The osteogenic transcription factor runx2 controls genes involved in sterol/steroid metabolism, including CYP11A1 in osteoblasts

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Steroid hormones including (1,25)-dihydroxyvitamin D3, estrogens, and glucocorticoids control bone development and homeostasis. We show here that the osteogenic transcription factor Runx2 controls genes involved in sterol/steroid metabolism, including Cyp11a1, Cyp39a1, Cyp51, Lss, and Dhcr7 in murine osteoprogenitor cells. Cyp11a1 (P450scc) encodes an approximately 55-kDa mitochondrial enzyme that catalyzes side-chain cleavage of cholesterol and is rate limiting for steroid hormone biosynthesis. Runx2 is coexpressed with Cyp11a1 in osteoblasts as well as nonosseous cell types (e.g. testis and breast cancer cells), suggesting a broad biological role for Runx2 in sterol/steroid metabolism. Notably, osteoblasts and breast cancer cells express an approximately 32-kDa truncated isoform of Cyp11a1 that is nonmitochondrial and localized in both the cytoplasm and the nucleus. Chromatin immunoprecipitation analyses and gel shift assays show that Runx2 binds to the Cyp11a1 gene promoter in osteoblasts, indicating that Cyp11a1 is a direct target of Runx2. Specific Cyp11a1 knockdown with short hairpin RNA increases cell proliferation, indicating that Cyp11a1 normally suppresses osteoblast proliferation. We conclude that Runx2 regulates enzymes involved in sterol/steroid-related metabolic pathways and that activation of Cyp11a1 by Runx2 may contribute to attenuation of osteoblast growth. (Molecular Endocrinology 23: 849–861, 2009)
The potent osteogenic activity of Runx2 is linked to its principal function as an epigenetic regulator of phenotype commitment and cell growth (45–49). Loss of Runx2 deregulates normal osteoblast growth (47–50), whereas forced expression of Runx2 suppresses proliferation of osteoblasts (48, 51) and non-bone cells (52), consistent with its proposed general role as a gene related to cancer (53). To accommodate its role as a regulator of osteoblast proliferation, the levels of Runx2 oscillate during the cell cycle and are highest in G1 (48, 54). Multiple Runx2 target genes have been identified that contribute to osteogenic or proliferation-related functions of Runx2 (51, 55–58), but our understanding of Runx2-responsive genes remains incomplete.

In this study, we examined whether Runx2 is capable of controlling genes involved in steroid hormone signaling or metabolism. We identified a panel of genes encoding enzymes that control sterol metabolism. One of these genes (Cyp11a1) is up-regulated during osteoblast differentiation and expresses a unique short Cyp11a1 isoform that, unlike the full-length protein, is not concentrated into mitochondria. Short hairpin RNA (shRNA) knockdown of this isoform increases osteoblast proliferation, suggesting Cyp11a1 contributes to Runx2-mediated attenuation of cell growth.

Results

Identification of Runx2 target genes related to sterol metabolism

To address whether the biological interrelationships between Runx2 and steroid hormones are reflected by direct regulatory pathways, we examined whether Runx2 is capable of controlling the expression of genes related to steroid hormone metabolism. We have previously used immortalized mouse calvaria osteoprogenitors derived from Runx2-null mice as a cell culture model (59) to identify Runx2 target genes during recapitulation of a developmental transition when proliferating mesenchymal stem cells become osteoprogenitors and exhibit Runx2-attenuated cell growth (51). Gene expression profiling was used to assess which genes respond to the introduction of Runx2, a transcriptionally inert deletion mutant (Runx2Δ361) or a green fluorescent protein (GFP)-expressing empty vector into Runx2-null cells. Duplicate RNA samples were harvested from adenovirus Runx2-infected cells at 24 h after induction of Runx2 gene expression and hybridized to Affymetrix mouse cDNA arrays (Mouse Genome 430 2.0 Array). Statistical analysis of the data set revealed that a series of genes involved in sterol metabolism is coordinately controlled by Runx2, along with known Runx2 target genes (Table 1 and Fig. 1).

We tested a representative subset of six genes using quantitative PCR (qPCR) analysis for responsiveness to Runx2 expression (Fig. 2) in parallel with a prototypical Runx2 target gene (osteocalcin) as positive control and GAPDH as negative control. Our results validate Runx2-dependent expression for five of these six genes (i.e. P450 cytochrome proteins Cyp11a1, Cyp39A1, and Cyp51 as well as Lss and Dhcr7). Thus, Runx2 modulates a number of genes linked to sterol/steroid metabolism through direct or indirect mechanisms.

Modulation of Cyp11a1 gene expression by Runx2 in committed osteoblasts

The most prominently up-regulated sterol-related gene in our Affymetrix analysis encodes the cholesterol side-cleaving enzyme Cyp11a1 (60, 61). Cyp11a1 protein expression is normally below the level of detection in osteoprogenitors that do not express Runx2. However, Cyp11a1 mRNA expression is dramatically induced within 24 h after introduction of Runx2 protein into Runx2-null cells as determined by Affymetrix expression analysis (Table 1) and qPCR analysis (Fig. 2). To assess whether Runx2 can up-regulate Cyp11a1 in committed osteoblasts, we performed semiquantitative PCR analysis. We analyzed RNA samples from mouse Runx2-null osteoprogenitors, mouse MC3T3 osteoblasts, and SV40 transformed human O4T8 osteoblasts infected with wild-type Runx2 and the corresponding empty adenoviral vector (Fig. 3). The forced expression of Runx2 rapidly induces Cyp11a1 expression (Fig. 3). Exogenous Runx2 also stimulates osteocalcin and osteopontin expression but does not alter GAPDH or 18S rRNA levels (Fig. 3). Thus, Runx2 selectively regulates expression of the Cyp11a1 gene.

To assess whether CYP11A1 up-regulation by Runx2 is dose-dependent, we transfected Runx2-null cells and MC3T3 cells with different amounts of a cytomegalovirus (CMV)-based expression vector encoding Runx2. Runx2-null osteoprogenitors and immature MC3T3 osteoblasts have very low levels of endogenous Cyp11a1, but Cyp11a1 mRNA levels increase in proportion to the amount of exogenous Runx2 gene induction (data not shown; see also Fig. 5B below). Taken together, Runx2 is a key rate-limiting factor for Cyp11a1 gene expression in both preosteoblastic progenitors and committed osteoblasts.

Cyp11a1 gene expression is induced during osteoblastic differentiation

We further investigated the physiological relevance of Cyp11a1 induction by Runx2 by characterizing endogenous expression of Cyp11a1 during MC3T3 osteoblast differentiation in relation to endogenous Runx2 levels and other osteoblast marker genes (Fig. 4A). There is a significant elevation of Cyp11a1 gene expression throughout the MC3T3 differentiation time course, along with osteocalcin (Fig. 4A) and other osteoblastic markers (e.g. osteopontin and alkaline phosphatase; data not shown). The data show that Cyp11a1 is expressed at maximal levels in mature osteoblasts in parallel with the Runx2-dependent expression of the osteocalcin. Hence, Cyp11a1 is physiologically expressed in differentiated bone cells that express Runx2.

We also investigated Cyp11a1 expression in Runx2-null progenitor cells that were reconstituted with wild-type Runx2 and stimulated to differentiate into the osteoblastic lineage in the presence of osteogenic medium (Fig. 4B). The combination of exogenous Runx2 and osteogenic conditions induces alkaline phosphatase expression (Fig. 4B), and is known to restore the ability of Runx2-null cells to differen-
tiate and express other mature osteoblastic markers (59). Importantly, the presence of Runx2 clearly stimulates Cyp11a1 gene expression, and this effect becomes more pronounced as differentiation progresses. Thus, Runx2 is rate limiting for Cyp11a1 gene expression during differentiation along the osteoblastic lineage.

We analyzed expression of Runx2, Runx1, and Cyp11a1 by qPCR analysis of total cellular RNA from a panel of osseous and reproductive tissues. Cyp11a1 mRNA levels are low but detectable in calvaria and tibia, where Runx2 is expressed at very high levels (Fig. 4D). High levels of Cyp11a1 mRNA expression as well as Runx1 and Runx2 are observed in mature ovary and

### TABLE 1. Runx2 regulates a panel of genes related to sterol/steroid hormone synthesis, metabolism, and signaling in osteoblasts

<table>
<thead>
<tr>
<th>Gene symbol</th>
<th>Gene name</th>
<th>Runx2 WT vs. GFP</th>
<th>WT vs. Δ361</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Enzymes involved in sterol metabolism</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyp11a1</td>
<td>Cytochrome P450, family 11, subfamily a, polypeptide 1</td>
<td>4.2</td>
<td>3.9</td>
</tr>
<tr>
<td>Lss</td>
<td>Lanosterol synthase</td>
<td>3.1</td>
<td>2.7</td>
</tr>
<tr>
<td>Dhcr7</td>
<td>7-Dehydrocholesterol reductase</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Cyp39a1</td>
<td>Cytochrome P450, family 39, subfamily a, polypeptide 1</td>
<td>2.3</td>
<td>2.7</td>
</tr>
<tr>
<td>Hsd3b7</td>
<td>Hydroxy-â-5-steroid dehydrogenase, 3â- and steroid â-isomerase 7</td>
<td>1.7</td>
<td>1.5</td>
</tr>
<tr>
<td>Fdps</td>
<td>Farnesyl diphosphate synthetase</td>
<td>1.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Sult2b1</td>
<td>Sulfoxidase family, cytosolic, 2B, member 1</td>
<td>1.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Hsd17b7</td>
<td>Hydroxysteroid (17-â) dehydrogenase 7</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Fdxr</td>
<td>Ferredoxin reductase</td>
<td>1.5</td>
<td>1.7</td>
</tr>
<tr>
<td>Cyp51</td>
<td>Cytochrome P450, family 51</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Sc5d</td>
<td>Sterol C5 desaturase</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Ch25 h</td>
<td>Cholesterol 25-hydroxylase</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Cyp1b1</td>
<td>Cytochrome P450, family 1, subfamily b, polypeptide 1</td>
<td>-3.0</td>
<td>-2.3</td>
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<tr>
<td>Por</td>
<td>Cytochrome P450 oxidoreductase</td>
<td>-1.7</td>
<td>-1.5</td>
</tr>
<tr>
<td>Cyp20a1</td>
<td>Cytochrome P450, family 20, subfamily a, polypeptide 1</td>
<td>-1.7</td>
<td>-1.5</td>
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<tr>
<td><strong>Kinases and gene regulators involved in sterol metabolism</strong></td>
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<td></td>
<td></td>
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<tr>
<td>Stat5a</td>
<td>Signal transducer and activator of transcription 5A</td>
<td>2.0</td>
<td>1.7</td>
</tr>
<tr>
<td>Pbx1</td>
<td>Pre B-cell leukemia transcription factor 1</td>
<td>-1.8</td>
<td></td>
</tr>
<tr>
<td>Prkaa1</td>
<td>Protein kinase, AMP-activated, â1 catalytic subunit</td>
<td>-1.8</td>
<td></td>
</tr>
<tr>
<td><strong>Transporters, binding proteins and receptors involved in sterol metabolism</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abca2</td>
<td>ATP-binding cassette, subfamily A (ABC1), member 2</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>Ebpl</td>
<td>Emopamil binding protein-like</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Gg51</td>
<td>Glucocorticoid induced gene 1</td>
<td>-2.2</td>
<td>-1.5</td>
</tr>
<tr>
<td>Nr3c1</td>
<td>Nuclear receptor subfamily 3, group c, member 1</td>
<td>-2.0</td>
<td>-1.7</td>
</tr>
<tr>
<td>Abca1</td>
<td>ATP-binding cassette, subfamily A (ABC1), member 1</td>
<td>-1.9</td>
<td>-1.8</td>
</tr>
<tr>
<td>Plekhh2</td>
<td>Pleckstr homology domain containing, family H, member 2</td>
<td>-1.7</td>
<td></td>
</tr>
<tr>
<td>Ldhr</td>
<td>Low density lipoprotein receptor</td>
<td>-1.6</td>
<td>-1.6</td>
</tr>
<tr>
<td>Osbpl2</td>
<td>Oxysterol binding protein-like 2</td>
<td>-1.6</td>
<td>-1.6</td>
</tr>
<tr>
<td>Osbpl3</td>
<td>Oxysterol binding protein-like 3</td>
<td>-1.6</td>
<td>-1.5</td>
</tr>
<tr>
<td>Osbpl9</td>
<td>Oxysterol binding protein-like 9</td>
<td>-1.5</td>
<td></td>
</tr>
<tr>
<td>Osbpl8</td>
<td>Oxysterol binding protein-like 8</td>
<td>-1.4</td>
<td></td>
</tr>
<tr>
<td>Hdlbp</td>
<td>High-density lipoprotein binding protein</td>
<td>-1.5</td>
<td></td>
</tr>
<tr>
<td><strong>Known Runx2 target genes</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spp1</td>
<td>Secreted phosphoprotein 1 (osteopontin)</td>
<td>13.6</td>
<td>23.1</td>
</tr>
<tr>
<td>Bglap1</td>
<td>Bone γ carboxyglutamate protein 2 (osteocalcin)</td>
<td>6.3</td>
<td>7.7</td>
</tr>
<tr>
<td>Mmp13</td>
<td>Matrix metalloproteinase 13</td>
<td>7.8</td>
<td>6.1</td>
</tr>
</tbody>
</table>

Selected genes exhibit a statistically significant increase or decrease in expression 24 h after the infection based on Student’s t test (P < 0.05). The data are presented as a fold change in the expression signal between cells expressing Runx2 wild type (WT) vs. Δ361 mutant or Runx2 WT vs. GFP. The cluster of steroid signaling- and metabolism-related genes was extracted by functional annotation clustering of Affymetrix data in the David 2.0 web-based environment (Database for Annotation, Visualization and Integrated Discovery, http://david.abcc.ncifcrf.gov/).
testis (Fig. 4D), corroborating previous reports showing robust Runx1-dependent expression of Cyp11a1 in granulosa cells and periovulatory follicles in rat and mouse (62, 63). Interestingly, during fetal development or postnatal testicular development, total Runx levels correlate with Cyp11a1 expression (data not shown). Taken together, Runx2 and Runx1 may both regulate Cyp11a1 during development in osseous and reproductive tissues.

**Runx2 induces a small isoform of Cyp11a1 in osteoblasts**

We performed Western blot analysis to assess whether the increase in Cyp11a1 mRNA expression that we observed translates into a corresponding induction of Cyp11a1 protein levels. As expected, forced expression of wild-type Runx2 but not Runx2Δ361 results in robust levels of Cyp11a1 protein (Fig. 5A). Expression of Cyp11a1 is proportional to the amount of Runx2 expression, indicating that Runx2 titrates Cyp11a1 protein levels (Fig. 5B), consistent with a direct effect of Runx2 on Cyp11a1 gene transcription (see below). Interestingly, lysates from testis or prostate tissues yield the expected approximately 55-kDa Cyp11a1 protein, whereas osteoblasts and Runx2-null osteoprogenitors express primarily an approximately 32-kDa species upon induction by Runx2 (Fig. 5C). Breast cancer-derived MDA-MB-231 cells express both the 55- and 32-kDa isoforms (Fig. 5C). Although the 55-kDa isoform of Cyp11a1 is normally localized in mitochondria (64, 65), the N-terminally truncated form of human CYP11A1 (isoform B) lacks the N-terminal mitochondrial localization signal (66) (GenBank accession no. NM_001099773 and NP_0010933). Thus, the short murine Cyp11a1 isoform that is induced by Runx2 may not be localized in mitochondria (see below).

Expression of the 32-kDa isoform of human Cyp11a1 is regulated by alternative splicing and utilization of an internal translational start codon. We examined the distribution of exons present in mouse Cyp11a1 mRNA using RT-qPCR (Fig. 6). Cyp11a1 mRNA is clearly expressed endogenously in testis and upon induction by Runx2 in MC3T3 osteoblasts and Runx2-null osteoprogenitors. More importantly, exons encoding the first and second ATG start codon of the mouse Cyp11a1 mRNA are detected at comparable abundance in all three RNA samples (Fig. 6), suggesting that each sample expresses a full-length Cyp11a1 mRNA. It appears that the murine 32-kDa isoform of Cyp11a1 is not produced by omission of the first ATG-containing exon (as is the case for human CYP11A1) but perhaps by alternative translational initiation.

**Cyp11a1 gene is directly regulated by Runx2 at the promoter level**

Forced expression data clearly indicate that Cyp11a1 gene expression is responsive to modulations in the levels of Runx2 (Figs. 2–4). To investigate whether Runx2 can directly control Cyp11a1 gene transcription, we first tested whether the induction of endogenous Cyp11a1 expression requires the DNA binding and trans-activation functions of Runx2 upon introduction into Runx2-null cells (Fig. 7A). The data show that Cyp11a1 is robustly up-regulated by wild-type Runx2 but not when its C-terminal trans-activation domain is deleted (Runx2ΔC)}.
mutants ΔA32 and ΔA361) or when its DNA-binding domain (mutant DBDM) is mutated (Fig. 7A). Hence, transcriptional activation by Runx2 is critical for induction of Cyp11a1.

Both the mouse and human Cyp11a1 gene promoters contain at least five Runx2 consensus motifs, although their locations within the respective 5′-flanking regions are not strictly conserved (Fig. 7B). We performed EMSAs to examine whether these sites can support Runx2 binding in vitro. To permit a quantitative comparison of relative binding strengths for each of these sites, we performed competition analyses using unlabeled oligos spanning the Runx2 motifs and a known probe that encompasses a classical Runx2 binding site in the rat osteocalcin gene (site C or OSE2). Nuclear extracts from rat ROS17/2.8 osteosarcoma cells were used in binding reactions, because these cells are known to express high endogenous levels of Runx2 and were used to define site C/OSE2 in previous studies (35–37). The EMSA results show that one motif (Cyp3, nucleotides −1005 to −999) is an effective competitor, and three motifs are moderately effective competitors (Cyp2, Cyp4, and Cyp5) (Fig. 7, C and D). The most upstream motif we tested (Cyp1) did not compete for Runx2 binding to the established Runx2 element site C (Fig. 7, C and D). Thus, we have empirically validated that there is at least one high-affinity Runx2 site in the mouse Cyp11a1 gene promoter and that three additional sites may contribute to transcriptional control of the Cyp11a1 gene.

We next performed transient transfection assays with Cyp11a1 promoter fragments fused to the luciferase promoter. For luciferase reporters, we selected a promoter fragment spanning about 1.4 kb of 5′ sequence that contains the four validated Runx2 motifs, including the high-affinity Runx2 element (Cyp3) (Fig. 8A). Coexpression of Runx2 clearly enhances reporter gene activity of the −1.4-kb Cyp11A gene promoter by about 3- to 4-fold (Fig. 8A). However, Runx2 does not activate the −0.3-kb Cyp11A gene promoter that lacks three Runx2 motifs (Cyp2, Cyp3, and Cyp4), or the −0.2-kb promoter that does not contain any discernable Runx2 motifs (Fig. 8A). We note that the single Runx2 site in the −0.3-kb promoter is not sufficient for Runx2-mediated transcriptional stimulation. The transfection data indicate that Runx2 directly activates Cyp11a1 transcription and that this activation requires cognate sites between −1.4 and −0.3 kb.
To provide further in vivo evidence that Cyp11a1 is a direct Runx2 target, we analyzed Runx2 interactions with the Cyp11a1 promoter by chromatin immunoprecipitation analysis. Runx2-null cells do not exhibit Runx2 binding to the Cyp11a1 promoter above background levels (Fig. 8B). Robust interactions are observed throughout the promoter when Runx2 is reintroduced by adenoviral infection (Fig. 8B). Chromatin immunoprecipitates prepared using an IgG antibody exhibit signals at or below background levels. We conclude that Cyp11a1 is a Runx2-responsive gene and may represent an integral component of a biological program that is controlled by Runx2 to regulate enzymes mediating sterol/steroid metabolism.

The 32-kDa isoform of Cyp11a1 is not localized in mitochondria

Forced expression of Runx2 in Runx2-null cells induces a 32-kDa isoform of Cyp11a1 that is shorter than the full-length 55-kDa isoform that is localized in part in mitochondria (see Fig. 5). To assess the subcellular localization of the 32-kDa isoform, we performed immunofluorescence microscopy analysis using a Cyp11a1 antibody and find that the localization of Cyp11a1 varies between MC3T3 osteoblasts and Runx2-null cells (Fig. 9A). In most MC3T3 cells (85%), we observe diffuse cytoplasmic/nuclear staining, although perinuclear tubular (12%) or vesicular (3%) staining patterns are also detected. In Runx2-null cells, the majority of cells exhibit perinuclear tubular staining (80%) or diffuse cytoplasmic/nuclear staining (19%) and rarely cytoplasmic vesicular staining (1%). The specificity of Cyp11a1 antibodies is indicated by recognition of exogenously expressed flag and GFP-tagged Cyp11a1 proteins (see supplemental Fig. S1, published as supplemental data on The Endocrine Society’s Journals Online web site at http://mend.endojournals.org). Therefore, similar to the full-length 55-kDa Cyp11a1 protein, the majority of the 32-kDa protein variant is expressed in the cytoplasm.

The 55-kDa Cyp11a1 protein is a full-length isoform of 526 amino acids (aa). The 32-kDa short isoform is predicted to be generated by alternative translation at an internal ATG to yield a 371-aa protein that is analogous to human CYP11A1 isoform B. We investigated the subcellular localization of the 371-aa isoform relative to the full-length 526-aa isoform using the exogenous expression of either Flag epitope-tagged proteins (Fig. 9B) or GFP fusion proteins (Fig. 9C). Consistent with the data obtained using a Cyp11a1 antibody, we find that both short and long isoforms of Cyp11a1 are predominantly localized in the cytoplasm. However, the Flag-tagged 526-aa variant exhibits mostly a tubular pattern, whereas the 371-aa has a vesicular pattern. These results indicate that the two Cyp11a1 isoforms are localized in separate compartments.

We studied the subcellular localization of the long and short isoforms using MitoTracker dye, a cell-permeable probe that selectively labels mitochondria (Fig. 9D). The 526-aa isoform of Cyp11a1 clearly colocalizes with MitoTracker dye, albeit that there is also diffuse nonmitochondrial cytoplasmic staining for Cyp11a1 (Fig. 9D and data not shown). In contrast, the 32-kDa (371 aa) variant of Cyp11a1 does not colocalize with MitoTracker dye. Taken together, the short isoform of Cyp11a1 does not reside in mitochondria and may perform a novel cellular function.

shRNA knockdown of Cyp11a1 increases osteoblast proliferation

We studied the function of Cyp11a1 by shRNA-mediated depletion of its endogenous levels in Runx2-null cells or MC3T3 osteoblasts (Fig. 10). shRNA for Cyp11a1 decreases its mRNA levels with limited effects on the expression of other genes (Fig. 10A) and diminishes Cyp11a1 protein levels (Fig. 10B). In Runx2 null cells that do or do not express exogenous Runx2, knockdown of Cyp11a1 causes a statistically significant, albeit quantitatively modest, increase in cell growth (Fig. 10C). A comparable stimulatory effect on cell proliferation is observed upon knockdown of Cyp11a1 expressed endogenously in MC3T3 cells (Fig. 10D). Thus, consistent with the cell growth-suppressive potential of Runx2, its target Cyp11a1 may support attenuation of cell proliferation.

Discussion

Runx2 is known to control a number of phenotypic genes that are coregulated by steroid hormone receptors (31, 32, 67), as well as genes for steroid receptors (68). In this study, we show that Runx2 controls a series of genes encoding enzymes involved in...
in sterol and steroid metabolism. Cyp11a1, a representative sterol/steroid-related gene, is directly regulated by Runx2 in osteoblasts through Runx2 elements in the Cyp11a1 promoter. The finding that Runx2 controls expression of sterol-related genes indicates that Runx2 may locally modulate sterol and steroid compounds within the osteoblast microenvironment. The biological relevance of these modulations is reflected by the importance of cholesterol metabolism in osteoblasts and bone homeostasis (69).

Our observation that Cyp11a1 is a Runx2 target gene complements previous studies that have shown that Cyp11a1 and Runx1 are coregulated and that Cyp11a1 is Runx1 responsive in ovulating follicles (62, 63). Interestingly, data presented here and in other studies (70) indicate that Runx2 is also highly expressed in testis, a reproductive tissue in which Cyp11a1 is also abundantly expressed. Hence, the Cyp11a1 gene may perhaps be regulated by any of the three Runx transcription factors, depending on the cell type and tissue context in which specific Runx members are expressed. We consider it less likely, nevertheless, that Cyp11a1 induction by Runx2 may have a systemic endocrine effect. Cyp11a1 null mice die within the first 2 d after birth and survive slightly longer than Runx2-null mouse pups. Both Runx2 and Cyp11a1 null mice exhibit severe growth retardation. However, unlike Cyp11a1 knockout mice, Runx2-null mice do not develop muscular atrophy and gonadal defects (71), indicating that Runx2 deficiency does not have dominant effects on circulating hormone levels. Based on the inhibitory effects of Cyp11a1 in immature osteoblasts and the prominent expression of Cyp11a1 in late-stage osteoblasts, we propose that Runx2 control of Cyp11a1 supports metabolic functions in both proliferating and postproliferative bone cells (i.e. mature osteoblasts and/or mineral-embedded osteocytes).

The full-length Cyp11a1 protein (~55 kDa) is localized in mitochondria. Immunoblotting experiments show that Runx2 up-regulates a short isoform (~32 kDa) of Cyp11a1 that is localized in both the cytoplasm and the nucleus but not in mitochondria. Alternative mRNA splicing is known to generate a short (~32 kDa) isoform in human cells, because the human CYP11A1 gene contains an alternative S′ exon that eliminates the normal ATG, whereas an internal methionine codon functions as an alternative ATG start codon. Although this alternative exon is conserved in the primate lineage, it appears to be absent in the rodent lineage. The truncated mouse Cyp11a1 isoform may be generated without alternative splicing in mouse cells by alternative translational initiation (by preferred recognition of the internal ATG) and/or posttranslational cleavage.

Because we observe that a subset of the short 32-kDa isoform of Cyp11a1 localizes in the nucleus (supplemental Fig. S2), the possibility arises that the function of Cyp11a1 in mature osteoblasts may be related to metabolism of sterol and steroid compounds inside the nucleus. Recent data suggest that Cyp11a1 can hydroxylate vitamin D2 and vitamin D3 (72–74). At least some of these vitamin D metabolites have...
attenuation of osteoblast proliferation. Thus, intranuclear production of biologically active vitamin D compounds by Cyp11a1 may support the antiproliferative properties (e.g. reflected by reduced DNA synthesis). This, intranuclear production of biologically active vitamin D compounds by Cyp11a1 may support the antiproliferative properties of Runx2 in osteoblasts. Indeed, we observed a modest increase in cell proliferation after specific shRNA knockdown of Cyp11a1 expression, suggesting that induction of Cyp11a1 expression by Runx2 functionally contributes to Runx2-dependent attenuation of osteoblast proliferation.

Materials and Methods

Tissue culture and mouse tissues

MC3T3-E1 and Runx2-null cells were grown in αMEM from GIBCO/Invitrogen (Grand Island, NY), catalog item 11900-024. U2OS human osteosarcoma cells were cultured in McCoy’s 5A medium (HyClone Laboratories, Inc., Logan, UT), ROS 17/2.8 cells were cultured in Ham’s F12 medium (HyClone), and HEK293T cells were cultured in DMEM/high-glucose medium (HyClone). All cell types were maintained at 37 °C and 5% CO2 humidified atmosphere. Runx2-null cells are calvarial osteoprogenitor cells derived from Runx2 knockout mice that were generated by stable mouse telomerase gene (mTERT) integration in our laboratory as described (59). HOB 04T8 cells represent T-antigen transformed, conditionally immortalized human osteoblast cells, which grow at a permissive temperature of 34 °C as described previously (75). HOB 04T8 osteoblasts were grown in DMEM-F12 medium (GIBCO/Invitrogen) at 34 °C and 5% CO2 humidified atmosphere.

Media for MC3T3, Runx2-null, U2OS, and HOB cells were supplemented with 10% fetal bovine serum (FBS) from Atlanta Biologicals (Lawrenceville, GA). The medium for ROS cells was supplemented with 5% FBS from HyClone. All media were also supplemented with 30 mM penicillin-streptomycin and 100 mM l-glutamine.

For analysis of in vivo gene expression, mouse tissues were collected in 2 ml Trizol reagent and sonicated for 10–30 sec, and RNA was extracted by standard protocols. All procedures involving the care and use of C57 mice were approved by the Animal Research Committee at the University of Massachusetts Medical School.

Gene delivery by transfections and infections

For transfections, MC3T3 and Runx2-null cells were plated in 100-mm plates at a density of 0.4 × 10^6 cells per plate or in six-well plates at a density of 8.3 × 10^5 cells per well. After 24 h, cells were transfected using Lipofectamine Plus reagents according to the manufacturer’s protocol (Invitrogen, Carlsbad, CA). U2OS cells were plated at 6.7 × 10^5 cells per well in six-well plates and transfected after 24 h using FuGENE 6 transfection reagent (Roche Diagnostics GmbH, Mannheim, Germany) according to the manufacturer’s protocol. Cells were collected 36 h after transfection.

For adenoviral infections, Runx2-null or MC3T3 cells were plated in six-well plates (12.5 × 10^5 cells per well). After 24 h, cells were infected with a 100 multiplicity of infection (MOI) of each virus for Runx2-null cells and 400 MOI for MC3T3 cells in 600 μl medium complemented with 1% FBS for 4 h. Then 400 μl αMEM containing 1% FBS medium was added, and cells were incubated for an additional 10 h. HOB cells were plated in six-well plates (12.5 × 10^5 cells per well) and infected after 24 h with 25 MOI of each virus for 4 h in 400 μl MEM-F12 medium supplemented with 1% FBS. Infection efficiency was monitored by an Independent Ribosomal Entry Site (ires)-driven GFP signal.

For shRNA-mediated knockdown of Cyp11a1 expression, Runx2-null cells were plated in six-well plates (1 × 10^5 cells per well) and infected 24 h later with lentivirus or lentivirus expressing Cyp11a1 shRNA and non-specific shRNA. Briefly, cells were treated with 1.5 ml nonpurified virus supernatant from packaging cells (HEK293T) and 0.5 ml nonpurified virus supernatant from packaging cells (HEK293T) and 0.5 ml complete fresh αMEM per well with a final concentration of 8 μg/ml hexadimethrine bromide (Polybrene; Sigma-Aldrich, Inc., St. Louis, MO). Plates were centrifuged upon addition of the virus at 1460 × g at 37 °C for 1 h. Infection efficiency was monitored by GFP coexpression at 3 d after infection.

Expression constructs and viruses

A pCMV5-Runx2 expression vector was generated by cloning the mouse Runx2 cDNA (MASNS isoform) into pCMV5. The cDNA of full-length Runx2 and its deletion mutants 1-361 and 1-432 were subcloned into the TOPO TA PCR cloning vector (Invitrogen) and subsequently inserted to TOPO TA PCR cloning vector (Invitrogen) and subsequently subcloned into the EcoRI restriction site of pCMV-tag2B vector to obtain Cyp11a1 proteins with an N-terminal Flag tag (Stratagene, La Jolla, CA). The medium for ROS cells was supplemented with 5% FBS from HyClone. All media were also supplemented with 30 mM penicillin-streptomycin and 100 mM l-glutamine.

For analysis of in vivo gene expression, mouse tissues were collected in 2 ml Trizol reagent and sonicated for 10–30 sec, and RNA was extracted by standard protocols. All procedures involving the care and use of C57 mice were approved by the Animal Research Committee at the University of Massachusetts Medical School.
CA) or into pEGFP-C2 vector (Clontech, Mountain View, CA) to yield an N-terminal GFP tag. All constructs were sequences to validate the correct reading frame and absence of mutations.

Rodent Cyp11a1-specific shRNA-expressing lentiviral vectors (pGIPz) and nonsilencing RNA in pGIPz were purchased from Open Biosystems/Thermo Fisher Scientific (Huntsville, AL). Lentiviruses were packaged in HEK293T cells by standard procedures. Briefly, HEK293T cells were seeded at 1 × 10^6 cells per 10-cm plate and cotransfected the next day with 6 µg expressing plasmid with 4 µg of the packaging plasmid pCMV-DR8.91 and 2 µg envelop plasmid pMD2.G using FuGene6 reagent. The medium was changed after 24 h and 11 mg/ml BSA was added. Culture media were collected at 48 or 72 h after transfection and centrifuged at 330 × g for 5 min to spin down cell debris. The resulting supernatant was used directly for infection of cells.

### Proliferation and differentiation experiments

For proliferation assays, Runx2-null calvaria cells were plated at 10^5 cells per well in six-well plates and infected with lentivirus as described above. Cells were passaged at d 3 after lentiviral infection and infected the next day with adenoviruses as described. After adenoviral infection for 24 h, cells were transferred to six-well plates at 10^5 cells per well. Growth curves were obtained by cell counting for 4 d.

For differentiation studies, mineralizing MC3T3-E1 cells or Runx2-null cells reconstituted with Runx2 expressed using an adenoviral vector were plated at a density of 0.4 × 10^6 cells per 100-mm plate in αMEM complemented with 30 mM penicillin-streptomycin, 100 mM L-glutamine, and 10% FBS (Hyclone). Cells were treated with 10 mM β-glycerophosphate and 25 µg/ml ascorbic acid in fresh media at d 4 after plating. The culture medium was supplemented with 10 mM β-glycerophosphate and 50 µg/ml ascorbic acid every other day for the remainder of the experiment.

### Western blot analysis

For Western blotting, cell pellets were boiled in 100 µl direct lysis buffer [50 mM Tris-HCl (pH 6.8), 2% SDS, 10% glycerol, 12% urea, 25 µM MG132 (Calbiochem, EMD Biosciences, Inc., La Jolla, CA), 100 mM dithiothreitol, and 1% Triton X-100] of each lysate were separated using 10% SDS-PAGE and subjected to semi-wet transfer to polyvinylidene difluoride membranes (Millipore, Billerica, MA). PBS (1×) or 0.1% Tween with 5% milk was used for 1 h to block nonspecific binding. Primary and secondary antibodies were used in a 1:2000 dilution for 1 h in PBS0.1% Tween/1% milk. Signals were detected by chemiluminescence (PerkinElmer Western Lightning Chemiluminescence Reagent Plus; PerkinElmer, Waltham, MA). Cyp11a1 rabbit antiserum was a kind gift of Dr. Walter Miller (Department of Pediatrics, University of California at San Francisco) (76) and was incubated at 1:1000 dilution for 1 h in PBS0.1%. Tween/1% milk. Signals were detected by chemiluminescence (PerkinElmer Western Lightning Chemiluminescence Reagent Plus; PerkinElmer, Waltham, MA). Cyp11a1 rabbit antiserum was a kind gift of Dr. Yoshi Ino (Institute for Molecular and Cellular Biology, Singapore). CDK2 rabbit polyclonal antibodies (M2) and β-actin goat polyclonal antibodies (C11) were purchased from Santa Cruz Biotechnology (Santa Cruz, CA).

### qPCR analysis

Total RNA was extracted with Trizol reagent (Invitrogen) and purified on columns after deoxyribonucle-
levels. Cells were replated after 3 d and counted for the next 4 d.

infected with shRNA-lentivirus to knock down endogenous Cyp11a1 protein of endogenous Cyp11a1 increases cell proliferation. MC3T3 cells were obtained by cell counting.

five to 75 times, and 5 hexamers (Invitrogen). The resulting cDNA products were diluted from standard procedures. Briefly, cells were grown on gelatin-coated cover-slips and transfected or infected as described above, and 36 h after cells were fixed with 3.8% formaldehyde in PBS for 10 min and permeabilized with 0.25% Triton X-100 in PBS for 20 min. Nonspecific binding was blocked for 20 min with PBSA solution (PBS containing 0.5% BSA). The following primary antibodies were used for staining: rabbit antiserum to Cyp11a1 from Chemicon/Millipore (Chemicon International, Inc., Temecula, CA; catalog item 1294), at a dilution of 1:300 in PBSA at 37 C for 1 h and mouse monoclonal antibodies to Flag tag peptide from Sigma (clone M2, catalog item F1804) at a 1:1000 dilution at 37 C for 1 h. Secondary goat antihorse 488 (green) and goat antirabbit 568 (red) or goat antirabbit 488 (green) (Molecular Probes/Invitrogen, Eugene, OR) antibodies were used at a 1:800 dilution in PBSA for 1 h at 37 C. After the 4',6-diamidino-2-phenylindole (DAPI) staining for 5 min for visualization of cell nuclei, coverslips were washed with PBS and mounted to the slides with Pro-long Gold mounting medium (Invitrogen). Double staining for Cyp11a1 and mitochondria was carried out using the Cyp11a1 antiserum and a mitochondrial marker (MitoTracker Red CMXRos from Invitrogen/Molecular Probes; catalog number M7512) according to protocols provided by the manufacturer. Fluorescence images were taken on an Axioiplan 2 Carl Zeiss fluorescence microscope (Carl Zeiss, Thornwood, NY) with a Hamamatsu C4742-95 digital camera (Hamamatsu, Bridgewater, NJ). Digital images were acquired within the MetaMorph Imaging Series software environment (version 7.1.3) (Molecular Devices, Sunnyvale, CA).

In situ immunofluorescence

Immunofluorescence microscopy was performed according to standard procedures. Briefly, cells were grown on gelatin-coated coverslips and stained with antibodies according to the manufacturer's instructions. Fluorescence images were taken on a fluorescence microscope (Carl Zeiss, Thornwood, NY) with a Hamamatsu C4742-95 digital camera (Hamamatsu, Bridgewater, NJ). Digital images were acquired within the MetaMorph Imaging Series software environment (version 7.1.3) (Molecular Devices, Sunnyvale, CA).

Chromatin immunoprecipitation assay

Runx2-null calvaria cells were infected for 30 h with adenoviral vectors expressing Runx2 wild-type and IRES-GFP or GFP alone. Cells were then cross-linked with 1% formaldehyde for 10 min at room temperature followed by chromatin immunoprecipitations using Runx2 rabbit polyclonal antibodies M70 (Santa Cruz) as described previously (77). The primer pairs used for amplification of Runx2-bound fragments within the mouse Cyp11a1 promoter are listed in Table 2. Primers within the mouse GAPDH gene promoter were used as negative control.

Reporter gene assays

The −1.4-kb upstream sequence of the mouse Cyp11a1 gene (ENSEMUSG 00000032323) was amplified with specific primers and cloned into the XhoI/HindIII sites of the pGL4 vector (Promega, Madison, WI). Subsequently, −0.3- and −0.2-kb promoter deletions were obtained by amplifying corresponding fragments, and the resulting PCR products were recloned into the XhoI/HindIII sites of pGL4. The sequences of specific primers that were used for promoter cloning are listed in Table 2. For reporter assays, Runx2-null mouse calvaria cells were seeded at 105 cells per well of a six-well plate. After 24 h, cells were infected with adenovirus expressing Runx2, its DNA-binding mutant, or GFP-expressing empty vector as described above. Cells were transfected 24 h after infection with each reporter construct (200 ng/well) and a renilla luciferase reporter vector (20 ng/well) (pRL-null; Promega) using Lipofectamine/Plus transfection reagents (Invitrogen). Luciferase activity was detected in cell lysates 24 h after transfection using the dual luciferase reporter system from Promega.

EMSA

ROS 17/2.8 cells were cultured to 90% of confluence and harvested in ice-cold PBS buffer by scraping. Cell pellets were lysed, and nuclear extracts prepared as previously described (78). Protein concentrations were determined by the Bradford method (Pierce Chemical Co., Rockford, IL). Sense and antisense oligonucleotides spanning a classical Runx2 motif (Rx2-C1) were end-labeled with [γ-32P]ATP by use of T4 polynucleotide kinase (New England Biolabs, Beverly, MA) as documented in previous studies (78). Wild-type and mutant oligonucleotides (double stranded) were used as competitors. Nuclear protein extracts (5 μg) were incubated for 30 min at room temperature with 1 μg nonspecific competitor DNA poly (alternating dI-dC · dI-dC · dI-dC) (Pharmacia, Piscataway, NJ) and 80,000 cpm labeled oligonucleotides. Competition assays were performed by adding 100-fold molar excess of unlabeled competitor.
excess of unlabeled oligonucleotides to the binding reaction. Protein-DNA complexes were separated in native 6% polyacrylamide gels and visualized by autoradiography of the dried gels.

For EMSA oligos, only the sense strand is shown. Runx2 motifs are underlined; mutations are shown in italics.

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