Domain-dependent Function of the rasGAP-binding Protein p62Dok in Cell Signaling*

Received for publication, June 22, 2000, and in revised form, October 3, 2000
Published, JBC Papers in Press, October 19, 2000, DOI 10.1074/jbc.M005504200

Zhou Songyang‡§, Yuji Yamanashi‡, Dan Liu‡, and David Baltimore¶

From the ‡Verna and Marrs McLean Department of Biochemistry and Molecular Biology, Baylor College of Medicine, Houston, Texas 77030, §Department of Oncology, Institute of Medical Science, University of Tokyo, Tokyo, Japan, and ¶California Institute of Technology, Pasadena, California 91125

p62Dok, the rasGAP-binding protein, is a common target of protein-tyrosine kinases. It is one of the major tyrosine-phosphorylated molecules in v-Src-transformed cells. Dok consists of an amino-terminal Pleckstrin homology domain, a putative phosphotyrosine binding domain, and a carboxyl-terminal tail containing multiple tyrosine phosphorylation sites. The importance and function of these sequences in Dok signaling remain largely unknown. We have demonstrated here that the expression of Dok can inhibit cellular transformation by the Src tyrosine kinase. Both the phosphotyrosine binding domain and the carboxyl-terminal tail of Dok (in particular residues 336–363) are necessary for such activity. Using a combinatorial peptide library approach, we have shown that the Dok phosphotyrosine binding domain binds phosphopeptides with the consensus motif of Y/MXXNL-phosphotyrosine. Furthermore, Dok can homodimerize through its phosphotyrosine binding domain and Tyr146 at the amino-terminal region. Mutations of this domain or Tyr146 that block homodimerization significantly reduce the ability of Dok to inhibit Src transformation. Our results suggest that Dok oligomerization through its multiple domains plays a critical role in Dok signaling in response to tyrosine kinase activation.

The PH domain is likely to be necessary for targeting Dok to the membrane, because PH domains preferentially bind phospholipids (7). The putative PTB domain is most homologous to the IRS-1 and FRS2/SNT-1 PTB domains, which recognize phosphotyrosine (pY)-containing sequences (8–11). In the case of SNT-1, its PTB domain can also bind distinct unphosphorylated sequences (11). It remains to be determined whether the Dok PTB domain can bind phosphopeptides and, if it does, whether it recognizes sequences distinct from those recognized by the IRS-1 and SNT-1 PTB domains. The multiple tyrosine residues in the Dok carboxyl-terminal tail are candidate sites for tyrosine kinases. When phosphorylated, they become potential docking sites for Src homology 2-containing proteins such as p120 rasGAP and Nck (5, 12). Consistent with this notion, both rasGAP and Nck have been shown to bind tyrosine-phosphorylated Dok (4, 13). Therefore, the carboxyl-terminal tail of Dok likely functions as a molecular platform for signal complex assembly induced by activated PTKs. However, the functional significance of the Dok PTB domain and the carboxyl-terminal tail has yet to be addressed.

Additional Dok homologues such as Dok-L (or Dok-3) and Dok-R (or Dok-2 and FRIP) have been identified recently (14–18), indicating that Dok and its homologues may constitute a growing family of proteins involved in a range of signaling pathways downstream of PTKs. However, the physiological roles of Dok and its homologues remain to be elucidated. Despite their structural similarities to the IRS-1 family molecules, Dok family proteins have different PTB domains and carboxyl-terminal tails that potentially mediate different signal responses by recruiting distinct sets of Src homology 2-containing signaling molecules. The mechanism by which Dok is phosphorylated and primed to form specific signaling complexes thus becomes a key issue in understanding Dok signaling. We have demonstrated here that the Dok PTB domain is a functional phosphotyrosine binding module that facilitates tyrosine phosphorylation and rasGAP binding of Dok. We have also found that Dok can inhibit Src-induced cellular transformation. This inhibitory effect depends on both the PTB domain and the carboxyl-terminal tail of Dok. Furthermore, we have shown that Dok can oligomerize via its PTB domain and Tyr146. This oligomerization appears critical for the inhibition of v-Src-induced transformation. These results suggest that the multiple domains of Dok are required for Dok signaling.

EXPERIMENTAL PROCEDURES

Cell Lines and Antibodies—NIH3T3 cells were maintained in Dulbecco’s modified Eagle’s media containing 10% calf serum (HyClone). The anti-hemagglutinin (HA) monoclonal antibody was purchased from Berkeley Antibody Company. The anti-His-tag, anti-rasGAP, and anti-phosphotyrosine monoclonal antibodies (4G10 and PY20) were purchased from Santa Cruz Biotechnology. Anti-Ras monoclonal antibody was from Upstate Biotechnology.

This paper is available on line at http://www.jbc.org

This is an Open Access article under the CC BY license.
DNA Constructs—The coding region of the murine Dok cDNA (4) tagged with the HA epitope was cloned into the HpaI site of the murine stem cell retroviral vector MSCVpuro (19). The HA epitope was joined to the 5' end of Dok cDNA by polymerase chain reaction (PCR) using the pfu polymerase (4). The carboxy-terminal truncated forms of Dok were similarly cloned. The Dok277, 313, 336, and 363 constructs encode amino acids 1–277, 313, 336, and 363, respectively. The PTB domain mutant Dok-AA (Arg207 and Arg208 to Ala) and the Y146F mutants (DokN-Y146F, Dok313-Y146F, and Dok363-Y146F) were generated by site-directed mutagenesis using PCR with the pfu polymerase. All constructs were confirmed by DNA sequencing. Sequences encoding wild-type and mutant Dok and Src were coexpressed with Src viruses followed by selection in G418-containing media. Two days after infection, Dok- or Src-expressing cells were selected in puromycin- or G418-containing media. Cells that divided NIH3T3 cells. We postulated that the biological effect of Dok is to inhibit cellular transformation by the Src-tyrosine kinase. The Dok PTB Domain and Carboxy-terminal Region Are Necessary for Its Inhibitory Effects—Because Dok consists of multiple domains, we went on to map the functional domains in Dok that are responsible for its inhibitory effects. Mutant Dok molecules that were HA epitope-tagged were generated and coexpressed with Src in NIH3T3 cells. We postulated that the multiple potential tyrosine phosphorylation sites within the Dok carboxy terminus might contribute to Dok inhibition of Src transformation. Consistent with this notion, deletion of the carboxy-terminal tail (Dok277) abolished the inhibitory activity of Dok (Fig. 1B). Using a panel of carboxy-terminal deletion constructs, we further defined the regions within the Dok carboxy terminus necessary for transformation inhibition. Although Dok363 still blocked Src transformation, Dok313 and Dok336 no longer retained the inhibitory abilities (Fig. 1B). These data indicate that the residues between 336 and 363 constitute a functional domain for the inhibitory action of Dok.

To determine the role of the amino-terminal portion, mutations were made in the putative PTB domain of Dok. On the basis of sequence homology with the IRS-1 PTB domain (4), amino acids Arg207 and Arg208 of Dok are predicted to coordinate phosphotyrosine binding. We therefore reasoned that mutation of Arg207 might block phosphotyrosine binding and thereby affect Dok function. Supporting an hypothesis, mutation of Arg207 and Arg208 to Ala residues (Dok-AA) eliminated the inhibitory function of Dok (Fig. 1B). These results strongly suggest that the Dok amino-terminal PTB domain represents a distinct regulatory domain of Dok that may associate with tyrosine-phosphorylated proteins.

Tyrosine Phosphorylation of Dok Mutant Proteins—Because tyrosine phosphorylation of Dok may be critical for its in vivo activities, we examined tyrosine phosphorylation of various HA-tagged Dok mutants in Src527F-transformed NIH3T3 fibroblasts. The different Dok proteins including the PTB domain mutant (Dok-AA) and all carboxy-terminal deletion mutants (Dok277, -313, -336, and -363) were expressed (Fig. 2, A and B). Western blots of whole cell lysates indicated that they were all tyrosine-phosphorylated (data not shown). Surprisingly, Western blots of anti-HA immunoprecipitates that were probed with anti-phosphotyrosine antibodies showed that even Dok277 (which lacks the carboxy-terminal region with its mu-
FIG. 1. Expression of Dok can inhibit Src transformation. Parental and HA-tagged Dok-expressing NIH3T3 fibroblast cells were infected with c-Src or Src527F retroviruses. The effect of various Dok mutants on Src transformation was studied using a focus formation assay in these cells. A, culture morphology of cells expressing c-Src alone (left) or both c-Src and Dok (right). B, comparison of the focus-forming abilities of parental NIH3T3 cells or those that coexpressed Dok variants with either c-Src (left) or Src527F (right). The numbers indicate the numbers of foci formed per 10⁴ Src viral particles. C, diagram of different Dok deletion mutants and mapping of domains that are required for Dok inhibitory function. +, inhibition; −, no inhibition.
multiple potential phosphorylation sites) was still tyrosine-phosphorylated (Fig. 2B), suggesting that a major tyrosine phosphorylation site is located in the amino-terminal domain of Dok. Therefore, changes in the gross tyrosine phosphorylation levels of various Dok mutants induced by the Src PTK may not account for the differences in their inhibitory abilities. However, phosphorylation of specific tyrosine sites on Dok may be necessary for inhibition of Src-mediated transformation.

Dok PTB Domain Binds to Specific Phosphopeptide Sequences—We have shown here that the Dok PTB domain (residues 125–264) is functional and necessary for Dok to inhibit Src-induced transformation, possibly through its interaction with phosphotyrosine-containing proteins. However, whether the Dok PTB domain does indeed bind specific phosphotyrosine-containing sequences remains to be determined. To this end, we used a combinatorial peptide library approach (see “Experimental Procedures”).

Briefly, GST fusion proteins containing either the Dok amino-terminal PH and PTB domains (GST-Dok) or the Dok PTB domain alone (GST-PTB) were purified and captured on GSH beads. The beads were then incubated with a soluble degenerate phosphopeptide library mixture to select for specific peptides that would bind to the PTB domains. The peptide library used had a sequence of MAXXXXNXpYYAKKK. The amino acid at position −3 to the phosphotyrosine was fixed (Asn), because PTB domains prefer turn-forming sequences (9, 22). The phosphopeptide mixtures that bound specifically to the GST alone revealed that the Dok PTB domain recognizes phosphopeptides with the unique motif of YMXNNXLpY (Fig. 3). At position pY-1, Leu was exclusively selected, indicating the importance of this residue. At position pY-6, hydrophobic amino acids Tyr, Met, and Phe were strongly selected. Similar preferences for hydrophobic residues at positions pY-5 to pY-8 have been reported for other PTB domains as well (8, 22).

A region within the Dok PTB domain (amino acids 204–232) is 41 and 52% identical to those of IRS-1 and SNT-1, respectively. The latter two PTB domains bind phosphopeptides with the consensus motif of NPXXpY (8–11). Importantly, two critical Arg residues (Arg207 and Arg222) that are known to mediate phosphotyrosine recognition in the IRS-1 PTB domain are conserved in the Dok PTB domain as well (Arg207 and Arg222). To test whether Arg207 also mediates the interaction between the Dok PTB domain and the phosphotyrosine moiety, we examined the Dok-AA mutant in which Arg207 was replaced with Ala. As predicted, this mutation eliminated the ability of the Dok PTB domain to bind phosphopeptides (data not shown). Combined with the observation that Dok-AA could no longer inhibit Src transformation, these data support the model that Dok function depends on the PTB domain. Furthermore, despite their similarities in the structural basis for phosphotyrosine recognition, the Dok PTB domain recognizes distinct sequences (NXpY) compared with the IRS-1 PTB domain (NPXXpY). Therefore, the Dok PTB domain may associate in vivo with a set of tyrosine-phosphorylated proteins distinct from those bound by IRS-1.

The Dok PTB Domain Mediates Phosphotyrosine-dependent, Homotypic Interactions of Dok—We have shown that the PTB domain recognizes specific tyrosine-phosphorylated sequences and is required for the inhibitory activity of Dok. It is likely that Dok may exert its inhibitory function by binding to specific phosphoproteins through the PTB domain. To further investigate the phosphoproteins that might associate with the PTB domain and the mechanism by which the PTB domain might
Domain-dependent Function of Dok

FIG. 4. The Dok PTB domain mediates oligomerization of Dok proteins. A, the amino-terminal domain of Dok binds to phospho-proteins at ~60 kDa. The Dok amino-terminal domain fusion protein (GST-DokN) or GST alone was incubated with lysates from Src527F-expressing NIH3T3 cells. The associated proteins were then detected by anti-phosphotyrosine antibodies and enhanced chemiluminescence. B, the amino-terminal domain of Dok interacts with different Dok mutant proteins. The GST-DokN fusion protein was incubated with lysates from cells expressing various HA-tagged Dok mutants. As a negative control, GST proteins were incubated with cell lysates from HA-Dok and Src527-coexpressing cells. Proteins that bound to GST or GST-DokN were visualized using an anti-HA monoclonal antibody and enhanced chemiluminescence. +, cross-reactive bands. C, the Dok PTB domain mediates homotypic interaction through Tyr146 of Dok. GST fusion proteins of DokN (GST-DokN), Dok PTB (GST-PTB), and Dok PTB mutant (GST-PTB AA) were incubated with lysates from cells coexpressing Src527F and HA-tagged Dok277 or Dok313 with and Tyr146 to Phe mutation (Dok313Y146F). Proteins that bound to GST fusion proteins were visualized using an anti-HA monoclonal antibody and enhanced chemiluminescence. D, the Dok PTB domain binds directly to the phosphorylated Tyr146 site. GST-PTB fusion proteins were incubated with purified His-tagged DokN (right) or c-Src-phosphorylated, His-tagged DokN (His-DokN) and DokN-Y146F (His-DokNY146F; left). Proteins that bound to the GST PTB domain were visualized using anti-His tag or anti-phosphotyrosine antibodies and enhanced chemiluminescence.

Dok Interacts with the Ras Pathway—Src is known to activate Ras proteins (24). We hypothesized that Tyr146 might be necessary for the homotypic interactions mediated by the Dok PTB domain. Consistent with our hypothesis, the HA-tagged Dok mutant with its Tyr146 mutated to Phe (Dok313-Y146F) failed to copurify with the GST-PTB domain, even though the GST-PTB domain fusion proteins were able to pull down the Dok amino-terminal region (Fig. 4C). These data strongly indicate a PTB domain-mediated, direct interaction between Dok molecules.

PTB domains have been shown to mediate both phosphotyrosine-dependent and -independent interactions. To confirm that Dok-PTB interactions through the PTB domain were direct and tyrosine phosphorylation-dependent, we generated the His-tagged Dok amino-terminal domain (His-DokN) and His-DokN with the Y146F mutation (His-DokN-Y146F) in E. coli. These fusion proteins were in vitro-phosphorylated using recombinant c-Src and incubated with GST-Dok PTB. As shown in Fig. 4D, only His-DokN was able to bind GST-Dok PTB, although His-DokN and His-DokN-Y146F were equally phosphorylated by c-Src. In addition, the GST-PTB domain failed to bind His-DokN in the absence of c-Src. These data demonstrate that the Dok PTB domain mediates phosphotyrosine-dependent homotypic interactions through residue Tyr146.

Tyr146 Is Important for Regulating Dok Activity—We showed that Dok363 was the shortest mutant to still retain the inhibitory activity (Fig. 1). To determine the role of Tyr146 on Dok function, Dok363 with the Tyr146 to Phe mutation (Dok363Y146F) was generated and compared with Dok363 for its effect on Src-induced transformation in NIH3T3 cells. Notably, the Tyr146 mutation significantly reduced the inhibitory activity of Dok363 (Fig. 5). Therefore, mutations (in either the PTB domain or Tyr146) that prevent Dok oligomerization also abrogated its inhibitory activity. These results indicate that the homotypic interaction through Tyr146 and the Dok PTB domain is necessary for Dok function.

Dok interacts with the Ras pathway—Src is known to acti-
Full-length Dok and Dok363 were able to associate with rasGAP; however, Dok336, Dok277, and the PTB domain mutant Dok-AA were impaired in their abilities to bind rasGAP. The inability to bind rasGAP may explain the failure of Dok336, Dok277, and Dok-AA to inhibit Src transformation (Fig. 1B). These results further imply that the PTB domain together with the carboxyl-terminal region of Dok may function in clustering and recruiting rasGAP to the site of action. We further speculated that the recruitment of rasGAP by Dok may lead to inhibition of Ras GTP loading. Consistent with this idea, the amount of Ras GTP (active Ras) was found to be significantly reduced in Src-transformed cells coexpressing Dok compared with Src-transformed cells (Fig. 6C).

**DISCUSSION**

We have shown that expression of Dok can block c-Src-induced transformation in NIH3T3 fibroblasts, indicating that Dok may negatively regulate signal pathways that are activated by PTKs. It is possible that Dok functions to recruit negative regulators of PTK cascades. For example, Csk family kinases are known to down-regulate c-Src activity by phosphorylating Tyr527 on c-Src (26, 27). Furthermore, Dok family proteins have been reported to associate directly with Csk (18, 28, 29). These data suggest that Dok may attenuate Src signaling by regulating Csk. However, this model was ruled out because Dok also inhibits transformation by activated Src (527F).

Alternatively, Dok may exert its inhibitory effects via the GTPase-activating protein rasGAP. Several lines of evidence support this hypothesis. First, Dok is a rasGAP-binding protein. Association of Dok with rasGAP can be readily detected during activation of PTKs such as Src, Abl, and the Eph receptor kinase (1–5). Among the seven potential tyrosine phosphorylation sites of Dok, five are predicted docking sites for the Src homology 2 domains of rasGAP (4, 5). The presence of multiple rasGAP binding sites on Dok suggests that Dok may provide the molecular platform necessary for high local rasGAP activity. In addition, the Ras pathway is activated by Src and required for Src transformation of fibroblast cells (30, 31). Dok may block Src transforming activity by interfering with Ras GTP loading and mitogen-activated protein kinase activation. Consistent with this model, we showed that Dok reduced Ras GTP loading and did not affect cellular transformation triggered by V12Ras, which is resistant to rasGAP activity. Furthermore, in correlation with their inability to inhibit Src-mediated transformation, Dok336, Dok277, and Dok-AA mutants failed to associate with rasGAP in Src527F-transformed cells. These observations suggest that one major function of Dok is to cluster rasGAP and thereby negatively regulate the Ras signal pathways. Increased PTK activity can result in hyperphosphorylation of Dok. In turn, more negative regulators such as rasGAP are recruited to the site of PTK activation to prevent Ras activation. Consistent with this model, it was demonstrated that Dok inhibits Ras activity in 293 cells (32). However, this model may not be universal, because Dok could inhibit rather than enhance rasGAP activity in some cells (33). One potential target of Dok is the mitogen-activated protein kinase pathway. We have shown recently that mitogen-activated protein kinase activity is up-regulated in B lymphocytes from Dok−/− mice (34). In addition, Dok is required to mediate the inhibitory effect of FcRIIB on Erk activation (35).

Furthermore, recent evidence has indicated that the Dok homologues Dok-R and Dok-L inhibit mitogen-activated protein kinase activation induced by the epidermal growth factor receptor and v-Abl (17, 36).

Our results have indicated that there are at least two independent functional domains in Dok, the carboxyl-terminal tail...
and the amino-terminal PH and PTB domains. We have shown that the carboxy-terminal tail of Dok is necessary for Dok in vivo activity. Dok relies on its carboxy-terminal tail to recruit Src homology 2-containing molecules such rasGAP and Nck (5, 12). Deletion of residues 278–481, which encompass the cluster of potential tyrosine phosphorylation sites, was found to impair the inhibitory ability of Dok. Deletional analysis has located a minimum region (residues 336–363) on Dok that is essential for its function. Interestingly, the sequence DPIY^{361}DEPE within this region is conserved among the Dok family proteins. Furthermore, Tyr^{361} is also the major docking site for Nck and rasGAP (4, 13). A recent study has demonstrated that Tyr^{361} plays a central role in Dok-mediated cell migration on insulin stimulation (13). It is therefore possible that Tyr^{361} is important for the inhibitory activity of Dok.

How does the amino-terminal domain of Dok modulate Dok activities? The PTB and PH domains of Dok-R were shown to be necessary for Dok-R phosphorylation by the epidermal growth factor receptor (36). Therefore, the amino-terminal PH and PTB domains may be important for efficient phosphorylation by protein-tyrosine kinases. In addition, phosphorylated Dok-AA proteins had significantly decreased binding with endogenous rasGAP, suggesting that an intact PTB domain may be required to phosphorylate the rasGAP binding sites on Dok or to recruit Dok to where rasGAP is localized.

Importantly, the amino-terminal region of Dok may be needed for oligomerization of Dok and may recruit other signaling proteins. Our data on the Dok PTB domain and Tyr^{146} support this model. We have shown that the Dok PTB domain is capable of binding to phosphorytrosine-containing sequences. Such binding is required for Dok function, because the Dok PTB domain mutant that failed to bind phosphopeptides also lost its ability to inhibit Src-mediated transformation. Furthermore, we have demonstrated that the PTB domain also mediates Dok oligomerization by binding to the phosphorylated Tyr^{146} site (located between the PH and PTB domains). The Dok homotypic interaction may cluster Dok molecules at sites of PTK activation. Consistent with the importance of oligomerization, the Y146F mutation significantly decreased Dok inhibitory activity. Alternatively, the Dok PTB domain may bind negative regulators such as phosphatase SHIP1 (23). Therefore, the Dok amino-terminal domain may not only facilitate tyrosine phosphorylation of Dok but also cluster Dok and its associated proteins at the location for negative signaling.

Acknowledgments—We thank Drs. Xiaohong Yang and Zongkai Li for technical assistance. We also thank the Department of Biology, Massachusetts Institute of Technology, for support.

REFERENCES
1. Ellis, C., Liu, X. Q., Anderson, D., Abraham, N., Veillette, A., and Pawson, T. (1991) Oncogene 6, 895–901
2. Koch, C. A., Moran, M. F., Anderson, D., Liu, X. Q., Mhamalou, G., and Pawson, T. (1992) Mol. Cell. Biol. 12, 1366–1374
3. Bhat, A., Johnson, K. J., Oda, T., Corbin, A. S., and Druker, B. J. (1998) J. Biol. Chem. 273, 32360–32368
4. Yamanashi, Y., and Baltimore, D. (1997) Cell 88, 205–211
5. Holland, S. J., Gale, N. W., Gish, G. D., Roth, R. A., Songyang, Z., Cantley, L. C., Henkemeyer, M., Yancopoulos, G. D., and Pawson, T. (1997) EMBO J. 16, 3677–3688
6. Carpino, N., Wisniewski, D., Strife, A., Marshak, D., Kobayashi, R., Stillman, B., and Clarkson, B. (1997) Cell 88, 197–204
7. Harlan, J. E., Hajduk, P. J., Yoon, H. S., and Fesik, S. W. (1994) Nature 371, 198–199
8. Wolf, G., Trub, T., Ottinger, E., Groninga, L., Lynch, A., White, M. F., Miyazaki, M., Lee, J., and Shoelson, S. E. (1995) J. Biol. Chem. 270, 27407–27410
9. Shoelson, S. E. (1997) Curr. Opin. Chem. Biol. 1, 237–244
10. Kouhara, H., Hadari, Y. R., Spivak-Kroizman, T., Schilling, J., Bar-Sagi, D., Lax, I., and Schlessinger, J. (1997) Cell 89, 693–702
11. Ong, S. H., Guy, G. R., Hadari, Y. R., Laks, S., Gotov, N., Schlessinger, J., and Lax, I. (2000) Mol. Cell. Biol. 20, 979–989
12. Songyang, Z., Shoelson, S. E., Chaudhuri, M., Gish, G., Pawson, T., Haser, W. G., King, F., Roberts, T., Ratzofsky, S., Lechleider, R. J., Neel, B. G., R. B. B., Fajardo, J. E., Chou, M. M., Hanafusa, H., Schaffhausen, B., and Cantley, L. C. (1993) Cell 72, 767–778
13. Noguchi, T., Matuzaki, T., Inagaki, K., Tsuda, M., Fukunaga, K., Kitamura, Y., Kitamura, T., Shii, K., Yamanashi, Y., and Kasuga, M. (1999) EMBO J. 18, 1714–1760
14. Nlms, K., Snow, A. L., Hu-Li, J., and Paul, W. E. (1998) Immunity 9, 13–24
15. Di Cristofano, A., Carpino, N., Dunant, N., Friedland, G., Kobayashi, R., Strife, A., Wisniewski, D., Clarkson, B., Pandolfi, P. P., and Resh, M. D. (1998) J. Biol. Chem. 273, 4827–4830
16. Jones, N., and Dumont, D. J. (1998) Oncogene 17, 1097–1108
17. Cong, F., Yuan, B., and Goff, S. P. (1999) Mol. Cell. Biol. 19, 8314–8325
18. Lemay, S., Davidson, D., Latour, S., and Veillette, A. (2000) Mol. Cell. Biol. 20, 2743–2754
19. Hawley, R. G., Lieu, F. H., Feng, A. Z., and Hawley, T. S. (1994) Gene Ther. 1, 158–168
20. Alexandropoulos, K., and Baltimore, D. (1996) Genes Dev. 10, 1341–1355
21. Pear, W. S., Nulan, G. P., Scott, M. L., and Baltimore, D. (1993) Proc. Natl. Acad. Sci. U. S. A. 90, 8392–8396
22. Songyang, Z. (1999) Prog. Biophys. Mol. Biol. 71, 359–372
23. Dunant, N. M., Wisniewski, D., Strife, A., Clarkson, B., and Resh, M. D. (2000) Cell Signal 12, 317–326
24. Songyang, Z., Carraway, K. L., Eck, M. J., Harrison, S. C., Feldman, R. A., Mohammadi, M., Schlessinger, J., Hubbard, S. R., Smith, D. P., Eng, C., et al. (1995) Nature 373, 536–539
25. Khoaravi-Far, R., Campbell, S., Rossman, K. L., and Der, C. J. (1998) Adv. Cancer Res. 72, 57–107
26. Okada, M., Nada, S., Yamanashi, Y., Yamamoto, T., and Nakagawa, H. (1991) J. Biol. Chem. 266, 24249–24252
27. Chow, L. M., and Veillette, A. (1995) Semin. Immunol. 7, 207–226
28. Darby, C., Geashien, R. L., and Schreiber, A. D. (1994) J. Immunol. 152, 5429–5437
29. Neet, K., and Hunter, T. (1995) Mol. Cell. Biol. 15, 4908–4920
30. Nori, M., Vogel, U. S., Gibbs, J. B., and Weber, M. J. (1991) Mol. Cell. Biol. 11, 2812–2818
31. DeChue, J. B., Zhang, K.,Redford, P., Vaas, W. C., and Lowy, D. R. (1991) Mol. Cell. Biol. 11, 2819–2825
32. Yoshida, K., Yamashita, Y., Miyazato, A., Ohyama, K., Kitanaka, A., Ikeda, U., Shimada, K., Yamanaka, T., Ozawa, K., and Mano, H. (2000) J. Biol. Chem. 275, 24945–24952
33. Kashige, N., Carpino, N., and Kobayashi, R. (2000) Proc. Natl. Acad. Sci. U. S. A. 97, 2093–2098
34. Yamanashi, Y., Tamura, T., Kanamori, T., Yamane, H., Nariuchi, H., Yamamoto, T., and Baltimore, D. (2000) Genes Dev. 14, 11–16
35. Tamir, I., Stolpa, J. C., Helgason, C. D., Nakamura, K., Brubns, P., Daeron, M., and Cambier, J. C. (2000) Immunity 12, 347–358
36. Jones, N., and Dumont, D. J. (1999) Curr. Biol. 9, 1057–1060