FEBS Letters 443 (1999) 20–24 FEBS 21414

Stimulation of the catalytic activity of poly(ADP-ribosyl) transferase by transcription factor Yin Yang 1

Joachim Griesenbeck[1,a], Mathias Ziegler[a], Nikolai Tomilin[b], Manfred Schweiger[a], Shiao Li Oei[a,*]

[a]*Institut für Biochemie, Freie Universität Berlin-Dahlem, Thielallee 63, D-14195 Berlin, Germany*
[b]*Institute of Cytology, The Russian Academy of Sciences, Tikhoretskii Ave. 4, 194064 St. Petersburg, Russia*

Received 4 November 1998; received in revised form 11 December 1998

Abstract The transcriptional regulator Yin Yang 1 (YY1) has previously been demonstrated to physically interact with poly-(ADP-ribosyl) transferase (ADPRT). This nuclear enzyme catalyzes the synthesis of ADP-ribose polymers and their attachment to target proteins. It is reported here that YY1 associates preferably with the extensively auto(ADP-ribosyl)ated form of ADPRT, but not with deproteinized ADP-ribose polymers. In the presence of YY1 the catalytic rate of ADPRT is enhanced about 10-fold. This stimulation is in part due to modification of YY1, thus serving as a substrate of the reaction. In addition, automodification of ADPRT is also substantially increased. The activation by YY1 is most pronounced at low concentrations of ADPRT suggesting that the presence of YY1 may either facilitate the formation of catalytically active dimers of ADPRT or lead to the occurrence of active heterooligomers. The potential significance of these observations was verified by analyzing the activity of ADPRT in HeLa nuclear extracts. The endogenous enzyme exhibited an about 10-fold higher activity as compared to the isolated recombinant protein. It is likely that the heat-stable transcription factor YY1 contributed to the increased activity of ADPRT detected in the nuclear extracts, because heated extracts had a similar stimulatory effect on isolated ADPRT as isolated YY1 used at comparable concentrations. It is concluded that YY1 may be an important regulator of ADPRT and, therefore, could support the function of ADPRT to facilitate DNA repair.

1. Introduction

The transcription factor Yin Yang 1 (YY1) is a nuclear protein that has been described to be a regulator of polymerase II-dependent transcription. Different mechanisms have been implicated in the regulation of gene transcription by YY1. Depending on the context, YY1 was shown to either stimulate or repress gene expression (for reviews see [1,2]). YY1 was found to tightly associate with the enzyme poly-(ADP-ribosyl) transferase (ADPRT; EC 2.4.2.30) [3]. ADPRT is a nuclear protein which catalyzes the formation of poly- (ADP-ribose) chains using NAD^+ as a substrate. These polymers are covalently attached to specific acceptor proteins. Poly(ADP-ribosyl)ation appears to be involved in a number of fundamental processes including cell differentiation, neoplastic transformation, DNA repair, transcription and others (reviewed in [4]). The occurrence of DNA damage, especially single strand breaks, causes the initiation of the poly(ADP-ribosyl)ation reaction. Although the synthesized ADP-ribose polymers are primarily attached to the enzyme itself [5], other proteins may serve as acceptors as well. As potential target proteins of heteromodification histones, DNA polymerases, ligases, topoisomerases, and high and low mobility group proteins have been identified (reviewed in [4]). Among transcription factors TFIIF [6] and p53 [7] have been reported to be acceptors of poly(ADP-ribose). ADPRT has been implicated in the regulation of gene expression [8–12]. While in the absence of NAD this protein serves as a coactivator of activator-dependent transcription [10], initiation of poly(ADP-ribosyl)ation results in silencing of polymerase II-dependent transcription [11]. We have recently shown that YY1 may function as an acceptor of ADP-ribose polymers. In addition, the modification prevented the specific binding of YY1 to DNA [12].

In this study YY1 and ADPRT were investigated with regard to their direct functional interaction. YY1 served as a specific and efficient acceptor of poly(ADP-ribose). In the presence of YY1 the poly(ADP-ribosyl)ation reaction was substantially stimulated owing to both increased automodification of ADPRT and modification of YY1. Experiments using HeLa nuclear extracts indicated that YY1 may be a physiologically important activator of ADPRT.

2. Materials and methods

Reagents were purchased from Sigma unless otherwise noted. HeLa nuclear extracts were obtained from Promega. Reinforced nitrocellulose membrane (BA-S 85) was purchased from Schleicher and Schuell. [α-^{32}P]NAD^+ was supplied by NEN DuPont. All chemicals were of analytical grade.

2.1. Purification of recombinant proteins

After overexpression in *Escherichia coli* cells the human His-tagged ADPRT was purified as described previously [13]. Recombinant human His-tagged YY1 (plasmid pHisYY1) produced in *E. coli* cells was purified as described by Shy et al. [14].

2.2. Gel electrophoresis and electrophoretic transfer

Proteins were separated on 6×10 cm SDS-PAGE minigels according to Laemmli [15]. Electrotransfer of proteins onto nitrocellulose sheets was performed as described by Towbin et al. [16].

*Corresponding author. Fax: (49) (30) 8386509.
E-mail: lity@chemie.fu-berlin.de

[1]Present address: Stanford University, Medical Center, Department of Structural Biology, Stanford, CA 94305, USA.

Abbreviations: ADPRT, poly(ADP-ribosyl) transferase; BSA, bovine serum albumin; EDTA, ethylenediamine tetraacetic acid; PAG(E), polyacrylamide gel (electrophoresis); PAR, poly(ADP-ribose) polymers; SDS, sodium dodecyl sulfate; TCA, trichloroacetic acid; YY1, Yin Yang 1

PII: S0014-5793(98)01671-8

2.3. Blot overlay

Blot overlay with radiolabeled probes was performed as described previously [17]. Briefly, for radiolabeling purified His-tagged ADPRT (5 μg) was incubated in a total volume of 100 μl of 'binding buffer' (10 mM Tris-HCl, pH 8.0, 7 mM $MgCl_2$, 50 μM $ZnCl_2$) with 6 nM [α-^{32}P]NAD^+ (0.3 μCi/nmol) and 10 μg sonicated salmon sperm DNA (Boehringer Mannheim) for 30 min at 25°C. In the absence of supplementary unlabeled NAD^+ the reaction resulted in ^{32}P-labeled oligo(ADP-ribosyl)ated enzyme. To obtain the radioactively labeled poly(ADP-ribosyl)ated ADPRT, labeling was carried out as described above for 30 min at 25°C and the reaction was subsequently continued for a further 30 min with unlabeled NAD^+ at a final concentration of 1 mM. Residual [α-^{32}P]NAD^+ was removed by G50 gel filtration. After radiolabeling both oligo- and poly(ADP-ribosyl)ated ADPRT had the same specific radioactivity. For synthesis of ^{32}P-labeled poly(ADP-ribose) after the poly(ADP-ribosyl)ation reaction and TCA precipitation modified proteins were treated with 100 μg/ml of proteinase K in the presence of 0.1% SDS at 37°C for 1 h. ^{32}P-labeled ADP-ribose polymers were extracted with phenol/chloroform, precipitated with ethanol and dissolved in 10 mM Tris-HCl, pH 8.0, 1 mM EDTA. For blot overlay, proteins were electrophoretically separated in SDS-PAGs and transferred onto nitrocellulose. Transblotted proteins were renatured overnight in 'overlay buffer' (0.5% BSA, 0.25% gelatin, 0.2% Triton X-100, 50 mM Tris-HCl, pH 7.4, 5 mM β-mercaptoethanol) at 4°C. Incubation of the blots with radiolabeled probes was carried out in overlay buffer containing 250 mM NaCl for 2 h at 4°C. Blots were washed three times for 10 min with 10 mM Tris-HCl, pH 8.0, 150 mM NaCl, and 0.05% Tween-20 and then subjected to autoradiography.

2.4. Determination of ADPRT activity

Recombinant ADPRT in the absence or presence of different proteins or HeLa nuclear extract [18] as indicated in the legends was incubated in binding buffer containing 1% BSA. Reactions were started by the addition of [^{32}P]NAD^+ and 10 μg/ml sonicated salmon sperm DNA (Boehringer, Mannheim) and carried out at 25°C. Incubations were stopped by the addition of TCA to give a final concentration of 20%. After centrifugation TCA precipitates were washed with 5% TCA and ethanol. Relative incorporation of [^{32}P]ADP-ribose was determined by Cerenkov counting.

2.5. Poly(ADP-ribosyl)ation of YY1

Poly(ADP-ribosyl)ation reactions were carried out by incubation of purified recombinant ADPRT with the indicated proteins in the presence of ^{32}P-labeled NAD^+ under conditions indicated in the legends. Incubations were stopped by the addition of SDS-containing sample buffer. Proteins were separated by SDS-PAGE. After electrophoresis gels were stained with Coomassie blue and subsequently subjected to autoradiography.

3. Results

Interaction of ADPRT with partner proteins depends on the functional state of the enzyme, which can be simulated by varying the extent of auto(ADP-ribosyl)ation [17]. The specific association of transblotted potential partner proteins can be visualized in a blot overlay using two forms of radiolabeled automodified ADPRT carrying ADP-ribose polymers of different size. The ability of these two forms of ADPRT to interact with transblotted YY1 was tested. Oligo(ADP-ribosyl)ated ADPRT (Fig. 1, lane 1) with fewer than 20 ADP-ribose units per chain or poly(ADP-ribosyl)ated ADPRT (Fig. 1, lane 2) with polymer lengths of up to 200 ADP-ribose residues were incubated with transblotted YY1. Since equal amounts of enzyme carrying similar amounts of radioactivity were used, the results shown in Fig. 1, lanes 1 and 2, can be directly compared. It is obvious that the oligo(ADP-ribosyl)ated ADPRT, which tightly interacts with histones [17], had no affinity to transblotted YY1, while poly(ADP-ribosyl)ated ADPRT bound efficiently to YY1 (Fig. 1, lane 2). No association with YY1 was detectable if deproteinized ^{32}P-labeled poly(ADP-ribose) detached from the enzyme molecule (Fig. 1, lane 3) was used. This is in accordance with the observation that isolated polymers did not affect spe ific DNA-binding of YY1 [12]. These data suggest that poly(ADP-ribosyl)ated ADPRT interacts with YY1 primarily via protein-protein contacts. As opposed to YY1, p53 exerted a high affinity not only to poly(ADP-ribosyl)ated ADPRT, but also to isolated polymers (not shown), supporting a direct interaction of p53 with poly(ADP-ribose) polymers as has been suggested previously [19].

The enzymatic activity of ADPRT depends on the availability of DNA [20]. In the presence of small amounts of DNA (10 μg/ml), presumably insufficient to tightly bind both YY1 and ADPRT, YY1 was ADP-ribosylated, even though NAD^+ was added after a preincubation of 15 min (Fig. 2A, first lane). In contrast, modification of YY1, but not ADPRT, was virtually absent under these conditions, if the DNA concentration was raised to 80 μg/ml (Fig. 2A, third

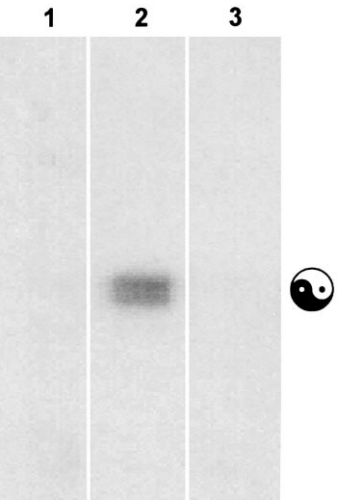

Fig. 1. Specific interaction of YY1 with poly(ADP-ribosyl)ated ADPRT. Recombinant YY1 was separated by SDS-PAGE and gels were transblotted onto nitrocellulose and subjected to blot overlay experiments as described in Section 2. Autoradiograms of blots after incubation with the additions indicated below are shown. Lane 1, ^{32}P-labeled oligo(ADP-ribosyl)ated ADPRT (50 000 cpm/μg, 50 000 cpm/ml); lane 2, ^{32}P-labeled poly(ADP-ribosyl)ated ADPRT (50 000 cpm/μg, 50 000 cpm/ml); lane 3, ^{32}P-labeled deproteinized poly(ADP-ribose) (100 000 cpm/ml). The position of YY1 is indicated by the yin-yang sign.

Table 1
Stimulation of ADPRT activity by nuclear proteins

	Relative activity of ADPRT
ADPRT	1
NE	9.8
$NE^{60°C}$	0
ADPRT+YY1	1.8
ADPRT+$NE^{60°C}$	2.4

Proteins were incubated at the concentrations given below with 1 μM of ^{32}P-labeled NAD^+ and 10 μg/ml sonicated DNA. ADPRT, 1.5 μg/ml; YY1, 1 μg/ml; HeLa nuclear extract (NE), 1.5 mg/ml. $NE^{60°C}$, prior to the reaction HeLa nuclear extract was incubated for 15 min at 60°C and then cooled to ambient temperature. Incubations were continued for 1 min and then stopped by TCA precipitation. Incorporated radioactivity was related to the value obtained for ADPRT in the absence of other proteins.

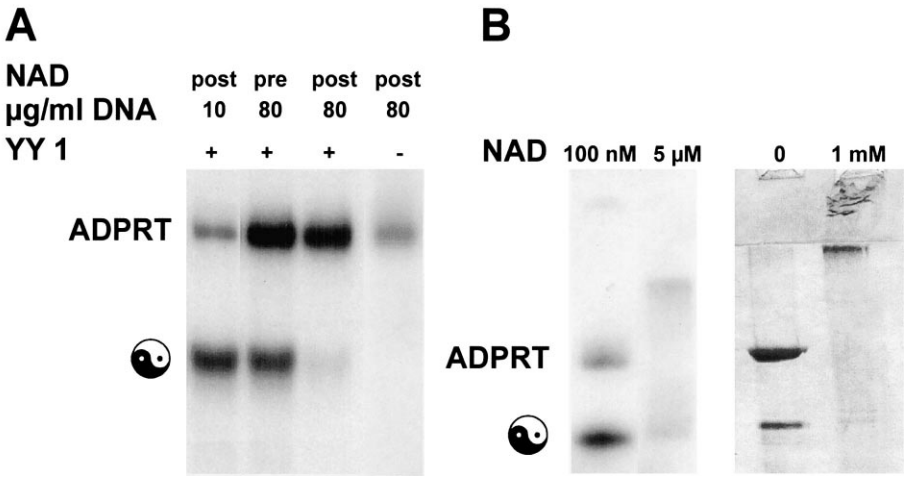

Fig. 2. Poly(ADP-ribosyl)ation of YY1. A: 100 ng of purified recombinant ADPRT were incubated in binding buffer with 50 ng of recombinant YY1 as indicated (+) and reactions were carried out in a final volume of 10 µl. For the first, third and last lanes, reactions were started by the addition of 100 nM ^{32}P-labeled NAD$^+$ (post). For the second lane, 100 nM ^{32}P-labeled NAD$^+$ was preincubated (pre) with proteins and the reaction then started by adding 80 µg/ml DNA. After 15 min incubations were stopped with SDS-containing sample buffer and proteins were separated by SDS-PAGE. An autoradiogram of the gel is shown. The positions of ADPRT and YY1 (yin-yang sign) are indicated. B, left panel: Purified recombinant ADPRT (10 ng) and YY1 (1 µg) were incubated. Reactions were started by the addition of 10 µg/ml DNA and ^{32}P-labeled NAD$^+$ as indicated. After 10 min incubations were stopped by the addition of SDS-containing sample buffer. Proteins were separated by SDS-PAGE and an autoradiogram of the gel is shown. Right panel: Purified recombinant ADPRT (4 µg) and YY1 (1 µg) were incubated in the absence or presence of 1 mM NAD$^+$ as indicated. Reactions were started by the addition of 100 µg/ml DNA. After 60 min incubations were stopped by the addition of SDS-containing sample buffer. Proteins were separated by SDS-PAGE and stained with Coomassie blue. The positions of ADPRT and YY1 (yin-yang sign) are indicated.

lane). This finding suggested that DNA binding of YY1 rendered this protein inaccessible to poly(ADP-ribosyl)ation. At high DNA concentrations (80 µg/ml) YY1 was still effectively poly(ADP-ribosyl)ated, but only if NAD$^+$ was added before the proteins had bound to DNA (Fig. 2A, second lane). Thus, for efficient heteromodification of the transcription factor the reaction needs to take place prior to DNA binding. Nevertheless, when YY1 is bound to DNA and thus inaccessible to modification, it is still an efficient stimulator of auto(ADP-ribosyl)ation of ADPRT (compare the last two lanes of Fig. 2A).

In Fig. 2B the poly(ADP-ribosyl)ation of YY1 is shown. In the presence of low concentrations of NAD$^+$ oligo(ADP-ribosyl)ation of ADPRT and YY1 occurred (Fig. 2B), while in the presence of 1 mM NAD$^+$ the majority of ADPRT and YY1 remained in the stack of the gel due to their modification with large poly(ADP-ribose) chains (Fig. 2B).

The stimulation of the catalytic activity of ADPRT by interaction with YY1 was analyzed by quantifying the amount of protein-associated poly(ADP-ribose) in the presence of varying amounts of the two proteins. Small amounts of purified recombinant ADPRT catalyzed the poly(ADP-ribosyl)ation reaction at a slow rate (Fig. 3). The addition of YY1 resulted in a dose-dependent rate enhancement approaching a maximum at about 10-fold stimulation (Fig. 3A). The occurrence of heteromodification and the maximal rate (for a given concentration of ADPRT) were always observed independently of the time point at which YY1 was added. That is, if the auto(ADP-ribosyl)ation reaction had been allowed to proceed in the absence of YY1, subsequent addition of saturating amounts of YY1 led always to a maximal stimulation of the reaction (not shown). In Fig. 3B poly(ADP-ribosyl)ation is represented as a function of the ADPRT concentration. Under the conditions used (0.5 µM NAD) a maximum of 5–6 pmol ADP-ribose units could be incorporated due to the limited substrate supply. In the absence of YY1 the initial nonlinear slow increase of incorporation is likely to reflect the requirement of ADPRT to dimerize for efficient catalysis [21–23]. If, however, YY1 (500 ng per 25 µl reaction) was added, a significant stimulation of ADP-ribose incorporation was observed (Fig. 3B). These results may indicate that heterooligomerization of ADPRT with YY1 may mimic the dimerization of the enzyme. Alternatively, YY1 may greatly facilitate the dimerization of ADPRT at low concentrations of the enzyme. Even though saturating amounts of YY1 (150 µg/ml) were used, ADPRT was still readily modified (Fig. 3C, lanes 3 and 4). Only at very low concentrations of ADPRT (1 ng/ml) ADP-ribosylation appeared to be limited to moderate heteromodification of YY1 (Fig. 3C, lane 2).

The significance of the observed influence of YY1 on the catalytic activity of ADPRT was tested in HeLa nuclear extracts. The contents of both YY1 and ADPRT in the extracts was estimated by immunoblot titrations with specific antibodies using the isolated recombinant proteins as standards (not shown).

The poly(ADP-ribosyl)ation activity of endogenous ADPRT in nuclear extracts of HeLa cells appears to be stimulated 10-fold as compared to the same concentration of isolated recombinant ADPRT (1.5 µg/ml) (Table 1). The addition of HeLa nuclear extract after heating to inactivate endogenous ADPRT (Table 1) resulted in a 2.4-fold stimulation of the poly(ADP-ribosyl)ation reaction catalyzed by the isolated recombinant enzyme (Table 1). Since YY1 activity is heat-stable [24], this enhancement is likely to be due to endogenous YY1. Moreover, the addition of the same amount of recombinant YY1 (about 1 µg/ml YY1) led to a 1.8-fold increase of the activity of the recombinant ADPRT (Table 1).

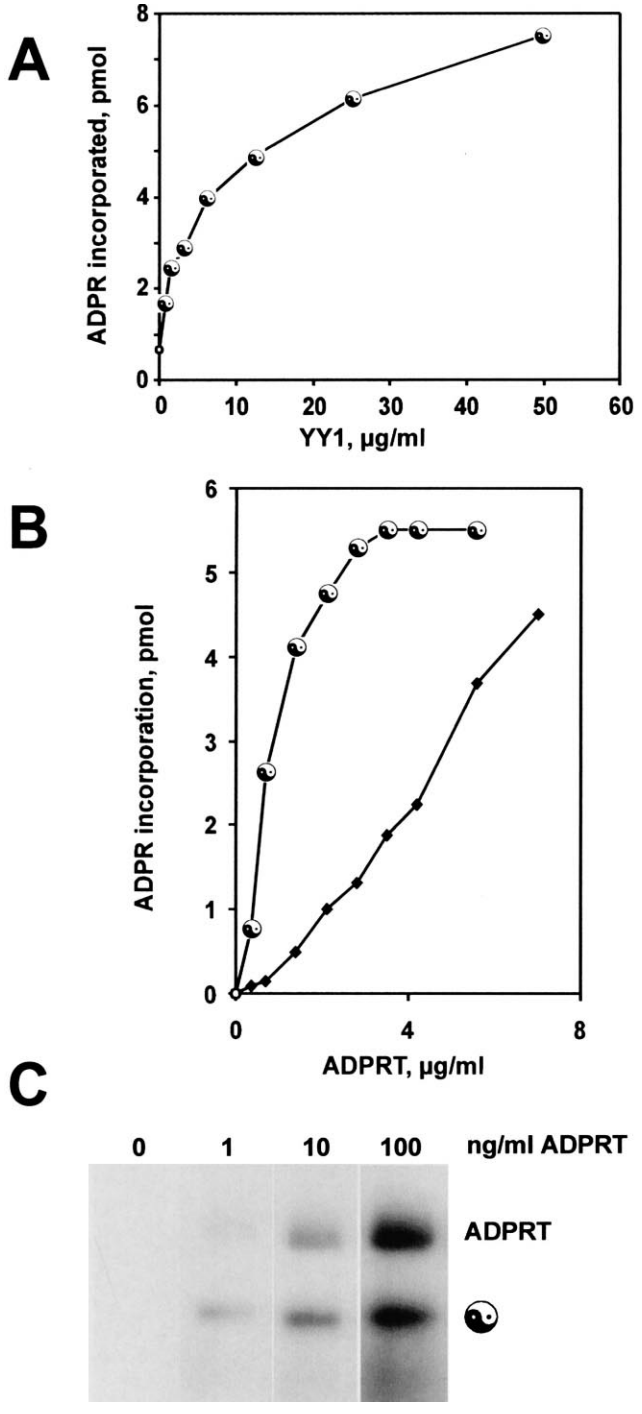

Fig. 3. Stimulation of ADPRT activity by YY1. All incubations were carried out in binding buffer containing 1% BSA and 10 μg/ml DNA in a final volume of 25 μl. [^{32}P]ADP-ribose incorporation was quantified by Cerenkov counting. A: Purified recombinant ADPRT (1 μg/ml) was incubated with increasing amounts of YY1 as indicated. Reactions were started by adding 1 μM of ^{32}P-labeled NAD$^+$. Incubations were stopped after 10 min by TCA precipitation of the proteins. B: Indicated amounts of purified recombinant ADPRT were incubated with no further addition (♦) or in the presence of 150 μg/ml purified recombinant YY1 (yin-yang sign). Reactions were started by adding 0.5 μM of ^{32}P-labeled NAD$^+$. Incubations were stopped after 10 min by TCA precipitation of the proteins. C: Purified recombinant YY1 (150 μg/ml) and increasing amounts of ADPRT as indicated were incubated with 100 nM ^{32}P-labeled NAD$^+$. Reactions were started by the addition of 10 μg/ml DNA and after 10 min incubations were stopped by the addition of SDS-containing sample buffer. Proteins were separated by SDS-PAGE. An autoradiogram of the gel is shown. The positions of ADPRT and YY1 (yin-yang sign) are indicated.
←

4. Discussion

This study provides insight into the functional consequences of the recently observed protein-protein interaction between the transcriptional regulator YY1 and ADPRT [3]. It is demonstrated here that YY1 is a substrate for poly(ADP-ribosyl)-ation and the extent of modification depends on both the amount of ADPRT and substrate present. The substantial stimulation of the catalytic activity of ADPRT by YY1, especially at low concentrations of ADPRT, may point to a function of YY1 that includes stabilization of ADPRT dimers or to the formation of heterooligomers of the two proteins. An important observation relating to this point is that, if previously bound to DNA, YY1 is inaccessible to ADP-ribosylation. Nevertheless, the activity of ADPRT is still substantially enhanced (Fig. 2A).

It has been noted before [17] that interaction of ADPRT with potential partner proteins is selective with regard to the extent of automodification of the enzyme. YY1 exhibited a pronounced preference to associate with the poly(ADP-ribosyl)ated, that is, the catalytically active form of the enzyme (Fig. 1). This is in contrast to histones which interact primarily with the oligo(ADP-ribosyl)ated ADPRT [17], although they also serve as acceptor proteins. On the other hand, p53 prefers to bind to ADP-ribose polymers, regardless of whether or not they are bound to ADPRT [19]. Thus, there are at least three different molecular entities (poly-, oligo(ADP-ribosyl)-ated ADPRT and ADP-ribose polymers) that appear to specifically interact with certain proteins. This observation may indicate a functional distinction between the partner proteins of ADPRT. For example, as opposed to YY1, histones have no significant stimulatory effect on the activity of ADPRT, although they are ADP-ribosylated. Moreover, other potential partners of ADPRT such as XRCC1 [25] or DNA-PK [26] inhibit ADPRT activity.

Transcription requiring YY1 as a cofactor is likely to be influenced by the activity of ADPRT. Recent reports suggest that YY1 may play an important role in development and differentiation and act as a negative regulator of cell growth with a possible involvement in tumor suppression [27]. The experiments presented here suggest an interaction between ADPRT and YY1 in the cell nucleus. It is of interest in this regard that isolated recombinant ADPRT exhibited a much lower catalytic activity as compared to the endogenous enzyme in HeLa extracts. It would appear that YY1 may significantly contribute to this stimulation (Table 1). Since it is a known function of ADPRT to support DNA repair, YY1 may also be involved in the regulation of this process by stimulating the catalytic activity of the enzyme. Besides the function of ADPRT as a coactivator of activator-dependent transcription [10], the catalytically active enzyme might also stimulate gene expression by indirect means. For example, YY1 is known to repress the transcription of specific genes including c-*fos* [28,29]. ADP-ribosylation would abolish the repression by preventing YY1 from binding to DNA. Therefore, such a mechanism could potentially apply to induce the expression of c-Fos.

Acknowledgements: This work was supported by joint grants of the Deutsche Forschungsgemeinschaft (Schw 532/4 and 436 RUS 113/126/1) and the Russian Fund for Fundamental Research (96-04-000416). We thank Drs. T. Shenk, T.C. Lee, W.M. Yang, and B. Lüscher for kindly providing plasmids for overexpression of recombinant YY1 and G. Buchlow for expert technical assistance.

References

[1] Hahn, S. (1992) Curr. Biol. 2, 152–154.
[2] Shrivastava, A. and Calame, K. (1994) Nucleic Acids Res. 22, 5151–5155.
[3] Oei, S.L., Griesenbeck, J., Schweiger, M., Babich, V., Kropotov, A. and Tomilin, N. (1997) Biochem. Biophys. Res. Commun. 240, 108–111.
[4] Oei, S.L., Griesenbeck, J. and Schweiger, M. (1997) Rev. Physiol. Biochem. Pharmacol. 131, 127–174.
[5] Ogata, N., Ueda, K., Kawaichi, M. and Hayashi, O. (1981) J. Biol. Chem. 256, 4135–4137.
[6] Rawling, J.M. and Alvarez-Gonzalez, R. (1997) Biochem. J. 324, 249–253.
[7] Wesierska-Gadeck, J., Schmid, G. and Cerni, C. (1996) Biochem. Biophys. Res. Commun. 224, 96–102.
[8] Matsui, T., Segall, J., Weil, P.A. and Roeder, R.G. (1980) J. Biol. Chem. 255, 11992–11996.
[9] Slattery, E., Dignam, J.D., Matsui, M. and Roeder, R.G. (1983) J. Biol. Chem. 258, 5955–5959.
[10] Meisterernst, M., Stelzer, G. and Roeder, R.G. (1997) Proc. Natl. Acad. Sci. USA 94, 2261–2265.
[11] Oei, S.L., Griesenbeck, J., Ziegler, M. and Schweiger, M. (1998) Biochemistry 37, 1465–1469.
[12] Oei, S.L., Griesenbeck, J., Schweiger, M. and Ziegler, M. (1998) J. Biol. Chem. 273, 31644–31647.
[13] Oei, S.L., Griesenbeck, J., Buchlow, G., Jorcke, D., Mayer-Kuckuk, P., Wons, T. and Ziegler, M. (1996) FEBS Lett. 397, 17–21.
[14] Shy, Y., Seto, E., Chang, L.-S. and Shenk, T. (1991) Cell 67, 377–388.
[15] Laemmli, U.K. (1970) Nature 227, 680–685.
[16] Towbin, H., Staehelin, T. and Gordon, J. (1979) Proc. Natl. Acad. Sci. USA 76, 4350–4354.
[17] Griesenbeck, J., Oei L, S., Mayer-Kuckuk, P., Ziegler, M., Buchlow, G. and Schweiger, M. (1997) Biochemistry 36, 7297–7304.
[18] Dignam, J.D., Lebowitz, R.M. and Roeder, R.G. (1983) Nucleic Acids Res. 11, 1475–1489.
[19] Malanga, M., Pleschke, J.M., Kleczkowska, H.E. and Althaus, F.R. (1998) J. Biol. Chem. 273, 11839–11843.
[20] Benjamin, R.C. and Gill, D.M. (1980) J. Biol. Chem. 255, 10502–10508.
[21] Bauer, P.I., Buki, K.G., Hakam, A. and Kun, E. (1990) Biochem. J. 270, 17–26.
[22] Mendoza-Alvarez, H. and Alvarez-Gonzalez, R. (1993) J. Biol. Chem. 268, 22575–22580.
[23] Panzeter, P.L. and Althaus, F.R. (1994) Biochemistry 33, 9600–9605.
[24] Usheva, A. and Shenk, T. (1994) Cell 76, 1115–1121.
[25] Masson, M., Niedergang, C., Schreiber, V., Müller, S., Ménissier-de Murcia, J. and de Murcia, G. (1998) Mol. Cell. Biol. 18, 3563–3571.
[26] Ruscetti, T., Lehnert, B.E., Halbrook, J., Trong, H.L., Hoekstra, M.F., Chen, D.J. and Peterson, S.R. (1998) J. Biol. Chem. 273, 14461–14467.
[27] Austen, M., Cerni, C., Lüscher-Firzlaff, J.M. and Lüscher, B. (1998) Oncogene 17, 511–520.
[28] Natesan, S. and Gilman, M.Z. (1993) Genes Dev. 7, 2497–2509.
[29] Gedrich, R.W. and Engel, D.A. (1995) J. Virol. 69, 2333–2340.