively regulates osteoblast proliferation through epigenetic control (30) and differentiation through the upregulation of bone-related target gene expression (1, 5). Moreover, Runx2 accelerates chondrocyte differentiation in response to the upregulation of Runx2 target genes, which include the Indian hedgehog (Ihh) and type X collagen (Col10A1) genes (32, 55). The control of chondrogenesis by Runx2 is further confirmed by the chondrocyte-specific overexpression of a dominant negative form of Runx2 in transgenic mice (42, 50). Runx2 also plays an important role in estrogen deficiency-mediated bone resorption in adult mice (20). Together, these studies establish Runx2 as a master regulator of bone formation through the modulation of the activity of a cohort of target genes.

Estrogen is essential for the maintenance of bone health in both men and women (41). Estrogen deficiency is associated with increased bone turnover, resulting in reduced bone mineral density (BMD) and increased fracture risk. One of the key roles of estrogen is to modulate osteoclast survival, revealed by a loss of osteoclast apoptosis in osteoclast-specific estrogen receptor alpha (ER-α) conditional knockout mice (24). In addition, estrogen inhibits osteoclast formation through the upregulation of osteoprotegerin production (53). Therefore, the mutation or ablation of genes in the pathway related to estrogen synthesis causes a disruption of bone homeostasis. For example, a mutation of the ER-α gene in males can lead to osteopenia and even osteoporosis (11). Mutations of the aromatase gene result in unfused epiphyses and osteoporosis in males, and aromatase-deficient mice exhibit osteoporosis (11).

The human aromatase gene (CYP19; *P450arom*) is comprised of a 30-kb coding region containing nine exons and a 93-kb regulatory region containing 10 untranslated exons I (2, 38). The gene is expressed in many tissues, including the ovaries (8), muscle, skin, adipose tissue (18, 19, 54), placenta (28), and bone (25, 26, 33, 34, 43). The unusually large regulatory region contains 10 tissue-specific promoters that are alternatively used in various cell types (2, 38). Each promoter is regulated by a distinct set of regulatory sequences in the DNA and transcription factors that bind to these specific sequences. The promoters specific for the ovary tissues (promoter II), bone tissues (I.4 and I.6), brain (I.1f), endothelial cells (I.7), fetal tissues (I.5), and placenta (2α; I.1) are localized in tandem at −0, 73, 1, 33, 36, 43, 78, and 93 kb upstream of the ATG translational start site in exon II. Previous findings suggested that the local expression of aromatase may regulate estrogen production and perhaps affect local bone homeostasis. The majority of aromatase transcripts in bone tissues contain exon 1.4 and exon 1.6 in the 5′ untranslated region (5′-UTR) (35, 52); however, there is little information on the regulation of the aromatase gene in bone.
Recent studies revealed that Runx2 is involved in the estrogen pathway through interactions with ER-α (21) or as a downstream target gene of estrogen or SERM (45, 48). Furthermore, Runx2 was recently shown to control the expression of GPR30/GPER, which represents a nongenomic cell surface receptor for estrogen that is essential for osteoblast proliferation in cell culture (47). Although accumulating evidence implicates a functional association of Runx2 with estrogen signaling (13, 21, 45, 48), Runx2 has not been directly shown to control estrogen biosynthesis. Aromatase is a rate-limiting enzyme in the conversion of testosterone into estrogen and plays a pivotal role in estrogen synthesis. Hence, in the present study, we addressed a possible functional link between aromatase and Runx2. We found that Runx2 increases aromatase gene expression, establishing the functional involvement of Runx2 in the estrogen biosynthesis pathway.

MATERIALS AND METHODS

Cell culture. Human mesenchymal stem cells (hMSC) and media (mesenchymal stem cell growth medium [MSCGM]) were purchased from Lonza (Walkersville, MD). HOS and MG63 cells (human osteosarcoma cell lines), HCS-2/8 cells (human chondrocyte cell line), primary cultured human chondrocytes, and HeLa cells were cultured and maintained in Dulbecco’s modified Eagle’s medium (DMEM; Gibco, Grand Island, NY) supplemented with 10% fetal bovine serum (FBS; Gibco), 100 μM penicillin, and 100 μg/ml streptomycin at 37°C in a humidified atmosphere containing 5% CO₂. CHO cells were cultured in a humidified atmosphere containing 5% CO₂. CHO cells were cultured in modified minimum essential medium supplemented with 10% FBS. HeLa and CHO cells in six-well plates were plated at a density of 4 × 10⁵ cells/well for transfection experiments. Cells were transfected with a total of 2 μg DNA, including 0.8 μg of the aromatase promoter L4 gene-Luc reporter construct, 0.2 μg pSV 5-galactosidase-dase, and various amounts of pcDNA3.1-Runx2 plasmids by using Lipofectamine 2000 (Invitrogen), and were grown for 16 h. The ER-α expression vector (kindly provided by K. O. Han, Kwandong University, Seoul, South Korea) was cotransfected with the reporter vector containing six copies of the RBS into CHO cells. pSV 5-galactosidase plasmids were included as an internal control for transfection efficiency. All transfections were performed in triplicate. At 16 h or 24 h after transfection, cells were washed twice with phosphate-buffered saline (PBS) (pH 7.4) and harvested with lysis buffer (Promega). Luciferase activity was determined with the luciferase assay system (Promega) and measured with a luminometer (AutoLumat LB953, EG & G Berthold, Germany). The ratio of Luciferase activity relative to 5-galactosidase activity and the total protein content in the lysates were used to normalize for transfection efficiency. Each transfection was conducted in triplicate, and the results are presented as means ± 2 standard deviations (SD).

EMSA. The human osteosarcoma cell line HOS was maintained in DMEM (Gibco) containing 10% FBS. The methods used for nuclear extraction preparation and electrophoretic mobility shift analysis (EMSA) were described previously (14). Sequences of the wild-type and mutant oligonucleotides used are as follows: 5'-GGAGAAATATGTTGGCTCACAACACACACACTG3' (5'-GGAGAAATATGTTGGCTCACAACACACACACTG3'-2) and 5'-GGAGAAATATGTTGGCTCACAACACACACACTG3' (1.4-Runx2-1; 5'-GGAGAAATATGTTGGCTCACAACACACACACTG3'-2-mut. Probes were end labeled with [γ-32P]dCTP by use of the Megaprime DNA labeling system (GE Healthcare UK Ltd., Buckinghamshire, United Kingdom). Nuclear extract (15 μg) was incubated with 1× gel shift binding buffer containing 15 μM Tris (pH 7.5), 1 mM MgCl₂, 0.5 mM EDTA, 0.5 mM dithiothreitol, 50 mM NaCl, 10% glycerol, and 1 μg poly(dI-dC) for 30 min at 4°C. Competition was performed with a 100-fold molar excess of unlabeled DNA probe. Reaction mixtures were separated on 6% nondenaturing polyacrylamide gels in 0.5× Tris-borate-EDTA (TBE) buffer (50 mM Tris-HCl [pH 8.5], 50 mM borate, and 1 mM EDTA). For supershift assays, the nuclear extract was pretreated with mouse monoclonal Runx2 antiserum (30) at room temperature for 30 min before the addition of the labeled probe.

ChIP analysis. Chromatin immunoprecipitation (ChIP) assays were performed with a human osteosarcoma cell line, HOS. HOS cells (2 × 10⁶ cells) were exposed to 1% formaldehyde in DMEM for 10 min at 37°C. Glycine was added to 0.125 M, and the cultures were incubated for 2 min. The cells were collected in cold PBS, pelleted by centrifugation, and incubated for 10 min on ice in 0.3 M SDS lysis buffer (1% SDS, 10 mM EDTA, 50 mM NaCl, 1% SDS, 1 mM Triton X-100, 1.2 M EDTA, 16.7 mM Tris-HCl [pH 8.1]), 167 mM NaCl) and precleared with 80 μl salmon sperm DNA-protein A-Sepharose for 2 h at 4°C. After the removal of the Sepharose beads by centrifugation, 2 μl anti-Runx2, 2 μl anti-heat-shock protein (Abcam Inc., Cambridge, MA), 5 μg normal mouse IgG (Santa Cruz Biotechnology, Santa Cruz, CA), or no antibody was added to the supernatant, and the reaction mixture was incubated overnight at 4°C. Antibody against DNA complexed with chromatin was purified with 45 μl of blocked protein A-Sepharose for 2 h at 4°C. After extensive washing, bound DNA fragments were eluted and analyzed by PCR. Cycling parameters were 1 cycle of 95°C for 10 min and 28 cycles of 95°C for 30 s, 65°C for 30 s, and 72°C for 30 s. The primers used for the amplification of the

the pl4.741-Luc and pl6.1023-Luc vectors by using the QuikChange XL site-directed mutagenesis kit (Stratagene, La Jolla, CA). Primers for the site-directed mutagenesis of pl4.741-Luc were 5'-AAA TAT GTA cTT CAT GGT GTA ATG CAT ATT T-3' and 5'-AAT AAT GTA cTA TGT CCA GTA CAT GA AAT CAT ATT T-3'. The products were purified and cloned into the pGL3 luciferase vector (Promega, Madison, WI). Luciferase (Luc) reporter vectors containing promoters L4 and L6 were named pl4.741-Luc/pl4.137-Luc and pl6.1023-Luc, respectively.

We performed site-directed mutagenesis of the Runx2 binding site (RBS) in

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Results

Runx2 increases aromatase gene expression. Tissue-specific aromatase gene expression is determined by alternative promoter usage. Among the multiple aromatase gene promoters, I.4 and I.6 have been shown to be bone specific (2, 7, 35, 36, 52). To confirm aromatase promoter utilization in bone cells, we performed RT-PCR analysis of RNA from various bone cell lines. The amplified PCR products were portions of the 5‘-UTR derived from promoter I.4 or promoter I.6, and both transcripts were successfully detected based on their expected size (Fig. 1A). Identities of the PCR products were confirmed by sequencing (Fig. 1B). Both promoters I.4 and I.6 were active in human primary mesenchymal stem cells, human chondrocytic HCS-2/8 cells, and the human osteoblast cell lines HOS and MG63 (Fig. 1A). Interestingly, we also identified novel 5‘-UTR sequences of aromatase mRNA containing exon 1.4 and exon 1.f joined to the exon 2 open reading frame in chondrocytes (Fig. 1B and 2A). The function of these novel 5‘-UTR variants in chondrocytes remains to be established. Our results confirm that aromatase is expressed in bone cells, including chondrocytes, osteoblasts, and mesenchymal stem cells, as previously reported (2, 7, 33, 35, 36, 52).

The promoter sequences for the bone-specific I.4 and I.6 aromatase gene transcripts were examined by using the TFSEARCH program (http://www.cbcr.jc/research/db/TFSSEARCH.html). Putative Runx2 binding sites were identified in both the I.4 and I.6 promoters (Fig. 2A and B). To investigate the aromatase gene as a downstream target gene of Runx2, we focused on the I.4 promoter because this promoter showed strong activity in mesenchymal stem cells, chondrocytes, and osteoblasts (Fig. 1A). First, we determined whether the putative Runx2 binding sites in the I.4 aromatase promoter exhibited Runx2 binding activity. Electrophoretic mobility shift analysis (EMSA) showed Runx2 DNA binding activity for site 1 (TGTGGT) and site 2 (ACCACA) (Fig. 3A). The specificity of Runx2 binding was revealed by supershifting mediated by anti-Runx2 antibody. Furthermore, Runx2 binding activity on the endogenous aromatase gene promoter was confirmed by ChIP analysis (Fig. 3B). There were no positive signals in various controls, including the PCR control (H2O), immunoprecipitation controls, and a 3.7-kb upstream unrelated primer control (Fig. 3B). In transient transfection assays, the forced expression of Runx2 increased pL.4-741-Luc activity in HeLa cells (Fig. 3C). The enhancing effect of Runx2 on pL.4-741-Luc activity was also observed for CHO cells. To determine the
contribution of Runx2 binding sites to pI.4-741-Luc activity, vectors pI.4-137-Luc and pI.4-741-Rm-Luc, containing deleted or mutated Runx2 binding sites, respectively, were constructed. As expected, Runx2 increased pI.4-741-Luc activity, but the mutant Luc reporters with deleted or mutated Runx2 binding sites exhibited basal levels of activity (Fig. 3D). We also determined the effect of Runx2 on the activity of promoter I.6. Runx2 increased pI.6-1023-Luc activity, and site-directed mutagenesis in the single Runx2 binding site of the pI.6-1023-Luc reporter abrogated this effect (data not shown). Taken together, these results indicate that Runx2 is a positive regulator of bone-specific aromatase gene expression.

**Runx2-mediated upregulation of aromatase gene expression increases estrogen production.** Our previous findings indicated that Runx2 is a positive regulator of aromatase gene expression (Fig. 3). We therefore investigated whether the Runx2-mediated upregulation of aromatase results in increased estrogen production. To test this hypothesis, the bone cell lines HOS and MG63 were infected with adenovirus-producing Runx2 (Fig. 4). The forced expression of Runx2 increased estrogen production in HOS cells (Fig. 4A) and MG63 cells (Fig. 4B); however, the progesterone concentration in the adenovirus-transduced culture medium was not changed (data not shown). These results were recapitulated in Runx2-negative HeLa cells.
only after making stably expressing Runx2. HeLa cells expressing Runx2 showed a strong correlation between aromatase mRNA and protein and estrogen production (data not shown). Interestingly, bone-type aromatase promoters I.4 and I.6 transcripts were not detected in HeLa cells (data not shown), suggesting that another promoter(s) may be involved in Runx2-mediated aromatase gene expression and the upregulation of estrogen production in Runx2-expressing HeLa cells. Runx2-expressing HeLa cells showed no morphological change (data not shown). These results suggest that the Runx2-mediated upregulation of aromatase gene expression increases estrogen production.

Aromatase gene expression is downregulated in Runx2 mutant mice. Increased estrogen production in response to Runx2-mediated aromatase gene expression in vitro is consistent with the notion that Runx2 controls steroidogenesis. We further investigated the relationship between Runx2, aromatase, and estrogen biosynthesis in vivo. Our strategy was to determine whether a downregulation of Runx2 decreases aromatase gene expression and estrogen production in intact animals by measuring aromatase expression and estrogen concentrations in Runx2 C-terminally truncated Runx2/H9004C/H9004C mice and bone marrow-derived stromal cells (BMSC) of Runx2 heterozygous mice, respectively. Western blot analysis showed decreased levels of expression of aromatase in total proteins isolated from vertebrae and ribs of embryonic day 17.5 (E17.5) embryos of Runx2^{AC/AC} mice (Fig. 5A). This decrease was comparable to the reduction in expression of MMP13, a well-
A known target of Runx2 (Fig. 5A) (9). A decreased level of expression of aromatase in the periosteum of Runx2/H9004C/H9004C mice by immunohistochemical staining (Fig. 5B) and in the vertebra of E17.5 embryos of Runx2 knockout mice by Western blot analysis (data not shown) was also observed. To confirm aromatase gene expression in skeletal tissues, we isolated skeletal tissues separately from 19 E17.5 embryos. Consistent with the immunohistochemical results, total aromatase mRNA expression was significantly decreased in the limbs of E17.5 Runx2-null embryos (Fig. 5C). Aromatase gene expression levels were similar for male and female embryos from each group, based on sex identification by PCR analysis (data not shown).

Runx2 is also expressed in BMSC. To explore estrogen production in BMSC from Runx2 heterozygotes, the amount of estrogen and progesterone in culture medium was determined after 1 day of culture. The level of estrogen production was decreased in Runx2 heterozygous BMSC without a change in progesterone production (Fig. 6A), consistent with the results for the forced expression of Runx2 in human osteosarcoma cell lines (Fig. 4). Taken together, the expression of aromatase shows a strong correlation with the production of estrogen, indicating that Runx2 functions as a positive regulator of aromatase in Runx2-expressing tissues.

**Low bone mass in Runx2 heterozygous mice.** Recently, Sjögren et al. reported that osteoblast-specific aromatase gene expression resulted in high bone mass (39), and those authors attributed this finding to the upregulation of osteoprotegerin production in aromatase-transgenic mice. Based on our in vitro and in vivo results, it seems likely that Runx2 heterozygotes with reduced aromatase gene expression levels in bone tissue would have low bone mass. To prove this hypothesis, we determined various bone parameters by micro-CT analysis. Compared with wild-type mice, Runx2 C-terminally truncated heterozygotes showed lower values with regard to trabecular bone...
volume, cortical bone thickness, and total bone mineral density (BMD) (Fig. 6B).

We next determined the role of ER-α in the Runx2-mediated transactivation function on downstream target genes in the presence or absence of estrogen. As shown in Fig. 7A, ER-α inhibited the Runx2 transactivation function, and this inhibition was enhanced in the presence of estrogen. This result suggests a negative regulatory loop in the Runx2-aromatase-estrogen axis. Our data indicate that the local activity of aromatase in bone tissue is important for the maintenance of bone homeostasis and that Runx2 is an upstream positive regulator for aromatase gene expression in bone tissues (Fig. 7B).

DISCUSSION

In this study, we demonstrate that Runx2 stimulates aromatase gene expression in skeletal tissues. The aromatase gene was identified as a Runx2 target gene by four independent criteria. First, Runx2 interacts directly with the aromatase gene promoter, as confirmed by EMSA and ChIP assays. Second,
The transient transfection of Runx2 increases aromatase promoter activity. Third, the estrogen production level is elevated in bone cell lines after the forced expression of Runx2 but is decreased in BMSC of Runx2 heterozygotes. Fourth, Runx2-deficient mice exhibited decreased aromatase expression levels in bone tissues. Together, these results indicate that the aromatase gene is a downstream target gene of Runx2 and that Runx2 functions as a positive regulator for aromatase. We also demonstrated that mice heterozygous for a defective Runx2 protein lacking its C terminus exhibit a low bone mineral density by micro-CT analysis compared with wild-type mice. These results suggest that the local production of estrogen may contribute to the maintenance of bone homeostasis.

Aromatase catalyzes the conversion of C19 steroids to estrogen and is encoded by a single gene (CYP19) in the human and mouse genomes (4, 37, 38). Mechanisms controlling aromatase gene expression are complicated by the existence of multiple tissue-specific promoters (2). Aromatase exons I.4 and I.6 were previously reported to be expressed in bone cells, and strong aromatase promoter activity in several bone cells was observed in this study. Dexamethasone (25), oncostatin M, forskolin (51, 52), interleukin-1β (IL-1β) (23, 34), IL-11, tumor necrosis factor alpha (TNF-α), transforming growth factor β (TGF-β) (6, 36), and 1,25-dihydroxyvitamin D₃ (44) are known upstream regulators of aromatase gene expression. Runx2 is a master regulator of osteoblast differentiation. Consistent with its role in the physiological control of osteoblastogenesis, Runx2 anabolically modulates bone formation and controls transcriptional signaling pathways that are linked to glucocorticoids and vitamin D₃ (27, 29). In this study, we demonstrate that Runx2 is also a strong positive regulator of aromatase gene expression in osteoblastic cells. The Runx2-mediated increase in cellular estrogen production through the upregulation of bone-specific aromatase gene expression may contribute to the maintenance of bone mineral density in conjunction with endocrine effects. Furthermore, the possibility arises that the exogenous expression of Runx2 may perhaps contribute to the control of steroidogenesis during breast cancer tumorigenesis and metastasis (31).

Two reports support the linkage of Runx2 with steroid hormone-mediated bone homeostasis; in one report, high doses of estrogen were administered (12), and in the other report, bone marrow ablation was performed for animals with reduced levels of Runx2 (49). Those two studies showed that Runx2 heterozygotes are less responsive to estrogen and exhibit delayed healing. The observed results may be due to a compromised relationship between Runx2 and an estrogen biosynthesis pathway or a modified regulatory circuit involving Runx2. The
precise relationship between estrogen levels and bone phenotypic properties in Runx2 heterozygotes requires further confirmation. Interestingly, Runx2 dominant negative transgenic mice show low bone turnover and low bone mass (20). In our study, Runx2/H9004C/H11001C-terminally truncated mice also showed a low bone mass. High bone turnover mediated by an estrogen deficiency requires intact Runx2 expression in bone tissues (20). Moreover, osteoblast-specific aromatase gene expression in transgenic mice results in high bone mass (39). Together, these findings suggest that the fidelity of Runx2 function is important for aromatase-estrogen-mediated bone homeostasis.

While these studies were in progress, it was revealed that osteoblasts produce endogenous estrogen receptor agonists (22). Moreover, Teplyuk and colleagues showed that Runx2 controls enzymes (e.g., Cyp11a1) that support the production of pregnenolone (46) as well as the expression of the nongenomic receptor for estrogen (Gpr30/Gper), which is necessary for osteoblast proliferation in cell culture (47). Our study shows that Runx2 increases the expression of aromatase, the key enzyme for the conversion of androgen to estrogen. Together, these findings strongly suggest that Runx2 expression in osteoblasts renders these cells competent to produce functional anabolic steroids that stimulate osteoblast function.

In summary, we conclude from our findings that the gene for aromatase, the key enzyme for estrogen synthesis from androgen, is a downstream target gene of Runx2 and a component of a physiological regulatory network between Runx2 and the estrogen pathway that may contribute to skeletal development and bone homeostasis.

REFERENCES


FIG. 7. ER-α plus estrogen inhibit Runx2 transactivation function. (A) Six-Runx2-binding-site Luc reporter and Runx2 expression vectors were cotransfected with an ER-α expression vector into CHO cells, and relative Luc activity was measured at 24 h after transfection. The expression of ER-α decreased Runx2 transactivation function, and treatment with 17β-estradiol (β-E2) enhanced this effect. Data represent the means ± SD from three independent experiments. (B) Relationship between Runx2 and the estrogen pathway through aromatase gene expression.


