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Estrogen plays an important role in the normal breast and breast cancer development. Estrogens exert their cellular effects through ER that is a member of nuclear receptor superfamily. PRIP (Peroxisome proliferator receptor interacting protein) is a nuclear receptor coactivator that is amplified and overexpressed in breast cancer. The proposal was to investigate how the PRIP dysregulation contributes to abnormal growth and neoplastic development of breast. During the first year of the award, we have generated transgenic mice with integrated MMTV-PRIP lineages and heterozygous mice with conditional inactivated PRIP gene. About fifty estrogen-inducible genes have been identified by microarray hybridization. PRIP overexpression and amplification were found in about 60% and 10% of the breast cancers, respectively. PIMT (PRIP interacting protein with a methyltransferase domain) which interacts with and enhances nuclear receptor coactivator PRIP function was identified. PRMT2 (protein arginine methyltransferase 2) was found to act as a coactivator for estrogen receptor alpha. These findings not only advanced our understanding of estrogen signaling pathway but also suggested that nuclear receptor coactivator PRIP plays an important role in the breast cancer development.

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INTRODUCTION

Estrogens play an important role in the normal breast and breast cancer development. Estrogens exert their cellular effects through ER that is a member of nuclear receptor superfamily. Nuclear receptors including estrogen receptor achieve transcriptional activation through the participation of additional factors known as nuclear receptor coactivators. PRIP (Peroxisome proliferator receptor interacting protein) is a nuclear receptor coactivator that is amplified and overexpressed in breast cancer. The proposal was to investigate how the PRIP dysregulation contributes to abnormal growth and neoplastic development of breast. Specifically, transgenic animal models overexpressing PRIP would be developed to determine if overexpression of PRIP is sufficient to cause abnormal growth of mammary glands and if such growth ultimately leads to the development of breast tumors. PRIP transgenic mouse and PRIP null mutation mouse would be used to examine the role of coactivator PRIP in determining the susceptibility of breast cancer development induced by estrogen and chemical carcinogen. The expression of estrogen responsive genes would be examined to test the role of PRIP as an estrogen receptor coactivator in vivo and identify the estrogen responsive genes that are specifically affected by PRIP overexpression and null mutation. The prevalence of PRIP upregulation and amplification in breast cancers would be examined in 300 breast cancer samples. The potential polymorphisms in PRIP genes would be identified and the linkage between the identified polymorphisms and breast cancer risk would be elucidated by examining a large number of normal female and breast cancer patients. The proposed studies would generate novel information regarding the role of nuclear receptor coactivator in breast cancer development and the importance of the variation of nuclear receptor coactivator in the etiology of breast cancer, and most likely provide new insights regarding prevention and treatment strategies.

BODY

Task 1a. Generation of transgenic animal models overexpressing PRIP to determine if overexpression of PRIP is sufficient to cause abnormal growth of mammary glands and if such growth ultimately leads to the development of breast tumors.

We have made a construct MMTV-PRIP (Fig.1) to overexpress PRIP in mammary gland. We then used this construct for microinjection. After the plasmid was linearized, the DNA fragment was purified and microinjected into the pronucleus of F1 (C57BL/6xDBA/2) fertilized mouse embryos which were transplanted into pseudopregnant surrogate mice. Transgenic founders were identified by PCR with primers recognizing the promoter region of the transcription unit. 7 transgenic mouse lineages were identified. The founder mice were bred with C57BL/6 mice to generate F1 progeny.

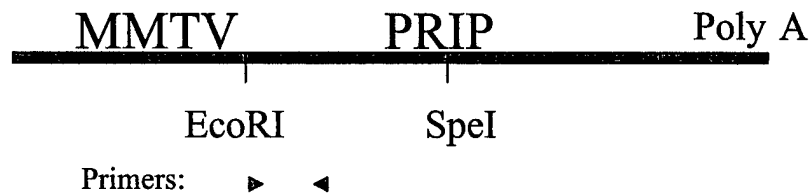


Fig. 1. MMTV-PRIP

Task 1b. Investigation of the role of coactivator PRIP in the susceptibility for breast cancer development to estrogen and chemical carcinogen using PRIP transgenic mouse and PRIP null mutation mouse.

We isolated a mouse P1 genomic clone which covers the entire PRIP gene and found that PRIP is ~47.5 kb in length consisting of 13 exons. The DNA from the P1 clone was used to construct the gene targeting vector loxP-PRIP (Fig. 2). Exons 8 and 9 was flanked with two loxP sites in the introns. Cre recombinase would delete these two exons leading to frame shift mutation after exon 9. The selective gene Neo was also flanked with two loxP sites. The targeting vector was then linearized and transfected into 129/Sv derived ES cells by electroporation. ES cells were selected positively by G418 and negatively by ganciclovir. After 10 days of selection, the surviving colonies were picked up and screened by PCR. Two positive clones were isolated and further confirmed by Southern blotting. ES cells with conditional allele were injected into 3.5-day old blastocysts and implanted into a pseudopregnant foster mother to produce chimeric mice. As 129/Sv ES cells have an agouti coat color genotype, and the C57BL6 embryo is black, the contribution of 129/Sv ES cells to the chimera can be judged by the percentage of agouti coat color. Chimeric males with a high contribution of 129/Sv genetic background were mated with C57BL/6 females to obtain the germ line transmission. The agouti offspring carried one of the two alleles from 129/Sv. Heterozygotes PRIP^{+/loxP} was identified by performing PCR with the tail DNA from the agouties. We have obtained three male heterozygotes PRIP^{+/loxP}.

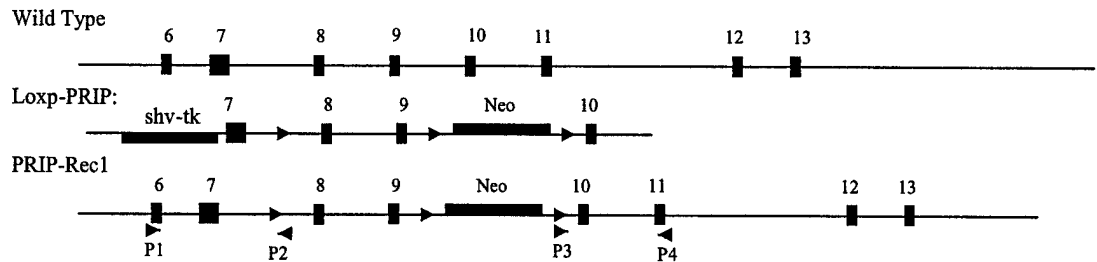


Fig.2. LoxP-PRIP constructs and targeting strategy. Schematic representation of the mouse PRIP gene, targeting vector, and the structure of the locus after gene targeting. Rec1 represents the locus after recombination. The locations of primers used for screening the recombinant ES cell are indicated.

Task 1c. Examination of the expression of estrogen responsive genes and identification of the estrogen responsive genes that are specifically affected by PRIP overexpression and null mutation.

Mammary glands were isolated from *ovariectomized* animals treated with 17β -estradiol or ICI 182,780 for three days. Total cellular RNA was prepared from the mammary glands and poly(A)⁺ RNA was isolated. cDNA probe was made from poly A⁺ RNA for hybridization to Mouse cDNA microarray filters as recommended by manufacturer (Affymatrix). The filters were then exposed to a phosphor imaging system and analyzed using software to obtain the relative expression level of each gene. We found that estrogen treatment increased the mRNA levels of about fifty genes.

We identified PIMT (PRIP interacting protein with a methyltransferase domain) which interacts with and enhances nuclear receptor coactivator PRIP function(1). We also found that PRMT2(protein arginine methyltransferase 2) to act as a coactivator for estrogen receptor α (2).

Task 2. Determination of the prevalence of PRIP upregulation and amplification in breast cancers.

We have collected about 80 breast cancer specimen from the Department of Pathology, Robert Lurie cancer center. RNA and DNA were isolated from the collected tumor samples. By using ribonuclease protection assay and Southern blot, we found about 60% of the breast cancer have PRIP overexpression and 10% have PRIP gene amplification. The overexpression of PRIP was confirmed by examining the protein by immunocytochemistry.

Task 3. Investigation of the polymorphism of PRIP gene in Breast cancer.

18 PCR were performed to cover all exons and 500 bp promoter region of PRIP gene. The PCR products were analyzed by SSCP(single strand conformational polymorphism). By examining 6 females, we found polymorphism A to G at nucleotide 289, G to A at nucleotide 2408.

KEY RESEARCH ACCOMPLISHMENTS

- * Transgenic mice with integrated MMTV-PRIP lineages were generated.
- * Heterozygous mice with conditional inactivated PRIP gene was created.
- * About fifty estrogen-inducible genes were identified.
- * PRIP overexpression and amplification were found in about 60% and 10% of the breast cancers, respectively.
- * PIMT (PRIP interacting protein with a methyltransferase domain) which interacts with and enhances nuclear receptor coactivator PRIP function was identified.
- * PRMT2 (protein arginine methyltransferase 2) was found to act as a coactivator for estrogen receptor α .

REPORTABLE OUTCOMES

1. Zhu YJ, Qi C, Cao WQ, Yeldandi AV, Rao MS, and Reddy JK. Cloning and characterization of PIMT, a protein with a methyltransferase domain, which interacts with and enhances nuclear receptor coactivator PRIP function. *Proc. Natl. Acad. Sci. USA* 98: 10380-10385, 2001.
2. Qi C, Chang J, Zhu YW, Yeldandi AV, Rao MS and Zhu YJ. Identification of PRMT2 as a coactivator for estrogen receptor alpha. *J. Biol. Chem.* (*in press*). 2002

CONCLUSIONS

We have created MMTV-PRIP transgenic mice and heterozygous mice with conditional inactivated PRIP gene which will finally help to reveal the function of this important coactivator. We isolated PIMT and PRMT2 as two components in the estrogen receptor transcriptional activation, advancing our understanding of estrogen signaling pathway. The finding that PRIP overexpression occurs in about 60% and gene amplification occurs 10% of the breast cancers suggested that this coactivator plays an important role in the breast cancer development.

REFERENCES

1. Zhu YJ, Qi C, Cao WQ, Yeldandi AV, Rao MS, and Reddy JK. Cloning and characterization of PIMT, a protein with a methyltransferase domain, which interacts with and enhances nuclear receptor coactivator PRIP function. *Proc. Natl. Acad. Sci. USA* 98: 10380-10385, 2001.
2. Qi C, Chang J, Zhu YW, Yeldandi AV, Rao MS and Zhu YJ. Identification of PRMT2 as a coactivator for estrogen receptor alpha. *J. Biol. Chem.* (in press). 2002.

APPENDICES

Two articles are attached.

Cloning and characterization of PIMT, a protein with a methyltransferase domain, which interacts with and enhances nuclear receptor coactivator PRIP function

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The nuclear receptor coactivators participate in the transcriptional activation of specific genes by nuclear receptors. In this study, we report the isolation of a nuclear receptor coactivator-interacting protein from a human liver cDNA library by using the coactivator peroxisome proliferator-activated receptor-interacting protein (PRIP) (ASC2/AIB3/RAP250/NRC/TRBP) as bait in a yeast two-hybrid screen. Human PRIP-interacting protein cDNA has an ORF of 2,556 nucleotides, encodes a protein with 852 amino acids, and contains a 9-aa VVDAFCGVG methyltransferase motif I and an invariant GXXGXXI segment found in K-homology motifs of many RNA-binding proteins. The gene encoding this protein, designated PRIP-interacting protein with methyltransferase domain (PIMT), is localized on chromosome 8q11 and spans more than 40 kb. PIMT mRNA is ubiquitously expressed, with a high level of expression in heart, skeletal muscle, kidney, liver, and placenta. Using the immunofluorescence localization method, we found that PIMT and PRIP proteins appear colocalized in the nucleus. PIMT strongly interacts with PRIP under *in vitro* and *in vivo* conditions, and the PIMT-binding site on PRIP is in the region encompassing amino acids 773–927. PIMT binds S-adenosyl-L-methionine, the methyl donor for methyltransferase reaction, and it also binds RNA, suggesting that it is a putative RNA methyltransferase. PIMT enhances the transcriptional activity of peroxisome proliferator-activated receptor γ and retinoid-X-receptor α , which is further stimulated by coexpression of PRIP, implying that PIMT is a component of nuclear receptor signal transduction apparatus acting through PRIP. Definitive identification of the specific substrate of PIMT and the role of this RNA-binding protein in transcriptional regulation remain to be determined.

The nuclear receptor superfamily consists of members of ligand-regulated transcriptional factors comprising receptors for steroid and thyroid hormones, vitamin D₃, retinoic acid, and peroxisome proliferators, among others (1, 2). All nuclear receptors share a common structure with a highly conserved DNA-binding domain consisting of two zinc fingers, a C-terminal hormone-binding domain, and two transcriptional activation function (AF) domains, termed AF-1 in the N-terminal domain and AF-2 in the hormone-binding domain (3). Transactivation of the AF-2 domain is ligand-dependent and can be blocked by the binding of antagonists. The activities of AF-1 and -2 vary depending on responsive cell types as well as a short DNA sequence, termed response element, located in the promoter regions of target genes (2, 3).

The molecular mechanism(s) by which nuclear receptors achieve transcriptional activation in a tissue-specific fashion is not fully understood. The current models call for the participation of additional factors for modifying the chromatin structure and mediating the interaction between the activated nuclear receptor and the basal transcriptional machinery in a ligand-dependent fashion. During the past few years, many nuclear receptor-binding proteins have been identified (4, 5). Most of

them contain the conserved LXXLL (where L is leucine and X is any amino acid) signature motif, which mediates recognition of nuclear receptors (4). The nuclear receptor coactivators identified to date include the well-characterized steroid receptor coactivator-1 (SRC-1) family with three members [SRC-1 (6), TIF-2 (SRC-2, GRIP1) (7), p/CIP (ACTR, AIB1, RAC3, and SRC-3) (8–10)], CREB-binding protein (CBP)/p300 (11), PPAR-binding protein (PBP) (12), and PPAR γ coactivator-1 (PGC-1) (13). SRC-1 and CBP/p300 possess intrinsic histone acetyltransferase activity and also recruit other proteins with histone acetyltransferase activity, indicating their role in chromatin modification (2, 4, 8, 14). In addition to histone acetylation, there is emerging evidence that suggests a role for histone methylation in the regulation of nuclear receptor transcriptional activity. A protein, designated as coactivator-associated arginine methyltransferase 1 (CARM1), which associates with SRC-2, can methylate histones, and the methyltransferase activity of CARM1 appears necessary for this protein to potentiate nuclear receptor activity (15). Furthermore, protein arginine methyltransferase 1, which shares a region of homology with CARM1, appears to enhance transcriptional activity by acting synergistically with CARM1 (16). Recent evidence suggests that coactivator proteins form distinct coactivator complexes, such as the one anchored by CBP/p300 that integrates the SRC-1 family of proteins and p/CAF to carry out histone acetyltransferase reactions, and the other thyroid hormone receptor-associated protein (TRAP)/vitamin D receptor-interacting protein (DRIP)/activator-recruited cofactor (ARC) complex anchored by PBP (TRAP220/DRIP205) (12, 17–19), which links to the basal transcription machinery (4, 20). PBP, with no histone acetyltransferase activity, serves as an anchor protein to recruit the multiprotein complex that appears to act more directly on the transcriptional apparatus, presumably after the unwinding of chromatin facilitated by the CBP/p300 anchored multiprotein complex (4). In agreement with the central role of CBP/p300 and PBP in the coactivator complex configuration and in nuclear receptor-mediated transcriptional activity, knockout experiments revealed that both CBP, p300, and PBP null mutations

Abbreviations: PPAR, peroxisome proliferator-activated receptor; PPRE, peroxisome proliferator response element; SRC-1, steroid receptor coactivator-1; CARM1, coactivator-associated arginine methyltransferase 1; PRIP, PPAR-interacting protein; PIMT, PRIP-interacting protein with methyltransferase domain; EST, expressed sequence tag; RXR, retinoid-X-receptor for 9-*cis*-retinoic acid; GST, glutathione S-transferase; AdoMet, S-adenosyl-L-methionine; PBP, PPAR-binding protein.

Data deposition: The sequences reported in this paper have been deposited in the GenBank database (accession nos. AY028423 and AF389908).

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lead to embryonic lethality (21–26), indicating that disruption of these pivotal anchoring coactivators affects the function of many nuclear receptors and possibly other transcription factors.

In this work, we report the cloning of a protein that binds the recently identified nuclear receptor coactivator peroxisome proliferator-activated receptor-(PPAR) interacting protein (PRIP) (ASC2/AIB3/RAP250/NRC/TRBP) (27–31). We cloned PRIP by using PPAR γ as bait in the yeast two-hybrid system (27); others have cloned this coactivator by using thyroid hormone receptor and retinoid-X-receptor for 9-*cis*-retinoic acid (RXR) (28–31). To elucidate the role of PRIP, we set out to isolate the PRIP-interacting protein(s) with a two-hybrid system. One of the proteins identified is designated PRIP-interacting protein with methyltransferase domain (PIMT); this protein is a ubiquitously expressed nuclear protein containing a methyltransferase domain. PIMT is able to enhance the transcriptional activity of PPAR γ and RXR α , which is further potentiated by overexpression of PRIP. We also show that PIMT binds *S*-adenosyl-L-methionine (AdoMet) and RNA, implying that PIMT may function as a putative RNA methyltransferase.

Materials and Methods

Plasmids. GAL4-PRIP (amino acids 773–2068), GAL4-PPAR γ , PCMV-PRIP, PCMV-PPAR γ , peroxisome proliferator response element (PPRE)-luciferase (LUC), PCMV-RXR α , and RXRE-LUC have been described elsewhere (12, 27, 32). PCMV-PIMT was constructed by inserting the full-length coding region of PIMT cDNA into *Hind*III/*Xho*I site of PCDNA 3.1(+) (Invitrogen). PCMV-PIMT-FLAG was made by inserting full-length PIMT cDNA into *Hind*III/*Bam*HI site of p3XFLAG-CMV-14 (Sigma).

Isolation of Human and Mouse PIMT cDNA. A partial cDNA encoding a protein that interacts with PRIP was first isolated by yeast two-hybrid screening of a human liver cDNA library, as described previously (12, 27). We then obtained the full-length cDNA by checking human expressed sequence tag (EST) in GenBank. The full-length cDNA we cloned has been designated PIMT to reflect its ability to bind PRIP and its putative functional domain. We then searched the mouse EST database in GenBank, by using the human PIMT cDNA sequence. Several ESTs, including ESTs covering the 5' and 3' of PIMT cDNA, were found. The primers 5'-GAGCCCCGATAACGAAATGT-3' and 5'-CTTCTCTGTCTCTCACTT-3' were synthesized on the basis of the EST sequences. The full-length mouse PIMT cDNA was amplified by using spleen mouse cDNA and sequenced.

Northern Blot Analysis and *In Situ* Hybridization. Human multiple tissue Northern blot (CLONTECH) containing 2 μ g of poly(A) RNA in each lane was probed with ³²P-labeled PIMT full-length cDNA, according to the conditions outlined by the manufacturer. For *in situ* hybridization, tissues were fixed in 4% paraformaldehyde at 4°C for 14–18 h, dehydrated, embedded in paraffin, and 7- μ m-thick sections were cut under ribonuclease-free conditions. RNA riboprobes (antisense and sense riboprobes) for PIMT were synthesized in the presence of digoxigenin-labeled UTP (Roche Diagnostics). Prehybridization, hybridization, washing, and immunological detection were performed as described (33).

Glutathione S-Transferase (GST) Pull-Down Assays. The GST alone or GST-fusion protein, GST-PRIP (amino acids 772–1317), was expressed in *Escherichia coli* BL21 and bound to glutathione-Sepharose-4B beads according to the manufacturer's instructions (Amersham Pharmacia). *In vitro* translation was performed by using rabbit reticulocyte lysate (Promega) and labeled with [³⁵S]methionine. In a GST pull-down assay, 15 μ l of GST fusion

protein on glutathione-Sepharose beads was incubated with 5 μ l of [³⁵S]methionine-labeled *in vitro*-translated proteins for 2 h in 600 μ l of 20 mM Tris-HCl, pH 7.5/100 mM KCl/0.7 mM EDTA/0.05% Nonidet P-40/1 mM phenylmethylsulfonyl fluoride (NETN). Bound proteins were washed four times with 800 μ l of NETN, eluted by boiling for 2 min in 24 μ l of SDS loading buffer, separated by SDS/PAGE, and autoradiographed.

Immunoprecipitation. COS-1 cells are transfected with PCMV-PIMT-FLAG by the calcium precipitation method. Twenty-four hours after transfection, the cell was harvested. The lysate was immunoprecipitated with anti-PRIP or preimmune serum. The precipitates were resolved on SDS/PAGE and subjected to Western blot analysis by using anti-FLAG (Sigma).

Cell Culture and Transfection. CV-1 cells (1×10^5) were plated in six-well plates and cultured in DMEM containing 10% FCS for 24 h before transfection. Cells were transfected for 5 h with 1.5 μ g of luciferase reporter plasmid DNA, 1.5 μ g of appropriate expression plasmid DNA, and 0.4 μ g of β -galactosidase expression vector pCMV β (CLONTECH) DNA by using the Lipofectamine 2000-mediated transfection method (GIBCO/BRL). Cell extracts were prepared 24 h after transfection and assayed for luciferase and β -galactosidase activities (Tropix, Bedford, MA).

Immunofluorescence. COS-1 cells were transfected with PCMV-PIMT-FLAG by using Lipofectamine 2000 (GIBCO/BRL), and 24 h after transfection, the cells were fixed in 1% formaldehyde and washed once with PBS, pH 7.4, after which autofluorescence was quenched with 50 mM ammonium chloride in PBS. Cells were washed with PBS, permeabilized with 0.5% saponin, and then blocked with 0.2% fish skin gelatin. The cells were incubated with the primary antibody anti-FLAG (Sigma) and anti-PRIP, followed by incubation with secondary antibodies. Fluorescence microscopy and digital image collection were performed by using an Olympus (New Hyde Park, NY) microscope and a photometrix cooled charge-coupled device camera driven by DELTAVISION software from Applied Precision (Seattle).

AdoMet-Binding Assay. Purified GST or GST-PIMT (10 μ g) was incubated with 20 μ Ci of *S*-adenosyl-L-[methyl-³H]methionine (Amersham Pharmacia) in a buffer containing 20 mM Tris-HCl, pH 7.5, 150 mM NaCl, and 2 mM MgCl₂, at 37°C for 10 min. The protein was trapped on a HAWP 02500 filter (Millipore). Unbound *S*-adenosyl-L-[methyl-³H]methionine was removed by washing with the buffer (20 mM Tris-HCl, pH 7.5/150 mM NaCl/2 mM MgCl₂). The filters were dried, and the amount of bound *S*-adenosyl-L-[methyl-³H]methionine was quantified by liquid scintillation counting.

RNA-Binding Gel Retardation Assay. The degenerate ³²P-labeled RNA (GGAGACCGGCCAGGAUCCAAGCUNNNNNNNN-CAUAAGGAUCCAAGCUAA) was generated by *in vitro* transcription (Ambion, Austin, TX). Reactions (20 μ l) containing 0.1 μ g of protein indicated, 1 μ g of anti-FLAG, 10,000 cpm of RNA, and 1 \times buffer (20 mM Tris-HCl, pH 7.5/150 mM NaCl/2 mM MgCl₂) was assembled and incubated for 15 min on ice. The reactions were loaded on a native polyacrylamide gel (Invitrogen) running at 300 V at 4°C in 0.5 \times TBE buffer (90 mM Tris/64.6 mM boric acid/2.5 mM EDTA, pH 8.3). The gels were dried and autoradiographed.

Results

Isolation of PIMT. Using PRIP (amino acids 773–2068) as bait in a yeast two-hybrid system, we isolated from human liver cDNA library a partial cDNA encoding a PRIP-interacting protein, which was designated as PIMT. The rest of the cDNA was obtained from a human EST clone that was identified by



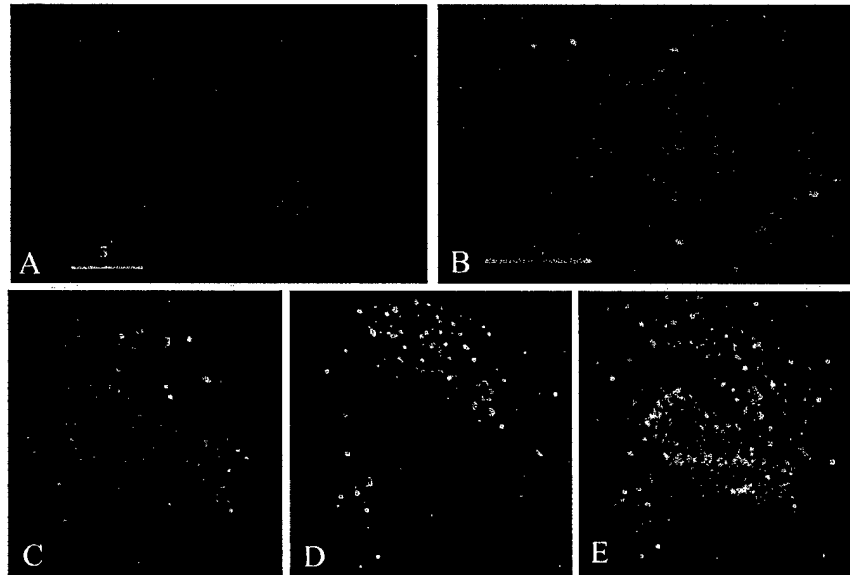


Fig. 4. PIMT and PRIP colocalize in the nucleus. PRIP was visualized by using conventional fluorescence microscopy (A) and by DELTA-VISION deconvolution microscopy (B). By DELTA-VISION microscopy, a speckled pattern of distribution of this coactivator is noted. PIMT was expressed transiently in COS-1 cells by using three FLAG epitopes linked to the C terminus of PIMT, and the FLAG epitope of PIMT was visualized by deconvolution microscopy by using anti-FLAG antibodies (C). Merging of the PIMT (D) and PRIP (D) localization images reveals overlapping localization (yellow) of these two proteins (E).

fluorescence with anti-FLAG revealed the expressed PIMT protein is localized in the nucleus (Fig. 4). Localization of PRIP by using anti-PRIP revealed that PRIP is also localized in the nucleus and, when the images of PIMT and PRIP localization were merged, an overlapping localization of PRIP and PIMT has been noted, suggesting colocalization of these molecules in the nucleus (Fig. 4).

Interaction of PIMT with PRIP *in Vitro* and *in Vivo*. The direct interaction between PRIP and PIMT was further tested by using *in vitro* a GST-binding assay with a bacterially generated GST-PRIP fusion protein (amino acids 773-1317) and radioactively labeled *in vitro*-translated PIMT. As shown in Fig. 5, PIMT specifically interacted with the immobilized GST-PRIP but not with GST. Using further truncated PRIP, we narrowed the PIMT-binding site on PRIP to a region encompassing amino acids 773-927 (Fig. 5A). To determine whether PIMT and PRIP interact within the context of intact cells, a vector encoding human PIMT with C-terminal FLAG epitopes was transfected into COS-1 cells. The potential complex between PRIP and PIMT was immunoprecipitated by using anti-PRIP, and the product was analyzed by immunoblotting by using anti-FLAG to demonstrate PIMT in the precipitate (Fig. 5B). The results showed that anti-PRIP precipitated PIMT but not control serum, demonstrating the existence of a PRIP and PIMT complex *in vivo* (Fig. 5B). Because PRIP is able to form homodimers, we examined whether PIMT can also form homodimers. A GST pull-down assay was performed with GST-PIMT fusion protein (amino acids 326-852) and *in vitro*-translated [³⁵S]methionine-labeled human PIMT. The results demonstrated that *in vitro*-translated PIMT interacts with GST-PIMT, suggesting that PIMT may form homooligomers (Fig. 5C).

PIMT Binds AdoMet. Human PIMT contains discernible methyltransferase motifs I, II, and III, and also a conserved motif called Post 1 (Figs. 1 and 2). Because motif I (FXGXG) is known to interact with an adenosyl moiety of the cofactor (34, 35), we assessed the ability of human PIMT to bind AdoMet by a filter-binding assay. The partial PIMT (amino acid residues

326-852), which contains the putative methyltransferase domain, binds AdoMet, whereas the N-terminal PIMT fragment (amino acids 1-384), which does not contain these motifs, failed to bind AdoMet (Fig. 6A).

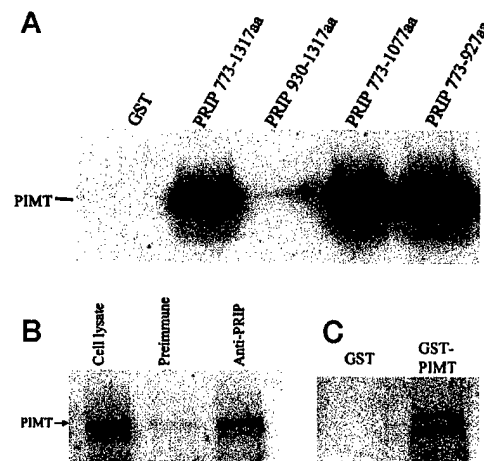


Fig. 5. *In vitro* interaction of PRIP with PIMT. (A) [³⁵S]Methionine-labeled full-length PIMT generated by *in vitro* translation was incubated with glutathione-Sepharose beads bound with purified *E. coli*-expressed GST-PRIP (amino acids 773-1317, 930-1317, 773-1077, and 773-927) or GST. The bound proteins were eluted and analyzed by using 10% SDS/PAGE and autoradiographed. (B) Coimmunoprecipitation of PIMT and PRIP in intact cells. pcDNA3.1-FLAG-PIMT were transfected into COS-1 cells and, 24 h after transfection, cells were harvested. Cell lysate was immunoprecipitated with anti-PRIP or control serum, and immunoprecipitates were subjected to immunoblotting with anti-FLAG. Epitope-tagged protein PIMT can be coprecipitated by anti-PRIP (lane 3) but not by preimmune serum (lane 2). Lane 1, 1/20 input cell lysate. (C) PIMT forms homodimers. GST-PIMT (326-852 aa) or GST alone was incubated with PIMT labeled with [³⁵S]methionine. The bound protein was electrophoresed and visualized by fluorography. GST-PIMT, but not GST alone, binds PIMT.

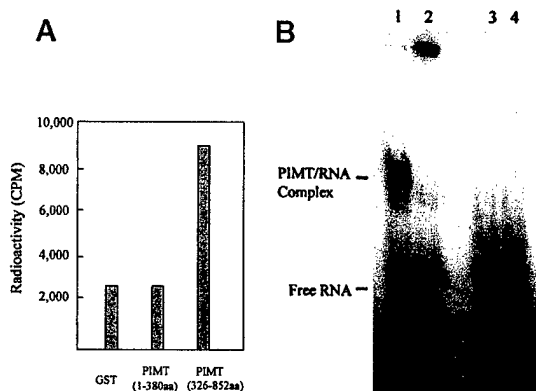


Fig. 6. PIMT binds AdoMet and RNA. (A) PIMT binds AdoMet. Purified protein was incubated with *S*-adenosyl-L-[methyl-³H]methionine, and the amount of protein bound to AdoMet was trapped on a filter and quantified by liquid scintillation. GST-PIMT (amino acids 326–852), which contained the methyltransferase domain, retained a significant amount of labeled AdoMet, whereas the filter with GST-PIMT (amino acids 1–384) showed background radioactivity as that with GST alone. (B) PIMT is an RNA-binding protein. ³²P-labeled RNA produced by *in vitro* transcription is incubated with purified FLAG-PIMT (amino acids 1–384). A PIMT–RNA complex is seen in addition to the free RNA (lane 1). The addition of anti-FLAG markedly diminished the complex; instead, antibody and PIMT–RNA formed a big complex, which hardly migrated into the gel (lane 2). Lanes 3 and 4 represent controls by using purified FLAG-PRIP (amino acids 786–1132) and purified FLAG-PRIP (amino acids 786–1132) plus anti-FLAG, respectively.

PIMT Is an RNA-Binding Protein. In an effort to search for the potential substrate of PIMT, we examined whether PIMT can bind to RNA by using a gel-shift assay. When purified FLAG-PIMT (amino acids 1–384) was incubated with ³²P-labeled RNA produced by *in vitro* transcription, a PIMT–RNA complex was produced (Fig. 6B, lane 1). The addition of anti-FLAG markedly diminished the formation of the PIMT–RNA complex; instead, antibody and PIMT–RNA formed a high molecular-weight complex, which failed to migrate into the gel (Fig. 6B, lane 2). As a control, when purified FLAG-PRIP (amino acids 786–1132) was used in an RNA-binding assay with or without anti-FLAG, no detectable RNA binding was observed (Fig. 6B, lanes 3 and 4). Close examination of PIMT amino acids 1–384 revealed that they contained a consensus sequence GXXGXXI (Fig. 1), which is present in virtually all K-homology domains of RNA-binding proteins (39, 40). A gel retardation experiment revealed that FLAG-PIMT (amino acids 1–384) was unable to bind single- and double-stranded DNA (data not shown).

PIMT Potentiates the Transcriptional Activity of PPAR γ . To determine the functional relevance of the interaction of PIMT with PRIP, we transiently overexpressed PIMT and PRIP in CV-1 cells along with PPAR γ and monitored the transcriptional activity of PPAR γ with expression of the PPRE-linked reporter luciferase gene. Both PIMT and PRIP, when transfected individually, consistently increased the transcription of the PPAR γ -mediated luciferase gene by about 1.6-fold in the presence of PPAR γ ligand BRL49653 (Fig. 7A). Cotransfection of PIMT and PRIP resulted in further enhancement of ligand-dependent reporter gene expression, indicating that PIMT synergizes PRIP action. The truncated PIMT (amino acids 1–384), without methyltransferase domains, can also enhance PPAR γ transcriptional activity by about 1.8-fold, suggesting the methyltransferase domain is not necessary for PIMT's ability to enhance the transcriptional activity of PPAR γ under the conditions of transient transfection. Similar results were observed with RXR α (Fig. 7B).

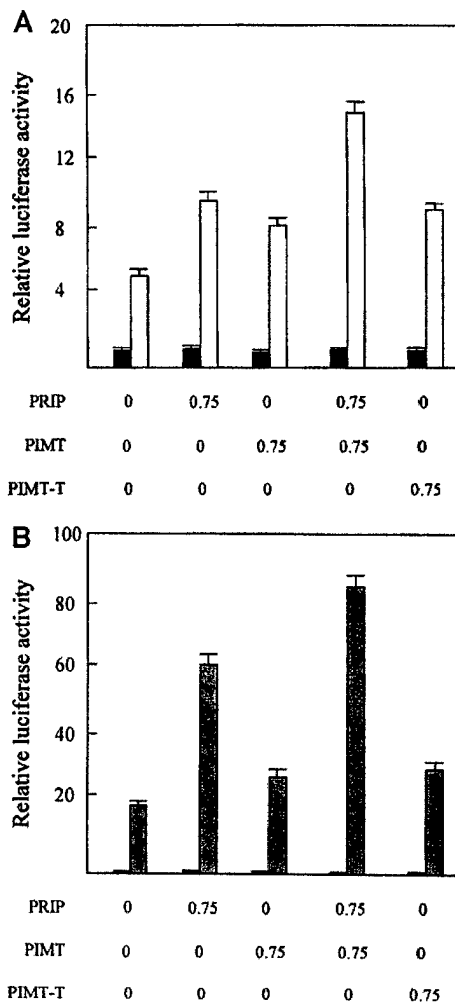


Fig. 7. PIMT increases PPAR γ - and RXR α -mediated transactivation of reporter expression in CV-1 cells. (A) CV-1 cells were cotransfected with 1.5 μ g of reporter construct PPRE-TK-LUC, 25 ng of PCMV-mPPAR γ , and 0.4 μ g of PCMV β , along with the indicated plasmid in the absence (solid bar) or presence (open bar) of 10⁻⁵ M BRL49653. Transfection, without the indicated plasmid, was compensated by adding the same amount of PCDNA3.1. The activity obtained on transfection of PPRE-TK-LUC, without exogenous PIMT in the absence of ligand was taken as 1. Results are the mean of three independent transfections. (B) Transfection analysis for RXR α was performed in the same way as PPAR γ , except for using RXRE-TK-LUC and PCMV-RXR α in the absence (solid bar) and presence (hatched bar) of ligand 9-*cis*-retinoic acid.

Discussion

In a previous study, using the yeast two-hybrid system, we isolated and characterized mouse PRIP as a PPAR coactivator (27). The cloning of this nuclear receptor coactivator from human and rat has also been reported (28–31). PRIP has been shown to interact with a variety of nuclear receptors and also CBP and is widely expressed with the highest expression in heart, ovary, testis, prostate, and skeletal muscle (27–31). These observations suggested this coactivator may prove as indispensable as CBP, p300, and PBP in mediating the transcriptional activity of nuclear receptors and other transcription factors. In this study, we used a two-hybrid system with PRIP as bait and isolated PIMT, a PRIP-interacting protein, which has a methyltransferase domain. The mRNA of PIMT is ubiquitously expressed, and its protein appears colocalized in the nucleus

with PRIP. It appears that both PRIP and PIMT are expressed abundantly in the same tissues and cell types, suggesting these two proteins play a synergistic function *in vivo*. The PIMT-binding region in PRIP (amino acids 773–927) has also been determined by using truncated portions of PRIP in GST pull-down assays; this region avidly binds PIMT. Overexpression of PIMT enhances the transcriptional activity of PPAR γ and RXR, and this enhancement is further stimulated by overexpression of PRIP, suggesting that PIMT is a component of nuclear receptor signal transduction that acts through PRIP.

PIMT reveals the presence of an AdoMet-binding site VVDAFCGVG, which is similar to the highly conserved methyltransferase motif I with a consensus hh(D/S)(L/P)FXGXG, (where “h” represents a hydrophobic residue, and “X” represents any amino acid) (34, 35). This motif is found in several methyltransferases and other enzymes that use AdoMet as substrate (34–36). Of considerable interest is that the motif FCGVG present in PIMT corresponds to the sequence (FXGXG) found in many RNA and DNA methyltransferases (34, 35, 41). The Phe in this motif is known to interact with the adenosyl moiety of the cofactor AdoMet (35). In other methyltransferases, particularly in protein arginine methyltransferases, Phe is often substituted by Gly (34, 35). The binding of AdoMet, the donor of methyl groups, to purified PIMT under *in vitro* conditions essentially confirms that PIMT is a putative methyltransferase, but the target of PIMT remains unknown. Although PIMT failed to methylate *in vitro* either histone, unlike CARM1 (15), or DNA (Y.Z., unpublished work), we found that it binds RNA. The segment of PIMT (amino acids 1–384) that binds RNA contains an invariant GXXGXIXI motif present in the K-homology domains of RNA-binding proteins (39, 40). It is estimated that the human genome contains \approx 1,500 RNA-binding proteins, but their distribution across global, group-specific, and type-specific classes is unknown (42). PIMT may function as a putative RNA methyltransferase, raising the possibility that some coactivators and/or their cofactors may influence transcription by binding and methylating RNA. PIMT

shows high homology with an uncharacterized protein YPL157W (GenBank accession no. Z73513) from yeast and a functionally unknown protein (GenBank accession no. T24696) from *C. elegans*. They most probably represent the homologues of PIMT and should have similar substrates. The yeast strain with null mutation of YPL157W gene has been generated by the *Saccharomyces* Genome Deletion Project and has turned out to be viable. We have analyzed the methyl proteins in the YPL157W mutated and wild strains by *in vivo* labeling with *S*-adenosyl-L-[methyl- 3 H]methionine. The methyl protein pattern in the mutated strain appeared similar to that of wild type, but we cannot rule out the possibility that the YPL157W protein methylates a less abundant protein not identified by SDS/PAGE gel (Y.Z., unpublished work).

Methylation plays an important role in the regulation of gene expression (43, 44). Methylation of the promoter participates in the inactivation of gene transcription, which contributes to the silencing of tumor suppressor genes in cancers, whereas methylation of sites downstream of transcriptional initiation is associated with increased transcription (41, 44). In addition to DNA methylation, the importance of histone methylation in the transcriptional regulation is increasingly appreciated (15, 16). Although PIMT does not methylate the histone, it could be involved in transcriptional regulation by methylating other transcriptional components. Truncated PIMT, without the methyltransferase domain, still showed its ability to enhance the transcriptional activity of PPAR γ and RXR α , suggesting this enzyme activity may not be crucial to transcription under transient transfection conditions. Given the oversimplified transient transfection system, the role of PIMT's methyltransferase activity in transcriptional regulation remains to be appreciated in the context of *in vivo* physiological condition.

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- Evans, R. M. (1988) *Science* **240**, 889–895.
- McKenna, N. J., Lanz, R. B. & O'Malley, B. W. (1999) *Endocrine Rev.* **20**, 321–344.
- Nagpal, S., Friant, S., Nakshatri, H. & Chambon, P. (1993) *EMBO J.* **12**, 2349–2360.
- Glass, C. K. & Rosenfeld, M. G. (2000) *Genes Dev.* **14**, 121–141.
- Shang, Y., Hu, X., DiRenzo, J., Lazar, M. A. & Brown, M. (2000) *Cell* **103**, 843–852.
- Onate, S.A., Tsai, S. Y., Tsai, M. J. & O'Malley, B. W. (1995) *Science* **270**, 1354–1357.
- Voegel, J. J., Heine, M. J. S., Zechel, C., Chambon, P. & Gronemeyer, H. (1996) *EMBO J.* **15**, 3667–3675.
- Chen, H., Lin, R. J., Schiltz, R. L., Chakravarti, D., Nash, A., Nagy, L., Privalsky, M. L., Nakatani, Y. & Evans, R. M. (1997) *Cell* **90**, 569–580.
- Anzick, S. L., Kononen, J., Walker, R. L., Azorsa, D. O., Tanner, M. M., Guan, X. Y., Sauter, G., Kallioniemi, O. P., Trent, J. M. & Meltzer, P. S. (1997) *Science* **277**, 965–968.
- Torchia, J., Rose, D. W., Inostroza, J., Kamei, Y., Westin, S., Glass, C. K. & Rosenfeld, M. G. (1997) *Nature (London)* **387**, 677–684.
- Kamei, Y., Xu, L., Heinzel, T., Torchia, J., Kurokawa, R., Glass, C. K., Lin, S. C., Heyman, R. A., Rose, D. W., Glass, C. K. & Rosenfeld, M. G. (1996) *Cell* **85**, 403–414.
- Zhu, Y., Qi, C., Jain, S., Rao, M. S. & Reddy, J. K. (1997) *J. Biol. Chem.* **272**, 25500–25506.
- Puigserver, P., Wu, Z., Park, C. W., Graves, R., Wright, M. & Spiegelman, B. M. (1998) *Cell* **92**, 829–839.
- Chakravarti, D., LaMorte, V. J., Nelson, M. C., Nakajima, T., Schulman, I. G., Jugulion, H., Montminy, M. & Evans, R. M. (1996) *Nature (London)* **383**, 99–102.
- Chen, D., Ma, H., Hong, H., Koh, S. S., Huang, S.-M., Schurter, B. T., Aswad, D. W. & Stallcup, M. R. (1999) *Science* **284**, 2174–2177.
- Koh, S. S., Chen, D., Lee, Y.-H. & Stallcup, M. R. (2001) *J. Biol. Chem.* **276**, 1089–1098.
- Yuan, C. X., Ito, M., Fondell, J. D., Fu, Z. Y. & Roeder, R. G. (1998) *Proc. Natl. Acad. Sci. USA* **95**, 7939–7944.
- Rachez, C., Lemon, B. D., Suldian, Z., Bromleigh, V., Gamble, M., Naar, A. M., Erdjument-Bromage, H., Tempst, P. & Freedman, L. P. (1999) *Nature (London)* **398**, 824–828.
- Naar, A. M., Beaurang, P. A., Zhou, S., Abraham, S., Solomon, W. & Tjian, R. (1999) *Nature (London)* **398**, 828–832.
- Qi, C., Zhu, Y. & Reddy, J. K. (1999) *Cell Biochem. Biophys.* **31**, 1–18.
- Yao, T.-P., Oh, S. P., Fuchs, M., Zhou, N.-D., Ch'ng, L.-E., Newsome, D., Bronson, R. T., Li, E., Livingston, D. L. & Eckner, R. (1998) *Cell* **93**, 361–372.
- Oike, Y., Takakura, N., Hata, A., Kaname, T., Akizuki, M., Yamaguchi, Y., Yasue, H., Araki, K., Yamamura, K. & Suda, T. (1999) *Blood* **93**, 2771–2779.
- Kung, A. L., Rebel, V. I., Bronson, R. T., Ch'ng, L.-E., Sieff, C. A., Livingston, D. M. & Yao, T.-P. (2000) *Genes Dev.* **14**, 272–277.
- Goodman, R. H. & Smolik, S. (2000) *Genes Dev.* **14**, 1553–1577.
- Zhu, Y., Qi, C., Jia, Y., Nye, J. S., Rao, M. S. & Reddy, J. K. (2000) *J. Biol. Chem.* **275**, 14779–14782.
- Ito, M., Yuan, C.-X., Okano, H. J., Darnell, R. B. & Roeder, R. G. (2000) *Mol. Cell* **5**, 683–693.
- Zhu, Y., Kan, L., Qi, C., Kanwar, Y. S., Yeldandi, A. V., Rao, M. S. & Reddy, J. K. (2000) *J. Biol. Chem.* **275**, 13510–13516.
- Lee, S.-K., Anzick, S. L., Choi, J.-E., Bubendorf, L., Guan, X.-Y., Jung, Y.-K., Kallioniemi, O. P., Kononen, J., Trent, J. M., Azorsa, D., et al. (1999) *J. Biol. Chem.* **274**, 34283–34293.
- Mahajan, M. & Samuels, H. H. (2000) *Mol. Cell Biol.* **20**, 5048–5063.
- Caira, F., Antonson, P., Pelto-Huikko, M., Treuter, E. & Gustafsson, J.-A. (2000) *J. Biol. Chem.* **275**, 5308–5317.
- Ko, L., Cardona, G. R. & Chin, W. W. (2000) *Proc. Natl. Acad. Sci. USA* **97**, 6212–6217.
- Zhu, Y., Qi, C., Calandra, C., Rao, M. S. & Reddy, J. K. (1996) *Gene Expression* **6**, 185–195.
- Komminoth, P., Merk, F. B., Leav, I., Wolfe, H. J. & Roth, J. (1992) *Histochemistry* **98**, 217–228.
- Lauster, R. (1989) *J. Mol. Biol.* **206**, 313–321.
- Kagan, R. M. & Clarke, S. (1994) *Arch. Biochem. Biophys.* **310**, 417–427.
- Kumar, S., Cheng, X., Klimasaukas, S., Mi, S., Posfai, J., Roberts, R. J. & Wilson, G. (1994) *Nucleic Acids Res.* **22**, 1–10.
- Tang, J., Garry, J. D., Clarke, S. & Herschman, H. R. (1998) *J. Biol. Chem.* **273**, 16935–16945.
- Jeltsch, A., Christ, F., Fatemi, M. & Roth, M. (1999) *J. Biol. Chem.* **274**, 19538–19544.
- Burd, C. G. & Dreyfuss, G. (1994) *Science* **265**, 615–621.
- Lewis, H. A., Musunuru, K., Jensen, K. B., Edo, C., Chen, H., Darnell, R. B. & Burley, S. K. (2000) *Cell* **100**, 323–332.
- Wu, G., William, H. D., Zamanian, M., Gibson, F. & Poole, R. K. (1992) *J. Gen. Virol.* **73**, 2101–2112.
- Keene, J. D. (2001) *Proc. Natl. Acad. Sci. USA* **98**, 7018–7024.
- Colota, V. & Rossignol, J.-L. (1999) *BioEssays* **21**, 402–411.
- Smith, S. S. (1998) *Int. J. Mol. Med.* **1**, 147–156.

Identification of Protein Arginine Methyltransferase 2 As a Coactivator for Estrogen Receptor α *

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AQ: A

In an attempt to isolate cofactors capable of influencing estrogen receptor α (ER α) transcriptional activity, we used yeast two-hybrid screening and identified protein arginine methyltransferase 2 (PRMT2) as a new ER α -binding protein. PRMT2 interacted directly with three ER α regions including AF-1, DNA binding domain, and hormone binding domain in a ligand-independent fashion. The ER α -interacting region on PRMT2 has been mapped to a region encompassing amino acids 133–275. PRMT2 also binds to ER β , PR, TR β , RAR α , PPAR γ , and RXR α in a ligand-independent manner. PRMT2 enhanced both ER α , AF-1, and AF-2 transcriptional activity, and the potential methyltransferase activity of PRMT2 appeared pivotal for its coactivator function. In addition, PRMT2 enhanced PR-, PPAR γ -, and RAR α -mediated transactivation. Although PRMT2 was found to interact with two other coactivators, the steroid receptor coactivator-1 (SRC-1) and the peroxisome proliferator-activated receptor-interacting protein (PRIP), no synergistic enhancement of ER α transcriptional activity was observed when PRMT2 was coexpressed with either PRIP or SRC-1. In this respect PRMT2 differs from coactivators PRMT1 and CARM1 (coactivator-associated arginine methyltransferase). These results suggest that PRMT2 is a novel ER α coactivator.

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The estrogen receptor (ER)¹ is a transcription factor that belongs to the nuclear receptor superfamily (1, 2). Upon estrogen binding, ER regulates the transcription of specific target genes by binding to specific DNA response elements referred to as estrogen response elements (EREs) in their promoters or by interacting with other transcription factors such as Jun and Fos (1, 2). In addition to hormone-mediated activation, ER is also activated by growth factors including epidermal growth

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¹ The abbreviations used are: ER, estrogen receptor; ERE, estrogen responsive element; AF, activation function; CREB, cAMP response element-binding protein; CBP, CREB-binding protein; PRMT, protein arginine methyltransferase; CARM1, coactivator-associated arginine methyltransferase 1; TK, thymidine kinase; LUC, luciferase; PPAR, peroxisome proliferator-activated receptor; PRIP, PPAR-interacting protein; PPRE, peroxisome proliferator response element; GST, glutathione S-transferase; SRC-1, steroid receptor coactivator-1; RXR, retinoid-X receptor; TR, thyroid hormone (T₃) receptor.

factor and insulin-like growth factor-1 probably through phosphorylation (3, 4). ER contains two transcriptional activation function (AF) domains: AF-1 located in the N terminus and the ligand-dependent AF-2 located in the ligand binding domain (5). The ability of AF-1 and AF-2 to activate transcription varies according to the promoter context and the cell type (6). There are two isoforms of estrogen receptors, namely ER α and ER β (7). ER α and ER β recognize identical DNA elements and have similar affinity for a certain estrogen, but exhibit distinct tissue distribution (7). Evidence provided by gene knock experiments indicates that ER α is the receptor responsible for the estrogen-induced growth of mammary gland and of the reproductive tract (8).

The precise mechanism by which ER modulates cell- and gene-specific transcription is not fully understood. Recent evidence suggests that ER activates transcription by recruiting coactivators that appear to act by modifying chromatin structure or facilitating the formation of transcriptional initiation complexes (9, 10). Among a growing list of cofactors that regulate nuclear receptors, including ER, are the well studied coactivators of the SRC-1 family (9), CREB-binding protein (CBP/p300) (11, 12), and PBP (13). PBP is a component of the thyroid hormone receptor-associated protein (TRAP)/vitamin D₃ receptor-interacting protein (DRIP) complexes (14–16). Both SRC-1 and CBP/p300 have intrinsic histone acetyltransferase activity and recruit other acetyltransferases (17–20). The acetylation of histone results in the modification of chromatin and increases the access of the DNA to other components of transcription apparatus. The multiprotein TRAP/DRIP complexes exhibit no intrinsic histone acetyltransferase activity and appear to function through the direct interaction with general transcriptional machinery (15, 16). The observation that certain coactivators such as SRC-3 (AIB1; ACTR, p/CIP, RAC3) (21–24), AIB3 (PRIP, ASC2, RAP250, NRC, TRBP) (25–29), and PBP (30) are amplified and overexpressed in some breast cancers underscores the importance of nuclear receptor coactivators in transcriptional activation and also points to their possible role in neoplastic conversion.

Post-translational modification of proteins by arginine methylation has recently been implicated in a variety of cellular processes including nuclear receptor transcriptional regulation (31). Among the five members of protein arginine methyltransferases (PRMTs) identified thus far based on protein sequences, PRMT1 is the first identified and the predominant PMRT in mammalian cells (32). PRMT1 has been shown to interact with SRC-2 (GRIP1) and enhance the nuclear receptor transactivation function (33). Coactivator-associated arginine methyltransferase 1 (CARM1)/PRMT4 was identified by its interaction with nuclear receptor coactivator SRC-2 (GRIP1) (34). PRMT1 and CARM1 are able to methylate the histones H4 and H3, respectively, suggesting their role in modulating the chromatin structure (34, 35). In addition, CARM1 also

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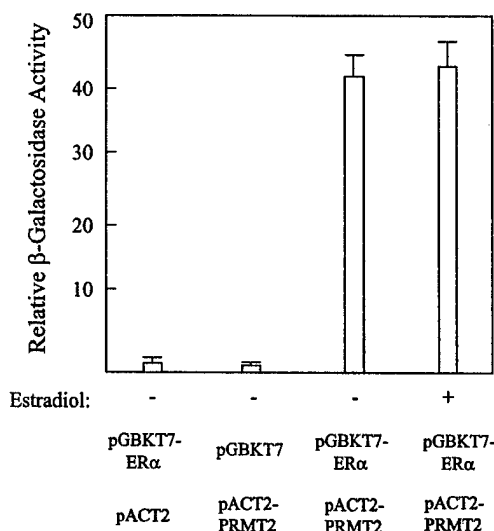


FIG. 1. The estrogen-independent interaction of PRMT2 with ER α in yeast. pACT2 expressing GAL4 activation domain alone, or pACT2-PRMT2 expressing the fusion protein between the GAL4 activation domain and PRMT2 was cotransformed into yeast HF7C with pGBKT7 expressing GAL4 DNA binding domain alone or pGBKT7-ER α expressing fusion protein between GAL4 DNA binding domain and ER α into yeast HF7C. The β -galactosidase activities from equal number of cells were measured as an indication of the relative strength of interaction in the presence or absence of ligand 17 β -estradiol.

methylates the CBP/p300, which disables the interaction between CREB and CBP/p300 and blocks the CREB activation (36). PRMT2 was isolated based on its sequence similarity with PRMT1 (37). So far no methyltransferase activity has been revealed for PRMT2 (37). Here we report the identification of PRMT2 as a new ER α -binding protein through yeast two-hybrid screening. We now demonstrate that PRMT2 binds to ER α directly and also enhanced both its AF-1 and AF-2 transcriptional activity. We also demonstrate that the potential methyltransferase activity was pivotal for PRMT2 coactivator function. These results suggest that PRMT2 is a new ER α coactivator.

EXPERIMENTAL PROCEDURES

Plasmids—pcDNA3.1-ER α , ERE-TK-LUC, PCMV-RAR α , RARE-TK-LUC, PCMV-PPAR γ , and PPRE-TK-LUC and the vectors for *in vitro* translation of PR, RXR α , TR β 1 have been described elsewhere (26). ER β is a gift from Dr. Laird D. Madison (Northwestern University). pGBKT7-ER α was constructed by inserting the full-length coding region of ER α cDNA into *NcoI/SalI* site of pGBKT7 (CLONTECH). PCMV-PRMT2 was an IMAGE clone purchased from Invitrogen and confirmed by sequencing. GST-PRMT2 was generated by inserting PRMT2 coding region into the *EcoRI/SalI* site of PGEX-5X-2. PRMT2 M, which encodes mutated PRMT2 with the mutation on the most conserved motif GCGTG (amino acids 145–149) (from GCGTG to GCRTR), was produced from PCMV-PRMT2 using a PCR site-directed mutagenesis kit (Stratagene). GST-ER α (1–184), GST-ER α (185–250), GST-ER α (251–301), and GST-ER α (302–595) were generated by inserting the corresponding ER α fragment amplified by PCR into the *EcoRI/SalI* site of PGEX-4T-3 and were confirmed by sequencing. Gal4-DBD-ER α (1–184) and Gal4-DBD-ER α (250–595) were created by inserting the corresponding fragments into *EcoRI/SalI* site of Gal4-DBD vector (CLONTECH) and were confirmed by sequencing. pCMV-FLAG-PRMT2, GST-PRMT1, and PRMT2 Δ SH3 expression vectors encoding PRMT2 with the SH3 domain deletion are gifts from Dr. Julia Kzhyshkowska (Regensburg University).

Yeast Two-hybrid Screening—Yeast two-hybrid screening was performed using the matchmaker two-hybrid system kit (CLONTECH). Briefly, the yeast strain HF7C was cotransformed with a human matchmaker mammary gland cDNA expression library and pGBKT7-ER α . The positive clones were selected by their growth in medium lacking histidine and the expression of β -galactosidase in the presence of 1×10^{-7} M of 17 β -estradiol.

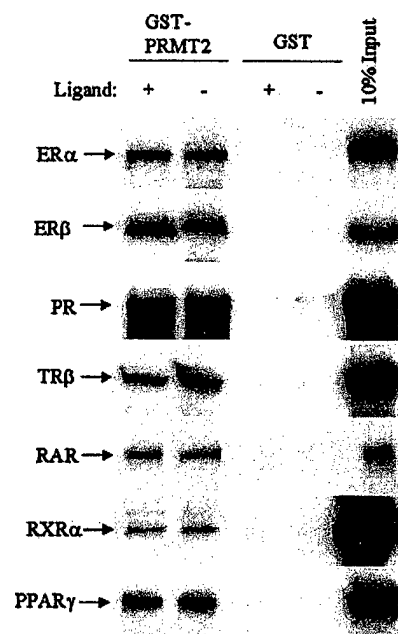


FIG. 2. *In vitro* interaction of PRMT2 with ER α , ER β , PR, TR β , RAR α , PPAR γ , and RXR α . GST-Sepharose beads bound with purified *E. coli* expressed GST-PRMT2 or with GST were incubated with [³⁵S]methionine-labeled ER α , ER β , PR, TR β , RAR α , PPAR γ , and RXR α in the presence (+) or absence (-) of ligand. The ligands used were: 17 β -estradiol for ER α and ER β , progesterone for PR, T $_3$ for TR β , 9-*cis*-retinoic acid for RAR α and RXR α , and Invitrogen 49653 for PPAR γ . Following four times washing with NETN solution, the bound proteins were eluted and separated using 10% SDS-polyacrylamide gel electrophoresis and autoradiographed.

Quantitative β -Galactosidase Assays—Appropriate plasmids were cotransformed into yeast strain HF7C, plated on selective media plates in the presence or absence of 10^{-7} M 17 β -estradiol, and then incubated for 4 days at 30 °C. Ten colonies from each plate were suspended in 150 μ l of buffer Z (60 mM Na $_2$ HPO $_4$, 40 mM NaH $_2$ PO $_4$, 10 mM KCl, 1 mM MgSO $_4$, 35 mM 2-mercaptoethanol). An equal number of cells in suspension was collected by centrifugation, and β -galactosidase activity was determined (Galacto-light kit, Tropix, Bedford, MA). Three independent assays were performed.

GST Pull-down Assays—The GST alone and GST fusion proteins were produced in *Escherichia coli* BL21 and bound to glutathione-Sepharose beads according to the manufacturer's instructions (Amersham Biosciences). *In vitro* translation was performed using rabbit reticulocyte lysate (Promega) and labeled with [³⁵S]methionine. In GST pull-down assays, a 25- μ l aliquot of GST fusion protein loaded on glutathione-Sepharose beads was incubated with 5 μ l of [³⁵S]methionine-labeled *in vitro* translated proteins for 2 h in 500 μ l of NETN (20 mM Tris-HCl, pH 7.5, 100 mM KCl, 0.7 mM EDTA, 0.05% Nonidet P-40, 1 mM phenylmethylsulfonyl fluoride). The binding was assayed in the presence or absence of specific ligands: 17 β -estradiol (1×10^{-6} M) for ER; BRL49653 (1×10^{-5} M) for PPAR γ ; 9-*cis*-retinoic acid (1×10^{-6} M) for RXR α and RAR α ; Wy-14, 643 (1×10^{-5} M) for PPAR α ; and T $_3$ (1×10^{-6} M) for TR β 1, respectively. Bound proteins were washed five times with binding buffer, eluted by boiling for 2 min in 20 μ l of SDS sample buffer, analyzed by SDS-PAGE, and autoradiographed.

Immunoprecipitation—COS-7 cells were transfected with 5 μ g of pcDNA3.1-ER α and 5 μ g of pCMV-FLAG-PRMT2 using LipofectAMINE 2000 (Invitrogen). 24 h after transfection, the cells were harvested. The lysate was immunoprecipitated with anti-FLAG (Sigma) or control serum. The precipitates were resolved by SDS-PAGE and subjected to Western blot analysis using anti-ER α .

S-adenosyl-L-methionine Binding Assay—Purified GST, GST-PRMT2, GST-PRMT2M, or GST-PRMT1 (10 μ g) was incubated with 20 μ Ci of S-adenosyl-L-[methyl-³H]methionine (Amersham Biosciences) in the buffer (20 mM Tris-HCl, pH 7.5, 150 mM NaCl, and 2 mM MgCl $_2$) at 37 °C for 10 min. The protein was trapped on HAWP 02500 filter (Millipore). The filter was washed with the buffer (20 mM Tris-HCl, pH 7.5, 150 mM NaCl, and 2 mM MgCl $_2$) to remove unbound S-adenosyl-L-[methyl-³H]methionine. The filters were dried, and the amount of bound S-adenosyl-L-[methyl-³H]methionine was quantified by liquid scintilla-

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PRMT2 and ER α

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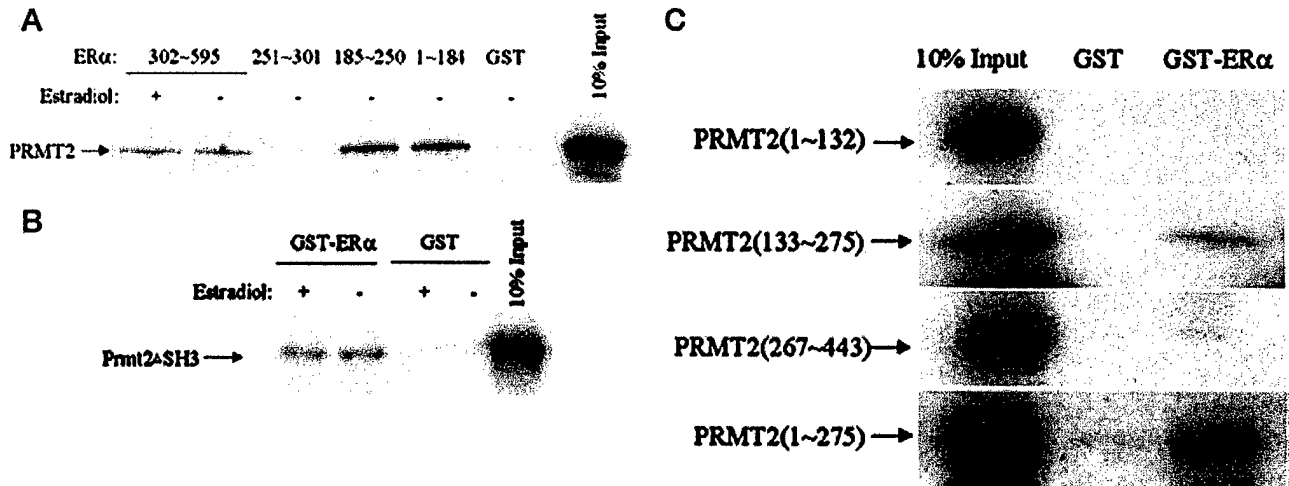


FIG. 3. Mapping the regions for ER α and PRMT2 interaction. A, GST pull-down assay was performed using [35 S]methionine-labeled PRMT2 and fusion proteins between GST and four different ER α fragment. Three ER α regions including AF-1 (amino acids 1–184), DNA binding domain (amino acids 185–250), and hormone binding domain (amino acids 302–595) interact with PRMT2. The binding of PRMT2 to the hormone binding domain is estrogen-independent. B, the SH3 domain on PRMT2 is dispensable for PRMT2 and ER α interaction. [35 S]methionine-labeled PRMT2 with SH3 domain deletion is able to bind to the GST-ER α fusion protein but not GST alone. C, the interaction region of PRMT2 to ER α was mapped to fragment from amino acid 133 to 275 by GST pull-down assay using [35 S]methionine-labeled truncated PRMT2 and GST-ER α fusion protein.

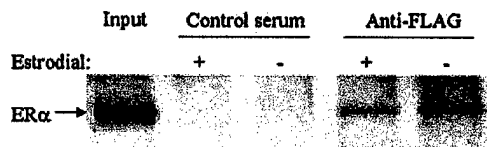


FIG. 4. PRMT2 interacts with ER α *in vivo*. Plasmids expressing FLAG-tagged PRMT2 and ER α were cotransfected into COS-7 cells in the presence or absence of 17 β -estradiol. The cell extracts were immunoprecipitated with either anti-FLAG or control serum. The precipitates were then analyzed by Western blot using anti-ER α antibody.

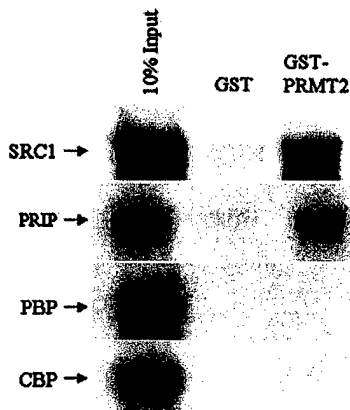


FIG. 5. PRMT2 interacts with SRC-1 and PRIP. GST or GST-PRMT2 fusion protein was incubated with [35 S]methionine-labeled SRC-1, PRIP, PBP, or CBP. Bound proteins were resolved by SDS-PAGE and detected by autoradiography.

tion counting.

Cell Culture and Transfection—CV-1 cells (1×10^5) were plated in 6-well plates and cultured in Dulbecco's modified Eagle's medium containing 10% fetal calf serum for 24 h before transfection. Cells were transfected for 5 h with 1.25 μ g of luciferase reporter DNA, 20 ng of plasmid expressing the receptor, and 1.25 μ g of appropriate expression plasmid DNA or as indicated in the figure legends using LipofectAMINE 2000 (Invitrogen); 0.1 μ g of β -galactosidase expression vector pCMV β (CLONTECH) DNA was always included as an internal control. Cell extracts were prepared 24 h after transfection and assayed for luciferase and β -galactosidase activities (Tropix). Three independent transfections were performed for each assay.

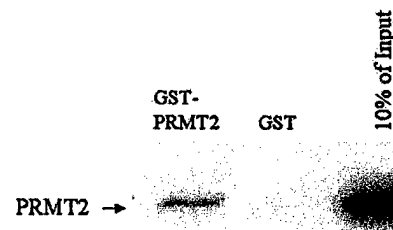


FIG. 6. PRMT2 forms homodimer or oligodimer. GST pull-down assay demonstrated that GST-PRMT2 fusion protein but not GST alone retained [35 S]methionine-labeled PRMT2.

RESULTS

Isolation of PRMT2 as an ER α -binding Protein by Two-hybrid Screening—Using full-length ER α as a bait in yeast two-hybrid system, we isolated from human mammary gland cDNA library a partial cDNA encoding PRMT2-(10–433). To examine the influence of estrogen on the interaction, pACT2-PRMT2, which was isolated by yeast two-hybrid screening and expressed as fusion protein between GAL4 activation domain and PRMT2-(10–433), or pACT2 was cotransformed with PG-BKT7-ER α expressing fusion protein between GAL4 DNA binding domain and ER α or PGBTKT7 into yeast HF7C. The β -galactosidase activity was measured as an indication of the relative strength of interaction in the presence or absence of ligand. In the absence of ligand, we observed an interaction between ER α and PRMT2 that resulted in an \sim 40-fold increase in the β -galactosidase activity (Fig. 1). The presence of the ligand estrogen did not significantly affect the interaction between PRMT2 and ER α (Fig. 1).

Interaction of PRMT2 with ER α and Other Nuclear Receptors *In Vitro*—The direct interaction between PRMT2 and ER α was further tested by *in vitro* GST binding assay. The immobilized GST-PRMT2, but not GST alone, retained [35 S]methionine-labeled ER α both in the presence and absence of estrogen (Fig. 2). Moreover, PRMT2 also showed the ligand-independent interaction with ER β , PR, TR β , RAR α , PPAR γ , and RXR α (Fig. 2).

To determine which region of ER α binds to PRMT2, a GST pull-down assay was performed using fusion proteins between

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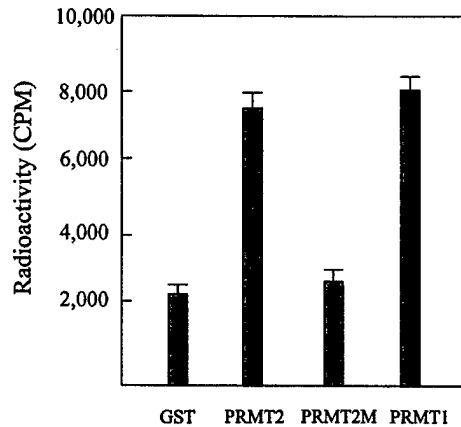


FIG. 7. PRMT2 binds S-adenosylmethionine. Purified protein was incubated with S-adenosyl-L-[methyl- 3 H]methionine. The protein was trapped on a filter and the bound S-adenosyl-L-[methyl- 3 H]methionine was quantified by liquid scintillation. GST-PRMT2, just as GST-PRMT1, retained a significant amount of S-adenosyl-L-[methyl- 3 H]methionine, while the filter with GST-PRMT2M showed the same background radioactivity as that with GST alone.

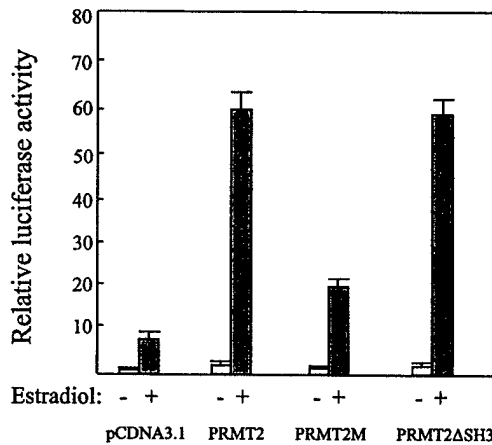


FIG. 8. PRMT2 enhances ER α -mediated transactivation and its potential methyltransferase activity is pivotal while its SH3 domain is dispensable for this function. 1.5 μ g of PRMT2, PRMT2M, PRMT2ASH3 expression vector, or control vector PCDNA3.1 was transfected with 1.5 μ g of the reporter construct ERE-TK-LUC and 25 ng of PCDNA3.1-ER α into CV-1 cells in the absence or presence of 10^{-7} M 17 β -estradiol. The activity obtained on transfection of the ERE-TK-LUC without exogenous PRMT2 in the absence of ligand was taken as 1.

GST and different regions of ER α . As shown in Fig. 3A, PRMT2 bound to the AF1 region, DNA binding domain, and hormone binding domain but not to the hinge region. The binding to ER α hormone binding domain was ligand-independent. The interaction between PRMT2 and ER α AF-1 region or DNA binding domain is stronger than that between PRMT2 and ER α hormone binding domain.

PRMT2 contains a Src homology 3 (SH3) domain that binds to proteins with proline-rich motif and plays a pivotal role in a wide variety of biological processes (38). A GST pull-down assay revealed that PRMT2 with an SH3 domain deletion was still able to bind to the GST-ER α fusion protein but not GST alone. Therefore, this domain is not considered necessary for PRMT2 and ER α interaction (Fig. 3B). The region of PRMT2 that interacts with ER α was further defined by GST pull-down assay using different truncated PRMT2 fragments. A fragment from amino acid 133 to 275 was found to interact with ER α (Fig. 3C).

PRMT2 Interacts with ER α in Vivo—The potential interaction between PRMT2 and ER α in the intact cell was examined

by coexpressing ER α and FLAG-tagged PRMT2 in COS-7 cells followed by immunoprecipitation and Western blot analysis. As shown in Fig. 4, PRMT2 interacts with ER α both in the presence and absence of estrogen. F4

Interaction of PRMT2 with PRIP, SRC-1, and with PRMT2 itself is as follows. The potential interaction between PRMT2 and other known nuclear receptor coactivators was investigated using the GST pull-down assay. We detected the interaction of PRMT2 with PRIP and SRC-1 (Fig. 5). No interaction was observed between PRMT2 and PBP or PRMT2 and CBP (Fig. 5). F5

The other methyltransferase PRMT1 is able to form homodimer or homooligomers (39, 40). A GST pull-down assay was performed to see if PRMT2 exhibits this property. GST and PRMT2 fusion protein but not GST alone retained [3 S]methionine-labeled PRMT2 suggesting that PRMT2 is capable of forming homodimer or homooligomers (Fig. 6). F6

PRMT2 Binds S-Adenosylmethionine—PRMT2 was initially isolated by its protein sequence similarity to other PRMTs and so far no methyltransferase activity has been revealed. Using bacterially expressed GST-PRMT2 fusion protein, we did not demonstrate that PRMT2 was capable of methylating histone and ER α (data not shown). We then tested the ability of PRMT2 to bind the methyl donor S-adenosylmethionine by a filter binding assay. Just like PRMT1, PRMT2 was found to be able to bind S-adenosylmethionine, whereas PRMT2 with point mutation in the S-adenosylmethionine binding motif (41) failed to bind S-adenosylmethionine (Fig. 7). F7

PRMT2 Potentiates ER α Transcriptional Activity and Its Potential Methyltransferase Activity Is Pivotal While Its SH3 Domain Is Dispensable for This Function—Having established that PRMT2 is an ER α -binding protein, we investigated the effect of increased levels of PRMT2 upon ER α transcriptional activity in CV-1 cells. The luciferase activity expressed from ERE-TK-LUC that contains one copy of ERE serves as the indicator of the ER α transcriptional activity. Expression of PRMT2 increased the estrogen-dependent transcription of luciferase gene by about 8-fold with minimal effort on basal transcription, which provided evidence that PRMT2 acts as a coactivator for ER α (Fig. 8). However, the mutated PRMT2 that was incapable of binding S-adenosylmethionine enhanced the ER α transcriptional activity by about 2.5-fold, which is much less than the 8-fold obtained with wild-type PRMT2 indicating the importance of the potential methyltransferase activity for the role of PRMT2 as a coactivator (Fig. 8). On the other hand, PRMT2 with deletion of the SH3 domain increased ER α activity to the same extent as that for wild-type PRMT2, indicating that the SH3 domain is dispensable for its coactivator function (Fig. 8). F8

PRMT2 Increases Both AF-1 and AF-2 Transcriptional Activity of ER α —As ER α contains the autonomous activation domain AF-1 and ligand-dependent activation domain AF-2, we further examined the effect of increased expression of PRMT2 on their individual activities. The AF-1-(1-184) and AF-2-(251-595) were fused to GAL4 DNA binding domain, respectively, and then cotransfected with GAL4 responsive element-directed luciferase as the reporter gene. In comparison with the GAL4 DNA binding domain alone, AF-1 increased the luciferase activity by about 3-fold. The expression of PRMT2 further increased AF-1-mediated luciferase expression by about 4.5-fold (Fig. 9A). Therefore, PRMT2 is able to enhance the ER α AF-1 activity. Just as other nuclear receptors show transcription repression in the absence of their corresponding ligands, the hormone-dependent AF-2 slightly decreased the luciferase activity without estrogen over the control. The addition of estrogen increased the AF-2-mediated luciferase expres- F9

PRMT2 and ER α

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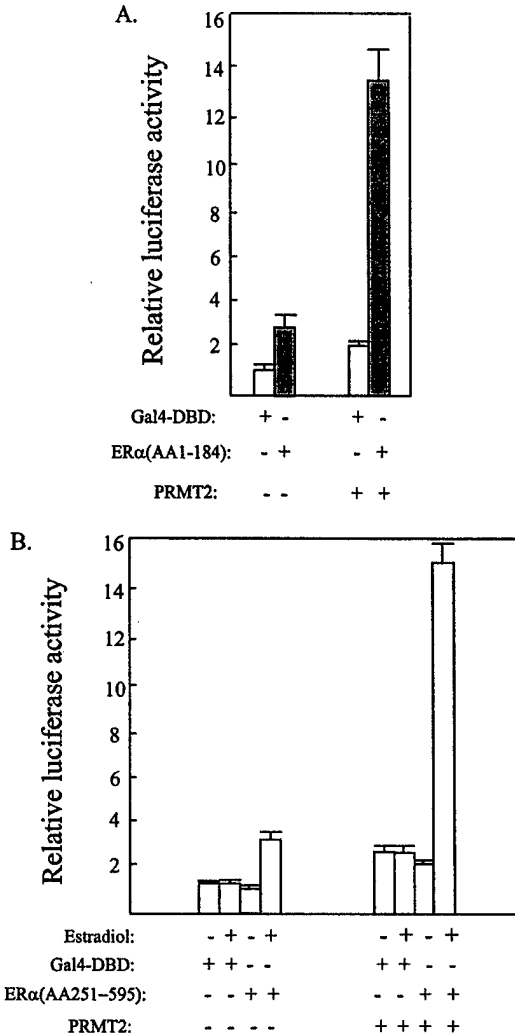


FIG. 9. The effects of PRMT2 on AF-1 and AF-2 transcriptional activities of ER α . Gal4-DBD-ER α (1-184) and Gal4-DBD-ER α (251-595) were generated by inserting the corresponding ER α cDNA fragment downstream of the Gal4 DNA binding domain (Gal4-DBD). The Gal4 responsive element-directed luciferase vector (Gal4-TK-LUC) was used as the reporter of activities. **A.** PRMT2 increases AF-1 activity. CV-1 cells were cotransfected with 1.5 μ g of GAL-TK-LUC, 25 ng of Gal4-DBD or Gal4-DBD-ER α (1-184), and 1.5 μ g of PRMT2 expression vector or control PCDNA3.1. The activity obtained on transfection of GAL-TK-LUC and Gal4-DBD without exogenous PRMT2 was taken as 1. **B.** PRMT2 also increases AF-2 activity. CV-1 cells were cotransfected with 1.5 μ g of GAL-TK-LUC, 25 ng of Gal4-DBD or Gal4-DBD-ER α (251-595), and 1.5 μ g of PRMT2 expression vector or control PCDNA3.1. The activity from transfection of GAL-TK-LUC and Gal4-DBD without exogenous PRMT2 in the absence of ligand was taken as 1.

sion by about 3-fold, which is further enhanced by coexpression of PRMT2 by about 5-fold, demonstrating that PRMT2 also potentiates the AF-2 activity (Fig. 9B).

No Synergistic Enhancement of ER α Activity by Coexpression of PRMT2 and SRC-1 or PRIP—Given that PRMT2 binds to SRC-1 and PRIP, we sought to determine whether there was synergistic enhancement of ER α activity by PRMT2 and SRC-1 or PRIP. In transient transfection assay with ER α and its reporter gene, PRMT2, SRC-1, and PRIP all enhanced the expression of reporter gene to different levels (Fig. 10). When PRMT2 was cotransfected with either SRC-1 or PRIP, the expression of the reporter gene luciferase was modestly decreased in comparison with PRMT2 alone (Fig. 10). Therefore, there appears no synergistic activation when PRMT2 are coexpressed with either PRIP or SRC-1.

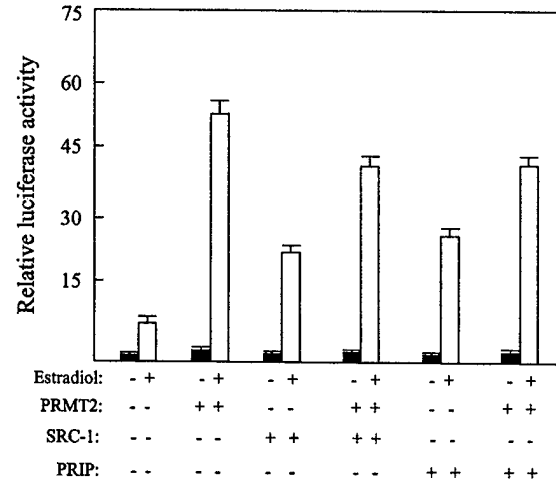


FIG. 10. No synergistic activation was observed for coexpression of PRMT2 and SRC-1 or PRIP. CV-1 cells were transfected with 1.5 μ g of reporter construct ERE-TK-LUC, 35 ng of PCDNA3.1-ER α , and 0.8 μ g of expression vector as indicated in the absence (-) or presence (+) of 10^{-7} M 17β -estradiol. Transfection without indicated expression vector was compensated by adding the same amount of PCDNA3.1. The activity obtained on transfection of ERE-TK-LUC without exogenous PRMT2 in the absence of ligand was taken as 1.

PRMT2 Also Enhances PR-, PPAR γ , and RAR α -mediated Transactivation—To investigate whether PRMT2 acts as a coactivator for other nuclear receptors, transient transfection assays were performed with PR, PPAR γ , and RAR α responsive element-directed luciferase gene. PRMT2 enhanced the PR ligand-dependent transcriptional activity by about 8-fold. In comparison with ER α and PR, PRMT2, which also increased the ligand-dependent PPAR γ and RAR α transactivation by about 5- and 4.5-fold, respectively, showed less effect on PPAR γ and RAR α transactivation (Fig. 11).

PRMT2 Contains No Intrinsic Transcriptional Activity—In an effort to define the mechanism by which PRMT2 acts as a coactivator, we tested if PRMT2 contains intrinsic transcriptional activity similar to that reported with other coactivators such as SRC-1 (42). PRMT2 was linked to the GAL4 DNA binding domain and transfected into CV-1 cells along with GAL4 responsive element-directed reporter gene luciferase. In comparison with GAL4 DNA binding domain alone, GAL4-PRMT2 fusion protein produced no additional activity whereas GAL4-SRC-1 fusion protein increased the luciferase activity by about 7-fold and served as a positive control (Fig. 12). Therefore, PRMT2 does not have intrinsic transcriptional activity.

DISCUSSION

Using a yeast two-hybrid system with ER α as bait to screen a human mammary gland cDNA library, we isolated PRMT2 as a new ER α -interacting protein. The interaction between PRMT2 and ER α was confirmed by *in vitro* binding and *in vivo* immunoprecipitation assay. A transient transfection assay demonstrated that PRMT2 increased the ER α transcriptional activity. In agreement with the finding that PRMT2 bound to both ER α AF-1 domain and the hormone binding domain, PRMT2 enhanced both ER α AF-1 and AF-2-mediated transactivation. These results established that PRMT2 is a coactivator of ER α . However, unlike other coactivators such as SRC-1 family and CBP that show ligand-dependent binding to the nuclear receptors, PRMT2 binds to ER α both in the presence and absence of estrogen but enhances the ER α activity only with the estrogen. It appears that the interaction between ER α and PRMT2 is not enough for ER α transcriptional activation, which occurs only after the binding of estrogen resulting in

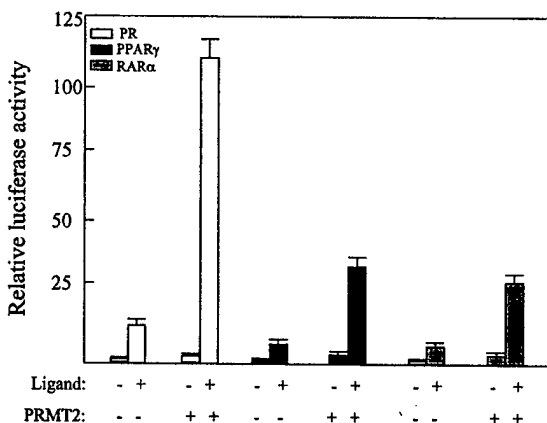


FIG. 11. PRMT2 also enhances PR-, PPAR γ , and RAR α -mediated transactivation. CV-1 cells were transfected with 1.5 μ g of reporter vector (PRE-TK-LUC for PR, PPRE-TK-LUC for PPAR γ , RARE-TK-LUC for RAR α), 25 ng of receptor expression vector, and 1.5 μ g of control pCDNA3.1 or PRMT2 expression vector in the presence or absence of ligand (10^{-7} M progesterone for PR, 10^{-6} M BRL49653 for PPAR γ , and 10^{-6} M 9-*cis*-retinoic acid for RAR α). The activity obtained on transfection of the reporter vector without exogenous PRMT2 in the absence of ligand was taken as 1.

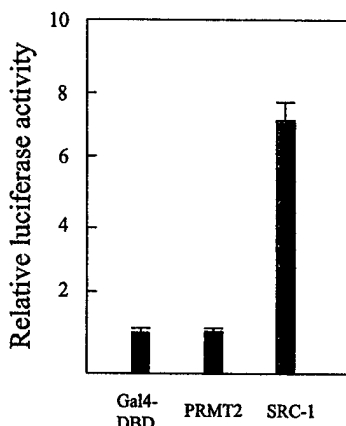


FIG. 12. PRMT2 does not have intrinsic transcriptional activity. 1 μ g Gal4-DBD, Gal4-DBD-PRMT2, or Gal4-DBD-SRC-1 was cotransfected with 2 μ g of GAL-TK-LUC into CV-1 cells. The activity of luciferase on transfection of GAL-TK-LUC with Gal4-DBD was taken as 1.

most probably the recruitment of other ligand-dependent coactivators.

Two types of PMRT activities have been identified in mammalian cells (31). Type 1 PRMT enzymes including PRMT1, PRMT3, and CARM1 catalyze the formation of monomethylarginine and asymmetric dimethylarginine. Type 2 PRMT enzymes catalyze the formation of monomethylarginine and symmetric dimethylarginine. PRMT2/JBP1 is the only type II enzyme identified so far (43). Based on the protein sequence, PRMT2 was identified as a methyltransferase most probably belonging to type I enzyme, but so far its methyltransferase activity has not been identified (37). Although we demonstrated PRMT2 is capable of binding *S*-adenosylmethionine, we failed to detect any methyltransferase activity using bacterially expressed GST-PRMT2 fusion protein with substrates including histone and ER α (data not shown). A systematic approach to identify the substrates for PRMT2 will be required, and it is also possible that some modification such as phosphorylation or some cofactor may be required for its activity. Nevertheless, the mutation in the conserved PRMT2 binding site for *S*-adenosylmethionine, which would abolish the potential

methyltransferase activity, substantially diminished the PRMT2 coactivator function. The finding that PRMT2 does not have any intrinsic transcriptional activity favors the hypothesis that PRMT2 acts by modifying chromatin structure or the transcriptional apparatus through methylation. The elucidation of the substrates will be crucial for the understanding of PRMT2 coactivator function.

PRMT1 and CARM1 are two arginine methyltransferases that have been found to participate in the nuclear receptor transcriptional activation. Both PRMT1 and CARM1 interact with the carboxyl-terminal activation domain of coactivator GRIP1 and are able to methylate histones H4 and H3, respectively. PRMT1 or CARM1 enhance the nuclear receptor activity mildly by itself but substantially when coexpressed with GRIP1, suggesting that PRMT1 and CARM1 act as the secondary coactivators that are recruited by the first coactivator to modify the chromatin structure. Instead, PRMT2 strongly enhances the ER α transcriptional activity by direct interaction with ER α . Although PRMT2 was found to interact with other coactivators SRC-1 and PRIP, no synergistic activation was found with coexpression of PRMT2 and PRIP or SRC-1. The coexpression of SRC-1 or PRIP even modestly decreased PRMT2 coactivation. Therefore, although PRMT2 is a protein arginine methyltransferase highly homologous to PRMT1 and CARM1, PRMT2 may have a very different mechanism by which it acts as a coactivator, possibly because it has different substrates involved in transcriptional activation.

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REFERENCES

- Evans, R. M. (1988) *Science* **240**, 889–895
- Mangelsdorf, D. J., Thummel, C., Beato, M., Herrlich, P., Schutz, G., Umesono, K., Blumberg, B., Kastner, P., Mark, M., Chambon, P., and Evans, R. M. (1995) *Cell* **83**, 835–839
- Smith, C. L. (1998) *Biol. Reprod.* **58**, 627–632
- Curtis, S. W., Washburn, T., Sewall, C., DiAugustine, R., Lindzey, J., Couse, J. F., and Korach, K. S. (1996) *Proc. Natl. Acad. Sci. U. S. A.* **93**, 12626–12630
- Tora, L., White, J., Brou, C., Tasset, D., Webster, N., Scheer, E., and Chambon, P. (1989) *Cell* **59**, 477–487
- Tzukerman, M. T., Esty, A., Santiso-Mere, D., Danielian, P., Parker, M. G., Stein, R. B., Pike, J. K., and McDonnell, D. P. (1994) *Mol. Endocrinol.* **8**, 21–30
- Kuiper, G. G. J. M., Enmark, E., Pelto-Huikko, M., Nilsson, S., and Gultafsson, J. A. (1996) *Proc. Natl. Acad. Sci. U. S. A.* **93**, 5925–5930
- Couse, J. F., and Korach, K. S. (1999) *Endocr. Rev.* **20**, 358–417
- Xu, L., Glass, C. K., and Rosenfeld, M. G. (1999) *Curr. Opin. Genet. Dev.* **9**, 140–147
- Qi, C., Zhu, Y., and Reddy, J. K. (1999) *Cell Biochem. Biophys.* **31**, 1–18
- Chakravarti, D., LaMorte, V. J., Nelson, M. C., Nakajima, T., Schulman, I. G., Juguilon, H., Montminy, M., and Evans, R. M. (1996) *Nature* **383**, 99–102
- Yao, T. P., Ku, G., Zhou, N., Scully, R., and Livingston, D. M. (1996) *Proc. Natl. Acad. Sci. U. S. A.* **93**, 10626–10631
- Zhu, Y., Qi, C., Jain, S., Rao, M. S., and Reddy, J. K. (1997) *J. Biol. Chem.* **272**, 25500–25506
- Yuan, C. X., Ito, M., Fondell, J. D., Fu, Z. Y., and Roeder, R. G. (1998) *Proc. Natl. Acad. Sci. U. S. A.* **95**, 7939–7944
- Ito, M., Yuan, C. X., Malik, S., Gu, W., Fondell, J. D., Yamamura, S., Fu, Z. Y., Zhang, X., Qin, J., and Roeder, R. G. (1999) *Mol. Cell* **3**, 361–370
- Rachez, C., Lemon, B. D., Suldan, Z., Bromleigh, V., Gamble, M., Naar, A. M., Erdjument-Bromage, H., Tempst, P., and Freedman, L. P. (1999) *Nature* **398**, 824–828
- Spencer, T. E., Jenster, G., Burcin, M. M., Allis, C. D., Zhou, J. X., Mizzen, C. A., McKenna, N. J., Onate, S. A., Tsai, S. Y., Tsai, M. J., and O'Malley, B. W. (1997) *Nature* **389**, 194–198
- Ogryzko, V. V., Schiltz, R. L., Russanova, V., Howard, B. H., and Nakatani, Y. (1996) *Cell* **87**, 953–959
- Korzus, E., Torchia, J., Rose, D. W., Xu, L., Kurokawa, R., McLnerney, E. M., Mullen, T. M., Glass, C. K., and Rosenfeld, M. G. (1998) *Science* **279**, 703–707
- Bannister, A. J., and Kouzarides, T. (1996) *Nature* **384**, 641–643
- Anzick, S. L., Kononen, J., Walker, R. L., Azorsa, D. O., Tanner, M. M., Guan, X. Y., Sauter, G., Kallioniemi, O. P., Trent, J. M., and Meltzer, P. S. (1997) *Science* **277**, 965–968
- Torchia, J., Rose, D. W., Inostroza, J., Kamei, Y., Westin, S., Glass, C. K., and Rosenfeld, M. G. (1997) *Nature* **387**, 677–684
- Chen, H., Lin, R. J., Schiltz, R. L., Chkavartsi, D., Nash, A., Nagy, L., Privalsky, M. L., Nakatani, Y., and Evans, R. M. (1997) *Cell* **90**, 569–580
- Li, H., Gomes, P. J., and Chen, J. D. (1997) *Proc. Natl. Acad. Sci. U. S. A.* **94**, 8479–8484

PRMT2 and ER α

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25. Lee, S.-K., Anzick, S. L., Choi, J.-E., Bubendorf, L., Guan, X.-Y., Jung, Y.-K., Kallioniemi, O. P., Kononen, J., Trent, J. M., Azorsa, D., Jhun, B.-H., Cheong, J. H., Lee, Y. C., Meltzer, P. S., and Lee, J. W. (1999) *J. Biol. Chem.* **274**, 34283-34293
26. Zhu, Y., Kan, L., Qi, C., Kanwar, Y. S., Yeldandi, A. V., Rao, M. S. & Reddy, J. K. (2000) *J. Biol. Chem.* **275**, 13510-13516
27. Mahajan, M., and Samuels, H. H. (2000) *Mol. Cell. Biol.* **20**, 5048-5063
28. Caira, F., Antonson, P., Pelto-Huikko, M., Treuter, E., and Gustafsson, J.-A. (2000) *J. Biol. Chem.* **275**, 5308-5317
29. Ko, L., Cardona, G. R., and Chin, W. W. (2000) *Proc. Natl. Acad. Sci. U. S. A.* **97**, 6212-6217
30. Zhu, Y., Qi, C., Jain S., Le Beau, M. M., Espinosa III, R., Atkins, G. B., Lazar, M. A., Yeldandi, A. V., Rao, M. S., and Reddy, J. K. (1999) *Proc. Natl. Acad. Sci. U. S. A.* **96**, 10848-10853
31. McBride, A. E., and Silver, P. A. (2001) *Cell* **106**, 508
32. Tang, J., Frankel, A., Cook, R. J., Kim, S., Paik, W. K., Williams, K. R., Clarke, S., and Herschman, H. R. (2000) *J. Biol. Chem.* **275**, 7723-7730
33. Koh, S. S., Chen, D., Lee, Y.-H., and Stallcup, M. R. (2001) *J. Biol. Chem.* **276**, 1089-1098
34. Chen, D., Ma, H., Hong, H., Koh, S. S., Huang, S.-M., Schurter, B. T., Aswad, D. W., and Stallcup, M. R. (1999) *Science* **284**, 2174-2177
35. Wang, H., Huang, Z. Q., Xia, L., Feng, Q., Erdjument-Bromage, H., Strahl, B. D., Briggs, S. D., Allis, C. D., Wong, J., Tempst, P., and Zhang, Y. (2001) *Science* **293**, 853-857
36. Xu, W., Chen, H., Du, K., Asahara, H., Tini, M., Emerson, B. M., Montminy, M., and Evans, R. M. (2001) *Science* **294**, 2507-2511
37. Scott H. S., Antonarakis, S. E., Lalioti, M. D., Rossier, C., Sliver, P. A., and Henry, M. F. (1998) *Genomics* **48**, 330-340
38. Mayer, B. J. (2001) *J. Cell Sci.* **114**, 1253-1263
39. Tang, J., Gary, J. D., Clarke, S., and Herschman, H. R. (1998) *J. Biol. Chem.* **273**, 16935-16945
40. Weiss, V. H., McBride, A. E., Scorianò, M. A., Filman, D. J., Silver, P. A., and Hogle, J. M. (2000) *Nat. Struct. Biol.* **7**, 1165-1171
41. McBride, A. E., Weiss, V. H., Kim, H. K., Hogle, J. M., and Silver, P. A. (2000) *J. Biol. Chem.* **275**, 3128-3136
42. Zhu, Y., Qi, C., Calandra, C., Rao, M. S., and Reddy, J. K. (1996) *Gene Expr.* **6**, 185-195
43. Branscombe, T. L., Frankel, A., Lee, J. H., Cook, J. R., Yang, Z. H., Pestka, S., and Clarke, S. (2001) *J. Biol. Chem.* **276**, 32971-32976