

PACT, a protein activator of the interferon-induced protein kinase, PKR

Rekha C.Patel and Ganes C.Sen¹

Department of Molecular Biology, The Lerner Research Institute, The Cleveland Clinic Foundation, 9500 Euclid Avenue, Cleveland, OH 44195, USA

¹Corresponding author
e-mail: seng@cesmtp.ccf.org

PKR, a latent protein kinase, mediates the antiviral actions of interferon. It is also involved in cellular signal transduction, apoptosis, growth regulation and differentiation. Although in virus-infected cells, viral double-stranded (ds) RNA can serve as a PKR activator, cellular activators have remained obscure. Here, we report the cloning of PACT, a cellular protein activator of PKR. PACT heterodimerized with PKR and activated it *in vitro* in the absence of dsRNA. In mammalian cells, overexpression of PACT caused PKR activation and, in yeast, co-expression of PACT enhanced the anti-growth effect of PKR. Thus, PACT has the hallmarks of a direct activator of PKR.

Keywords: double-stranded RNA/heterodimer/interferon/PKR/protein kinase

Introduction

The interferon (IFN)-induced, double-stranded (ds) RNA-activated protein kinase (PKR), is a key mediator of the antiviral and antiproliferative effects of IFN (Hovanessian, 1989; Sen and Ransohoff, 1993; Williams, 1995; Clemens and Elia, 1997). PKR is present at low constitutive levels in cells and its expression can be induced by treatment with IFN. The most well known activator of PKR is dsRNA, but other polyanionic agents such as heparin have also been shown to activate it *in vitro* (Galabru and Hovanessian, 1987; Hovanessian and Galabru, 1987). The only known physiological substrate of PKR activity is the α subunit of the eukaryotic initiation factor eIF-2 (Lengyel, 1993; Samuel, 1993). Phosphorylation of eIF-2 α on Ser51 by PKR leads to inhibition of protein synthesis (Colthurst *et al.*, 1987; Hershey, 1991). eIF-2 α phosphorylation leads to its increased affinity for eIF-2B, thus sequestering eIF-2B in an inactive complex with phosphorylated eIF-2 and GDP (Clemens *et al.*, 1994; De Haro *et al.*, 1996). As a result, eIF-2B is not available to catalyze nucleotide exchange on non-phosphorylated eIF-2. Because eIF-2B is present in cells at a lower molar concentration than eIF-2, phosphorylation of a small fraction of cellular eIF-2 α can lead to a severe block in protein synthesis.

Upon viral infection of IFN-treated cells, PKR is activated by viral dsRNA which leads to an inhibition of viral and cellular protein synthesis (Samuel *et al.*, 1984; Rice *et al.*, 1985). Thus, PKR plays a major role in the antiviral activity of IFN. The importance of antiviral

effects of PKR is manifested by the fact that many viruses employ a variety of mechanisms to counteract the actions of PKR (Sonenberg, 1990; Katze, 1992). Although the majority of research on PKR has focused on its participation in the inhibitory action of IFN on viral infection, there is now substantial evidence for PKR's role in uninfected cells as well (Proud, 1995). PKR has been implicated in several diverse cellular functions such as growth regulation, apoptosis, differentiation and signaling pathways (Proud, 1995; Williams, 1997). A potential role for PKR in cell growth regulation has been suggested by the fact that overexpression of human PKR inhibits cell proliferation in yeast (Chong *et al.*, 1992), insect (Barber *et al.*, 1992) and mammalian cells (Koromilas *et al.*, 1992). On the other hand, expression of catalytically inactive mutants of PKR in NIH 3T3 cells results in tumorigenicity in nude mice (Koromilas *et al.*, 1992; Meurs *et al.*, 1993). This result has been ascribed to a transdominant inhibitory effect of mutant enzyme on the endogenous wild-type PKR, resulting in derepression of growth. It is relevant to the proposed role of PKR in growth regulation that oncogenic Ras protein has been reported to induce an inhibitor of PKR activation (Mundschaug and Faller, 1992, 1994). Surprisingly, mice devoid of functional PKR develop normally and are free of any tumors (Yang *et al.*, 1995), suggesting that a cellular system, absent in NIH 3T3 cells, may be able to replace PKR functionally in the PKR null mice. Several studies have shown the involvement of PKR in cellular apoptosis (Yeung *et al.*, 1996; Kibler *et al.*, 1997). Overexpression of PKR in HeLa cells leads to apoptosis (Lee and Esteban, 1994), and recent studies with mouse embryonic fibroblasts derived from the PKR null mice have also shown its involvement in dsRNA- and lipopolysaccharide (LPS)-induced apoptosis (Der *et al.*, 1997).

PKR has also been implicated in the onset of differentiation. Activation of PKR has been shown to be an important regulatory signal in controlling growth arrest of mouse 3T3-F442A fibroblasts and subsequent differentiation to adipocytes (Judware and Petryshyn, 1991, 1992; Petryshyn *et al.*, 1997). However, the identity of an activator of PKR under differentiation permissive conditions has remained unknown. A more recent observation also correlates the levels of active PKR with the degree of cellular differentiation. It was observed that in the myogenic line L8, transforming growth factor- β (TGF- β) and EGTA reduced both the PKR activity and the level of muscle-specific proteins (Salzberg *et al.*, 1995).

PKR participates in transcriptional signaling pathways used by dsRNA and IFN- γ : in PKR null cells, dsRNA fails to activate NF κ B and IRF-1, and the IFN- γ responses of these cells are also impaired (Maran *et al.*, 1994; Yang *et al.*, 1995; Kumar *et al.*, 1997; Wong *et al.*, 1997). Treatment of cells with IFN- γ has been shown to result

in phosphorylation and activation of PKR (Kumar *et al.*, 1997). However, no cellular activator of PKR in response to IFN- γ in the absence of dsRNA has been identified thus far. In addition, PKR has also been implicated in platelet-derived growth factor (PDGF) (Mundschau and Faller, 1995) and interleukin-3 (IL-3) (Ito *et al.*, 1994) signaling.

The dsRNA-binding domain (DRBD) of PKR lies near its N-terminus (Katze *et al.*, 1991; Feng *et al.*, 1992; Green and Mathews, 1992; McCormack *et al.*, 1992; Patel and Sen, 1992) and it contains two dsRNA-binding motifs conserved in a large family of dsRNA-binding proteins (St. Johnston *et al.*, 1992). Deletion or specific substitution mutations in this region result in the loss of the dsRNA binding and activation (McCormack *et al.*, 1994; Patel *et al.*, 1994, 1996; Green *et al.*, 1995; McMillan *et al.*, 1995). These mutants can, however, be activated *in vitro* by heparin (Patel *et al.*, 1994, 1996) and may be functionally active in yeast (Millan *et al.*, 1995; Romano *et al.*, 1995) and mammalian cells (Lee *et al.*, 1994), suggesting the existence of additional cellular activators of PKR. The N-terminal domain of PKR also mediates its dsRNA-independent dimerization *in vitro* and *in vivo* (Cosentino *et al.*, 1995; Patel *et al.*, 1995; Romano *et al.*, 1995; Wu and Kaufman, 1997). Similar dimerization domains are present in other dsRNA-binding proteins, and these proteins can heterodimerize with PKR through these domains (Cosentino *et al.*, 1995; Benkirane *et al.*, 1997). Since dsRNA is thought to be present only in virally infected cells, it is unclear what activates PKR in the absence of virus infection, and potential protein activators of PKR are likely to exist in cells. Here we report the identification of a new protein, PACT, which interacts with PKR through dimerization domains similar to PKR's own and can activate PKR *in vitro* and *in vivo* in the absence of dsRNA.

Results

Cloning of PACT, a new dsRNA-binding protein that interacts with PKR

PACT was cloned by virtue of its interaction with PKR. K296R, an enzymatically inactive mutant of PKR (Katze *et al.*, 1991), was used as the bait in a yeast two-hybrid screen of a human cDNA library, and a novel 1.8 kb PKR-interacting cDNA containing an open reading frame encoding a protein of 313 residues was isolated (Figure 1A). PACT was represented in the database only as several expressed sequence tags, and its sequence contains three motifs (Figure 1A, underlined residues) similar to the dimerization motifs present in PKR and other dsRNA-binding proteins. A comparison of the first two motifs of PACT with the first motif of PKR and two motifs of TAR RNA-binding protein (TRBP) (St. Johnston *et al.*, 1992), another human protein of this family, revealed strong sequence conservation (Figure 1B). Primer extension analysis of cellular mRNA confirmed that the clone represented a full-length cDNA (data not shown), and Northern analysis showed a corresponding mRNA of 2.0 kb. PACT mRNA was expressed at varying levels in all of the cell lines tested (Figure 1C). Since PKR is an IFN-inducible protein, it was of interest to investigate if either IFN or dsRNA treatment had any effect on PACT mRNA levels. To test this, we have used the human glioblastoma cell

line, GRE, in which the IFN genes have been deleted. This makes it suitable for studying the dsRNA-mediated transcriptional induction because these cells do not induce IFN production upon treatment with dsRNA. The transcriptional induction of PACT was assessed by an RNase protection assay. As represented in Figure 1C, PACT mRNA levels were the same in untreated cells as in cells treated with IFN- β , - γ or dsRNA. As expected, the 561 mRNA was induced both by IFN- β and dsRNA treatments, and the IRF-1 mRNA was induced by treatment with IFN- γ (Leonard and Sen, 1997).

PACT interacts with PKR through its dsRNA-binding motifs

The interaction of PACT with PKR was confirmed by co-immunoprecipitation of the *in vitro* translated products. ³⁵S-Labeled, flag epitope-tagged PACT protein was synthesized by *in vitro* translation (Figure 2A, lane 1). This protein could be immunoprecipitated using anti-flag monoclonal antibody (mAb)-agarose (Figure 2A, lane 2), but not by agarose alone (lane 3). The specificity of this immunoprecipitation is shown by the fact that PKR protein, similarly synthesized, was not immunoprecipitated either with the anti-flag mAb-agarose or with agarose alone (lanes 5 and 6). Since flag-PACT could be immunoprecipitated specifically, we then assayed for PKR's interaction with PACT by co-immunoprecipitation and mapped the PACT-interacting domain within PKR. PKR could be co-immunoprecipitated with flag epitope-tagged PACT (Figure 2B, lane 5). A similar interaction was also observed between DRBD, the dimerization domain of PKR, and PACT (lane 6). Δ 170, the C-terminal half of PKR (residues 171-551), did not co-immunoprecipitate with PACT (lane 7), thereby indicating that PACT interacts with PKR through its DRBD. The specificity of these co-immunoprecipitations was confirmed by the fact that another dsRNA-binding protein, the 69 kDa 2'-5' oligoadenylate synthetase (Marie *et al.*, 1997), did not co-immunoprecipitate with PKR. We further checked if when a fixed amount of PACT protein was mixed with increasing amounts of PKR protein, the same stoichiometric ratio was maintained in the co-immunoprecipitations. Since we were using flag-PACT to pull down untagged PKR, we varied the amount of PKR in the mixture while keeping the amount of flag-PACT constant. As seen in Figure 2C (lanes 6-10), a fixed amount of PACT was able to co-immunoprecipitate increasing quantities of PKR from the mixtures containing increasing amounts of PKR. About 30% of the total PKR protein could be co-immunoprecipitated from the mixture at all ratios. The amount of PKR co-immunoprecipitated with PACT followed the same ratio at which these two proteins were mixed. The ratios at which these proteins were mixed (lanes 1-5) were 1, 2, 5, 10 and 30, and the ratios of the immunoprecipitated PKR (lanes 6-10) were 1, 1.8, 4.25, 9.4 and 21.3.

PACT binds dsRNA

Since the same motifs of PKR that mediate interaction with PACT also mediate dsRNA binding by PKR, we examined the ability of PACT to bind dsRNA (Figure 3). This was assayed by a poly(I)-poly(C)-agarose binding assay previously described for assaying the binding of PKR to dsRNA (Patel and Sen, 1992). The ³⁵S-labeled

associated with PACT after purification under denaturing conditions. This amount of dsRNA is far less ($\sim 10^4$ -fold less) than that required for activation of PKR. Denatured PACT, thus purified, was renatured by stepwise dialysis against decreasing concentrations of urea. The purified renatured PACT was homogeneous as confirmed by silver staining after SDS-PAGE analysis (data not shown). Purified PACT, devoid of any associated RNA, was incubated with immunopurified PKR, eIF-2 and $[\gamma\text{-}^{32}\text{P}]\text{-ATP}$. In the absence of activators, neither PKR nor eIF-2 was phosphorylated (Figure 4A, lane 1), whereas the addition of two known activators, dsRNA and heparin, caused phosphorylation of both proteins (lanes 8 and 9). PACT could also activate PKR, causing the phosphorylation of both PKR and eIF-2. PKR activation by PACT was dose-dependent and biphasic: the maximum activation was observed between 400 pg and 4 ng of PACT, which was similar to that achieved by 1 $\mu\text{g}/\text{ml}$ of dsRNA (lane 8). These results clearly demonstrated that PACT could activate PKR directly. To confirm further that PACT activates PKR without the involvement of any dsRNA, we assayed the ability of heat-inactivated and micrococcal nuclease-treated PACT to activate PKR (Figure 4B, lanes 3 and 4). Heat inactivation is expected to result in loss of activity due to protein denaturation, but the dsRNA-dependent activation will be unaffected by this treatment. As expected, the heat inactivation resulted in a loss of PACT's ability to activate PKR (lane 3), while micrococcal nuclease treatment did not (lane 4). To rule out the possibility of any dsRNA remaining protected because it is bound by PACT, we assayed the effect of artificially added dsRNA during the micrococcal nuclease treatment.

However, since PACT treated in such a way would activate PKR in the absence of dsRNA, we needed to inactivate PACT by heat after the nuclease treatment. Any protected dsRNA during this treatment could now be assayed for its ability to activate PKR. As seen in lane 5, the artificially added dsRNA was not protected during the nuclease treatment. As seen in lane 6, dsRNA's ability to activate PKR is not destroyed by heat inactivation. When an activating amount of PACT was incubated in the kinase assay buffer with purified K296R, an inactive mutant of PKR, no phosphorylation of K296R protein was detected (data not shown). This result rules out the possibility of a bacterial kinase co-purifying with PACT and phosphorylating PKR.

We previously have identified two mutants of PKR, K150A and A158D, which can neither bind to nor be activated by dsRNA (Patel *et al.*, 1996). These mutants retained their ability to interact with PACT in a co-immunoprecipitation assay (Figure 5A), thereby enabling us to test if they could be activated by PACT. As shown in Figure 5B, these mutants could be activated by PACT, confirming that activation of PKR by PACT can be achieved in the absence of dsRNA binding. Although these mutants are unable to bind dsRNA, it is conceivable that their interaction with PACT may complement this defect, thereby enabling them to bind dsRNA that may be associated with either protein. Since our preparation

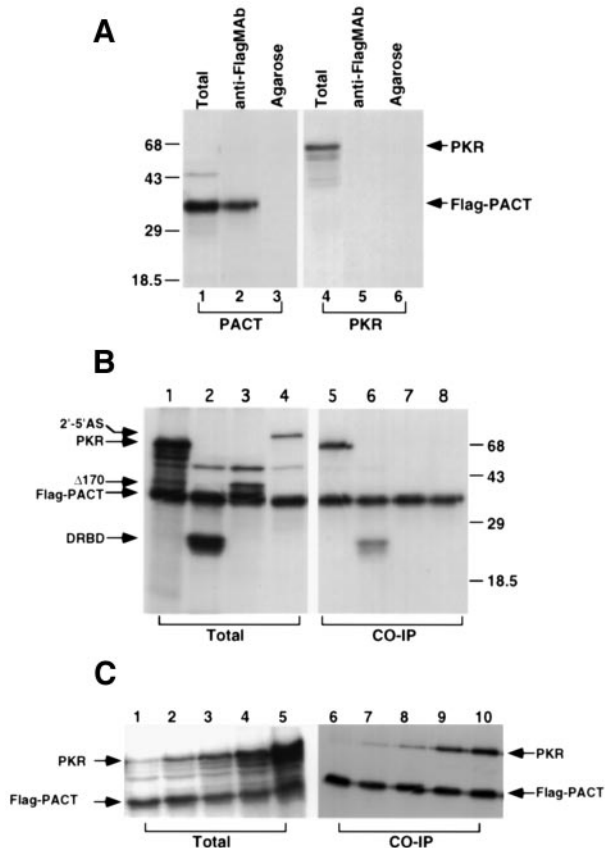


Fig. 2. (A) *In vitro* translation and immunoprecipitation of flag-tagged PACT. *In vitro* translated, ^{35}S -labeled wild-type PKR and flag-PACT were synthesized using the TNT T₇ coupled rabbit reticulocyte lysate system from Promega. Three μl of the reticulocyte lysate proteins were immunoprecipitated using anti-flag mAb-agarose (IBI). Total lanes represent proteins from 1 μl of the lysate, and the anti-flag mAb and agarose lanes represent the proteins immunoprecipitated from 3 μl of the lysates. The positions of the molecular weight markers are indicated on the left. The positions of the two proteins are as indicated on the right. (B) PACT interacts with PKR through its DRBD. *In vitro* translated, ^{35}S -labeled proteins were synthesized using the TNT T₇ coupled rabbit reticulocyte lysate system from Promega. Flag-tagged PACT, wild-type PKR, $\Delta 170$, 2'-5' oligoadenylate synthetase and DRBD were translated independently. Three μl of the reticulocyte lysate containing the flag-PACT were mixed with 3 μl of the lysates containing either wild-type PKR, $\Delta 170$, 2'-5' oligoadenylate synthetase or DRBD. Flag-tagged PACT was immunoprecipitated from the reticulocyte lysate using the anti-flag mAb-agarose (IBI), and the proteins co-immunoprecipitating with it were analyzed by SDS-PAGE analysis followed by fluorography. Lanes 1-4 show all proteins in the mixture before immunoprecipitation, and lanes 5-8 represent immunoprecipitated proteins. Lanes 1 and 5, wild-type PKR and flag-PACT; lanes 2 and 6, flag-PACT and DRBD; lanes 3 and 7, flag-PACT and $\Delta 170$; lanes 4 and 8, flag-PACT and 2'-5' oligoadenylate synthetase. The 'total' lanes contain 1 μl of the reticulocyte lysates each and the 'CO-IP' lanes contain 3 μl of the lysates each. The positions of the molecular weight markers are indicated on the right. The positions of different proteins are as indicated on the left. (C) Dose-dependent association between PKR and PACT. *In vitro* translated, ^{35}S -labeled wild-type PKR and flag-PACT proteins were mixed in different proportions. Two μl of the reticulocyte lysate containing the flag-PACT was mixed with 0.1-3 μl of the lysate containing wild-type PKR. Flag-tagged PACT was immunoprecipitated from the reticulocyte lysate using the anti-flag mAb-agarose (IBI), and the wild-type PKR co-immunoprecipitating with it was analyzed by SDS-PAGE analysis followed by fluorography. The relevant bands were quantitated by phosphorimager analysis. Lane 1, 3 μl of flag-PACT + 0.1 μl of wild-type PKR; lane 2, 3 μl of flag-PACT + 0.2 μl of wild-type PKR; lane 3, 3 μl of flag-PACT + 0.5 μl of wild-type PKR; lane 4, 3 μl of flag PACT + 1 μl of wild-type PKR; lane 5, 3 μl of flag-type PKR + 3 μl of wild-type PKR. The positions of PKR and flag-PACT are as indicated on the right.

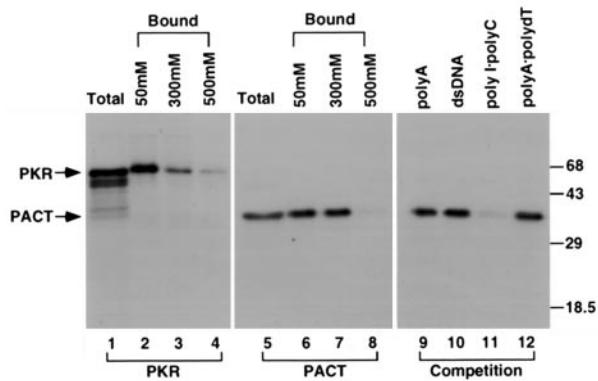


Fig. 3. PACT binds dsRNA. The ^{35}S -labeled PKR and PACT protein were synthesized using the TNT T₇ coupled reticulocyte lysate system from Promega. The dsRNA-binding activity was measured by poly(I)-poly(C)-agarose binding assay, using 4 μl of translation products at 50, 300 or 500 mM NaCl concentrations. The proteins bound to beads after washing were analyzed by SDS-PAGE followed by fluorography. The relevant bands were quantitated by phosphorimager analysis. Competition by different nucleic acids for binding of PACT to poly(I)-poly(C)-agarose is shown in the extreme right panel. The competitor nucleic acid was added during the binding reaction at 10 $\mu\text{g}/\text{ml}$ concentration. The lanes are labeled on top with the competitor used. Lanes 1–4, poly(I)-poly(C)-agarose binding activity of PKR; lanes 5–8, poly(I)-poly(C)-agarose binding activity of PACT; and lanes 9–12, competition of PACT's poly(I)-poly(C)-agarose binding activity. The positions of the molecular weight markers are indicated on the right.

of purified PACT was devoid of any dsRNA, we needed to ascertain that no dsRNA was associated with the *in vitro* translated mutant PKR molecules. For this purpose, we added labeled dsRNA to the reticulocyte lysate containing the *in vitro* translated PKR mutant proteins and analyzed its association with these proteins after the immunoprecipitation. No significant counts were found to be associated with immunoprecipitates. Since neither of the protein partners (PACT and PKR mutants) in the kinase reaction mix had any dsRNA bound to them, it can be concluded that PACT activates K150A and A158D mutants by direct interaction.

Overexpression of PACT in mammalian cells leads to activation of PKR, enhanced phosphorylation of eIF-2 α and inhibition of translation

To determine if PACT could activate PKR *in vivo*, an expression construct of flag-tagged PACT was transfected into human HT1080 cells and co-immunoprecipitation experiments performed. The endogenous cellular PKR could be co-immunoprecipitated with transfected PACT protein (Figure 6A). PKR precipitated from PACT-expressing cells was more active, as judged by autophosphorylation and eIF-2 α phosphorylation (Figure 6B), than PKR from the vector control. As expected, PKR from the K296R-transfected cells was even less active than the vector control, since K296R inhibits PKR activity. Western blotting confirmed that all immunoprecipitates contained similar amounts of PKR.

The above results suggested that PACT could activate PKR *in vivo*. This was confirmed by examining the level of phosphorylation of PKR and eIF-2 *in vivo* in the transfected cells. The cells transfected with expression constructs of PACT and K296R were labeled with [^{32}P]orthophosphate and levels of ^{32}P -labeled PKR and

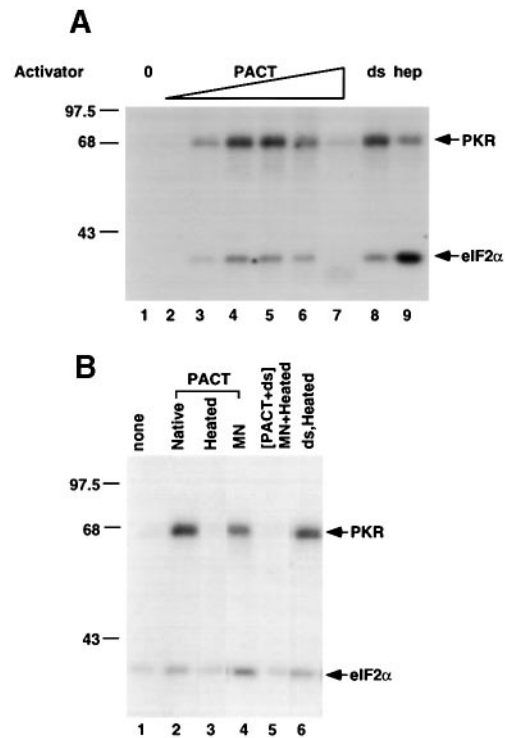


Fig. 4. (A) Purified PACT activates PKR. PACT was expressed as a hexahistidine-tagged protein in *E. coli*, purified by Ni affinity chromatography under denaturing conditions and renatured by stepwise dialysis. A 100 μg aliquot of total protein from HeLa M cells was immunoprecipitated using PKR monoclonal antibody (Ribogene) and PKR assay was performed in activity buffer containing 500 ng of purified eIF-2, 0.1 mM ATP and 10 μCi of [γ - ^{32}P]ATP at 30°C for 10 min. Poly(I)-poly(C) (100 ng/ml; lane 8) or heparin (10 U/ml; lane 9) was used as the standard activator for the enzyme. Purified PACT in amounts of 4 μg (lane 2), 40 μg (lane 3), 400 μg (lane 4), 4 ng (lane 5), 40 ng (lane 6) and 400 ng (lane 7) was added to PKR prior to addition of eIF-2 and [γ - ^{32}P]ATP to test its effect on PKR activity. PKR activity without any added activator is in lane 1. (B) Heat inactivation of PACT's PKR activating capacity. The PKR activity assay was done as described in (A). The additions to the assay mixture were as follows: lane 1, no activator; lane 2, 4 ng of native PACT; lane 3, 4 ng of heat-inactivated (90°C for 15 min) PACT; lane 4, 4 ng of PACT treated with micrococcal nuclease; lane 5, 4 ng of PACT with 1 ng of poly(I)-poly(C), treated with micrococcal nuclease and then heat inactivated; and lane 6, 1 ng of dsRNA heated at 90°C for 15 min.

eIF-2 α were assayed by immunoprecipitation with monoclonal antibodies (Figure 7A). There was ~2-fold more label in PKR and eIF-2 α isolated from PACT-transfected cells as compared with vector-transfected cells. As expected, phosphorylation was inhibited in the K296R-transfected cells. Western blotting confirmed that the same amounts of PKR protein and eIF-2 α protein were present in the immunoprecipitates. PACT also regulates PKR function *in vivo*. This was shown by using a translation inhibition assay in IFN-treated HT1080 cells (Kaufman and Murtha, 1987; Davies *et al.*, 1989; Kaufman *et al.*, 1989; Park *et al.*, 1994; Patel *et al.*, 1996). In this assay, the translation of a transfected reporter gene such as luciferase is measured in the presence of a co-transfected effector. The assay is based on the fact that transfection of certain plasmids into cells results in activation of PKR and selectively inhibits the translation of a reporter carried on it in a *cis*-acting manner. Co-transfection of a PKR inhibitor such as K296R has been shown to lead to

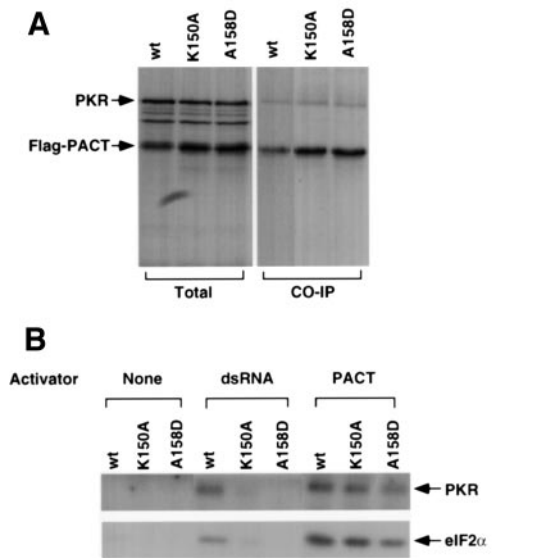


Fig. 5. (A) PACT interacts with the dsRNA binding-defective mutants of PKR. *In vitro* translated, ^{35}S -labeled proteins were synthesized using the TNT T_7 coupled rabbit reticulocyte lysate system from Promega. Flag-tagged PACT was co-translated either with wild-type PKR, K150A or A158D. Three μl of the reticulocyte lysate containing the synthesized proteins were used for immunoprecipitation. The flag-PACT was immunoprecipitated using the anti-flag mAb-agarose (IBI), and the proteins co-immunoprecipitating with it were analyzed by SDS-PAGE analysis followed by fluorography. 'Total' lanes show all proteins in the mixture before immunoprecipitation, and CO-IP lanes represent immunoprecipitated proteins. The positions of PKR and flag-PACT proteins are as indicated on the left. (B) PACT can activate dsRNA-unresponsive PKR mutants. Wild-type PKR, K150A mutant and A158D mutant were translated *in vitro*. Five μl of the reticulocyte lysates were immunoprecipitated with the anti-PKR monoclonal antibody and the immunoprecipitates were assayed for PKR in activity buffer containing 500 ng of purified eIF-2, 0.1 mM ATP and 10 μCi of [γ - ^{32}P]ATP at 30°C for 10 min in the presence of [γ - ^{32}P]ATP without any added activator or in the presence of either 1 $\mu\text{g}/\text{ml}$ of poly(I)-poly(C) or 4 ng of purified PACT.

enhanced translation of the reporter, and co-transfection of a PKR activator would be expected to result in inhibition of its translation. As shown previously by us and others (Patel *et al.*, 1996; Wu and Kaufman, 1996), co-transfection with expression constructs of K296R and DRBD caused a marked increase in luciferase activity. In contrast, co-expression of PACT decreased the level of luciferase expression, indicating an enhanced activation of PKR (Figure 7B), further demonstrating that PACT expression leads to activation of PKR in mammalian cells.

Co-expression of PKR and PACT gives an anti-growth phenotype in *Saccharomyces cerevisiae*

Since expression of PKR in yeast causes pronounced inhibition of growth (Chong *et al.*, 1992; Romano *et al.*, 1995), we determined whether PACT could enhance this effect by activating PKR co-expressed in yeast. The yeast strain that we have used for this analysis is H17 (Bushman *et al.*, 1993), which carries a mutation in the α subunit (GCN3) of the yeast eIF-2B. This mutation reduces the deleterious effect of eIF-2 α phosphorylation on growth. It has been shown that phosphorylation of eIF-2 regulates translation by reducing eIF-2B function, and that GCN3 interacts directly with the α subunit of eIF-2 and mediates

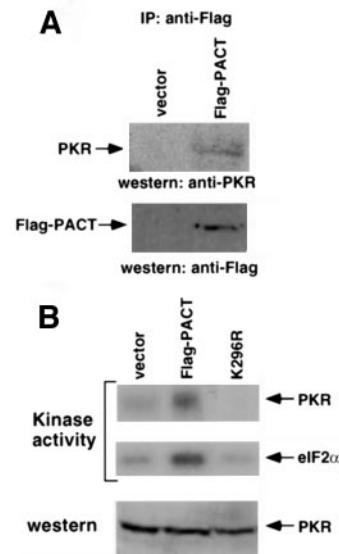


Fig. 6. (A) PKR can be co-immunoprecipitated with PACT from mammalian cells. HT 1080 cells were transfected in 100 mm culture dishes with 5 μg of pCB6 $^{+}$ vector and flag-PACT/pCB6 $^{+}$ DNAs. At 24 h post-transfection, cells were harvested and cell extracts were prepared. A 100 μg aliquot of total cell extracts was used to immunoprecipitate flag-PACT with anti-flag mAb-agarose as described in Materials and methods. The immunoprecipitates were then analyzed by a Western blot analysis with the anti-PKR and anti-flag polyclonal antibodies (Santa Cruz Biotech. Inc.). (B) Expression of PACT in mammalian cells leads to PKR activation. HT 1080 cells were transfected in 100 mm culture dishes with 5 μg of pCB6 $^{+}$ vector, flag-PACT/pCB6 $^{+}$ or K296R/pCB6 $^{+}$ DNAs. At 24 h post-transfection, cells were harvested and 100 μg of total cell extracts were used to immunoprecipitate PKR with monoclonal antibody. The immunoprecipitates were assayed for kinase activity in the presence of [γ - ^{32}P]ATP and purified eIF-2. No activator of PKR was added to these kinase assays. Western blot analysis performed with anti-PKR monoclonal antibody with the extracts is shown in the lower strip. The order of samples is the same in all three strips.

the increased binding of phosphorylated eIF-2 to eIF-2B, thereby preventing recycling of eIF-2 for the next round of translation initiation. Expression of wild-type PKR in H17 does not cause as pronounced an effect as in wild-type yeast strains (Dever *et al.*, 1993), making it possible to assay for enhancement of the slow growth phenotype by PACT. PACT, K296R or DRBD were expressed alone or together with PKR in the H17 strain using a galactose-inducible promoter. In glucose-containing medium, as expected, all transfectants grew equally well, but, in the presence of galactose, wild-type PKR, but not PACT, caused a mild slow growth (data not shown). Upon co-expression of PKR and PACT, the slow growth phenotype was enhanced (compare 2 with 1 in Figure 8A, plate B). Wild-type PKR was needed for the action of PACT, and the K296R mutant could not substitute for it (compare 3 with 1). As reported previously, unlike PACT, DRBD inhibited the anti-growth effect of PKR (compare 4 with 1). A Western blot analysis confirmed that comparable levels of PKR, PACT and DRBD were expressed in the different transfected yeasts (Figure 8B). The growth rates of the different transfected yeast strains in liquid cultures were also determined (Figure 8C). It was seen that co-expression of PACT and PKR resulted in a significantly slower growth rate compared with cells expressing PKR alone. As seen with growth on solid medium, co-expression

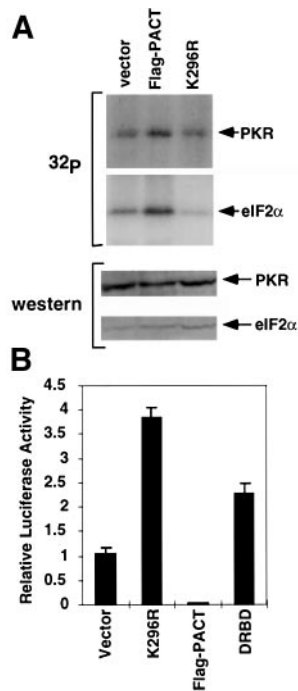


Fig. 7. (A) Enhanced *in vivo* phosphorylation of PKR and eIF-2 in PACT-expressing cells. HT 1080 cells were transfected as in Figure 6B and, 24 h post-transfection, cells were metabolically labeled with 100 μ Ci/ml of [32 P]orthophosphate for 3 h in phosphate-free medium. Cell extracts were prepared and subjected to immunoprecipitation with monoclonal antibodies to PKR and eIF-2 α and analyzed by SDS-PAGE followed by autoradiography. Western blot analysis, performed on these extracts to ascertain that equal amounts of PKR and eIF-2 α were analyzed for phosphate labeling, is shown in the lower two strips. The order of samples is the same in all the strips. (B) *In vivo* translation inhibition assay. HT 1080 cells were transfected with 200 ng of each of the two (expression construct and the reporter plasmid pGL2-control from Promega) plasmid DNAs. At 24 h after transfection, cells were treated with 100 U/ml of IFN- β . Cells were harvested 24 h after IFN treatment and assayed for luciferase activity after normalizing for the transfection efficiency by measuring the total protein. The error bars represent the standard error calculated from six independent values.

of DRBD with PKR resulted in reversal of the slow growth phenotype. Expression of PACT alone or K296R alone did not show any slow growth rate phenotype. These experiments demonstrated that PACT could activate PKR in yeast and enhance its anti-growth effects. We reasoned that the K150A and A158D mutants of PKR may not have a slow growth phenotype in yeast because they do not bind dsRNA. When assayed for their effect on yeast growth rate, however, it was seen that they were as inhibitory as wild-type PKR (Figure 8D). Similar results have been reported by other workers for the mutant K150P (Romano *et al.*, 1995). Like wild-type PKR, our mutants showed an enhancement of their slow growth phenotype when PACT was co-expressed (Figure 8D), thereby confirming our *in vitro* activation results. A Western blot analysis was done to confirm that all proteins were expressed at comparable levels (Figure 8E).

Discussion

PACT is a new member of the family of dsRNA-binding proteins to which PKR belongs. These proteins are characterized by structural motifs (St. Johnston *et al.*, 1992)

which mediate their homo- (Patel *et al.*, 1995; Romano *et al.*, 1995; Ortega *et al.*, 1996; Wu and Kaufman, 1997) and heterodimerization (Cosentino *et al.*, 1995) and binding to dsRNA. PACT contains three such motifs without any other remarkable structural features. PACT clearly binds PKR and activates it by a dsRNA-independent mechanism. This was shown by the purification scheme, which precluded the co-purification of associated dsRNA. Moreover, treatment of the purified PACT with micrococcal nuclease, which degrades dsRNA, had no effect on its ability to activate PKR (Figure 4B). Genetic evidence for a dsRNA-independent activation of PKR by PACT was provided by the activation of two PKR dsRNA-binding mutants. The conclusion that PACT activates PKR directly, and not by recruiting dsRNA, is supported further by the observation that other dsRNA-binding proteins, such as the DRBD of PKR and TRBP that can also heterodimerize with PKR, do not activate PKR but rather inhibit the activation of PKR (Cosentino *et al.*, 1995; Patel *et al.*, 1995; Benkirane *et al.*, 1997; Wu and Kaufman, 1997). dsRNA is known to activate PKR by promoting a conformational change of the protein (Carpick *et al.*, 1997). Our data suggest that PACT, by binding to the same region of PKR as dsRNA, may induce a similar conformational change. The observed diminution of PKR activation by PACT at higher concentrations could be due to promotion of PACT homodimerization or due to two different PACT molecules binding to the two dimerization motifs of PKR under those conditions. Since PACT has more than one DRBD, it is also possible that PACT may bind to a PKR dimer, thus allowing one PKR molecule to trans-phosphorylate its partner. At high PACT concentrations, this is less likely to occur since, under these conditions, only one PKR molecule may be bound to each PACT molecule. Further studies such as determination of the exact subunit composition are likely to throw some light on the exact mechanism of activation.

The demonstration of PKR activation by PACT in mammalian cells *in vivo* relied on transient transfection and, thus, underestimates the extent of the effect because not all cells were transfected. However, repeated attempts to isolate permanent overexpressors of PACT in several mammalian cell lines failed (data not shown), presumably because of its anti-cellular effects. The small, but consistent, enhanced phosphorylation of eIF-2 α observed in the PACT-transfected cells is significant physiologically because phosphorylation of only 30% of the cellular pool of eIF-2 α has been shown to cause a severe inhibition of protein synthesis (Hershey, 1989). Several other proteins which belong to the same family of dsRNA-binding proteins have been cloned. Two of the mammalian proteins in this family, human TRBP (Park *et al.*, 1994) and mouse Prbp (Lee *et al.*, 1996), have been shown to be involved in translational regulation. The TRBP gene was cloned from a HeLa cell expression library based on its ability to bind to the HIV-1 TAR RNA *in vitro* (Gatignol *et al.*, 1991) and then was cloned again based on its ability to bind the HIV-1 Rev-responsive element (Park *et al.*, 1994). The function of TRBP in non-infected cells is unknown, but it has been suggested to regulate translation by functioning as an inhibitor of PKR in a dsRNA-independent manner. Overexpression of TRBP in mouse cells leads to a transformed phenotype, which is consistent with its

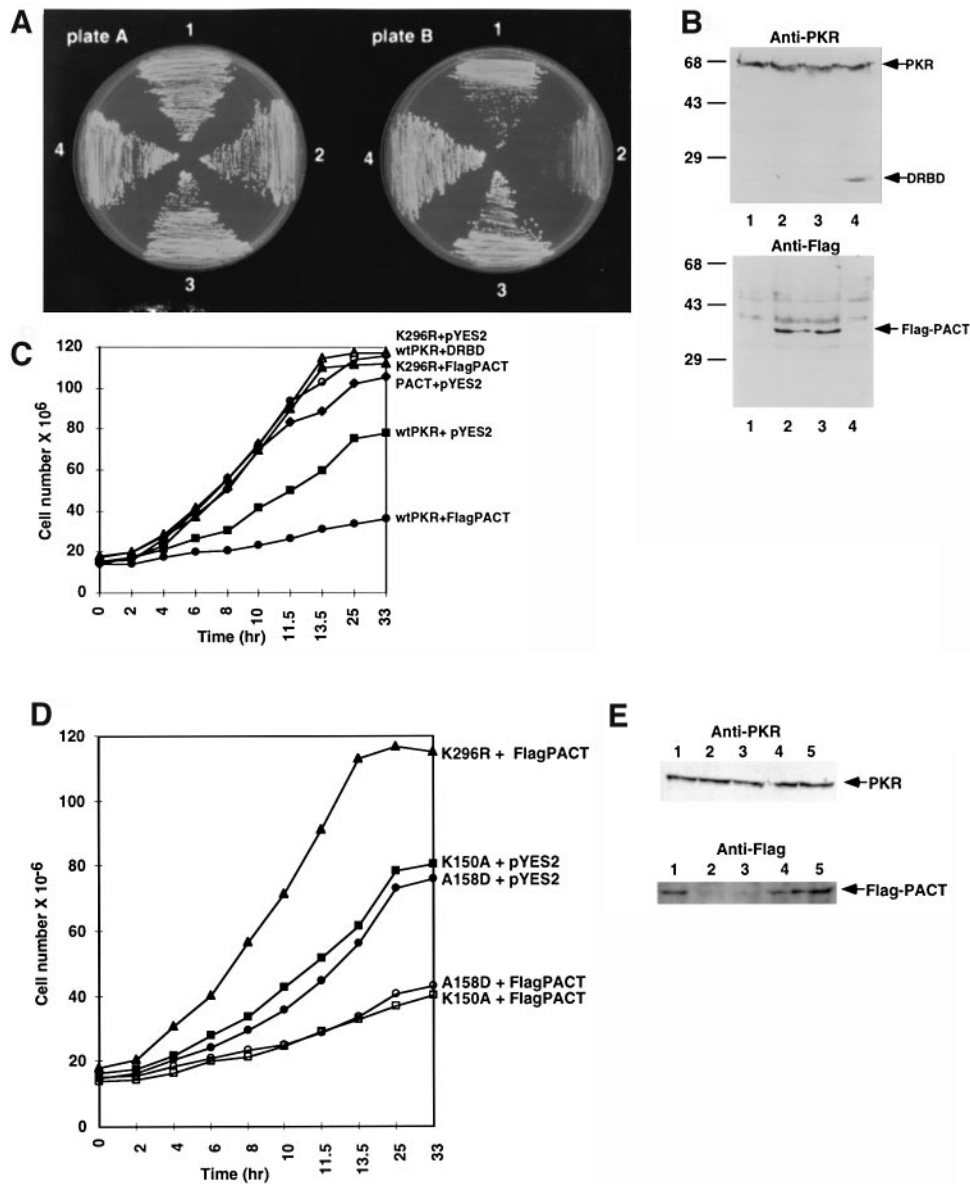


Fig. 8. (A) PACT enhances the slow growth phenotype of PKR in yeast. Growth of transformed yeast strains containing (1) GAL1-wild-type PKR/pRS315 + pYES2, (2) GAL1-wild-type PKR/pRS315 + PACT/pYES2, (3) GAL1-K296R/pRS315 + PACT/pYES2 and (4) GAL1-wild-type PKR/pRS315 + DRBD/pYES2. Cells were grown for 2 days at 30°C on synthetic medium lacking uracil and leucine with 2% glucose (plate A) or 10% galactose and 1% raffinose (plate B) as sole carbon source. (B) Western blot analysis. A 100 µg aliquot of the total protein extracts from transformed yeast strains was analyzed by Western blot analysis with anti-PKR and anti-flag monoclonal antibodies. Lane 1, GAL1-wild-type PKR/pRS315 + pYES2; lane 2, GAL1-wild-type PKR/pRS315 + PACT/pYES2; lane 3, GAL1-K296R/pRS315 + PACT/pYES2; and lane 4, GAL1-wild-type PKR/pRS315 + DRBD/pYES2. (C) Growth rate analysis. The growth rate of the transformed yeast strains was analyzed in synthetic medium containing 10% galactose and 1% raffinose. At various time points, cell growth was monitored by measuring OD₆₀₀. △, GAL1-K296R/pRS315 + pYES2; ◆, GAL1-PACT/pRS315; ■, GAL1-wild-type PKR/pRS315 + pYES2; ●, GAL1-wild-type PKR/pRS315 + PACT/pYES2; ○, GAL1-wild-type PKR/pRS315 + DRBD/pYES2; and ▲, GAL1-K296R/pRS315 + PACT/pYES2. (D) PACT enhances the slow growth phenotype of PKR's dsRNA-unresponsive mutants. The growth rate of the transformed yeast strains was analyzed in synthetic medium containing 10% galactose and 1% raffinose. At various time points, cell growth was monitored by measuring the OD₆₀₀. ▲, GAL1-K296R/pRS315 + pYES2; ■, GAL1-K150A/pRS315 + pYES2; ●, GAL1-A158D/pRS315 + pYES2; ○, GAL1-A158D/pRS315 + PACT/pYES2; and □, GAL1-K150A/pRS315 + PACT/pYES2. (E) Western blot analysis. A 100 µg aliquot of the total protein extracts from transformed yeast strains was analyzed by Western blot analysis with anti-PKR and anti-flag monoclonal antibodies. Lane 1, GAL1-K296R/pRS315 + PACT/pYES2; lane 2, GAL1-K150A/pRS315 + pYES2; lane 3, GAL1-A158D/pRS315 + pYES2; lane 4, GAL1-K150A/pRS315 + PACT/pYES2; and lane 5, GAL1-A158D/pRS315 + PACT/pYES2.

inhibitory role towards PKR activity (Benkirane *et al.*, 1997). Prbp, a mouse homolog of TRBP, was cloned from mouse testis based on its ability to bind the 3'-untranslated region of mouse protamine-1 mRNA. Prbp has been proposed to be a general translational inhibitor and was found to repress translation of protamine-1 mRNA in a

non-specific manner. Thus, TRBP and PACT, in spite of sharing a high degree of homology, have different effects on PKR activity. Only PACT has the ability to activate PKR by direct protein-protein interaction. It should be noted that several mutants of PKR, that cannot bind to or be activated by dsRNA *in vitro*, still maintain their anti-

growth effects in yeast (Romano *et al.*, 1995). Two examples are shown in Figure 8D. Many of these mutants have been shown to be activated *in vitro* by heparin, and it is conceivable that similar polyanionic compounds activate them in yeast. It is also possible that yeast contains a functional homolog of PACT that can activate PKR. The anti-growth effect of PACT required the presence of PKR. This effect was specific because other dsRNA-binding proteins such as DRBD had the opposite effect of neutralizing PKR's anti-growth effect. Thus, PACT's ability to activate PKR *in vitro* and *in vivo* is unique among the known dsRNA-binding proteins.

PACT is the first identified protein activator of PKR. In addition to activating PKR directly, PACT may also recruit dsRNA in virus-infected cells to the enzyme and thus enhance the PKR activation process. In principle, it has the potential to modulate intracellular PKR activity under a variety of growth and differentiation conditions and in response to various extracellular stimuli. Such modulations may be triggered by a change in the intracellular levels of PACT and/or PKR proteins, or additional, as yet unidentified, activation mechanisms of PACT may also operate.

It remains to be determined which of the several cellular processes that involve PKR, uses PACT as its activator. The eIF-2 α kinases are important regulators of translation in eukaryotic cells (Samuel, 1993; De Haro *et al.*, 1996). These kinases have been shown to mediate both gene-specific (Hinnebusch, 1993) and general regulation of translation. Several environmental conditions such as serum starvation, amino acid or glucose deprivation, heat shock and ischemia have been shown to lead to enhanced eIF-2 α phosphorylation (Clemens, 1996). The identity of cellular kinases that are involved in phosphorylation of eIF-2 α under these conditions is unknown at present. It would be of interest to study whether PACT levels or its activity is modulated by any of these stimuli, leading to activation of PKR and subsequent eIF-2 α phosphorylation.

Materials and methods

Yeast two-hybrid screening

The *trans*-dominant PKR mutant K296R expressed as a GAL DNA-binding domain fusion protein was used as a bait. A total of 5×10^6 transformants from a human placenta matchmaker library (Clontech) were screened in the yeast strain HF7c (Clontech) and 250 colonies were recovered as His⁺, out of which 37 tested positive for β -galactosidase. On further analysis, 30 of these were dependent on K296R to give a positive β -galactosidase reaction. These clones were subjected to a second screen to ensure that they gave a positive β -galactosidase reaction in a manner specific for co-expression of K296R. One of these clones (PACT), which contained a full-length cDNA insert, was analyzed further. Sequence analysis of the cDNA clones revealed that they originated from two unrelated genes. There were 16 clones isolated that coded for the PACT protein and the other 12 encoded a protein that is not as yet characterized. Two of the clones were found to encode extremely short peptides (6–8 residues).

Northern blot analysis

A multiple human cancer cell line blot (Clontech) was hybridized to random primer-labeled PACT cDNA insert according to Church and Gilbert (1984).

Ribonuclease protection assay

GRE cells were grown in 150 mm dishes in 10% fetal calf serum (FCS) in Dulbecco's modified Eagle's medium (DMEM). They were left untreated or were treated with 500 U/ml of human IFN- β or - γ or

100 μ g/ml of poly(I)-poly(C) for 6 h. Total RNA was isolated from the cells using the RNazol B reagent according to the manufacturer's protocol. The PACT probe was transcribed with T3 RNA polymerase from the PACT/Bluescript II KS⁺ cut with S₁I to generate a 296 nucleotide probe. All other probes were synthesized as described before (Leonard and Sen, 1997). The ribonuclease protection assay was performed as described before (Kessler *et al.*, 1998).

In vitro interaction assay

In vitro translated, ³⁵S-labeled PKR and flag epitope-tagged PACT proteins were synthesized using the TNT T₇ coupled reticulocyte system from Promega. The PKR and DRBD were translated alone or co-translated with flag-tagged PACT. Five μ l of the *in vitro* translated ³⁵S-labeled proteins were incubated with 20 μ l of anti-flag mAb-agarose (IBI) in 200 μ l of IP buffer [20 mM Tris-HCl pH 7.5, 100 mM KCl, 1 mM EDTA, 1 mM dithiothreitol (DTT), 100 U/ml aprotinin, 0.2 mM phenylmethylsulfonyl fluoride (PMSF), 20% glycerol, 1% Triton X-100] at 4°C for 30 min on a rotating wheel. The beads were washed in 500 μ l of IP buffer four times and the washed beads were then boiled in 2 \times Laemmli buffer (150 mM Tris-HCl pH 6.8, 5% SDS, 5% β -mercaptoethanol, 20% glycerol) for 2 min and eluted proteins were analyzed by SDS-PAGE on a 12% gel. Fluorography was performed at -80°C with intensifying screens.

dsRNA binding assay

The *in vitro* translated, ³⁵S-labeled PACT protein was synthesized using the TNT T₇ coupled reticulocyte lysate system from Promega. The dsRNA-binding activity was measured by poly(I)-poly(C)-agarose binding assay. The translation products (4 μ l) diluted with 25 μ l of binding buffer (20 mM Tris-HCl, pH 7.5, 0.3 M NaCl, 5 mM MgCl₂, 1 mM DTT, 0.1 mM PMSF, 0.5% NP-40, 10% glycerol) were mixed with 25 μ l of poly(I)-poly(C)-agarose (Pharmacia) beads and incubated at 30°C for 30 min with intermittent shaking. The beads were then washed with 500 μ l of binding buffer four times. The proteins bound to beads after washing were analyzed by SDS-PAGE followed by fluorography.

Expression and purification of PACT from E.coli

The PACT protein coding region was subcloned into pET15b (Novagen) to generate PACT/pET15b. This results in the in-frame fusion of PACT sequence to the histidine tag. The expression host BL21(DE3) was transformed with PACT/pET15b. The bacteria were grown overnight in Luria broth and harvested at 5000 g for 10 min at 25°C. The cell pellet was suspended in 3-fold the initial culture volume of fresh LB, and isopropyl- β -D-thiogalactoside (IPTG) was added at a final concentration of 2 mM. The culture was incubated at 37°C with vigorous shaking for 2–3 h, at which point the cells were harvested. The cell pellet from 500 ml of culture typically was suspended in 10 ml of binding buffer (5 mM imidazole, 200 mM NaCl, 20 mM Tris-HCl pH 7.9, 0.1% NP-40) and sonicated at a high setting for five 30 s pulses on ice. The homogenate was centrifuged at 12 000 g for 30 min. The pellet was resuspended in 25 ml of the same buffer and pelleted again at 12 000 g for 30 min. The pellet was then resuspended in 10 ml of denaturing buffer (6 M urea, 5 mM imidazole, 200 mM NaCl, 20 mM Tris-HCl pH 7.9, 0.1% NP-40). It was incubated on ice for 1 h to dissolve the proteins completely. The insoluble material was removed by centrifugation at 30 000 g for 30 min. The supernatant was mixed with 2 ml of Ni-charged his-bind resin (Novagen). The mixture was incubated at 4°C for 30 min on a slow rotating shaker. After binding, the resin was washed four times with 50 ml each of denaturing buffer and six times with 50 ml each of wash buffer (6 M urea, 60 mM imidazole, 200 mM NaCl, 20 mM Tris-HCl pH 7.9, 0.1% NP-40). The washed resin was packed into a column and his-PACT was eluted with 25 ml of strip buffer (6 M urea, 100 mM EDTA, 200 mM NaCl, 20 mM Tris-HCl pH 7.5). The eluted protein was dialyzed against 2 l of buffer at 4°C in four steps of decreasing urea concentrations (4, 2, 1 and 0.5 M, and finally no urea). The refolded protein was then concentrated to 400 μ g/ml using Centrprep concentrators.

Kinase assays

HeLa M cells were maintained in DMEM with 10% FCS. The cells were harvested when they were at 70% confluency. Cells were washed in ice-cold phosphate-buffered saline (PBS) and packed by centrifugation at 600 g for 5 min. They were lysed by addition of an equal volume of lysis buffer (20 mM Tris-HCl pH 7.5, 5 mM MgCl₂, 50 mM KCl, 400 mM NaCl, 2 mM DTT, 1% Triton X-100, 100 U/ml aprotinin, 0.2 mM PMSF, 20% glycerol). The lysates were centrifuged at 10 000 g for 5 min and the supernatants were assayed for PKR activity. A 100 μ g

aliquot of total protein was immunoprecipitated using PKR monoclonal antibody (Ribogene) in the high salt buffer (20 mM Tris-HCl pH 7.5, 50 mM KCl, 400 mM NaCl, 1 mM EDTA, 1 mM DTT, 100 U/ml aprotinin, 0.2 mM PMSF, 20% glycerol, 1% Triton X-100) at 4°C for 30 min on a rotating wheel. Then 10 µl of protein A-Sepharose slurry was added and incubation was carried out for a further 1 h. The protein A-Sepharose beads were washed in 500 µl of high salt buffer four times and twice in activity buffer (20 mM Tris-HCl pH 7.5, 50 mM KCl, 2 mM MgCl₂, 2mM MnCl₂, 100 U/ml aprotinin, 0.1 mM PMSF, 5% glycerol). PKR assay was performed with PKR still attached to the beads in activity buffer containing 500 ng of purified eIF-2, 0.1 mM ATP and 10 µCi of [γ -³²P]ATP at 30°C for 10 min. One µg/ml of poly(I)-poly(C) or 10 U/ml of heparin was used as the standard activator for the enzyme. Purified PACT in amounts varying from 4 pg to 400 ng was added to test its effect on PKR activity. Micrococcal nuclease (Boehringer) treatment was done on 50 µg of purified PACT as suggested by the manufacturer. The treated PACT protein was then re-purified on the Ni-agarose column and was used in the kinase assays. Heat inactivation of PACT was done at 90°C for 15 min. Labeled proteins were analyzed by SDS-PAGE on a 12% gel. Autoradiography was performed at -80°C with intensifying screens.

Expression in mammalian cells and co-immunoprecipitation assay

HT 1080 cells were transfected in 100 mm culture dishes with 5 µg of pCB6⁺ vector and flag-PACT/pCB6⁺ DNAs using the lipofectamine (Gibco-BRL) reagent. At 24 h post-transfection, cells were harvested and cell extracts were prepared; 100 µg of total cell extracts were used to immunoprecipitate flag-PACT with anti-flag mAb-agarose as described under *In vitro* interaction assay. The immunoprecipitates were then analyzed by a Western blot analysis with the anti-PKR and anti-flag polyclonal antibodies (Santa Cruz Biotech. Inc.). For the kinase assays from transfected cells, HT 1080 cells were transfected in 100 mm culture dishes with 5 µg of pCB6⁺ vector, flag-PACT/pCB6⁺ or K296R/pCB6⁺ DNAs. At 24 h post-transfection, cells were harvested and cell extracts were prepared; 100 µg of total cell extracts were used to immunoprecipitate PKR with monoclonal antibody. The immunoprecipitates were assayed for kinase activity as described under Kinase assays. No activator of PKR was added to these kinase assays.

In vivo phosphate labeling

HT 1080 cells were transfected in 100 mm culture dishes with 5 µg of pCB6⁺ vector, flag-PACT/pCB6⁺ or K296R/pCB6⁺ DNAs. At 24 h post-transfection, cells were metabolically labeled with 100 µCi/ml of [³²P]orthophosphate (DuPont NEN, 8500 Ci/mmol) for 3 h in phosphate-free medium. Cell extracts were prepared as described under Kinase assays and were subjected to immunoprecipitation with monoclonal antibodies to PKR and eIF-2 α and analyzed by SDS-PAGE followed by autoradiography. Western blot analysis was performed on these extracts to ascertain that equal amounts of PKR and eIF-2 α were analyzed by phosphate labeling.

Translation inhibition assay

The effect of co-transfection of pCB6⁺ vector, flag-PACT/pCB6⁺, K296R/pCB6⁺ and DRBD/pCB6⁺ on the reporter pGL2-Control (Promega) in HT 1080 cells was measured as described before (Patel *et al.*, 1996). HT 1080 cells were transfected in 6-well plates in triplicate with 200 ng of each of the two (expression construct and the reporter plasmid pGL2-Control from Promega) plasmid DNAs by the lipofectamine procedure. At 24 h after transfection, the cells were treated with 100 U/ml of IFN- β . Cells were harvested 48 h after transfection and assayed for luciferase activity after normalizing for the transfection efficiency by measuring the total protein.

Expression in yeast and growth analysis

Wild-type PKR and K296R coding regions were subcloned into the pYES2 vector (Invitrogen). The fragments which contained the Gal1 promoter-wild-type PKR or Gal1 promoter-K296R were then subcloned into pRS 315 vector (Sikorski and Hieter, 1989). This gave us the galactose-inducible expression of wild-type PKR or K296R in a vector with a Leu⁺ marker. The PACT and DRBD coding regions were subcloned into the pYES2 vector to obtain their expression in yeast in a galactose-inducible manner. Expression plasmids were introduced into the yeast strain H17 (*Mat α* , *gcn3-102*, *ura 3-52*, *leu2-3*, *leu2-112*) using the lithium acetate procedure (Chong *et al.*, 1992). Transformed yeast strains were selected on synthetic medium containing 2% glucose and lacking the appropriate amino acids (either ura⁻, or ura⁻ and leu⁻). The

colonies were then streaked on synthetic medium plates lacking the appropriate amino acids and containing either 2% glucose or 1% raffinose and 10% galactose. The growth of yeast was monitored every day. For liquid growth curves, the transformed yeast strains were grown to an OD₆₀₀ of ~1.5 in synthetic medium containing 2% glucose lacking uracil and leucine. The cultures were then harvested and washed with synthetic medium containing 10% galactose and 1% raffinose. The cultures were then diluted to an OD₆₀₀ of ~0.4 in synthetic medium lacking uracil and leucine and containing 10% galactose and 1% raffinose. At various time points, cell growth was monitored by measuring the OD₆₀₀.

Acknowledgements

We thank William Merrick for purified rabbit eIF-2, Bryan Williams for eIF-2 α monoclonal antibody, Tom Dever for the yeast strain H17, Michael Katze and Nahum Sonenberg for useful suggestions, and Paul Stanton and Theresa Rowe for technical assistance. We also thank Bryan Williams, Bob Silverman and George Stark for careful readings of the manuscript, and Dorthy Herzberg for editorial assistance. This work was partly supported by grants CA-62220 and CA-68782 from the National Institutes of Health to G.C.S. and grant 133-BG1A from the American Heart Association, Northeast Ohio Chapter to R.C.P.

References

- Barber,G.N., Tomita,J., Garfinkel,M.S., Meurs,E., Hovanessian,A. and Katze,M.G. (1992) Detection of protein kinase homologues and viral RNA-binding domains utilizing polyclonal antiserum prepared against a baculovirus-expressed ds RNA-activated 68,000-Da protein kinase. *Virology*, **191**, 670-679.
- Benkirane,M., Neuvet,C., Chun,R.F., Smith,S.M., Samuel,C.E., Gagnol,A. and Jeang,K.T. (1997) Oncogenic potential of TAR RNA binding protein TRBP and its regulatory interaction with RNA-dependent protein kinase PKR. *EMBO J.*, **16**, 611-624.
- Bushman,J.L., Fojani,M., Cigan,A.M., Paddon,C.J. and Hinnebusch,A.G. (1993) Guanine nucleotide exchange factor for eukaryotic translation initiation factor 2 in *Saccharomyces cerevisiae*: interactions between the essential subunits GCD2, GCD6 and GCD7 and the regulatory subunit GCN3. *Mol. Cell. Biol.*, **13**, 4618-4631.
- Carpick,B.W., Graziano,V., Schneider,D., Maitra,R.K., Lee,X. and Williams,B.R.G. (1997) Characterization of the solution complex between the interferon-induced, double-stranded RNA-activated protein kinase and HIV-I trans-activating region RNA. *J. Biol. Chem.*, **272**, 9510-9516.
- Chong,K.L., Feng,L., Schappert,K., Meurs,E., Donahue,T.F., Friesen, J.D., Hovanessian,A.G. and Williams,B.R. (1992) Human p68 kinase exhibits growth suppression in yeast and homology to the translational regulator GCN2. *EMBO J.*, **11**, 1553-1562.
- Church,G.M. and Gilbert,W. (1984) Genomic sequencing. *Proc. Natl Acad. Sci. USA*, **81**, 1991-1995.
- Clemens,M.J. (1996) Protein kinases that phosphorylate eIF2 and eIF2B and their role in eukaryotic cell translational control. In Hershey,J.W.B., Mathews,M.B. and Sonenberg,N. (eds), *Translational Control*. Cold Spring Harbor Laboratory Press, Cold Spring Harbor, NY, pp. 139-172.
- Clemens,M.J. and Elia,A. (1997) The double-stranded RNA-dependent protein kinase PKR: structure and function. *J. Interferon Cytokine Res.*, **17**, 503-524.
- Clemens,M.J., Laing,K.G., Jeffrey,I.W., Schofield,A., Sharp,T.V., Elia,A., Matys,V., James,M.C. and Tilleray,V.J. (1994) Regulation of the interferon-inducible eIF-2 alpha protein kinase by small RNAs. *Biochimie*, **76**, 770-778.
- Colthurst,D.R., Campbell,D.G. and Proud,C.G. (1987) Structure and regulation of eukaryotic initiation factor eIF-2. Sequence of the site in the alpha subunit phosphorylated by the haem-controlled repressor and by the double-stranded RNA-activated inhibitor. *Eur. J. Biochem.*, **166**, 357-363.
- Cosentino,G.P., Venkatesan,S., Serluca,F.C., Green,S.R., Mathews,M.B. and Sonenberg,N. (1995) Double-stranded-RNA-dependent protein kinase and TAR RNA-binding protein form homo- and heterodimers *in vivo*. *Proc. Natl Acad. Sci. USA*, **92**, 9445-9449.
- Davies,M.V., Furtado,M., Hershey,J.W., Thimmapaya,B. and Kaufman, R.J. (1989) Complementation of adenovirus virus-associated RNA I gene deletion by expression of a mutant eukaryotic translation initiation factor. *Proc. Natl Acad. Sci. USA*, **86**, 9163-9167.
- De Haro,C., Mendez,R. and Santoyo,J. (1996) The eIF-2alpha kinases and the control of protein synthesis. *FASEB J.*, **10**, 1378-1387.

- Der, S.D., Yang, Y.L., Weissmann, C. and Williams, B.R. (1997) A double-stranded RNA-activated protein kinase-dependent pathway mediating stress-induced apoptosis. *Proc. Natl Acad. Sci. USA*, **94**, 3279–3283.
- Dever, T.E., Chen, J.J., Barber, G.N., Cigan, A.M., Feng, L., Donahue, T.F., London, I.M., Katze, M.G. and Hinnebusch, A.G. (1993) Mammalian eukaryotic initiation factor 2 alpha kinases functionally substitute for GCN2 protein kinase in the GCN4 translational control mechanism of yeast. *Proc. Natl Acad. Sci. USA*, **90**, 4616–4620.
- Feng, G.S., Chong, K., Kumar, A. and Williams, B.R. (1992) Identification of double-stranded RNA-binding domains in the interferon-induced double-stranded RNA-activated p68 kinase. *Proc. Natl Acad. Sci. USA*, **89**, 5447–5451.
- Galabru, J. and Hovanessian, A. (1987) Autophosphorylation of the protein kinase dependent on double-stranded RNA. *J. Biol. Chem.*, **262**, 15538–15544.
- Gatignol, A., Buckler, W.A., Berkhout, B. and Jeang, K.T. (1991) Characterization of a human TAR RNA-binding protein that activates the HIV-1 LTR. *Science*, **251**, 1597–1600.
- Green, S.R., Manche, L. and Mathews, M.B. (1995) Two functionally distinct RNA-binding motifs in the regulatory domain of the protein kinase DAI. *Mol. Cell. Biol.*, **15**, 358–364.
- Green, S.R. and Mathews, M.B. (1992) Two RNA-binding motifs in the double-stranded RNA-activated protein kinase, DAI. *Genes Dev.*, **6**, 2478–2490.
- Hershey, J.W.B. (1989) Protein phosphorylation controls translation rates. *J. Biol. Chem.*, **264**, 20823–20826.
- Hershey, J.W.B. (1991) Translational control in mammalian cells. *Annu. Rev. Biochem.*, **60**, 717–755.
- Hinnebusch, A.G. (1993) Gene-specific translational control of the yeast GCN4 gene by phosphorylation of eukaryotic initiation factor 2. *Mol. Microbiol.*, **10**, 215–223.
- Hovanessian, A.G. (1989) The double stranded RNA-activated protein kinase induced by interferon: dsRNA-PK. *J. Interferon Res.*, **9**, 641–647.
- Hovanessian, A.G. and Galabru, J. (1987) The double-stranded RNA-dependent protein kinase is also activated by heparin. *Eur. J. Biochem.*, **167**, 467–473.
- Ito, T., Jagus, R. and May, W.S. (1994) Interleukin 3 stimulates protein synthesis by regulating double-stranded RNA-dependent protein kinase. *Proc. Natl Acad. Sci. USA*, **91**, 7455–7459.
- Judware, R. and Petryshyn, R. (1991) Partial characterization of a cellular factor that regulates the double-stranded RNA-dependent eIF-2 alpha kinase in 3T3-F442A fibroblasts. *Mol. Cell. Biol.*, **11**, 3259–3267.
- Judware, R. and Petryshyn, R. (1992) Mechanism of action of a cellular inhibitor of the dsRNA-dependent protein kinase from 3T3-F442A cells. *J. Biol. Chem.*, **267**, 21685–21690.
- Katze, M.G. (1992) The war against the interferon-induced dsRNA-activated protein kinase: can viruses win? *J. Interferon Res.*, **12**, 241–248.
- Katze, M.G., Wambach, M., Wong, M.L., Garfinkel, M., Meurs, E., Chong, K., Williams, B.R., Hovanessian, A.G. and Barber, G.N. (1991) Functional expression and RNA binding analysis of the interferon-induced, double-stranded RNA-activated, 68,000-Mr protein kinase in a cell-free system. *Mol. Cell. Biol.*, **11**, 5497–5505.
- Kaufman, R.J. and Murtha, P. (1987) Translational control mediated by eucaryotic initiation factor-2 is restricted to specific mRNAs in transfected cells. *Mol. Cell. Biol.*, **7**, 1568–1571.
- Kaufman, R.J., Davies, M.V., Pathak, V.K. and Hershey, J.W. (1989) The phosphorylation state of eucaryotic initiation factor 2 alters translational efficiency of specific mRNAs. *Mol. Cell. Biol.*, **9**, 946–958.
- Kessler, S.P., Rowe, T.M., Blendy, J.A., Erickson, R.P. and Sen, G.C. (1998) A cyclic AMP response element in the angiotensin-converting enzyme gene and the transcription factor CREM are required for transcription of the mRNA for the testicular isozyme. *J. Biol. Chem.*, **273**, 9971–9975.
- Kibler, K.V., Shors, T., Perkins, K.B., Zeman, C.C., Banaszak, M.P., Biesterfeldt, J., Langland, J.O. and Jacobs, B.L. (1997) Double-stranded RNA is a trigger for apoptosis in vaccinia virus-infected cells. *J. Virol.*, **71**, 1992–2003.
- Koromilas, A.E., Roy, S., Barber, G.N., Katze, M.G. and Sonenberg, N. (1992) Malignant transformation by a mutant of the IFN-inducible dsRNA-dependent protein kinase. *Science*, **257**, 1685–1689.
- Kumar, A. et al. (1997) Deficient cytokine signaling in mouse embryo fibroblasts with a targeted deletion in the PKR gene: role of IRF-1 and NF-kappaB. *EMBO J.*, **16**, 406–416.
- Lee, K., Fajardo, M.A. and Braun, R.E. (1996) A testis cytoplasmic RNA-binding protein that has the properties of a translational repressor. *Mol. Cell. Biol.*, **16**, 3023–3034.
- Lee, S.B. and Esteban, M. (1994) The interferon-induced double-stranded RNA-activated protein kinase induces apoptosis. *Virology*, **199**, 491–496.
- Lee, S.B., Green, S.R., Mathews, M.B. and Esteban, M. (1994) Activation of the double-stranded RNA (dsRNA)-activated human protein kinase *in vivo* in the absence of its dsRNA binding domain. *Proc. Natl Acad. Sci. USA*, **91**, 10551–10555.
- Leonard, G.T. and Sen, G.C. (1997) Restoration of interferon responses of adenovirus E1A-expressing HT1080 cell lines by overexpression of p48 protein. *J. Virol.*, **71**, 5095–5101.
- Lengyel, P. (1993) Tumor-suppressor genes: news about the interferon connection. *Proc. Natl Acad. Sci. USA*, **90**, 5893–5895.
- Maran, A., Maitra, R.K., Kumar, A., Dong, B., Xiao, W., Li, G., Williams, B.R., Torrence, P.F. and Silverman, R.H. (1994) Blockage of NF-kappa B signaling by selective ablation of an mRNA target by 2–5A antisense chimeras. *Science*, **265**, 789–792.
- Marie, I., Blanco, J., Rebouillat, D., Hovanessian, A.G. (1997) 69-kDa and 100-kDa isoforms of interferon-induced (2'–5')oligoadenylate synthetase exhibit differential catalytic parameters. *Eur. J. Biochem.*, **248**, 558–566.
- McCormack, S.J., Thomis, D.C. and Samuel, C.E. (1992) Mechanism of interferon action: identification of a RNA binding domain within the N-terminal region of the human RNA-dependent P1/eIF-2 alpha protein kinase. *Virology*, **188**, 47–56.
- McCormack, S.J., Ortega, L.G., Doohan, J.P. and Samuel, C.E. (1994) Mechanism of interferon action. Motif I of the interferon-induced, RNA-dependent protein kinase (PKR) is sufficient to mediate RNA-binding activity. *Virology*, **198**, 92–99.
- McMillan, N.A., Carpick, B.W., Hollis, B., Toone, W.M., Zamanian-Daryoush, M. and Williams, B.R. (1995) Mutational analysis of the double-stranded RNA (dsRNA) binding domain of the dsRNA-activated protein kinase, PKR. *J. Biol. Chem.*, **270**, 2601–2606.
- Meurs, E.F., Galabru, J., Barber, G.N., Katze, M.G. and Hovanessian, A.G. (1993) Tumor suppressor function of the interferon-induced double-stranded RNA-activated protein kinase. *Proc. Natl Acad. Sci. USA*, **90**, 232–236.
- Mundschauf, L.J. and Faller, D.V. (1992) Oncogenic ras induces an inhibitor of double-stranded RNA-dependent eukaryotic initiation factor 2 alpha-kinase activation. *J. Biol. Chem.*, **267**, 23092–23098.
- Mundschauf, L.J. and Faller, D.V. (1994) Endogenous inhibitors of the dsRNA-dependent eIF-2 alpha protein kinase PKR in normal and ras-transformed cells. *Biochimie*, **76**, 792–800.
- Mundschauf, L.J. and Faller, D.V. (1995) Platelet-derived growth factor signal transduction through the interferon-inducible kinase PKR. Immediate early gene induction. *J. Biol. Chem.*, **270**, 3100–3106.
- Ortega, L.G., McCotter, M.D., Henry, G.L., McCormack, S.J., Thomis, D.C. and Samuel, C.E. (1996) Mechanism of interferon action. Biochemical and genetic evidence for the intermolecular association of the RNA-dependent protein kinase PKR from human cells. *Virology*, **215**, 31–39.
- Park, H. et al. (1994) TAR RNA-binding protein is an inhibitor of the interferon-induced protein kinase PKR. *Proc. Natl Acad. Sci. USA*, **91**, 4713–4717.
- Patel, R.C. and Sen, G.C. (1992) Identification of the double-stranded RNA-binding domain of the human interferon-inducible protein kinase. *J. Biol. Chem.*, **267**, 7671–7676.
- Patel, R.C., Stanton, P. and Sen, G.C. (1994) Role of the amino-terminal residues of the interferon-induced protein kinase in its activation by double-stranded RNA and heparin. *J. Biol. Chem.*, **269**, 18593–18598.
- Patel, R.C., Stanton, P., McMillan, N.M., Williams, B.R. and Sen, G.C. (1995) The interferon-inducible double-stranded RNA-activated protein kinase self-associates *in vitro* and *in vivo*. *Proc. Natl Acad. Sci. USA*, **92**, 8283–8287.
- Patel, R.C., Stanton, P. and Sen, G.C. (1996) Specific mutations near the amino terminus of double-stranded RNA-dependent protein kinase (PKR) differentially affect its double-stranded RNA binding and dimerization properties. *J. Biol. Chem.*, **271**, 25657–25663.
- Petryshyn, R.A., Ferrenz, A.G. and Li, J. (1997) Characterization and mapping of the double-stranded regions involved in activation of PKR within a cellular RNA from 3T3-F442A cells. *Nucleic Acids Res.*, **25**, 2672–2678.
- Proud, C.G. (1995) PKR: a new name and new roles. *Trends Biochem. Sci.*, **20**, 241–246.

- Rice,A.P., Duncan,R., Hershey,J.W. and Kerr,I.M. (1985) Double-stranded RNA-dependent protein kinase and 2–5A system are both activated in interferon-treated, encephalomyocarditis virus-infected HeLa cells. *J. Virol.*, **54**, 894–898.
- Romano,P.R., Green,S.R., Barber,G.N., Mathews,M.B. and Hinnebusch, A.G. (1995) Structural requirements for double-stranded RNA binding, dimerization and activation of the human eIF-2 alpha kinase DAI in *Saccharomyces cerevisiae*. *Mol. Cell. Biol.*, **15**, 365–378.
- Salzberg,S., Mandelboim,M., Zalcborg,M. and Shainberg,A. (1995) Interruption of myogenesis by transforming growth factor beta 1 or EGTA inhibits expression and activity of the myogenic-associated (2'–5') oligoadenylate synthetase and PKR. *Exp. Cell Res.*, **219**, 223–232.
- Samuel,C.E. (1993) The eIF-2 α protein kinases, regulators of translation in eukaryotes from yeasts to humans. *J. Biol. Chem.*, **268**, 7603–7606.
- Samuel,C.E., Duncan,R., Knutson,G.S. and Hershey,J.W. (1984) Mechanism of interferon action. Increased phosphorylation of protein synthesis initiation factor eIF-2 alpha in interferon-treated, reovirus-infected mouse L929 fibroblasts *in vitro* and *in vivo*. *J. Biol. Chem.*, **259**, 13451–13457.
- Sen,G.C. and Ransohoff,R.M. (1993) Interferon-induced antiviral actions and their regulation. *Adv. Virus Res.*, **42**, 57–102.
- Sikorski,R.S. and Heiter,P. (1989) A system of shuttle vectors and yeast host strains designed for efficient manipulation of DNA in *Saccharomyces cerevisiae*. *Genetics*, **122**, 19–27.
- Sonenberg,N. (1990) Measures and countermeasures in the modulation of initiation factor activities by viruses. *New Biol.*, **2**, 402–409.
- St. Johnston,D., Brown,N.H., Gall,J.G. and Jantsch,M. (1992) A conserved double-stranded RNA-binding domain. *Proc. Natl Acad. Sci. USA.*, **89**, 10979–10983.
- Williams,B.R.G. (1995) The role of the dsRNA-activated kinase, PKR, in signal transduction. *Semin. Virol.*, **6**, 191–202.
- Williams,B.R. (1997) Role of the double-stranded RNA-activated protein kinase (PKR) in cell regulation. *Biochem. Soc. Trans.*, **25**, 509–513.
- Wong,A.H., Tam,N.W., Yang,Y.L., Cuddihy,A.R., Li,S., Kirchhoff,S., Hauser,H., Decker,T. and Koromilas,A.E. (1997) Physical association between STAT1 and the interferon-inducible protein kinase PKR and implications for interferon and double-stranded RNA signaling pathways. *EMBO J.*, **16**, 1291–1304.
- Wu,S. and Kaufman,R.J. (1996) Double-stranded (ds) RNA binding and not dimerization correlates with the activation of the dsRNA-dependent protein kinase (PKR). *J. Biol. Chem.*, **271**, 1756–1763.
- Wu,S. and Kaufman,R.J. (1997) A model for the double-stranded RNA (dsRNA)-dependent dimerization and activation of the dsRNA-activated protein kinase PKR. *J. Biol. Chem.*, **272**, 1291–1296.
- Yang,Y.L., Reis,L.F., Pavlovic,J., Aguzzi,A., Schafer,R., Kumar,A., Williams,B.R., Aguet,M. and Weissmann,C. (1995) Deficient signaling in mice devoid of double-stranded RNA-dependent protein kinase. *EMBO J.*, **14**, 6095–6106.
- Yeung,M.C., Liu,J. and Lau,A.S. (1996) An essential role for the interferon-inducible, double-stranded RNA-activated protein kinase PKR in the tumor necrosis factor-induced apoptosis in U937 cells. *Proc. Natl Acad. Sci. USA*, **93**, 12451–12455.

Received February 4, 1998; revised May 21, 1998;
accepted June 4, 1998