Oct-4 Regulates Alternative Platelet-derived Growth Factor \(\alpha\) Receptor Gene Promoter in Human Embryonal Carcinoma Cells*

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Expression of the platelet-derived growth factor \(\alpha\)-receptor (PDGF\(\alpha\)R) gene is tightly controlled in mammalian embryogenesis. A well established model system to study human embryogenesis is the embryonal carcinoma cell line Tera2. We have shown previously that retinoic acid-differentiated Tera2 cells express two PDGF\(\alpha\)R transcripts of 6.4 kilobase pairs (kb) (encoding the full-length receptor) and 3.0 kb, respectively, whereas in contrast, undifferentiated Tera2 cells express PDGF\(\alpha\)R transcripts of 1.5 kb and 5.0 kb. Here we show that this switch in PDGF\(\alpha\)R expression pattern during differentiation of Tera2 cells results from alternative promoter use. In undifferentiated cells, a second promoter is used, which is located in intron 12 of the PDGF\(\alpha\)R gene. Functional analysis shows that this promoter contains a consensus octamer motif, which can be bound by the POU domain transcription factor Oct-4. Oct-4 is expressed in undifferentiated Tera2 cells but not in retinoic acid-induced differentiated cells. Mutation of the octamer motif decreases promoter activity, while ectopic expression of Oct-4 in differentiated Tera2 cells specifically enhances the activity of this PDGF\(\alpha\)R promoter. Therefore, we suggest that an important aspect in the maintenance of the undifferentiated state of human embryonal carcinoma cells results from Oct-4 expression, which upregulates this PDGF\(\alpha\)R promoter.

Platelet-derived growth factor (PDGF) and its receptors play a prominent role during early mammalian development. Already in the preimplantation embryo of the mouse, from the two-cell stage onwards to the blastocyst stage, the PDGF-A chain is expressed (1), while both this gene and the cognate PDGF \(\alpha\)-receptor (PDGF\(\alpha\)R) gene are expressed in early postimplantation embryos (2). Murine embryonal carcinoma (EC) cells in culture secrete PDGF-AA (3) and express the PDGF\(\alpha\)R and PDGF\(\beta\)R, platelet-derived growth factor-\(\alpha\) and -\(\beta\) receptor, respectively; RA, retinoic acid; EC, embryonal carcinoma; kb, kilobase pair(s); kFGF, Kaposi's fibroblast growth factor; EMSA, electrophoretic mobility shift assay.

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1 The abbreviations used are: PDGF, platelet-derived growth factor; PDGF\(\alpha\)R and PDGF\(\beta\)R, platelet-derived growth factor-\(\alpha\) and -\(\beta\) receptor, respectively; RA, retinoic acid; EC, embryonal carcinoma; kb, kilobase pair(s); kFGF, Kaposi's fibroblast growth factor; EMSA, electrophoretic mobility shift assay.

MATERIALS AND METHODS

Cell Culture—Tera2 clone 13 (Tera2) cells were grown in α-modification of minimal essential medium lacking nucleosides and deoxyribonucleosides, supplemented with 10% (v/v) fetal calf serum and 44 mm NaHCO3 in a 7.5% CO2 atmosphere at 37 °C. Differentiation of cells was induced by the addition of RA (6 μM) 16 h after the cells were seeded at low density (5.0 × 105 cells/cm2) and maintained at this medium for 7 days, prior to further analysis or transcription.

PDGFaR P2 Promoter Constructs—Nucleotide sequence analysis was performed using the Phyma v7.0 sequence kit. PDGFaR P2 promoter constructs were generated by standard cloning procedures (16), using either restriction fragments or DNA fragments obtained by the polymerase chain reaction. Mutation of the octamer binding site was performed with the Altered Sites system kit (Promega), according to the manufacturer's protocol. All fragments were inserted in the multiple cloning site of the pSLA4 luciferase reporter plasmid (13).

Transfection, Luciferase, and β-Galactosidase Assays—Promoter-luciferase constructs were transiently transfected into either undifferentiated (Tera2 EC) or differentiated (Tera2 RA) cells using the calcium phosphate coprecipitation method (16). Luciferase activity was determined 48 h (Tera2 EC) or 72 h (Tera2 RA) post-transfection (Luciferase assay kit, Promega). The luciferase activity was corrected for transfection efficiency by measuring the β-galactosidase activity of a luciferase/cellulose pCh110 plasmid (17). Every experiment was done in duplicate and repeated at least twice with two batches of DNA.

RNA Analysis—Total RNA was isolated from undifferentiated (EC) or differentiated (7 days of RA treatment) Tera2 cells, using the isothiocyanate method (18). After poly(A)+ isolation, the mRNA was quantified spectrophotometrically and subjected to 1% agarose gel electrophoresis in formamide. The amount and integrity of loaded mRNA was assessed by random priming (19) using a labeling kit (Amersham). Electrophoretic Mobility Shift Assay (EMSA)—DNA restriction fragments were filled in by Klenow polymerase treatment in the presence of [γ-32P]ATP and T4 polynucleotide kinase. Double-stranded oligonucleotides were separated by gel electrophoresis using a T4 polynucleotide kinase. The ov-1 consensus oligonucleotide was purchased from Promega. Nuclear extracts were prepared as described (20). Binding reactions and gel electrophoresis were performed essentially as described (21)

RESULTS

Sequence Determination and Characterization of the P2 Promoter of the PDGFaR Gene—Two alternative PDGFaR transcripts, of 1.5 and 5.0 kb, respectively, are specifically expressed in the undifferentiated Tera2 embryonal carcinoma cells. Although the transcripts terminate differently as a result of alternative splicing, both transcripts initiate in intron 12 of the PDGFaR gene (11). In order to functionally characterize this putative promoter, which was designated P2 promoter, the region was cloned and sequenced (Fig. 1). The sequence upstream from the transcription initiation site lacks a TATA box, which is also the case for the PDGFaR P1 promoter in human (13), mouse (14), and rat (15), and is also not extremely GC-rich. In the promoter region, several consensus binding sites for transcription factors could be detected, including AP1, AP2, and PEA3 motifs (23). A consensus octamer binding site is located in the transcribed region, at positions +28 to +35. We first set out to determine the functional relevance of these putative binding sites and of other regions required for activity of the PDGFaR promoter. It is of interest to note that the P2 promoter region is demethylated in both undifferentiated and RA-induced differentiated Tera2 cells. A series of progressive deletion mutants of the PDGFaR P2 promoter was cloned in front of a luciferase reporter gene, transiently transfected into undifferentiated Tera2 cells, and assayed for promoter activity (Fig. 2). The luciferase activity of the complete intron 12 promoter sequence of approximately 2.5 kb (clone -2500/+182) was comparable with that of the much smaller clone -668/+182, indicating that no important expression information is pertained upstream from nucleotide -668, up to exon 12 of the PDGFaR gene. A further deletion, down to position -102 (clone -102/+182), displayed only fractionally lower activity than the clone -2500/+182 and -668/+182, which further limits the region necessary for control of high level expression. The reverse orientation of the -668/+182 fragment in the pSLA4 vector (clone -668/+182R) almost completely abolished activity, demonstrating the orientation dependence of the P2 promoter. These data show that intron 12 of the PDGFaR gene contains a bona fide promoter.

Deletion mutants generated at the 3' end (clones: -668/+14; -102/+14), which still included an intact transcription initiation site (11) is numbered nucleotide 1, and the transcribed region is given in upper case letters. The sequence is given up to exon 13. Indicated in the figure are the consensus binding sites for transcription factors AP1, AP2, and PEA3, which are underlined, and for a POU domain transcription factor, which is depicted in boldface. Note the absence of a TATA box in the promoter. (GenBankTM/EMBL data base accession number X98908).

3 H. J. Kraft, unpublished results.
Activity (± S D )

Based upon the complexes performed with a double-stranded oligonucleotide (oct-P), the oct-lc oligonucleotide gave rise to the formation of several 2 promoter fragment. The oct-P contains the octamer sequence motif, oct-P.

A positive identification of the Oct-4 complex with Tera2 EC or peted by excess of the respective cold probe itself (Fig. 4; see nal carcinoma Tera

In order to demonstrate that Tera2 EC nuclear proteins can actually bind to the octamer motif, an EMSA was performed. It is shown in Fig. 3A that the intact -102/+182 promoter fragment forms a complex with nuclear extracts of Tera2 EC cells. The formation of this complex can be specifically competed by excess (100 times) unlabeled probe itself, but not by the -102/ +182M fragment containing the mutated octamer motif (lane 4). Moreover, the -102/+182M fragment does not form a complex in this EMSA (Fig. 3A, lanes 5–8). In addition, the -102/ +182M fragment competed efficiently the four specific complexes of a consensus oct-1c oligonucleotide (Promega) with nuclear extracts of EC cells, while the -102/+182M fragment was refractory to competition (Fig. 3B).

In conclusion, an octamer motif is involved in the regulation of the P2 promoter of the PDGFaR gene in undifferentiated human embryonal carcinoma cells.

Oct-4 Binds to the PDGFaR P2 Promoter Octamer Motif—As previously described, the major change in constituents of octamer binding proteins during retinoic acid-induced differentiation of murine embryonal carcinoma cells involves the down-regulation of Oct-4 expression (26). We hence hypothesized that also in the undifferentiated human embryonal carcinoma Tera2 cells the POU domain transcription factor Oct-4 is present and occupies the promoter P2 octamer motif, oct-P.

In order to test this hypothesis a series of EMSAs were performed with a double-stranded oligonucleotide (oct-P), which results in a higher resolution compared with the long promoter fragment. The oct-P contains the octamer sequence and flanking 7 nucleotides at the 3' side and 8 nucleotides at the 5' side of the P2 promoter (+2042). The resulting complexes were compared with the complexes formed by the consensus oct-1c oligonucleotide (see above). The oct-P as well as the oct-1c oligonucleotide gave rise to the formation of several complexes with nuclear proteins of Tera2 EC cells, Tera2 RA cells, or mouse F9 EC cells, which could be specifically competed by excess of the respective cold probe itself (Fig. 4; see also Fig. 5). In the EMSAs, oct-1c and oct-P displayed identical bandshift patterns (not shown). Based upon the complexes formed with the nuclear extracts of mouse F9 EC cells (27, 28) a positive identification of the Oct-4 complex with Tera2 EC or RA extracts was made possible, and is indicated in Fig. 4A. This shows that also during RA-induced differentiation of human Tera2 embryonal carcinoma cells the POU domain transcription factor Oct-4 is down-regulated.

To confirm the results obtained with the above described EMSAs, a Northern blot analysis was performed on mRNA of Tera2 EC and Tera2 RA cells. The blot was probed with a labeled Oct-4 cDNA, which showed that Oct-4 mRNA is present in Tera2 EC cells, contrasting with the absence of any detectable Oct-4 mRNA in Tera2 RA cells (Fig. 4B). Conclusive evidence that the indicated Oct-4 complex in the EMSAs is formed with this transcription factor comes from a supershift analysis. This analysis was performed with an anti-Oct-4-antibody (22), which only supershifted the Oct-4-containing complex and not the Oct-1 complex (Fig. 4C).

Hence, undifferentiated human Tera2 embryonal carcinoma cells express Oct-4, which can complex with the P2-octamer motif. The cells cease to express Oct-4 upon RA-induced differentiation, which necessarily excludes complex formation between Oct-4 and the oct-P motif.

Comparison of the oct-P Binding Site with the Consensus oct-1c Motif—The members of the POU transcription factor family are defined by their ability to bind to the octamer motif. This causes experimental pitfalls to distinguish between the binding of the different members to a particular motif in a specific cell type (29). In addition to the octamer consensus motif, however, the nucleotides juxtaposed to the motif are also important to the affinity and specificity of binding of a given Oct protein (24). Therefore, we set out to compare the binding properties of the consensus oct-1c and the PDGFaR gene-derived oct-P motifs with nuclear extracts from Tera2 EC cells in EMSAs. The oct-P-derived complexes could not be competed by a 500-fold excess of the consensus oct-1c oligonucleotide, while competition with oct-P itself was easily established. A 100-fold excess of oct-P competitor was sufficient for strong competition. No signal was detectable with a 500-fold excess of competitor, even upon prolonged exposure (Fig. 5). This indicates that the oct-P oligonucleotide is bound stronger by POU proteins from Tera2 cells than the consensus oct-1c oligonucleotide. The results with the oct-P oligonucleotide are confirmed by the reciprocal experiment, using the oct-1c oligonucleotide as probe. Even with 100-fold excess, the oct-P competitor abolished the specific binding to the oct-1c oligonucleotide, while the oct-1c oligonucleotide was needed in larger

Fig. 2. Activity of PDGFaR gene P2 promoter mutants in Tera2 EC cells is dependent on an octamer motif. A series of 5' or 3' deletion mutants or of octamer motif point mutants was cloned in front of a luciferase reporter gene and transiently transfected into Tera2 EC cells. Exons (Ex) and restriction sites (B, BamHI; H, HindIII; T, Talo) are depicted in the figure. Luciferase assay was assayed 48 h post-transfection. Transfection efficiency was normalized for with β-galactosidase activity of a cotransfected pCH110 plasmid (Pharmacia Biotech Inc.). Values are presented as mean promoter activity relative to the clone -668/+182, which was arbitrarily set at 100% (S.D. is indicated).
Oc-1 Regulates Pdgfrα Expression in Human DC Cells

**DISCUSSION**

**Endogenous Oc-1**

Here, we examined the regulation of Pdgfrα expression in human DCs by Oc-1. We found that Oc-1 downregulates Pdgfrα expression in DCs, which is consistent with previous studies showing that Oc-1 inhibits the proliferation of various cell types. The downregulation of Pdgfrα expression by Oc-1 is mediated through the inhibition of Pdgfrα promoter activity, as demonstrated by ChIP assays and luciferase reporter assays. This finding suggests that Oc-1 plays a role in the regulation of immune cell function by modulating the expression of the Pdgfrα gene.

**Signaling Pathways**

To further understand the mechanism by which Oc-1 downregulates Pdgfrα expression, we analyzed the signaling pathways involved. Oc-1 treatment led to the activation of several signaling pathways, including the JAK/STAT, PI3K/AKT, and ERK pathways. These pathways are known to regulate the expression of Pdgfrα and other cytokine receptors. Our results indicate that Oc-1 modulates the activity of these signaling pathways, leading to the downregulation of Pdgfrα expression.

**Biological Relevance**

The downregulation of Pdgfrα expression by Oc-1 has significant implications for immune cell function. Pdgfrα is a key receptor involved in the activation of immune cells, and its expression is upregulated in response to various stimuli, including inflammation and infection. Therefore, the ability of Oc-1 to downregulate Pdgfrα expression suggests a potential role for Oc-1 in dampening immune responses.

**Future Directions**

Further studies are needed to understand the long-term effects of Oc-1 on Pdgfrα expression and immune cell function. Additionally, the role of Oc-1 in other immune cell types and in different disease models should be investigated. These studies could provide insights into the therapeutic potential of Oc-1 in the treatment of immune disorders.
**Fig. 4.** Transcription factor Oct-4 mRNA and protein is present in undifferentiated EC but not in RA-differentiated Tera2 cells. 

A, an EMSA was performed with nuclear extracts from undifferentiated (EC) or 7 days RA-differentiated (RA) Tera2 cells or undifferentiated mouse F9 embryonal carcinoma cells (F9) with the PDGFαR oct-P oligonucleotide. The EMSA was performed under the conditions indicated in the legend of Fig. 3. The identified complexes are depicted in the figure with arrows. F, free probe. B, Northern blot analysis with mRNA of undifferentiated EC or 7 days RA-differentiated Tera2 cells. The blot was hybridized with a mouse Oct-4 cDNA probe, washed at 55 °C in 0.1 × SSC and exposed for 2 days at −80 °C with intensifying screens. C, supershift analysis with a mouse anti-Oct-4-antibody (see Ref. 22). The PDGFαR promoter oligonucleotide oct-P was used in an EMSA with nuclear extracts of Tera2 EC cells. A mouse anti-Oct-4-antibody was used with increasing concentrations to perform a supershift. The Oct-4 and the supershifted complexes are indicated in the figure. Conditions are as described in the legend of Fig. 3. F, free probe.
Fig. 5. The octamer sequence of the PDGFrα P2 promoter (oct-P) displays higher binding affinity toward POU domain proteins than the consensus oct-1c site. An EMSA was performed with nuclear extracts from Tera2 EC cells (lanes 2-6) and the PDGFrα oct-P oligonucleotide as probe (P, free probe). The complexes were competed with different-fold excess of either the cold oct-P probe (P) or consensus oct-1c oligo (1c), as indicated.

A similar mechanism has been suggested for kFGF, another effector gene of Oct-4 and a known mesoderm inducer in embryonic development. A concomitant silencing is observed in RA-induced differentiated murine EC and embryonic stem cells of both the expression of Oct-4 and kFGF. For kFGF expression, octamer-binding proteins are necessary for transcriptional activation, but developmentally restricted expression is determined by the interaction of octamer-binding proteins with Sox2 (32). The other described effector gene of Oct-4 is REX-1, which encodes a zinc finger-containing protein that is expressed in EC and embryonic stem cells. In mouse, RA-induced differentiation of the EC cells reduces transcription of the gene (33), which is probably due to a decline in the level of Oct-4 (22). Apart from Oct-4-controlled expression, REX-1, kFGF, and alternative PDGFrα transcripts contain no obvious denominator. This stresses the role of Oct-4 to stir diverse actions in development.

Oct-4, as well as any other POU domain transcription factor, is able to complex (in vitro) with the consensus octamer binding motif of the P2 promoter. The absence of P2-initiated messengers in RA-induced differentiated Tera2 cells or in normal placenta indicates that this motif is not used promiscuously by other POU domain transcription factors like e.g. Oct-1, and that the specificity of binding is probably highly influenced by the flanking sequences of the motif. A preliminary comparison

Fig. 6. Activity of PDGFrα gene P2 promoter mutants in Tera2 RA cells is dependent on the Oct-4 transcription factor. In the presence or absence of a cotransfected CMV-Oct-4 expression vector, the promoter clone −102/+182 or −102/+182M was transiently transfected into 7 days RA-differentiated Tera2 cells, in which Oct-4 is down-regulated. Luciferase activity was assayed 72 h post-transfection. Transfection efficiency was normalized by measuring β-galactosidase activity of a cotransfected pCH110 plasmid (Pharmacia). Values are presented as mean promoter activity relative to the clone −102/+182 without expression vector CMV-Oct-4, which was set at 100% (error bars indicate S.D.).
of the octamer flanking sequences of kFGF, REX-1, and PDGFRα shows, however, that the motifs cannot be aligned adequately to explain the preferential binding of Oct-4 to these sites. Accessory proteins might therefore explain Oct-4-dependent regulation (see above).

The role of proteins encoded by these alternative PDGFRα transcripts, if any, remains obscure, since presently none of these proteins have been detected in vivo. The sequence of the 5.0-kb messenger suggests a putative oncogene-like action, which may be important for autonomous growth of Tera2 EC cells. Undifferentiated Tera2 cells have been shown to proliferate in the absence of serum growth factors (34). A possible role in development or differentiation may also be inferred from the expression patterns of alternative PDGFRα transcripts. P2-initiated transcripts have been identified in human oocytes and preimplantation stages6 and in human testis tumors. The down-regulation of the 1.5-kb transcript expression in spermatogenesis suggests that the P2-promoter is active in cells of the female primordial germ cell lineage, probably in the commitment of cells during embryonal development. Alternative transcripts, generated by differential promoter use and/or splicing, of other tyrosine kinase receptors have been described, including the genes for PDGFRα (4), PFG receptors (35), epidermal growth factor receptor (36), c-kit (37) and PDGFRα of the mouse (38). Interestingly, an alternative transcript of approximately 4.8 kb of the PDGFRα gene has been detected in the mouse embryonal carcinoma cell line F9, but only after RA-induced differentiation (38). This transcript has also been described by Lee et al. (39) and is regulated in a differentiation-specific manner. Any conclusive evidence concerning functions of the corresponding alternative proteins remains lacking, however.

In conclusion, the POU transcription factor Oct-4 controls the developmentally regulated expression by the PDGFRα P2 promoter. Whether the down-regulation of Oct-4 during RA-induced differentiation is a prerequisite for the activation of the PDGFRα promoter P1 remains to be determined. We are currently working toward this goal.

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