



HAL
open science

Human TAF(II28) promotes transcriptional stimulation by activation function 2 of the retinoid X receptors.

Michael May, Gabrielle Mengus, Anne-Claire Lavigne, Pierre Chambon, Irwin Davidson

► To cite this version:

Michael May, Gabrielle Mengus, Anne-Claire Lavigne, Pierre Chambon, Irwin Davidson. Human TAF(II28) promotes transcriptional stimulation by activation function 2 of the retinoid X receptors.. EMBO Journal, 1996, 15 (12), pp.3093-104. hal-03108472

HAL Id: hal-03108472

<https://hal.science/hal-03108472v1>

Submitted on 15 Oct 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Human TAF_{II}28 promotes transcriptional stimulation by activation function 2 of the retinoid X receptors

Michael May, Gabrielle Mengus,
Anne-Claire Lavigne, Pierre Chambon and
Irwin Davidson¹

Institut de Génétique et de Biologie Moléculaire et Cellulaire, CNRS/
INSERM/ULP, Collège de France, BP 163-67404 Illkirch Cédex,
France

¹Corresponding author

Transcriptional activation *in vitro* involves direct interactions of transactivators with the TATA binding protein (TBP) and the TBP-associated factors (TAF_{II}s) which constitute the TFIID complex. However, the role of TAF_{II}s in transcriptional regulation in mammalian cells has not been addressed. We show that activation function 2 of the retinoid X receptors (RXR AF-2) does not activate transcription from a minimal promoter in Cos cells. However, coexpression of human (h) TAF_{II}28 promotes a strong ligand-dependent activity of the RXR AF-2 on a minimal promoter and potentiates the ability of the RXR α AF-2 to activate transcription from a complex promoter. The expression of hTAF_{II}28 also potentiated transactivation by several nuclear receptors, notably the oestrogen and vitamin D3 receptors (ER and VDR), whereas other classes of activator were not affected. The effect of hTAF_{II}28 on RXR AF-2 activities did not appear to require direct RXR-TAF_{II}28 interactions, but correlated with the ability of hTAF_{II}28 to interact with TBP. In contrast to Cos cells, the RXR AF-2s had differential abilities to activate transcription from a minimal promoter in HeLa cells, and a lesser increase in their activity was observed upon hTAF_{II}28 coexpression. Moreover, coexpression of hTAF_{II}28 did not increase but rather repressed activation by the ER and VDR AF-2s in HeLa cells. In agreement with these data, showing that TAF_{II}28 is limiting in the AF-2 activation pathway in Cos cells, TAF_{II}28 is selectively depleted in Cos cell TFIID.

Keywords: oestrogen receptor/TFIID/transcriptional intermediary factors/vitamin D3 receptor

Introduction

The transcription of protein coding genes in eukaryotes involves a multiprotein complex containing the RNA polymerase II (pol II) core enzyme and a series of auxiliary factors, TFIIA, TFIIB, TFIID, TFIIE, TFIIF and TFIIH (for reviews see Buratowski and Sharp, 1993; Conaway and Conaway, 1993; Buratowski, 1994; Zawel and Reinberg, 1995). Although these factors can be assembled in an ordered fashion *in vitro* to form a preinitiation complex, in yeast and also in mammalian cells many of these factors are associated with the RNA pol II core

enzyme in a holoenzyme complex (Kim *et al.*, 1994; Koleske and Young, 1994; Ossipow *et al.*, 1995).

One critical pol II transcription factor is TFIID, itself a multiprotein complex comprising the TATA binding protein (TBP) and TBP-associated factors (TAF_{II}s; Dynlacht *et al.*, 1991; Pugh and Tjian, 1991; Tanese *et al.*, 1991; Timmers *et al.*, 1992; Zhou *et al.*, 1992; Brou *et al.*, 1993a; Chiang *et al.*, 1993; for a review see Hernandez, 1993). In *Drosophila* (d) embryos, TFIID has been reported to exist as a homogenous complex comprising TBP and eight dTAF_{II}s (Chen *et al.*, 1994, and references therein). In contrast, we have shown that HeLa cell human (h) TFIID exists in several chromatographically separable and functionally distinct forms (Brou *et al.*, 1993a,b). Purification of hTFIID by chromatography and/or sequential immunoprecipitation with antibodies against hTBP and hTAF_{II}30 identified two hTFIID populations, hTFIID α and hTFIID β , which lack or contain hTAF_{II}30, respectively (Jacq *et al.*, 1994). An analysis of the hTAF_{II} composition of the hTFIID α and hTFIID β complexes led us to propose the existence of core hTAF_{II}s, exemplified by hTAF_{II}250, hTAF_{II}135, hTAF_{II}100 and hTAF_{II}28, present in all hTFIID complexes, and specific hTAF_{II}s, exemplified by hTAF_{II}30, hTAF_{II}20 and hTAF_{II}18, present in only the hTFIID β complexes (Jacq *et al.*, 1994; Mengus *et al.*, 1995).

The cDNAs encoding many *Drosophila* and human TAF_{II}s have been isolated (Hoey *et al.*, 1993; Yokomori *et al.*, 1993; Jacq *et al.*, 1994; Kokubo *et al.*, 1994; Chiang and Roeder, 1995; Klemm *et al.*, 1995, and references therein; Lu and Levine, 1995; Mengus *et al.*, 1995). More recently, yeast homologues of the metazoan TAF_{II}s have been identified and an analysis of their cDNA sequence shows that TAF_{II}s have been highly conserved during evolution (Reese *et al.*, 1994; Poon *et al.*, 1995). Nevertheless, hTAF_{II}30, hTAF_{II}18 and hTAF_{II}55 have no known *Drosophila* counterparts, while no human counterpart for dTAF_{II}150 (Verrijzer *et al.*, 1994) has as yet been described. These results suggest that either these dTAF_{II}s have not yet been isolated or that they are not expressed in *Drosophila* embryos but only in differentiated adult tissues.

Based on the observation that transactivation *in vitro* can be supported by TFIID, but not TBP (Hoey *et al.*, 1990; Pugh and Tjian, 1990; Zhou *et al.*, 1992; Brou *et al.*, 1993a), it was proposed that TAF_{II}s may function as coactivators required for activated, but not basal, transcription (for reviews see Tjian and Maniatis, 1994; Zawel and Reinberg, 1995). Indeed, many of the TAF_{II}s have been shown to act as coactivators *in vitro* by interacting selectively and directly with transcriptional activators. For example, Sp1 interacts with dTAF_{II}110, while the acidic activation domain of VP16 interacts with dTAF_{II}40 (Goodrich *et al.*, 1993; Hoey *et al.*, 1993; Gill *et al.*, 1994). We have also shown that ligand-independent transactivation *in vitro* by the DE region of the oestrogen

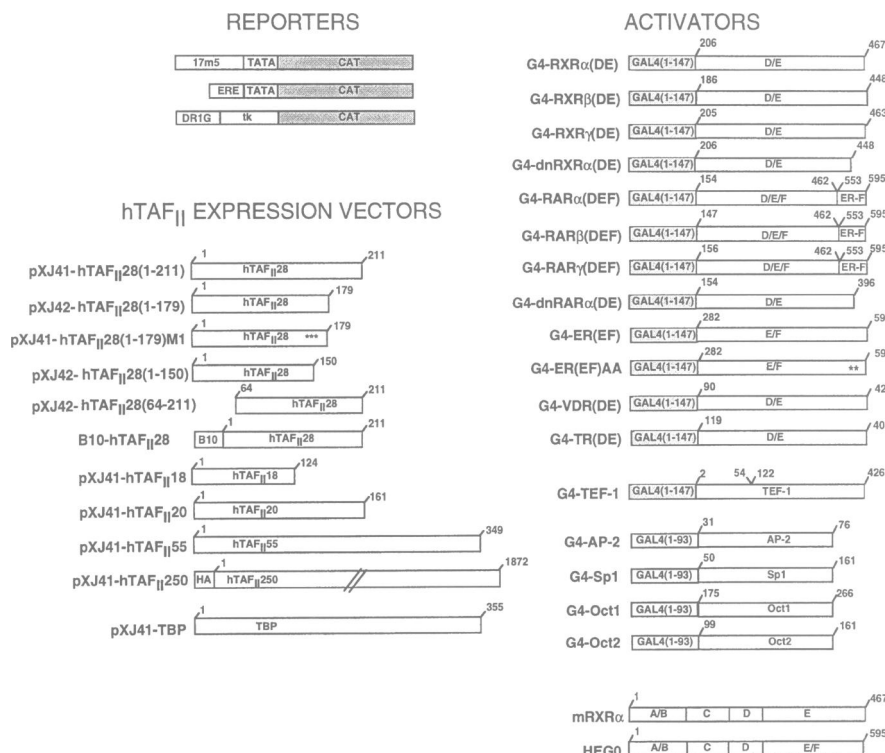


Fig. 1. Schematic representation of the reporter gene and expression vectors. Reporters: 17m5–TATA–CAT contains five GAL4 binding sites inserted 38 nucleotides upstream of the adenovirus major late promoter and the CAT gene. ERE–TATA–CAT and DR1G–tk–CAT containing the oestrogen and 9-*cis*-retinoic acid (RA) REs are as described previously (Tora *et al.*, 1989; Nagpal *et al.*, 1992). hTAF_{II} expression vectors: the vectors expressing wild-type, tagged and mutant derivatives of hTAF_{II}28, and wild-type hTAF_{II}18, hTAF_{II}20, hTAF_{II}55, hTAF_{II}250 and TBP are schematized. The asterisks in hTAF_{II}28(1–179)M1 indicate the positions of the E164P, E167P and E168R amino acid substitutions. The numbers are the amino acid coordinates in each case. HA is the haemagglutinin epitope for monoclonal antibody 12CA5, and B10 is the ER epitope for monoclonal antibody B10. Activators: the vectors expressing all mouse RAR, RXR derivatives, HEG0 and G4–TEF-1(2–426)Δ55–121 are schematized. GAL4 is abbreviated to G4. G4–ER(EF)AA contains amino acid substitutions M543A and L544A (indicated by asterisks) in G4–ER(EF). G4–AP-2, G4–Sp1, G4–Oct1 and G4–Oct2, containing proline- or glutamine-rich ADs from the respective activators, are also depicted. G4–VDR(DE) and G4–TR(DE) contain the DE regions of the human vitamin D3 and chicken thyroid hormone (α) receptors, respectively, cloned in vector pXJ440. In all cases, the numbers indicate the amino acid coordinates in the native proteins.

receptor (ER) involves direct interactions with hTAF_{II}30 (Jacq *et al.*, 1994). In addition to acting as coactivators, hTAF_{II}s also participate directly in promoter recognition and selectivity (Verrijzer *et al.*, 1995).

The mechanism by which transactivator proteins act through coactivators, such as the TAF_{II}s, to stimulate transcription is the subject of intense study. One class of activators whose activating domains, referred to also as activation functions (AFs), have been studied genetically, biochemically and biophysically is the nuclear receptor superfamily comprising the receptors for steroid/thyroid hormones, retinoic acid and vitamin D3. The ability of these factors to activate transcription is regulated by the binding of their cognate ligands (reviewed in Parker, 1993; Chambon, 1994; Giguère, 1994; Glass, 1994; Mangelsdorf *et al.*, 1994; Tsai and O'Malley, 1994). The nuclear receptors generally comprise two AFs: AF-1, located in the N-terminal A/B region, and AF-2, located in the ligand binding domain (LBD) in the C-terminal E region. The activity of the AF-2 is ligand inducible and requires a conserved amphipathic α-helix at the carboxyl end of the LBD, designated the AF-2 activating domain core (AF-2 AD core; Danielan *et al.*, 1992; Baretino *et al.*, 1994; Durand *et al.*, 1994). Comparison of the crystal structures of the unliganded retinoid X receptor (RXR) with the liganded retinoic acid (RAR) and thyroid hormone (TR)

receptors suggests that the binding of the ligand induces a conformational change bringing the AF-2 AD core into contact with α-helix H4 of the LBD (Bourguet *et al.*, 1995; Renaud *et al.*, 1995; Wagner *et al.*, 1995; Wurtz *et al.*, 1996). This conformational change generates an altered interaction surface, which allows the receptors to interact with several putative transcriptional intermediary factors (TIFs) required for AF-2 activity (Cavaillès *et al.*, 1995; LeDourain *et al.*, 1995; Lee *et al.*, 1995; Swaffield *et al.*, 1995; Vom Bauer *et al.*, 1995).

Although TAF_{II}s have been shown to function as transcriptional coactivators *in vitro*, their function in living mammalian cells has not yet been addressed directly. Here we show that the expression of hTAF_{II}28 promotes the transactivation of a minimal promoter by the AF-2s of the RXRs in Cos cells, where they are otherwise inactive. Transactivation by the AF-2s of several other nuclear receptors, in particular the ER and vitamin D3 receptor (VDR), was also stimulated by the coexpression of hTAF_{II}28, whereas no significant effect was seen with activators belonging to other families. The coactivator activity of hTAF_{II}28 did not appear to involve direct interactions with the receptor AF-2s, but did correlate with the ability of hTAF_{II}28 to interact with the TBP. In contrast to that observed in Cos cells, the RXR AF-2s activate transcription to varying degrees from a minimal

promoter in HeLa cells, and their activity is affected to a lesser extent by the coexpression of hTAF_{II}28. Furthermore, the expression of hTAF_{II}28 in HeLa cells did not increase but rather repressed transactivation by the ER and VDR AF-2s. In agreement with these results, showing that TAF_{II}28 is a limiting factor for AF-2 activity in Cos cells, the simian homologue of hTAF_{II}28 was selectively depleted in immunopurified Cos cell TFIID. These results show that TAF_{II}28 can act as a specific coactivator in mammalian cells.

Results

hTAF_{II}28 promotes transactivation by members of the nuclear receptor superfamily in transfected Cos cells

It has been shown previously that a chimera comprising the RXR β DE region (containing the ligand-inducible AF-2) fused to the DNA binding domain of the yeast activator GAL4 [G4-RXR β (DE)] does not activate transcription from a minimal promoter containing two GAL4 binding sites upstream of a TATA element in transfected Cos cells (Nagpal *et al.*, 1993). Similarly, this chimera does not activate transcription from a minimal promoter containing five GAL4 binding sites in either the presence or absence of ligand when between 0.25 and 1.00 μ g of expression vector were transfected (Figure 2A, lanes 1, 2 and 9, and data not shown; for reporter and activator plasmids, see Figure 1). Strikingly, when cotransfected with G4-RXR β (DE), hTAF_{II}28 promoted a strong ligand-dependent transcriptional activation (Figures 2A, lanes 13–15, and 3A and B). Coexpression of hTAF_{II}28 also promoted activation by the RXR α and RXR γ AF-2s (Figure 3A and B). Maximal transactivation was observed using 1.0 μ g RXR and 2.0 μ g hTAF_{II}28 expression vectors (Figure 2A, lane 15). A much weaker, yet significant, effect on the activity of the RXR β AF-2 was observed with another TFIID subunit, hTAF_{II}20 (Figure 2A, lanes 10–12).

The ability of hTAF_{II}28 to potentiate transactivation was not limited to the RXR AF-2s. Coexpression of hTAF_{II}28 increased transcriptional activation by 5- to 7-fold for the AF-2s of the ER [G4-ER(EF), Figures 2B, lanes 4 and 8–10, and 3A and B] and VDR [G4-VDR(DE), Figure 3A and B], by 4-fold for the AF-2 of the RAR γ [G4-RAR γ (DEF)], but by only 2- to 3-fold for the AF-2s of the RAR α , RAR β and thyroid hormone receptor [G4-TR(DE)]. Similar results were observed even when lower amounts of the RAR (α and β forms) and the TR expression vectors were transfected, showing that the modest effect of hTAF_{II}28 was not caused by saturating levels of activation (data not shown). For each AF-2, the ability of hTAF_{II}28 to potentiate activation was strictly dependent on the presence of the cognate ligands, with the exception of a modest (between 5 and 8% of that seen in the presence of ligand) ligand-independent activation of transcription observed with RAR α and RAR β (Figure 2A and B, and data not shown).

In contrast to the above results, the expression of hTAF_{II}28 had no significant effect on transactivation by five chimeric activators which do not belong to the nuclear receptor superfamily but have diverse classes of AFs (G4-Sp1 in Figure 2B, lanes 11 and 14–15; G4-TEF-1, G4-

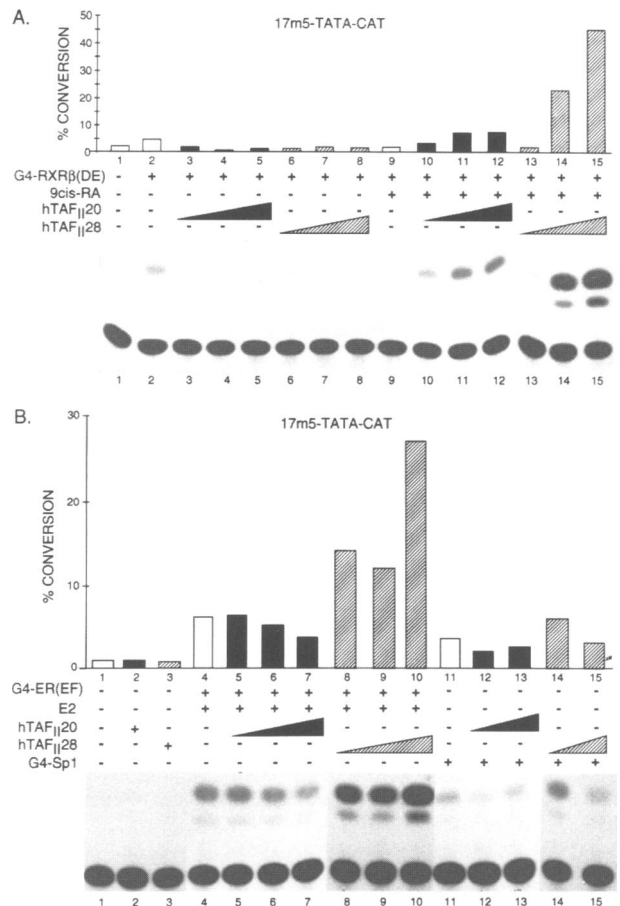


Fig. 2. (A) Expression of hTAF_{II}28 in Cos cells promotes transactivation by the RXR β AF-2. The lower panel shows the autoradiography of CAT assays performed with extracts from cells transfected with the expression vectors shown above each lane in the presence (+) or absence (-) of 100 nM 9-*cis*-RA. Transfections contained 1.0 μ g of the 17m5-TATA-CAT reporter and G4-RXR β (DE) expression plasmids with 0.0, 0.5, 1.0 or 2.0 μ g of the hTAF_{II}20 or hTAF_{II}28 expression vectors. The upper panel shows the quantitative phosphorimager analysis of the CAT assays represented in the lower panel. Values are expressed as percentages of the total chloramphenicol which was acetylated. (B) Expression of hTAF_{II}28 potentiates transactivation by G4-ER(EF) but not by G4-Sp1. The lower panel shows the autoradiography of CAT assays performed with extracts from cells transfected with the expression vectors indicated above each lane in the presence or absence of 15 nM oestradiol (E2). Transfections contained 1.0 μ g of the 17m5-TATA-CAT reporter plasmid, 250 ng of the G4-ER(EF) or G4-Sp1 expression vectors, and 0.0, 0.5, 1.0 and 2.0 μ g of the hTAF_{II}28 or hTAF_{II}20 expression vectors. In lanes 2 and 3, 2.0 μ g of the hTAF_{II} expression vectors were transfected. The upper panel shows the quantitative phosphorimager analysis, as in (A).

AP-2, G4-Oct1 and G4-Oct2 in Figure 3A and B]. Therefore, although hTAF_{II}28 may potentiate transactivation by activators other than those tested, hTAF_{II}28 is clearly an activator-specific coactivator.

Next we tested the ability of hTAF_{II}28 to promote transactivation by wild-type receptors bound to their cognate response elements. The transfection of wild-type RXR α results in a ligand-dependent activation of transcription from a reporter comprising the thymidine kinase (tk) promoter and a DR1G RXR response element (RE) (Nagpal *et al.*, 1992; see Figure 4A, columns 1 and 2). Cotransfection of hTAF_{II}28 and wild-type RXR α resulted in a 5-fold ligand-dependent increase in transcriptional

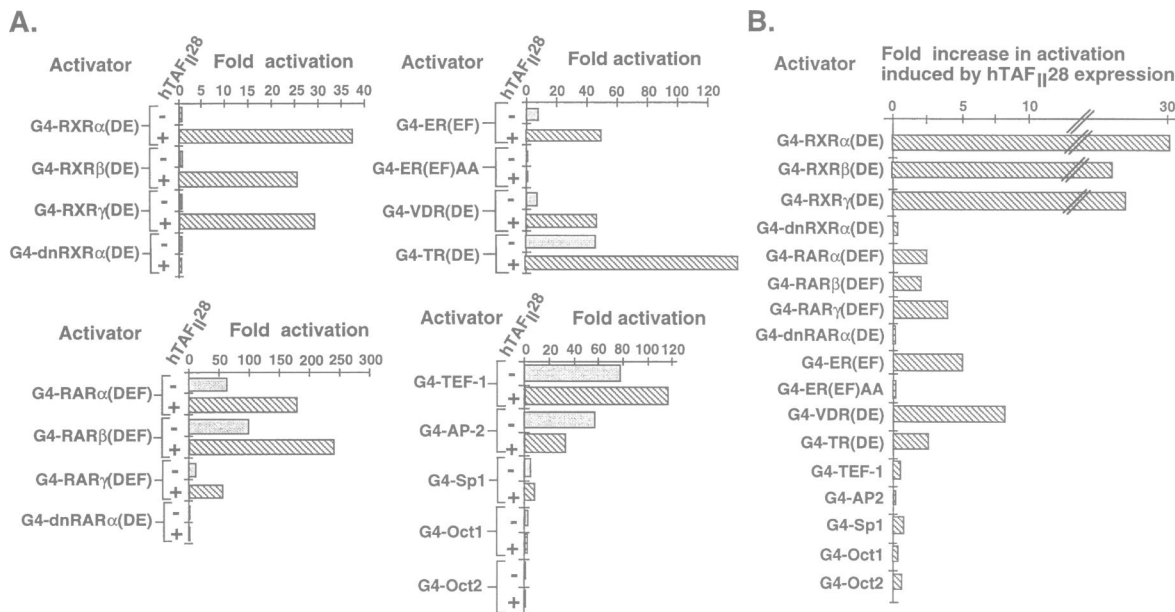


Fig. 3. (A) Transactivation by chimeric activators in the absence or presence of coexpressed hTAF₁₁₂₈. The ability of each activator to transactivate the 17m5-TATA-CAT reporter in transient transfections in Cos cells was determined by a quantitative phosphorimager analysis of the CAT assays. The transfected activator is shown to the left of the panels. All values ($\pm 20\%$) represent the average of at least three transfections. The fold activation, relative to basal transcription, in the absence or presence of hTAF₁₁₂₈ is shown by the filled or hatched bars respectively. All values were determined in the presence of the cognate ligands. *9-cis*-RA and *all trans*-RA were added to a final concentration of 100 nM, oestradiol to 15 nM, 1,25-dihydroxy-vitamin D3 to 100 nM and thyroid hormone (3,5,3'-triiodo-L-thyronine) to 1 μ M. In addition to pRSV-Luc as the internal standard and 0.0 or 2.0 μ g of hTAF₁₁₂₈, transfections contained 1.0 μ g of the 17m5-TATA-CAT reporter and RXR chimeras; 100 ng of the RAR, VDR, TR and TEF-1 chimeras; and 250 ng of the ER, AP-2, Sp1, Oct1 and Oct2 chimeras. The expression of G4-Oct1 and G4-Oct2, for which no activation was seen in the presence or absence of hTAF₁₁₂₈, was verified by a Western blot analysis using the anti-GAL4 antibodies 2GV3 and 3GV2. (B) Potentiation of transactivation by hTAF₁₁₂₈ expression. The effect of hTAF₁₁₂₈ shown in (A) is summarized. The value 1 represents no increase relative to activation in the absence of hTAF₁₁₂₈.

activation (Figure 4A, columns 2, 3 and 6). Similarly, cotransfection of hTAF₁₁₂₈ led to a 7-fold increase in activation by the wild-type ER from a minimal promoter with an upstream oestrogen response element (ERE) (Figure 4B, compare columns 2–3 with 5–6). These experiments show that hTAF₁₁₂₈ can also potentiate activation by wild-type receptors bound to their cognate REs, excluding the possibility that the effect of hTAF₁₁₂₈ requires a cryptic AF present in GAL4(1–147).

As described above, the activity of the nuclear receptor AF-2s requires a conserved amphipathic α -helical motif at the C-terminus of the LBD, designated the AF-2 AD core. Deletion of the AF-2 AD core abolishes transcriptional activation by the RARs and RXRs in both the absence (see also Durand *et al.*, 1994) and presence of hTAF₁₁₂₈ [G4-dnRAR α (DE) and G4-dnRXR α (DE) in Figure 3A and B]. Analogous results were obtained with a double amino acid substitution within the ER AF-2 AD core [M543A; L544A; G4-ER(EF)AA; Figure 3A and B]. These results indicate that hTAF₁₁₂₈ does not induce the activity of a novel AD functioning independently of the AF-2 AD core.

The ability of two further TFIID subunits, hTAF₁₁₅₅ and hTAF₁₁₂₅₀, to potentiate transactivation by the receptor AF-2s was also tested. While in the same experiment in which hTAF₁₁₂₈ potentiated activation by the RXR and ER AF-2s, no equivalent effect was seen with hTAF₁₁₂₅₀ or hTAF₁₁₅₅ (Figure 5A and B). Similarly (with the exception of the RXRs and hTAF₁₁₂₀; Figure 2A), the expression of hTAF₁₁₂₅₀, hTAF₁₁₅₅, hTAF₁₁₂₀ and hTAF₁₁₁₈ did not result in increased transcriptional activ-

ation using any of the activators tested (see Figure 2B, and data not shown). These results indicate that the ability to potentiate activation by these activators in Cos cells was not a general property of all hTAF_{11s} but was specific to hTAF₁₁₂₈.

The coactivator function of hTAF₁₁₂₈ correlates with its ability to interact with TBP and involves a putative amphipathic α -helical region

Transcriptional activation *in vitro* has been reported to require direct activator-hTAF₁₁ interactions (see above). Therefore we investigated whether hTAF₁₁₂₈ would interact with the AF-2 of the RXR. To analyse this interaction under conditions which most closely resemble those in which a functional effect is observed, vectors expressing wild-type hTAF₁₁₂₈(1–211) and G4-RXR β (DE) or, as a control, TBP were transfected into Cos cells in either the presence or absence of ligand. The transfected cell extracts were then immunoprecipitated with monoclonal antibodies (mAbs) against TBP (mAb 3G3), hTAF₁₁₂₈ (mAb 15TA) or the GAL4 DBD (mAb 2GV3). The precipitated proteins were analysed on Western blots. Under conditions where cotransfected hTAF₁₁₂₈ and TBP form a stable immunoprecipitable complex (Figure 6A, lanes 4–6; see also Mengus *et al.*, 1995 and below), no coimmunoprecipitation of hTAF₁₁₂₈ and G4-RXR β (DE) was observed in either the presence or absence of ligand (Figure 6B). Similarly, no significant hTAF₁₁₂₈-RXR interactions could be detected *in vitro* using GST-RXR and purified recombinant hTAF₁₁₂₈ or in the yeast two-hybrid system; nor were ligand-dependent interactions detected between hTAF₁₁₂₈

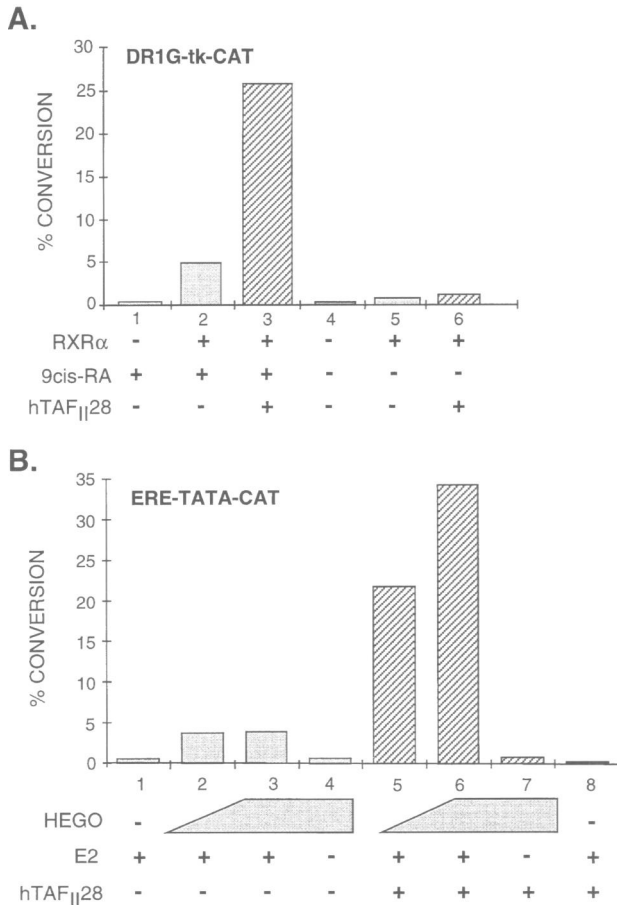


Fig. 4. (A) hTAF_{II}28 potentiates the transactivation of DR1G-tk-CAT by wild-type RXR α . A quantitative phosphorimager analysis of the CAT assays. Transfections contained 1.0 μ g of the DR1G-tk-CAT reporter and RXR α expression plasmids and 0.0 or 2.0 μ g of the hTAF_{II}28 expression plasmids, as indicated. (B) hTAF_{II}28 potentiates transactivation by the wild-type ER. Transfections contained 1.0 μ g of the ERE-TATA-CAT reporter, 1.0 or 2.0 μ g of the HEG0 expression vector and 0.0 or 2.0 μ g of the hTAF_{II}28 expression vector, as indicated.

and the AF-2s of the VDR or the TR (data not shown). Thus, the ability of hTAF_{II}28 to induce the activity of the RXR AF-2s does not appear to require direct activator-hTAF_{II} interaction.

We have shown previously that hTAF_{II}28 interacts with TBP both *in vitro* and in transfected Cos cells (see above and Mengus *et al.*, 1995). Next we asked whether the ability of hTAF_{II}28 to function as a coactivator required its ability to interact with TBP. A previous deletion analysis had shown that while wild-type hTAF_{II}28(1-211) interacted with TBP, no interaction was observed with the hTAF_{II}28 deletion mutant (1-150). To define further the region required for hTAF_{II}28-TBP interaction, a novel mutant, hTAF_{II}28(1-179), was made, and its ability to interact with TBP was determined. Following cotransfection, the hTAF_{II}28 deletion mutant (1-179) could be coimmunoprecipitated with TBP (Figure 6A, lanes 9-11). Together, these results indicate that hTAF_{II}28 amino acids between 150 and 179 are critical for interaction with TBP. A computer analysis indicated that amino acids 161-179 have the potential to form an amphipathic α -helix which can align the six acidic amino acids present in this region on one face of the helix (see Materials and methods).

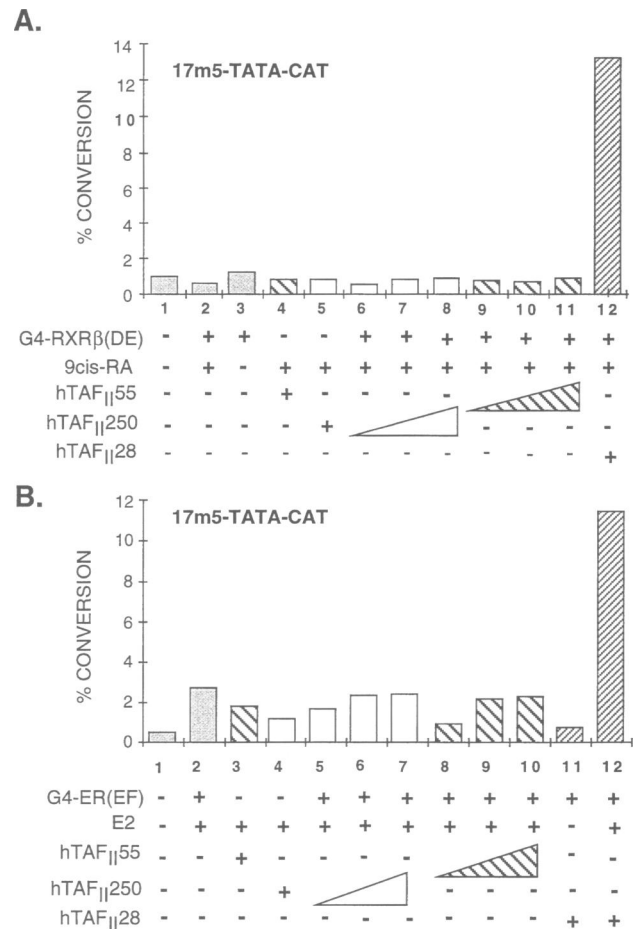


Fig. 5. (A) Coexpression of hTAF_{II}55 and hTAF_{II}250 does not potentiate transactivation by the RXR β AF-2. Transfections contained 1.0 μ g of the 17m5-TATA-CAT reporter and RXR β AF-2 expression plasmids, 0.5, 1.0 and 2.0 μ g of the hTAF_{II}55 expression plasmid, 1.0, 2.5 and 5.0 μ g of the hTAF_{II}250 expression plasmid, and 2.0 μ g of the hTAF_{II}28 expression plasmid, as indicated. The transfections shown in columns 4 and 5 contained 2.0 and 5.0 μ g of the corresponding hTAF_{II} expression vectors. (B) Cotransfection of hTAF_{II}55 or hTAF_{II}250 does not potentiate transactivation by the ER AF-2. Transfections contained the same amounts of each plasmid, except that the RXR β expression vector was replaced by 250 ng of the ER AF-2 expression vector. The transfections in columns 3 and 4 contained 2.0 and 5.0 μ g of the hTAF_{II} expression vectors.

Therefore we mutated three of the glutamic acid residues (E164P, E167P and E168R) to generate hTAF_{II}28(1-179)M1, disrupting the α -helix and changing the charge. This triple amino acid substitution reduced the interaction between cotransfected hTAF_{II}28 and TBP (Figure 6A, lanes 12-14). Surprisingly, however, deletion of the N-terminus of hTAF_{II}28, hTAF_{II}28(64-211), also reduced the interaction with TBP in transfected Cos cells, showing that determinants for interaction with TBP are present not only between amino acids 150 and 179 but also in the N-terminal 63 amino acids (Figure 6A, lanes 15-17).

In cotransfections with G4-RXR β (DE), wild-type hTAF_{II}28(1-211) and the (1-179) deletion mutant promoted AF-2 activity, whereas the (1-150), (64-211) and (1-179)M1 mutants had no significant effect (Figure 6C). These results show that the induction of RXR β AF-2 activity correlates with the ability of hTAF_{II}28 to bind efficiently to TBP.

The above results suggest that hTAF_{II}28 may act as a

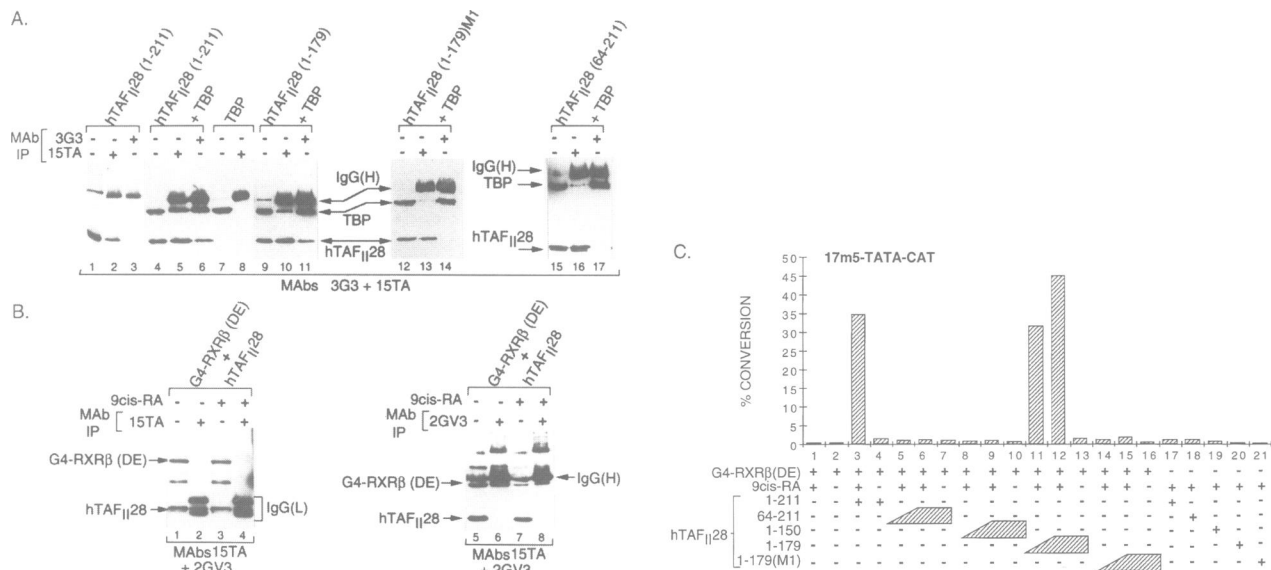


Fig. 6. (A) Coimmunoprecipitation of TBP with wild-type and mutated hTAF₁₁₂₈. Extracts of Cos cells transfected with the expression vectors shown above the panel were precipitated with the antibodies shown above each lane. Lanes 1, 4, 7, 9, 12 and 15 show aliquots of the unprecipitated starting extracts. The precipitated proteins were revealed on Western blots using the mAbs shown below the panel. mAb 3G3 is directed against TBP and mAb 15TA is directed against hTAF₁₁₂₈. The positions of hTAF₁₁₂₈ and TBP are indicated, along with that of the heavy chain [IgG(H)] of the antibody used in the immunoprecipitations (IP). (B) The RXRβ DE region does not coimmunoprecipitate with hTAF₁₁₂₈. Extracts from Cos cells transfected with the expression vectors shown above the panel were immunoprecipitated with the antibodies indicated above each lane. Lanes 1, 3, 5 and 7 show the unprecipitated cell extracts. The precipitated proteins were detected with the antibodies shown below the panel. The positions of the G4-RXRβ(DE) fusion and hTAF₁₁₂₈ are indicated. The presence or absence of 50 nM 9-*cis*-RA during the transfection and the immunoprecipitation is also indicated above the lanes. As the G4-RXRβ(DE) fusion migrates close to the heavy chain of the antibodies used in the immunoprecipitation, lanes 1–4 were revealed with a peroxidase-conjugated antibody directed against the light chain [IgG(L)], which detects two species (whose positions are indicated) migrating immediately above and below hTAF₁₁₂₈. Note that no coimmunoprecipitation of hTAF₁₁₂₈ and G4-RXRβ(DE) was detected, even when cell extracts and immunoprecipitations were performed under less stringent salt conditions (0.25 M KCl). (C) Effect of hTAF₁₁₂₈ mutants on RXRβ AF-2 activity. Cells were transfected with 1.0 μg of the 17m5-TATA-CAT reporter and RXRβ(DE) expression plasmids and 1.0 or 2.0 μg of the hTAF₁₁₂₈ expression vectors, as indicated. The transfections represented in columns 3, 4 and 17–21 contained 2.0 μg of the indicated hTAF₁₁₂₈ expression vectors.

bridging factor between TBP and the receptor AF-2s, if not directly, at least indirectly via one of the TIFs required for AF-2 function (see Discussion). If this were the case, the loss of function of the mutants described above may be ascribed to their inability to either interact efficiently with TBP and/or interact with another cofactor required for AF-2 function. Consequently, if hTAF₁₁₂₈ acts as a bridging factor and these mutations only affect interactions with TBP but not other factors required for RXR AF-2 activity, the mutants should act as dominant-negative repressors of hTAF₁₁₂₈-induced AF-2 activity. Alternatively, if the mutant hTAF₁₁₂₈ proteins no longer interact with any cellular factors required for AF-2 activity, they should have no effect. To distinguish between these possibilities, the hTAF₁₁₂₈(1–150) and (64–211) deletion mutants were cotransfected along with hTAF₁₁₂₈(1–179) in the presence of G4-RXRα(DE) and ligand. The coexpression of hTAF₁₁₂₈(1–179) and G4-RXRα(DE) resulted in transactivation (Figure 7A, column 3), while no effect was seen with either of the other two deletion mutants (Figure 7A, columns 7 and 10). Strikingly, coexpression of hTAF₁₁₂₈(64–211) or (1–150) repressed the hTAF₁₁₂₈(1–179)-induced activation (Figure 7A, columns 4–6 and 8–9). Similar results were obtained with the ER AF-2, where the increase in activation seen upon coexpression of hTAF₁₁₂₈(1–179) was strongly diminished in the presence of hTAF₁₁₂₈(1–150) or (64–211) (Figure 7B). In contrast, the expression of wild-type hTAF₁₁₂₈ or the deletion mutants had no significant effect on

transactivation by G4-TEF-1 (Figure 7C). These results strongly suggest that, although these mutants no longer interact efficiently with TBP, they can interact with and titrate other factors specifically required for receptor AF-2 activity.

Expression of hTAF₁₁₂₈ has distinct effects in Cos and HeLa cells on the activities of the RXR, VDR and ER AF-2s

Next the ability of hTAF₁₁₂₈ to act as a coactivator in HeLa cells was investigated. In transient transfection, hTAF₁₁₂₈ was coexpressed with the RXR, ER and VDR AF-2s because these are the activators for which the most dramatic effects were observed in Cos cells. In contrast to Cos cells, where all the RXR AF-2s were inactive on a minimal promoter, the RXR AF-2s had differential abilities to activate transcription in HeLa cells. The strongest activation was seen with the RXRα AF-2, where a 10-fold ligand-dependent activation was observed with 1.0 μg of expression vector (Figure 8A, columns 1–4). A lower activation (2.5-fold) was seen with the RXRβ AF-2 (Figure 8A, columns 7–9). In contrast, only a low 2-fold activation was seen with 1.0 μg of the RXRγ AF-2 expression vector (Figure 8A, columns 12–14). Coexpression of hTAF₁₁₂₈ with 0.25 μg of the RXRα or RXRβ AF-2 expression vector increased activation by a further 8.5- and 6.0-fold, respectively (Figure 8A, columns 3, 5, 8 and 10), whereas only a 1.5-fold stimulation was seen with 1.0 μg of the vector (Figure 8A, columns 4, 6, 9 and

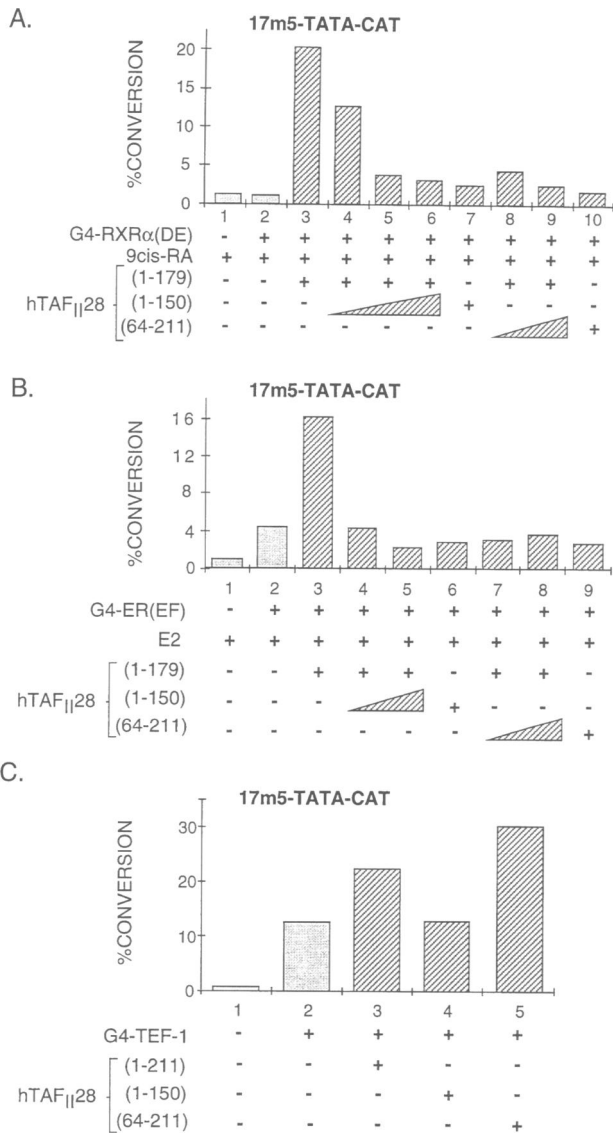


Fig. 7. (A) Dominant negative phenotype of hTAF_{II}28 deletion mutants. A quantitative phosphorimager analysis of the CAT assays from cells transfected with 1.0 μg G4-RXRα(DE), 2.0 μg hTAF_{II}28(1-179) and 2.0, 5.0 or 10.0 μg hTAF_{II}28(1-150) or 2.0 and 5.0 μg hTAF_{II}28(64-211), as indicated below each column. 2.0 μg of the hTAF_{II}28 mutant expression vectors were transfected in columns 7 and 10. (B) Transfections were performed as in (A), except that 250 ng G4-ER(EF) expression vector replaced the RXR expression vector. (C) Transfections contained 100 ng of the G4-TEF-1 expression vector and 2.0 μg of the indicated hTAF_{II}28 expression vectors.

11). In contrast, a strong increase in activation by the RXRγ AF-2 was seen at both concentrations of expression vector in the presence of hTAF_{II}28 (31- and 11-fold; see Figure 8A, columns 13-16). These results show that the RXR AF-2s have differential abilities to activate transcription from a minimal promoter in HeLa cells, but that, with the exception of the RXRγ AF-2, the effect of hTAF_{II}28 coexpression is less pronounced than in Cos cells.

A strong ligand-dependent stimulation of transcription was seen in HeLa cells with the ER and VDR AF-2s (Figure 8B, columns 3 and 4, and 8 and 9) in the absence of coexpressed hTAF_{II}28. In striking contrast to the

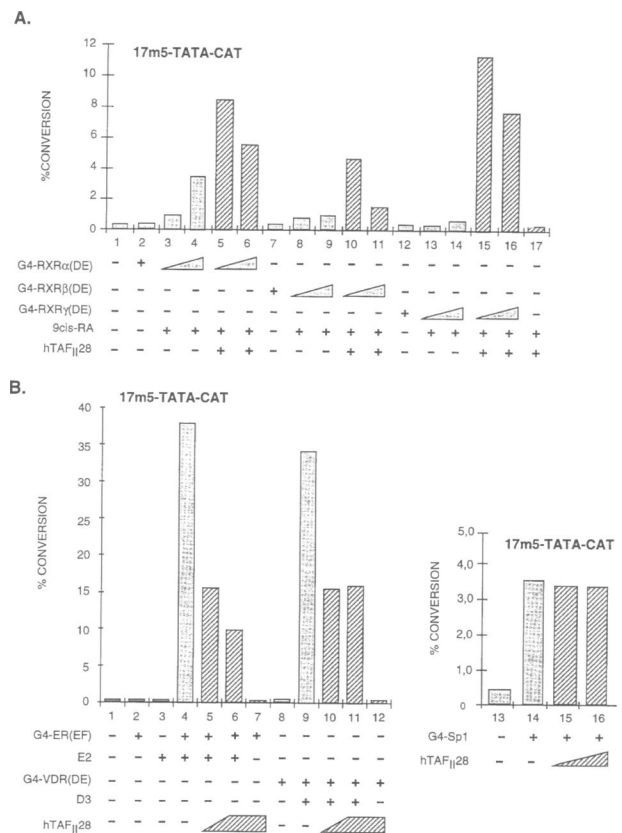


Fig. 8. (A) The effect of hTAF_{II}28 coexpression on the activity of the RXR AF-2s in HeLa cells. A quantitative phosphorimager analysis of the CAT assays from a representative experiment. In addition to 1.0 μg of the RSV-Luc internal standard, transfections contained 0.25 or 1.0 μg of the G4-RXR, and 0.0 or 2.0 μg of the hTAF_{II}28 expression vectors, as indicated below the graph. The presence or absence of 100 nM 9-cis-RA is also indicated. (B) Dominant-negative effect of hTAF_{II}28 on ER and VDR AF-2 activity in HeLa cells. Transfections contained 100 ng of the G4-ER(EF), 250 ng of the G4-VDR(DE) and 2.0 or 5.0 μg of the hTAF_{II}28 expression vectors, as indicated below the graph. Transfections contained 50 nM oestradiol (E2) or 100 nM vitamin D3, as indicated. Similar results for all transfections were obtained in two other independent experiments. The transfections in columns 13-16 contained 250 ng of the G4-Sp1 and 0.0, 2.0 or 5.0 μg of the hTAF_{II}28 expression vectors.

increase in activation seen in Cos cells, the coexpression of hTAF_{II}28 in HeLa cells in fact repressed activation by the VDR and ER AF-2s by 2- to 3-fold (Figure 8B, columns 4-6 and 9-11). However, as observed in Cos cells, coexpression of hTAF_{II}28 had no significant positive or negative effect on the 6-fold transactivation by G4-Sp1 in HeLa cells (Figure 8B, columns 13-16). Together, the above results show that hTAF_{II}28 has different effects on activation by the RXR, ER and VDR AF-2s in Cos and HeLa cells.

TAF_{II}28 is depleted in Cos cell TFIID

The above observations suggest that, while TAF_{II}28 is limiting for the activities of the RXR, VDR and ER AF-2s in Cos cells, it is less limiting in HeLa cells because the RXR AF-2s are active and, with the exception of the RXRγ AF-2, overexpression of hTAF_{II}28 has a lesser effect in HeLa than in Cos cells. This prompted us to ask whether HeLa and Cos cell TFIIDs contained equivalent amounts of TAF_{II}28. Total TFIID was immunopurified

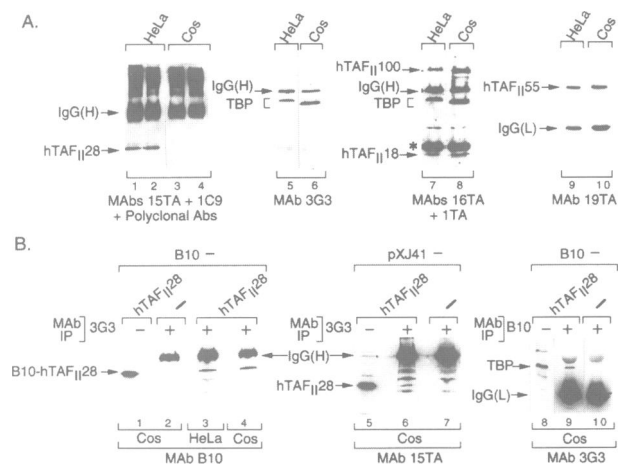


Fig. 9. (A) Cos cell TFIID is specifically depleted in hTAF_{II}28. Western blots of immunopurified HeLa and Cos cell TFIIDs were probed with the antibodies shown below each panel. As hTAF_{II}55 comigrates with the IgG(H) chain, it was detected using a secondary antibody directed against the IgG(L). The positions of hTAF_{II}28, TBP, hTAF_{II}18, hTAF_{II}55 and hTAF_{II}100 are indicated, along with the IgG(H) and IgG(L). The asterisk indicates an artifactual signal caused by the presence of the 3G3 epitope peptide used to elute the immunopurified TFIID. Lanes 1, 3 and 5–10 contain the first eluted fraction, and lanes 2 and 4 contain the wash fraction (see Materials and methods). (B) Transfected hTAF_{II}28 stably associates with endogenous Cos cell TBP/TFIID. In all, 15 dishes of Cos or HeLa cells were transfected with 3.0 μ g of the expression vectors indicated above each lane (the dash indicating the empty expression vector). The transfected cell extracts were pooled and immunoprecipitated with the mAbs indicated for each panel. For mAb 3G3, the immunoprecipitated material was eluted using the corresponding epitope peptide, while for mAb B10 the beads were resuspended directly and boiled in loading buffer. Lanes 1, 5 and 8 show aliquots of the transfected cell extracts to indicate the positions of the precipitated proteins. The heavy and light chains of the mAbs used in the immunoprecipitations are indicated.

from HeLa or Cos cell extracts using the anti-TBP monoclonal antibody 3G3 (mAb 3G3) and eluted with the corresponding epitope peptide (Brou *et al.*, 1993a; see Materials and methods). Aliquots of the immunopurified TFIIDs were subjected to SDS-PAGE and transferred to nitrocellulose filters. The filters were then probed with mAb 3G3 or a mixture of two mAbs, 15TA and 1C9, and two rabbit polyclonal antisera, all of which recognize distinct epitopes in hTAF_{II}28 (see Materials and methods). Although more immunopurified Cos cell TFIID was present on the filter, as proved by the amounts of TBP (Figure 9A, lanes 5 and 6), no TAF_{II}28 could be detected in the Cos cell TFIID, whereas hTAF_{II}28 was clearly detected in the HeLa cell TFIID (Figure 9A, compare lanes 1 and 2 with 3 and 4, containing two eluted TFIID fractions). The Cos and HeLa cell TFIIDs were probed further with antibodies against hTAF_{II}18, hTAF_{II}20, hTAF_{II}30, hTAF_{II}55, hTAF_{II}100 and hTAF_{II}135. Approximately equivalent amounts of each of these TAF_{II}s were observed in HeLa and Cos cell TFIIDs (Figure 9A, lanes 7–10, and data not shown). Therefore, although TBP and six other TAF_{II}s could readily be detected in Cos cell TFIID, no simian homologue of hTAF_{II}28 was detected. These results show that this TAF_{II} is either absent or dramatically depleted in Cos cell TFIID.

Next we verified that, as described previously for hTAF_{II}100, hTAF_{II}70 and hTAF_{II}30 (Weinzierl *et al.*,

1993; Jacq *et al.*, 1994; Dubrowskaya *et al.*, 1996), transfected hTAF_{II}28 associates with endogenous TBP/TFIID. As the anti-hTAF_{II}28 monoclonal antibodies do not efficiently immunoprecipitate the TFIID complex because of masking of the epitopes, a vector expressing a derivative of hTAF_{II}28 tagged at its N-terminus with the B10 epitope of the ER (Mengus *et al.*, 1995) was transfected into Cos cells. The transfected extracts were immunoprecipitated with mAb 3G3 against TBP or mAb B10 directed against the tag. Immunoprecipitation of the transfected cell extracts (10–15 times more extract than used in Figure 6A) with mAb 3G3 resulted in the coimmunoprecipitation of B10-hTAF_{II}28 (Figure 9B, lane 4). Similar results were obtained in extracts from HeLa cells transfected with B10-hTAF_{II}28 (Figure 9B, lane 3). In the converse experiment, TBP was coprecipitated by mAb B10 from Cos cells transfected with B10-hTAF_{II}28 but not from cells transfected with the empty B10 expression vector (Figure 9B, lanes 9 and 10). In analogous experiments, untagged hTAF_{II}28 was coprecipitated by mAb 3G3 from extracts of Cos cells transfected with the pXJ41-hTAF_{II}28 expression vector, whereas no TAF_{II}28 was detected after the precipitation of extracts from cells transfected with the empty vector (Figure 9B, lanes 6 and 7). Thus, although no endogenous TAF_{II}28 was detected stably associated with the Cos cell TFIID, the transfected hTAF_{II}28 does stably associate with the endogenous TBP/TFIID.

Discussion

TAF_{II}28 is an essential cofactor for the activity of the RXR AF-2s in vivo

We have shown previously (Mengus *et al.*, 1995) that hTAF_{II}28 is the homologue of dTAF_{II}30 β (Yokomori *et al.*, 1993). Although these *Drosophila* and human TAF_{II}s show 50% identity, indicating a high evolutionary conservation, several differences in their interactions with other TFIID subunits were observed, notably in their reported abilities to interact with TBP (Mengus *et al.*, 1995). Thus, despite the fact that TAF-TAF interactions involving dTAF_{II}30 β and hTAF_{II}28 had been studied, no function had been ascribed to either the *Drosophila* or human proteins.

The results presented here show that hTAF_{II}28 can function as a specific coactivator for several nuclear receptors in Cos cells. The most dramatic effect is observed with the RXR AF-2s, which do not activate transcription from a minimal promoter in the absence of coexpressed hTAF_{II}28, whereas a strong stimulation is seen in the presence of hTAF_{II}28. The ER and VDR AF-2s do activate transcription from a minimal promoter in Cos cells in the absence of hTAF_{II}28, but activation by these AF-2s is stimulated further by the expression of hTAF_{II}28. A weaker, yet significant, effect was observed with the AF-2s of the TR and RARs, which strongly stimulated transcription in the absence of hTAF_{II}28. The expression of hTAF_{II}28 also increased activation by wild-type RXR α or ER bound to their cognate REs. In addition, the results obtained with the DR1G-tk-chloramphenicol acetyl transferase (CAT) reporter show that the coactivator activity of hTAF_{II}28 is not limited to a minimal promoter, but that it can also be observed when the RXR α AF-2 cooperates with its own AF-1 and/or the AFs of upstream factors on

a more complex promoter. The coactivator effect of hTAF_{II}28 in Cos cells requires the integrity of the AF-2 AD core as deletions or mutations of this sequence abolish activation in both the absence and presence of hTAF_{II}28. This result shows that hTAF_{II}28 does not promote the activity of a novel AD functioning independently of the AF-2, although we do not exclude the possibility that hTAF_{II}28 mediates the activity of an AD located within the receptor DE region which would function only in cooperation with the AF-2. In comparison with these observations of nuclear receptors, the expression of hTAF_{II}28 had no effect on activation by a series of activators whose activating domains are characterized by high proline or glutamine contents, irrespective of whether they function as strong or weak activators.

In contrast to Cos cells, in which the RXR AF-2s were inactive on a minimal promoter, RXR AF-2s had differential abilities to activate transcription from this promoter in HeLa cells. The strongest activation was observed with the RXR α AF-2, while only weak activation was observed with the RXR γ AF-2. In Cos cells, the coexpression of hTAF_{II}28 promoted a strong increase in the activities of all of the RXR AF-2s, whereas in HeLa cells a comparable strong increase was seen only with the RXR γ AF-2. A more dramatic difference was observed when comparing the effect of hTAF_{II}28 expression on activation by the ER and VDR AF-2s in Cos and HeLa cells. In Cos cells, the expression of hTAF_{II}28 increased activation, whereas in HeLa cells activation was reduced. Thus, the ectopic expression of hTAF_{II}28 has distinct effects in Cos and HeLa cells on the activities of these AF-2s.

One interpretation of the above results is that TAF_{II}28 is limiting for AF-2 activity in Cos cells but less so in HeLa cells, although its concentration is clearly suboptimal for the RXR γ AF-2. For the ER and VDR AF-2s, the concentration of endogenous hTAF_{II}28 in HeLa cells may be close to the optimum because overexpression of hTAF_{II}28 may actually begin to titrate other factors required for the activity of these AF-2s, resulting in decreased activation. This interpretation is supported further by the fact that we did not detect TAF_{II}28 in immunopurified Cos cell TFIID. This shows that, relative to HeLa cell TFIID, Cos cell TFIID contains significantly lower amounts of this TAF_{II}. It is unlikely that our inability to detect Cos cell TAF_{II}28 may be explained by the absence of all four human epitopes in the simian protein because hTAF_{II}28 shows a high evolutionary conservation (note that 11 of the 15 amino acids of the mAb 1C9 epitope are conserved, even in dTAF_{II}30 β ; Mengus *et al.*, 1995). In accordance with this observation, the anti-hTAF_{II}28 antibodies recognize mouse TAF_{II}28 in TFIID immunopurified from F9 embryonal carcinoma cells (our unpublished data). Furthermore, the simian homologues of six other hTAF_{II}s were detected in Cos cell TFIID. Nevertheless, we could not detect TAF_{II}28 in Cos or HeLa cell nuclear extracts with the mAbs used here because of its low abundance (our unpublished data). Thus, we cannot rule out the possibility that Cos cells contain hTAF_{II}28 but that it is not stably and functionally associated with the TFIID as in HeLa cells. Importantly, however, the transfected hTAF_{II}28 does associate stably with Cos cell TBP/TFIID, thereby increasing significantly the level

of TAF_{II}28-containing TFIID; this correlates with the potentiation of transactivation by the receptor AF-2s.

Our experiments show that the RXR AF-2s can activate a minimal promoter in HeLa cells where the TFIID contains endogenous hTAF_{II}28, but are inactive in Cos cells where the TFIID is depleted in hTAF_{II}28. The ectopic expression of hTAF_{II}28 increases the levels of Cos cell TFIID containing TAF_{II}28, allowing activation by the RXR AF-2s. These observations imply that the activation of a minimal promoter by the RXR AF-2s absolutely requires the presence of TAF_{II}28 in the TFIID complex. On the other hand, TAF_{II}28 is not absolutely required for cooperation between the RXR α AF-2 and other AFs on complex promoters because full-length RXR α activated transcription from the DR1G-tk-CAT reporter in Cos cells. Similarly, the ER and VDR AF-2s activate transcription from a minimal promoter in Cos cells in the absence of TAF_{II}28, showing that, in contrast to the RXR AF-2s, they can function, albeit at reduced levels, via a TAF_{II}28-independent pathway perhaps involving other TFIID subunits. However, for the ER and VDR AF-2s, as well as for the RXR α AF-2 on a complex promoter, the ectopic expression of hTAF_{II}28 increases activation further, possibly by providing an additional pathway. In contrast to the RXRs, the RAR (at least the α and β forms) and the TR AF-2s strongly activate transcription in Cos cells, showing that these AF-2s work efficiently in the absence of TFIID-associated TAF_{II}28 and that their activity is only mildly stimulated by hTAF_{II}28 coexpression. These results show that the receptor AF-2s have differential abilities to activate transcription in the absence of TFIID-associated TAF_{II}28, and suggest that they can act by distinct molecular pathways, some of which are TAF_{II}28 dependent. The possible existence of alternative pathways for AF-2 activity has also been proposed to explain the E1A-dependent and -independent activation by the RAR (Berkenstam *et al.*, 1992; Keaveney *et al.*, 1993). It is also worth noting that although E1A and TBP cooperate to mediate activation by the RAR AF-2, like hTAF_{II}28, no direct E1A-RAR interactions were detected.

The coactivator function of hTAF_{II}28 requires interactions with TBP and other cofactors essential for the activities of the RXR AF-2s

Several different, but not mutually exclusive, molecular mechanisms may be invoked to explain the coactivator activity described here. It is possible that overexpressed hTAF_{II}28 acts by sequestering or inactivating a negatively acting factor(s) which would repress the receptor AF-2s to different degrees. Indeed, a negatively acting factor has been described recently which binds to the unliganded RAR and TRs (Chen and Evans, 1995; Hörlein *et al.*, 1995) and can in some conditions repress AF-2 activity (Kurokawa *et al.*, 1995). Although all our results cannot be explained by titration or inactivation of this factor, the existence of other related factors cannot be excluded at present.

Alternatively, as TAF_{II}28 is a TFIID subunit, the simplest interpretation of our results would be that it functions as a bridging factor between the receptor AF-2s and the basal transcription apparatus via TBP. However, we did not detect direct ligand-dependent receptor-hTAF_{II}28 interactions. This raises the possibility that hTAF_{II}28 exerts

its effect by interacting with a TIF(s) (see Introduction for references), which itself interacts with the receptors and is required for AF-2 function. This is supported further by the observation that deletions or mutations of the AF-2 AD core which affect the ability of the receptors to interact with putative TIFs, such as mSUG-1 or TIF1 (LeDourain *et al.*, 1995; Vom Bauer *et al.*, 1995), abolish activation in the presence of hTAF₁₁₂₈. At present, we have not detected significant interactions between hTAF₁₁₂₈ and TIF1 or mSUG1, but several other putative TIFs, such as RIP140 (Cavaillès *et al.*, 1995), ERAP160 (Halachmi *et al.*, 1994; Kurokawa *et al.*, 1995) and SRC-1 (Onate *et al.*, 1995), have been identified which interact with the receptors in a ligand- and/or AF-2 AD core-dependent manner. Further experiments will be required to determine whether these factors interact with hTAF₁₁₂₈. Alternatively, hTAF₁₁₂₈ may act via interactions with the SWI-SNF complex, some of whose components have been shown to influence receptor activity in yeast and mammalian cells (Yoshinaga *et al.*, 1992; Muchardt and Yaniv, 1993; Chiba *et al.*, 1994).

Further indication that hTAF₁₁₂₈ may act as a bridging factor between the nuclear receptors and their associated TIFs and the basal transcription machinery comes from the observation that the ability of hTAF₁₁₂₈ to act as a coactivator correlates with its ability to interact with TBP. We have shown previously that the carboxyl 61 amino acids of hTAF₁₁₂₈ were required for interaction with TBP in Cos cells (Mengus *et al.*, 1995). The results presented here delineate this region to amino acids 150–179. Previously we were unable to determine the effect of deletions in the N-terminal region of hTAF₁₁₂₈ on this interaction because of the low expression of the B10 epitope-tagged deletion mutants. Here we show that the untagged hTAF₁₁₂₈(64–211) mutant is expressed efficiently in transfected Cos cells but interacts only weakly with TBP. This shows that determinants for the TBP–hTAF₁₁₂₈ interaction are present in both the N- and C-terminal regions of hTAF₁₁₂₈. The deletion of either of these determinants abolishes the ability of hTAF₁₁₂₈ to promote RXR AF-2 activity. Furthermore, the amino acid substitutions within the putative amphipathic α -helical region between amino acids 161 and 179 reduce hTAF₁₁₂₈–TBP interactions and abolish transactivation.

Previously the RXR and ER have been reported to interact directly with TBP *in vitro* and/or in yeast two-hybrid assays (Sadovsky *et al.*, 1995; Schulman *et al.*, 1995). Hence, it is possible that hTAF₁₁₂₈ interacts with these receptors not via a TIF(s) but via a TBP. However, RXR and TBP could not be coimmunoprecipitated from extracts of cotransfected Cos cells, and the overexpression of TBP alone in Cos cells did not potentiate transactivation by RXR (our unpublished data). Moreover, the cotransfection of hTAF₁₁₂₈ deletion mutants (1–150) and (64–211), which do not interact with TBP, represses hTAF₁₁₂₈-mediated activation by the RXR and ER AF-2s but does not affect activation by the AF of TEF-1. Thus, although interactions with TBP are required to promote receptor AF-2 activity, hTAF₁₁₂₈ also interacts with other factors specifically required for the activity of the receptor AF-2s. Therefore it is possible that hTAF₁₁₂₈ acts as a bridging factor between the receptor and its associated TIF(s) and TBP, or that the receptor interacts with the basal

transcription complex directly via TBP, with hTAF₁₁₂₈ acting on a downstream target. Irrespective of the molecular mechanisms involved, our results clearly show that changes in the intracellular concentration of hTAF₁₁₂₈ modulate AF-2 activity, indicating that hTAF₁₁₂₈ can act as a novel regulator of nuclear receptors.

Materials and methods

Construction of recombinant plasmids

The hTAF₁₁₂₈ expression vectors were generated by PCR amplification using appropriately positioned primers containing *Bam*HI and *Eco*RI restriction sites. The resulting fragments were cloned in the corresponding sites in the pXJ41 or pXJ42 vectors (Xiao *et al.*, 1991). Computer predictions using the Chou and Fasman algorithm in the GCG (Genetics Computer Group, University of Wisconsin, WI) software package and the PHD programme (EMBL) indicated that amino acids 161–179 (FVGEVVEEALDVCEKWGEM) of hTAF₁₁₂₈ had the potential to form an amphipathic α -helix with a highly hydrophobic face (shown in *italic*) and a hydrophilic face where six out of the seven amino acids (with the exception of K175) are acidic (shown in *bold*). Site-directed mutagenesis of (1–179) single-strand DNA was performed to mutate E164, E167 and E168 to P, P and R, respectively, changing charge and disrupting the putative α -helix to generate hTAF₁₁₂₈(1–179)M1. hTAF₁₁₅₅ was cloned by screening a HeLa cell cDNA library with degenerate oligonucleotides derived from tryptic peptide sequences of hTAF₁₁₅₅ immunopurified using anti-TBP antibodies (our unpublished data). pXJ41–hTAF₁₁₅₅ was constructed by PCR amplification of a clone containing the complete hTAF₁₁₅₅ open reading frame, followed by cloning of the resulting fragment between the *Bam*HI and *Xho*I sites of pXJ41. pXJ41–hTAF₁₁₂₅₀ was constructed by inserting a *Spe*I fragment comprising the HA-tagged hTAF₁₁₂₅₀ open reading frame into the *Sma*I site in pXJ41 after filling in the *Spe*I extremities. The vectors expressing the other hTAF_{11s} have been described previously (Mengus *et al.*, 1995). G4–VDR(DE) was constructed by PCR amplification of the human VDR DE region and cloning of the resulting fragment between the *Xho*I and *Bam*HI sites in plasmid pXJ40–GAL4(1–147) (Xiao *et al.*, 1991). Similarly, G4–TR(DE) was constructed by PCR amplification of the chicken TR α with the appropriate oligonucleotide primers and cloning between the Asp718 and *Bam*HI sites of pXJ40–GAL4(1–147). All constructions were verified using an Applied Biosystems automated DNA sequencer.

The vectors expressing all mouse RXR derivatives, HEG0 and G4–TEF-1(2–426) Δ 55–121 have been described previously (Tora *et al.*, 1989; Nagpal *et al.*, 1992, 1993; Hwang *et al.*, 1993; Durand *et al.*, 1994). G4–AP-2, G4–Sp1, G4–Oct1 and G4–Oct2 containing proline- or glutamine-rich ADs from the respective activators are as described previously (Seipel *et al.*, 1992). All the reporter plasmids are as described previously (Tora *et al.*, 1989; Nagpal *et al.*, 1992).

Transfections, CAT assays and immunoprecipitations

Cos and HeLa cells were transfected by the Ca₃(PO₄)₂ precipitate technique, as described previously (Mengus *et al.*, 1995). In addition to the expression vectors or reporters described in each figure, all transfections contained 0.5 μ g (1.0 μ g in HeLa) of the luciferase reporter pRSV–Luc as an internal standard and pBSK⁺ DNA as a carrier. Cells were harvested 48 h after transfection, and luciferase and CAT assays were performed by standard procedures. Transfections were performed in dextran charcoal-treated medium, and ligands were added at the indicated concentrations at the same time as the DNA–Ca₃(PO₄)₂ coprecipitate. A quantitative phosphorimager analysis was performed on a Fujix BAS 2000 apparatus. Immunoprecipitations were performed essentially as described previously (Mengus *et al.*, 1995). Cells were transfected with 2.0 μ g of the TBP expression vector and 5.0 μ g of the hTAF₁₁₂₈ or G4–RXR β (DE) expression vector as indicated. Cell extracts were prepared by three cycles of freeze–thaw in 100 μ l buffer A (50 mM Tris–HCl, pH 7.9, 20% glycerol, 1 mM dithiothreitol, 0.1% NP-40) containing 0.5 M KCl and 2.5 μ g/ml leupeptin, pepstatin, aprotinin, antipain and chymostatin. Extracts were mixed with ~1.0 μ g of the monoclonal antibodies and 50 μ l protein G–Sepharose, and incubated at 4°C for 2 h with rotation. The precipitated proteins were washed four times with 1 ml buffer A containing 1.0 M KCl and once with buffer A containing 0.1 M KCl. The proteins were then detected on Western blots using an Amersham enhanced chemiluminescence kit.

Total TFIID was prepared from extracts of untransfected cells using

antibody 3G3, essentially as described previously (Brou *et al.*, 1993a; Chaudhary *et al.*, 1994). Briefly, total Cos or HeLa cell TFIID was immunoprecipitated with mAb 3G3 and eluted by the addition of an excess of the corresponding epitope peptide (Lescure *et al.*, 1994) in buffer A containing 0.1 M KCl. The resin was washed one more time with buffer A containing 0.1 M KCl.

Antibody preparation

The monoclonal antibodies against TBP (3G3), hTAF_{II}18 (16TA), hTAF_{II}100 (1TA), hTAF_{II}30 (4G2), the B10 and HA tags, and GAL4(1-147) (2GV3, 3GV2) have been described previously (White *et al.*, 1992; Brou *et al.*, 1993a; Eberhardt *et al.*, 1993; Jacq *et al.*, 1994; Lescure *et al.*, 1994; Mengus *et al.*, 1995). mAb IC9 was raised against a synthetic peptide corresponding to amino acids 106-120 (MQILVSSFS-EEQLNR) of hTAF_{II}28, as described previously (Mengus *et al.*, 1995). mAb 15TA was raised against purified GST-hTAF_{II}28, and the epitope was mapped first by immunofluorescence using hTAF_{II}28 deletion mutants. Subsequent fine mapping was performed by an enzyme-linked immunosorbent assay using a series of overlapping peptides. mAb 15TA recognizes the sequence between amino acids 71 and 86 (REDSSLLNP-AAKCLKI) of hTAF_{II}28. The rabbit polyclonal antisera were generated by immunizing rabbits with two hTAF_{II}28 peptides corresponding to amino acids 56-75 (GELESQDVSDLTVEREDSS) and 185-204 (KHMREAVRRLKSKGQIPNSK) coupled to ovalbumin. After three injections, the rabbit antisera were tested on Western blots for their ability to recognize recombinant hTAF_{II}28 and hTAF_{II}28 present in immunopurified HeLa cell TFIID. Monoclonal antibodies against hTAF_{II}20 (22TA), hTAF_{II}55 (19TA) and hTAF_{II}135 (20TA) were generated by immunization with the appropriate purified GST-hTAF_{II} fusion proteins, as described previously (Mengus *et al.*, 1995).

Acknowledgements

We thank K.Seipel, W.Schaffner, L.Tora, R.Tjian, T.Levellard and V.Vivat for the gift of recombinant plasmids; L.Tora and V.Dubrowskaya for mAb 1TA; Roussel-Uclaf for providing 1,25(OH)₂D₃; L.Carré for excellent technical assistance; Adrien Staub for peptide sequencing of hTAF_{II}55; P.Eberling and D.Stephane for peptide synthesis; the staff of the cell culture facility; S.Vicaire and P.Hamman for DNA sequencing; the oligonucleotide facility; Y.Lutz and the monoclonal antibody facility; G.Duval for the polyclonal rabbit antisera; B.Boulay, J.M.Lafontaine and C.Werlé for illustrations; and L.Tora and Z.Zehner for critical reading of the manuscript. M.M. is supported by a grant from the Deutsche Forschungsgemeinschaft. This work was supported by grants from CNRS, INSERM, the Centre Hospitalier Universitaire Régional, the Ministère de la Recherche et de la Technologie, the Association pour la Recherche contre le Cancer and the Collège de France.

References

- Barettoni,D., Ruiz,M.D.M.V. and Stunnenberg,H. (1994) Characterisation of the ligand-dependent transactivation domain of thyroid hormone receptor. *EMBO J.*, **13**, 3039-3049.
- Berkenstam,A., Ruiz,M.D.M.V., Barettoni,D., Horikoshi,M. and Stunnenberg,H.G. (1992) Cooperativity in transactivation between retinoic acid receptor and TFIID requires an activity analogous to E1A. *Cell*, **69**, 401-412.
- Bourguet,W., Ruff,M., Chambon,P., Gronemeyer,H. and Moras,D. (1995) Crystal structure of the ligand-binding domain of the human nuclear receptor RXR α . *Nature*, **375**, 377-382.
- Brou,C., Chaudhary,S., Davidson,I., Lutz,Y., Wu,J., Egly,J.M., Tora,L. and Chambon,P. (1993a) Distinct TFIID complexes mediate the effect of different transcriptional activators. *EMBO J.*, **12**, 489-499.
- Brou,C., Ali,S., Wu,J., Scheer,E., Lang,C., Davidson,I., Chambon,P. and Tora,L. (1993b) Different TBP-associated factors are required for mediating the stimulation of transcription *in vitro* by the acidic transactivator GAL-VP16 and the two nonacidic activation functions of the estrogen receptor. *Nucleic Acids Res.*, **21**, 5-12.
- Buratowski,S. (1994) The basics of basal transcription by RNA polymerase II. *Cell*, **77**, 1-3.
- Buratowski,S. and Sharp,P.A. (1993) Initiation of transcription by RNA polymerase II. In McKnight,S.L. and Yamamoto,K.R. (eds), *Transcriptional Regulation*. Cold Spring Harbor Laboratory Press, Cold Spring Harbor, NY, Vol. 1, pp. 227-246.
- Cavaillès,V., Dauvois,S., L'Horset,F., Lopez,G., Hoare,S., Kushner,P.J. and Parker,M.G. (1995) Nuclear factor RIP140 modulates transcriptional activation by the estrogen receptor. *EMBO J.*, **14**, 3741-3751.
- Chambon,P. (1994) The retinoid signalling pathway: molecular and genetic analyses. *Semin. Cell Biol.*, **5**, 115-125.
- Chaudhary,S., Brou,C., Valentin,M.E., Burton,N., Tora,L., Chambon,P. and Davidson,I. (1994) A cell-specific factor represses stimulation of transcription *in vitro* by transcriptional enhancer factor-1. *Mol. Cell Biol.*, **14**, 5290-5299.
- Chen,J.D. and Evans,R.M. (1995) A transcriptional co-repressor that interacts with nuclear hormone receptors. *Nature*, **377**, 454-457.
- Chen,J.L., Attardi,L.D., Verrijzer,C.P., Yokomori,K. and Tjian,R. (1994) Assembly of recombinant TFIID reveals differential coactivator requirements for distinct transcriptional activators. *Cell*, **79**, 93-105.
- Chiang,C.-M. and Roeder,R.G. (1995) Cloning of an intrinsic human TFIID subunit that interacts with multiple transcriptional activators. *Science*, **267**, 531-536.
- Chiang,C.-M., Ge,H., Wang,Z., Hoffman,A. and Roeder,R.G. (1993) Unique TATA-binding protein-containing complexes and cofactors involved in transcription by RNA polymerases II and III. *EMBO J.*, **12**, 2749-2762.
- Chiba,H., Muramatsu,M., Nomoto,A. and Kato,H. (1994) Two human homologs of *Saccharomyces cerevisiae* SWI2/SNF2 and *Drosophila brahma* are transcriptional coactivators cooperating with the estrogen receptor and the retinoic acid receptor. *Nucleic Acids Res.*, **22**, 1815-1820.
- Conaway,R.C. and Conaway,J.W. (1993) General initiation factors for RNA polymerase II. *Annu. Rev. Biochem.*, **62**, 161-190.
- Danielan,P.S., White,R., Lees,J.A. and Parker,M.G. (1992) Identification of a conserved region required for hormone-dependent transcriptional activation by steroid hormone receptors. *EMBO J.*, **11**, 1025-1033.
- Dubrowskaya,V., Lavigne,A.C., Davidson,I., Acker,J., Staub,A. and Tora,L. (1996) Distinct domains of RTAF_{II} 100 are required for functional interaction with transcription factor TFIIF β (RAP30) and incorporation into the TFIID complex. *EMBO J.*, **15**, in press.
- Durand,B., Saunders,M., Gaudon,C., Roy,B., Losson,R. and Chambon,P. (1994) Activation function 2 (AF-2) of the retinoic acid and 9-*cis*-retinoic acid receptors: presence of a conserved autonomous constitutive activating domain and influence of the nature of the response element on AF-2 activity. *EMBO J.*, **13**, 5370-5382.
- Dynlacht,B.D., Hoey,T. and Tjian,R. (1991) Isolation of coactivators associated with the TATA binding protein that mediate transcriptional activation. *Cell*, **55**, 563-576.
- Eberhardt,D., Tora,L., Egly,J.M. and Grummt,I. (1993) A TBP-containing multiprotein complex (TIF-IB) mediates transcription specificity of murine RNA polymerase I. *Nucleic Acids Res.*, **21**, 4180-4186.
- Giguère,V. (1994) Retinoic acid receptors and cellular retinoid binding proteins: complex interplay in retinoid signalling. *Endocr. Rev.*, **15**, 61-79.
- Gill,G., Pascal,E., Tseng,Z.H. and Tjian,R. (1994) A glutamine-rich hydrophobic patch in transcription factor Sp1 contacts the dTAF_{II}110 component of the *Drosophila* TFIID complex and mediates transcriptional activation. *Proc. Natl Acad. Sci. USA*, **91**, 192-196.
- Glass,C.K. (1994) Differential recognition of target genes by nuclear receptor monomers, dimers and heterodimers. *Endocr. Rev.*, **15**, 391-407.
- Goodrich,J.A., Hoey,T., Thut,C.J., Admon,A. and Tjian,R. (1993) *Drosophila* TAF_{II}40 interacts with both a VP16 activation domain and the basal transcription factor TFIIB. *Cell*, **75**, 519-530.
- Halachmi,S., Marden,E., Martin,G., MacKay,H., Abbondanza,C. and Brown,M. (1994) Estrogen receptor-associated proteins; possible mediators of hormone induced transcription. *Science*, **264**, 1455-1458.
- Hernandez,N. (1993) TBP, a universal eukaryotic transcription factor? *Genes Dev.*, **7**, 1291-1308.
- Hoey,T., Dynlacht,B.D., Peterson,M.G., Pugh,B.F. and Tjian,R. (1990) Isolation and characterisation of the *Drosophila* gene encoding the TATA box binding protein, TFIID. *Cell*, **61**, 1179-1186.
- Hoey,T., Weinzierl,R.O.J., Gill,G., Chen,J.L., Dynlacht,B.B. and Tjian,R. (1993) Molecular cloning and functional analysis of *Drosophila* TAF_{II}110 reveal properties expected of coactivators. *Cell*, **72**, 247-260.
- Hörlein,A.J. *et al.* (1995) Ligand independent repression by the thyroid hormone receptor mediated by a nuclear receptor corepressor. *Nature*, **377**, 397-404.
- Hwang,J.J., Chambon,P. and Davidson,I. (1993) Characterisation of the transcription activation function and the DNA binding domain of transcriptional enhancer factor-1. *EMBO J.*, **12**, 2337-2348.

- Jacq,X., Brou,C., Lutz,Y., Davidson,I., Chambon,P. and Tora,L. (1994) Human TAF_{II}30 is present in a distinct TFIID complex and is required for transcriptional activation by the estrogen receptor. *Cell*, **79**, 107–117.
- Keaveney,M., Berkenstam,A., Felgenbutz,M., Vriend,G. and Stunnenberg,H. (1993) Residues in the TATA-binding protein required to mediate a transcriptional response to retinoic acid in EC cells. *Nature*, **365**, 562–566.
- Kim,Y.J., Björklund,S., Li,Y., Sayre,H.M. and Kornberg,R.D. (1994) A multiprotein mediator of transcriptional activation and its interaction with the C-terminal repeat domain of RNA polymerase II. *Cell*, **77**, 599–608.
- Klemm,R.D., Goodrich,J.A., Zhou,S. and Tjian,R. (1995) Molecular cloning of the 32-kDa subunit of human TFIID reveals interactions with VP16 and TFIIB that mediate transcriptional activation. *Proc. Natl Acad. Sci. USA*, **92**, 5788–5792.
- Kokubo,T., Gong,D.W., Wootton,J.C., Horikoshi,M., Roeder,R. and Nakatani,Y. (1994) Molecular cloning of *Drosophila* TFIID subunits. *Nature*, **367**, 484–487.
- Koleske,A.J. and Young,R. (1994) An RNA polymerase II holoenzyme responsive to activators. *Nature*, **368**, 466–496.
- Kurokawa,R., Söderström,M., Hörlein,A., Halachmi,S., Brown,M., Rosenfeld,M.G. and Glass,C.K. (1995) Polarity-specific activities of retinoic acid receptors determined by a co-repressor. *Nature*, **377**, 451–454.
- LeDourain,B. et al. (1995) The N-terminal part of TIF1, a putative mediator of the ligand-dependent activation function (AF-2) of nuclear receptors, is fused to B-raf in the oncogenic protein T18. *EMBO J.*, **14**, 2020–2033.
- Lee,J.W., Ryan,F., Swaffield,J.C., Johnston,S.A. and Moore,D.D. (1995) Interaction of thyroid-hormone receptor with a conserved transcriptional mediator. *Nature*, **374**, 91–94.
- Lescure,A., Lutz,Y., Eberhardt,D., Jacq,X., Krol,A., Grummt,I., Davidson,I., Chambon,P. and Tora,L. (1994) The N-terminal domain of the human TATA-binding protein plays a role in transcription from the TATA-containing RNA polymerase II and III promoters. *EMBO J.*, **13**, 1166–1175.
- Lu,H. and Levine,A.J. (1995) Human TAF_{II}31 is a transcriptional coactivator of the p53 protein. *Proc. Natl Acad. Sci. USA*, **92**, 5154–5158.
- Mangelsdorf,D.J., Umesono,K. and Evans,R.M. (1994) The retinoid receptors. In Sporn,M.B., Roberts,A.B. and Goodman,D.S. (eds), *The Retinoids*. Raven Press Ltd, New York, pp. 319–349.
- Mengus,G., May,M., Jacq,X., Staub,A., Tora,L., Chambon,P. and Davidson,I. (1995) Cloning and characterisation of hTAF_{II}18, hTAF_{II}20 and hTAF_{II}28: three subunits of the human transcription factor TFIID. *EMBO J.*, **14**, 1520–1531.
- Muchardt,C. and Yaniv,M. (1993) A human homologue of *Saccharomyces cerevisiae* SNF2/SW12 and *Drosophila brm* genes potentiates transcriptional activation by the glucocorticoid receptor. *EMBO J.*, **12**, 4279–4290.
- Nagpal,S., Saunders,M., Kastner,P., Durand,B., Nakshatri,H. and Chambon,P. (1992) Promoter context- and response element-dependent specificity of the transcriptional activation and modulating functions of the retinoic acid receptors. *Cell*, **70**, 1007–1019.
- Nagpal,S., Friant,S., Nakshatri,H. and Chambon,P. (1993) RARs and RXRs: evidence for two autonomous transactivation functions (AF-1 and AF-2) and heterodimerisation *in vivo*. *EMBO J.*, **12**, 2349–2360.
- Onate,S.A., Tsai,S.Y., Tsai,M.J. and O'Malley,B.W. (1995) Sequence and characterisation of a coactivator for the steroid hormone receptor superfamily. *Science*, **270**, 1354–1357.
- Ossipow,V., Tassan,J.P., Nigg,E.A. and Schibler,U. (1995) A mammalian RNA polymerase II holoenzyme containing all components required for promoter-specific transcription initiation. *Cell*, **83**, 137–146.
- Parker,M.G. (1993) Steroid and related receptors. *Curr. Opin. Cell Biol.*, **5**, 499–504.
- Poon,D., Bai,Y., Cambell,A.M., Björklund,S., Kim,Y.L., Zhou,S., Kornberg,R.D. and Weil,P.A. (1995) Identification and characterisation of a TFIID-like multiprotein complex from *Saccharomyces cerevisiae*. *Proc. Natl Acad. Sci. USA*, **92**, 8224–8228.
- Pugh,B.F. and Tjian,R. (1990) Mechanism of transcriptional activation by Sp1: evidence for coactivators. *Cell*, **61**, 1187–1197.
- Pugh,B.F. and Tjian,R. (1991) Transcription from a TATA-less promoter requires a multisubunit TFIID complex. *Genes Dev.*, **5**, 1935–1945.
- Reese,J.C., Aponne,L., Walker,S.S., Griffen,L.A. and Green,M.R. (1994) Yeast TAF_{II}s in a multisubunit complex required for activated transcription. *Nature*, **371**, 523–527.
- Renaud,J.P., Rochel,N., Ruff,M., Vivat,V., Chambon,P., Gronemeyer,H. and Moras,D. (1995) Crystal structure of the ligand binding domain of the human nuclear receptor RAR γ complexed with *all-trans* retinoic acid. *Nature*, **378**, 681–689.
- Sadovsky,Y., Webb,G., Lopez,P., Baxter,J.D., Cavaillès,V., Parker,M.G. and Kushner,P.J. (1995) Transcriptional activators differ in their response to overexpression of TBP. *Mol. Cell. Biol.*, **15**, 1554–1563.
- Schulman,I.G., Chakravarti,D., Juguilon,H., Romo,A. and Evans,R.M. (1995) Interactions between the retinoid X receptor and a conserved region of the TATA-binding protein mediate hormone-dependent transactivation. *Proc. Natl Acad. Sci. USA*, **92**, 8288–8292.
- Seipel,K., Georgiev,O. and Schaffner,W. (1992) Different activation domains stimulate transcription from remote ('enhancer') and proximal ('promoter') positions. *EMBO J.*, **11**, 4961–4968.
- Swaffield,J.C., Melcher,K. and Johnson,S.A. (1995) A highly conserved ATPase protein as a mediator between acidic activation domains and the TATA binding protein. *Nature*, **374**, 88–91.
- Tanese,N., Pugh,B.F. and Tjian,R. (1991) Coactivators for a proline rich activator purified from the multisubunit human TFIID complex. *Genes Dev.*, **5**, 2212–2224.
- Timmers,H.T.M., Meyers,R. and Sharp,P.A. (1992) Composition of transcription factor B-TFIID. *Proc. Natl Acad. Sci. USA*, **89**, 8140–8144.
- Tjian,R. and Maniatis,T. (1994) Transcriptional activation: a complex puzzle with few easy pieces. *Cell*, **77**, 5–8.
- Tora,L., White,J.H., Brou,C., Tasset,D., Webster,N., Scheer,E. and Chambon,P. (1989) The human estrogen receptor has two independent non-acidic transcriptional activation functions. *Cell*, **59**, 477–487.
- Tsai,M.J. and O'Malley,B.W. (1994) Molecular mechanisms of action of steroid/thyroid receptor superfamily members. *Annu. Rev. Biochem.*, **63**, 451–486.
- Verrijzer,C.P., Yokomori,K., Chen,J.L. and Tjian,R. (1994) *Drosophila* TAF_{II}150: similarity to yeast gene TSM-1 and specific binding to core promoter DNA. *Science*, **264**, 933–941.
- Verrijzer,C.P., Chen,J.L., Yokomori,K. and Tjian,R. (1995) Binding of TAFs to core elements directs promoter selectivity by RNA polymerase II. *Cell*, **81**, 1115–1125.
- Vom Bauer,E. et al. (1995) Differential ligand-dependent interactions between the AF-2 activating domain of nuclear receptors and the putative transcriptional intermediary factors mSUG1 and TIF1. *EMBO J.*, **15**, 110–124.
- Wagner,R.L., Apriletti,J.W., McGrath,M.E., West,B.L., Baxter,J.D. and Fletterick,R.J. (1995) A structural role for hormone in the thyroid hormone receptor. *Nature*, **378**, 690–697.
- Weinzierl,R.O.J., Ruppert,S., Dynlacht,B.D., Tanese,N. and Tjian,R. (1993) Cloning and expression of *Drosophila* TAF_{II}60 and human TAF_{II}70 reveal conserved interactions with other subunits of TFIID. *EMBO J.*, **12**, 5303–5309.
- White,J.H., Brou,C., Wu,J., Lutz,Y., Moncollin,V. and Chambon,P. (1992) The acidic transcriptional activator GAL–VP16 acts on preformed template-committed complexes. *EMBO J.*, **6**, 2229–2240.
- Wurtz,J.M., Bouguet,W., Renaud,J.P., Vivat,V., Chambon,P., Moras,D. and Gronemeyer,H. (1996) A canonical structure for the ligand binding domain of nuclear receptors. *Nature Struct. Biol.*, **3**, 87–94.
- Xiao,J.H., Davidson,I., Matthes,H., Garnier,J.M. and Chambon,P. (1991) Cloning, expression and transcriptional properties of the human enhancer factor TEF-1. *Cell*, **65**, 551–568.
- Yokomori,K., Chen,J.L., Admon,A., Zhou,S. and Tjian,R. (1993) Molecular cloning and characterisation of dTAF_{II}30 α and dTAF_{II}30 β : two small subunits of *Drosophila* TFIID. *Genes Dev.*, **7**, 2587–2597.
- Yoshinaga,S.K., Peterson,C.L., Herskowitz,I. and Yamamoto,K.R. (1992) Roles of SW11, SW12 and SW13 proteins for transcriptional enhancement by steroid receptors. *Science*, **258**, 1598–1604.
- Zawel,L. and Reinberg,D. (1995) Common themes in assembly and function of eukaryotic transcription complexes. *Annu. Rev. Biochem.*, **64**, 533–561.
- Zhou,Q., Lieberman,P.M., Boyer,T.G. and Berk,A.J. (1992) Holo-TFIID supports transcriptional stimulation by diverse activators and from a TATA-less promoter. *Genes Dev.*, **6**, 1964–1974.

Received on December 13, 1995; revised on February 6, 1996