Characterization of Some Molecular Mechanisms Governing Autoactivation of the Catalytic Domain of the Anaplastic Lymphoma Kinase*

Carmen J. Tartari‡§,1, Rosalind H. Gunby†, Addolorata M. L. Coluccia†, Roberta Sottocornola†, Barbara Cimbro†, Leonardo Scapozza§, Arianna Donella-Deana§, Lorenzo A. Pinna§, and Carlo Gambacorti-Passerini**

From the ‡Department of Clinical and Prevention Medicine, University of Milano-Bicocca, via Cadore 48, Monza 20052, Italy, the §Department of Experimental Oncology, National Cancer Institute Foundation, 20133 Milan, the †School of Pharmaceutical Sciences, University of Lausanne, University of Geneva, CH-1211 Geneva, Switzerland, the ¶Department of Biological Chemistry, University of Padua, and Venetian Institute for Molecular Medicine, 35122 Padua, Italy, and the **Department of Internal Medicine, McGill University, Montreal H3A2T5, Canada

NPM/ALK is an oncogenic fusion protein expressed in ~50% of anaplastic large cell lymphoma cases. It derives from the t(2;5)(p23;q35) chromosomal translocation that fuses the catalytic domain of the tyrosine kinase, anaplastic lymphoma kinase (ALK), with the dimerization domain of the ubiquitously expressed nucleophosmin (NPM) protein. Dimerization of the ALK kinase domain leads to its autophosphorylation and constitutive activation. Activated NPM/ALK stimulates downstream survival and proliferation signaling pathways leading to malignant transformation. Herein, we investigated the molecular mechanisms of autoactivation of the catalytic domain of ALK. Because kinases are typically regulated by autophosphorylation of their activation loops, we systematically mutated (Tyr → Phe) three potential autophosphorylation sites contained in the “YYYYY” motif of the ALK activation loop, and determined the effect of these mutations on the catalytic activity and biological function of NPM/ALK. We observed that mutation of both the second and third tyrosine residues (YFF mutant) did not affect the kinase activity or transforming ability of NPM/ALK. In contrast, mutation of the first and second (FFY), first and third (FYF), or all three (FFF) tyrosine residues impaired both kinase activity and transforming ability of NPM/ALK. Furthermore, a DFF mutant, in which the aspartic residue introduces a negative charge similar to a phosphorylated tyrosine, possessed catalytic activity similar to the YFF mutant. Together, our findings indicate that phosphorylation of the first tyrosine of the YYYYY motif is necessary for the autoactivation of the ALK kinase domain and the transforming activity of NPM/ALK.

The anaplastic lymphoma kinase (ALK)2 is a receptor tyrosine kinase that belongs to the insulin receptor (IR) kinase subfamily of receptor tyrosine kinases (1). ALK is normally expressed in both the central and peripheral nervous systems during embryogenesis (2, 3). Expression of ALK is down-regulated before birth and in the adult ALK expression is restricted to specific cells in the central and peripheral nervous system (4). However, ALK is also aberrantly expressed in cancer as a result of chromosomal rearrangements involving the alv gene located on the 2p23 chromosome. ALK fusion proteins have been detected in anaplastic large cell lymphoma, diffuse large B-cell lymphoma, and in inflammatory myofibroblastic tumors (5–7).

The most commonly expressed ALK fusion protein in anaplastic large cell lymphoma is NPM/ALK, which derives from the t(2;5)(p23;q35) chromosomal translocation that fuses the kinase domain of ALK to the dimerization domain of nucleophosmin (NPM) (5). Dimerization of NPM/ALK stimulates autophosphorylation and activation of the ALK kinase domain (8, 9) and, subsequently, phosphorylation of other tyrosine residues within NPM/ALK that are important for the activation of oncogenic signaling pathways. Phosphorylated tyrosine residues act as docking sites for SH2 and PTB domains contained within signaling molecules or adaptor proteins (5, 6, 10–12). Several docking sites in NPM/ALK have already been described: pY156 for IRS-1, pY567 for SHC, and pY664 for phospholipase C-γ (13). The docking sites for other important downstream targets of NPM/ALK, the Janus tyrosine kinases and STATs, remain to be identified (14–16).

ALK, as a member of the IR kinase subfamily, is characterized by the “YYYYY” motif contained in the activation loop (A-loop). The IR kinase has been extensively studied and provides a model for the autoregulation of the kinase domain by autoinhibition (17). In the inactive conformation, the A-loop traverses the cleft between the N- and C-terminal lobes of the kinase domain occupying both the substrate and ATP binding sites. The second tyrosine in the YYYYY motif (Tyr-1162) interacts with the catalytic loop (Asp-1132) by H-bonds and

1 This work was supported by the Associazione Italiana per la Ricerca sul Cancro, Min. San. Ricerca Finalizzata (2003); the CNRS and Ministry of Education, University, and Research-COFIN and PRIN programs (2003, 2004, and 2005); Fondazione Cariplo; the European Union (Prokine Network 503467); the Canadian Fund for Innovation; and the National Cancer Institute of Canada. The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

2 The abbreviations used are: ALK, anaplastic lymphoma kinase; IR, insulin receptor; NPM, nucleophosmin; STAT, signal transducers and activators of transcription; IL-3, interleukin-3; FITC, fluorescein isothiocyanate; WT, wild type; MAPK, mitogen-activated protein kinase.
Autoactivation Mechanisms of the ALK Catalytic Domain

![FIGURE 1. NPM/ALK activation loop mutants. NPM/ALK schematic representation compared with ALK full-length protein is shown. The position of the Lys residue, the mutation of which causes catalytically inactive kinase (K210R), is also indicated. Details of the YXXXYY motif of the ALK A-loop are shown as well as the A-loop kinase (K210R), is also indicated. Details of the YXXXYY motif of the ALK A-loop are shown as well as the A-loop kinase (K210R), is also indicated.](image)

competes with peptide substrate for binding. Because Tyr-1162 is crucial for stabilizing the inactive conformation, it is not surprising that this second tyrosine is the preferred substrate of the IR kinase and is autophosphorylated first when the kinase undergoes autoactivation. Autophosphorylation of the A-loop tyrosines occurs in the order, second (Tyr-1162), first (Tyr-1158), and then third (Tyr-1163) (18). Sequential phosphorylation of the A-loop is accompanied by partial and then full activation of the kinase domain, when the A-loop is in the trisphosphorylated state. Conformational changes induced by phosphorylation leads to the opening of the A-loop, allowing access of ATP and substrates to the active site.

As ALK contains the YXXXYY motif in its A-loop (Tyr-1278, Tyr-1282, and Tyr-1283, respectively) it can be expected that ALK may be autoregulated in a similar fashion to the IR kinase. However, we have previously demonstrated that the amino acid sequence of the ALK A-loop differs significantly from the consensus sequence for the IR kinase family (19). In addition, we observed that purified ALK kinase domain preferentially phosphorylates the first tyrosine residue of the YXXXYY motif in synthetic peptides reproducing the ALK A-loop (19). These in vitro results suggest that the mechanism of autoregulation of ALK might differ from that of the IR kinase and that the first tyrosine in the A-loop may play a central role in its autoactivation. To test this hypothesis we assessed the role of the three tyrosine residues in the activation of full-length NPM/ALK (Tyr-338, Tyr-342, and Tyr-343). We generated mutants of NPM/ALK (Fig. 1) in which the A-loop tyrosine residues were replaced by either the neutral and non-phosphorylatable amino acid, phenylalanine, or by a negatively charged, acidic amino acid, aspartate. NPM/ALK mutants were stably expressed in BaF3 cells and the effect of these mutations on the NPM/ALK transforming abilities was determined.

**EXPERIMENTAL PROCEDURES**

**Mutagenesis and Generation of Stable BaF3 Cell Transfectants**—Full-length human NPM/ALK cDNA, subcloned in the expression vector pcDNA3, was kindly provided by Dr. S. W. Morris (Dept. of Pathology and Hematology-Oncology, St. Jude Children’s Research Hospital, Memphis, TN). Mutations in the NPM/ALK A-loop were generated using the QuikChangeXL site-directed mutagenesis kit (Stratagene, La Jolla, CA) according to the manufacturer’s instructions. The kinase-dead mutant was generated by mutating the residue Lys-210 to Arg (K210R) (9). The IL-3-dependent murine pro-B BaF3 cell line was transfected by electroporation of 5 × 10^6 cells with 10 μg of linearized plasmid DNA at 260 V and 960 microfarads using the Gene Pulser Electroporator (Bio-Rad, Hercules, CA). Transfected cells were selected by culturing in the presence of G418 (Sigma) at 800 μg/ml for 2 weeks. The expression of NPM/ALK protein was verified by immunoblotting. Single cell clones were obtained for each mutant by limiting dilution in 96-well plates, and clones with comparable expression levels of NPM/ALK were selected. Mutations were verified by reverse transcription-PCR on total RNA extracted from 10,000 cells and DNA sequencing as previously described (20). BaF3 cells transfected with empty vector or mutated NPM/ALK were maintained in RPMI 1640 (BioWhittaker, Walkersville, MD) supplemented with 10% fetal bovine serum, 100 units/ml penicillin, 100 μg/ml streptomycin, 2 mM L-glutamine, and 0.2% supernatant from Chinese hamster ovary cells expressing IL-3 growth factor. BaF3 cells expressing wild-type NPM/ALK were grown in the absence of IL-3. All cells were cultured in a humidified atmosphere at 37 °C and 5% CO₂.

**Immunoblotting Analysis**—Cells (2 × 10⁶) were collected by centrifugation, washed once with ice-cold phosphate-buffered saline, and lysed for 30 min in lysis buffer (25 mM Tris-HCl, pH 7.4, 150 mM NaCl, 1% Triton X-100, 5 mM EDTA, 5 mM EGTA, 1 mM NaVO₄, 1 mM dithiothreitol, 1 mM phenylmethylsulfonyl fluoride, 10 μg/ml of Pepstatin-A, leupeptin, and aprotonin). Lysates were clarified by centrifugation at 13,000 × g for 15 min at 4 °C. Protein concentration was determined in the supernatant using the Bio-Rad Protein Assay (Bio-Rad). Proteins (150 μg) were resolved by SDS-PAGE and transferred to a nitrocellulose membrane. NPM/ALK expression was detected using the anti-ALK#1 monoclonal antibody, kindly supplied by Dr. K. Pulford (Nuffield Department of Clinical Laboratory Sciences, John Radcliffe Hospital, Oxford, UK). Tyrosine-phosphorylated proteins were detected using the mouse monoclonal anti-phosphotyrosine 4G10 antibody (anti-PY) from Upstate Biotechnology (Lake Placid, NY). Signaling molecules were detected using anti-STAT3, anti-phospho-STAT3, anti-p70S6K, anti-phospho-
Autoactivation Mechanisms of the ALK Catalytic Domain

p70S6K, anti-MAPK, anti-phospho-MAPK, anti-Akt, anti-phospho-Akt, and anti-Bcl-xL antibodies from Cell Signaling Technology (Danvers, MA), and the anti-p27 antibody from Santa Cruz Biotechnology (Santa Cruz, CA). Protein loading was controlled using the anti-actin antibody (Sigma). The horseradish peroxidase-conjugated anti-mouse or anti-rabbit secondary antibodies were obtained from GE Healthcare (Princeton, NJ). Proteins were visualized by enhanced chemiluminescence (ECL) as recommended by the manufacturer (GE Healthcare).

Radioactive Kinase Assay—NPM/ALK was immunoprecipitated from 2 mg of protein from total cell lysate using the anti-ALKc antibody, kindly supplied by Dr. B. Falini (University of Perugia, Italy), and Gammabind™ G-Sepharose (GE Healthcare). Immunocomplexes were washed five times in lysis buffer and once in kinase buffer (25 mM Hepes, pH 7.0, 5 mM MgCl₂, 5 mM MnCl₂).

Phosphorylation of exogenous peptide substrate was measured by incubating immunocomplexes with kinase buffer, 1 mM dithiothreitol, 30 μM ATP, 1 μCi of [γ-32P]ATP, and 200 μM peptide substrate (ARDIYRASFFRKGGCAMLPVK) (19) at 30 °C for 15 min. The reaction was stopped by spotting the reaction mix onto P81 phosphocellulose paper (2 × 2 cm). Filters were washed three times for 10 min with 0.75% phosphoric acid and once with acetone for 5 min. After drying cpm values were measured by scintillation using the Wallac Betacounter System (PerkinElmer Life Sciences). Autophosphorylation of NPM/ALK was measured by incubating immunocomplexes with kinase buffer, 1 mM dithiothreitol, 30 μM ATP, and 10 μCi of [γ-32P]ATP at 30 °C for 15 min. The reaction was stopped by the addition of SDS-gel loading buffer and heating at 95 °C for 10 min. Samples were resolved by SDS-PAGE and visualized by autoradiography.

Proliferation Assay—Cells were washed twice in IL-3-free medium and plated (10,000 cells/well) in 96-well plates. At 24, 48, 72, and 96 h after IL-3 withdrawal, cells were labeled with 1 μCi per well of [3H]thymidine (GE Healthcare) for 8 h. Cells were harvested onto glass fiber filters (Printed Filtermat, PerkinElmer Life Sciences) and once in kinase buffer (25 mM Hepes, pH 7.0, 5 mM MgCl₂, 5 mM MnCl₂).

Annexin V Apoptosis Assay—Apoptosis in BaF3 cell transfecteds after 24, 48, and 72 h IL-3 withdrawal was detected using the Annexin V-FITC Assay kit (Bender Med System, Vienna, Austria) according to the manufacturer’s instructions. Briefly, BaF3 cells (1 × 10⁴) were incubated with Annexin V-FITC and propidium iodide for 10 min at room temperature. Samples were analyzed using Q-Cell software and FACSCalibur (BD Biosciences, Mountain View, CA).

Animal Studies—Female CD-1 nu/nu mice (7–9 weeks old) were supplied by Charles River (Calco, Lecco, Italy) and kept under standard laboratory conditions according to the local ethical guidelines. Mice were subcutaneously injected with BaF3-transfected cells (10 × 10⁶ cells/mouse) expressing different NPM/ALK mutants. Mice that developed tumors were sacrificed and tumor tissue was extracted and homogenized in 15 ml of RPMI medium. Cells were collected and lysed, and the expression of NPM/ALK protein was assessed by immunoblotting. Mutations were verified by reverse transcription-PCR and DNA sequencing.

RESULTS

In Vitro Kinase Activity of NPM/ALK Activation Loop Mutants—We systematically mutated tyrosine residues to phenylalanine in the YXXXY motif of the NPM/ALK A-loop (summarized in Fig. 1) and determined the effect of these mutations on ALK activity. The level of NPM/ALK tyrosine phosphorylation in BaF3-stable transfectants was assessed by anti-PY immunoblotting (Fig. 2A). The YFF mutant (Fig. 2A, lane 6) displayed a tyrosine phosphorylation level similar to WT NPM/ALK (Fig. 2A, lane 1). The FFY, FYF, and FFF mutants (Fig. 2A, lanes 7, 8, and 9, respectively) displayed a very low level of tyrosine phosphorylation that was only visible in an overexposed film (data not shown). The single mutants (Fig. 2A, lanes 3–5) were not tyrosine-phosphorylated, similar to the kinase-dead mutant, K210R (Fig. 2A, lane 2).
We assessed the ability of the NPM/ALK mutants to phosphorylate an exogenous peptide substrate (Fig. 2B). The YFF mutant displayed a phosphorylation activity comparable to WT NPM/ALK, whereas the FFY, FYY, and FFF mutants showed an impaired activity (35–50% of WT). The single mutants (FFY, FYY, and YYF) as well as the kinase-dead mutant were inactive. Similar results were also obtained in an in vitro radioactive autophosphorylation assay (Fig. 2C). In this semi-quantitative assay we observed that the activity of YFF mutant (Fig. 2C, lane 6) was comparable to WT NPM/ALK (Fig. 2C, lane 1), whereas the single mutants (FFY, FYY, and YYF) were inactive (Fig. 2C, lanes 3–5). The FFY and FYY mutants displayed reduced autophosphorylation activity (Fig. 2C, lanes 7 and 8, respectively). Interestingly, the autophosphorylation of FFF mutant appeared equivalent to WT NPM/ALK in this assay. This reflects autophosphorylation occurring outside the A-loop and is symptomatic of an active conformation of this mutant.

Together these data suggest that the presence of the first tyrosine alone in the YYYY motif of the A-loop is necessary for the ALK kinase domain to adopt a fully active conformation. Furthermore, the activity data of YYF and YYY mutants on one side (inactive despite the presence of the first tyrosine) as opposed to those of FFY, FYY, and FFF mutants on the other (active despite their lack of the first tyrosine) (Fig. 2, B and C) suggest that the second and third tyrosines may play a role in stabilizing an inactive conformation. The absence of all three tyrosine residues in the A-loop appears to cause the destabilization of the inactive conformation leading to a partially active conformation, whose activity does not require the phosphorylation of the first tyrosine.

**Stimulation of Downstream Signaling Pathways and Cellular Transformation by NPM/ALK Activation Loop Mutants**—To determine if the YFF mutant, in addition to possessing a fully activable kinase domain, was capable of activating downstream effectors of NPM/ALK in cells, we analyzed the phosphorylation of STAT3, p70S6K, MAPK, Akt, and p27 in total cell lysates after overnight IL-3 withdrawal. STAT3 phosphorylation has been associated with NPM/ALK activation in numerous studies and is crucial for NPM/ALK-mediated transformation (21–27). The p70S6K is a downstream target of the phosphatidylinositol 3-kinase/Akt pathway, which is also a key mediator of NPM/ALK transformation (28, 29). In addition the MAPK pathway has been implicated in NPM/ALK signaling (13, 30). Recent studies have shown that, at least in part, NPM/ALK mediates oncogenesis through phosphorylation/activation of Akt (12, 31). We observed that the YFF mutant was able to promote the phosphorylation of both STAT3 and p70S6K to an extent comparable to WT (Fig. 3A, panel i, lanes 5 and 1). Furthermore, the YFF mutant was able to induce phosphorylation of Akt and to reduce the expression of p27, similarly to NPM/ALK WT (Fig. 3A, panel ii, lanes 5 and 1). In contrast, other NPM/ALK mutants (including FFF) were defective in the activation of these pathways. Consistent with these data, only the YFF mutant promoted growth and survival of BaF3 cells in the absence of IL-3, an indication of cellular transformation (Fig. 3, A and C).

To determine if the A-loop mutants possessed in vivo transforming activity, nude mice were subcutaneously injected with BaF3 cells stably expressing similar levels of different NPM/ALK A-loop mutants. All mice injected with YFF-BaF3 cells developed tumors, although with a 7-day delay with respect to WT (Fig. 4A). Mice injected with FFY-BaF3 cells, FYY-BaF3 cells or FFF-BaF3 cells also developed tumors, albeit with a long delay (Fig. 4A) compared with WT. The FFF-positive tumors appeared after ~30–35 days, whereas the FFY- and FYY-positive tumors appeared after 50–70 days. All growing tumors were examined by Western blotting for the presence of NPM/ALK (Fig. 4B) and found to be positive. The kinetics of tumor
function of the first tyrosine of the NPM/ALK activation loop

We hypothesized that the first tyrosine can represent an important autophosphorylation site for the regulation of ALK activity. To test this hypothesis, we generated an A-loop mutant in which the first tyrosine was replaced by aspartic acid. Asparagine has a negatively charged side chain and therefore has been used to mimic phosphotyrosine (18). We generated a DFF mutant that mimics the NPM/ALK A-loop phosphorylated on the first tyrosine residue. As judged from in vitro autophosphorylation, the DFF mutant proved active (Fig. 5A, panel i, lane 3). In contrast, the FYF mutant, which has the potential to be phosphorylated on both the second and third tyrosines, was not (Fig. 2C, lane 3). These findings suggest that the conformation of the A-loop induced by the introduced negative charge in DFF, can allow the in vitro autophosphorylation of ALK. Similarly, when we analyzed the level of tyrosine phosphorylation in cells, DFF was phosphorylated to similar extent to YFF (Fig. 5A, panel ii, lanes 3 and 4, respectively). In addition, the DFF mutant was able to phosphorylate substrate (63% of WT) in a radioactive peptide kinase assay as the YFF mutant (Fig. 5A, panel iii). These results suggest that in cells the DFF mutant can mimic the YFF mutant resulting in phosphorylated NPM/ALK. Therefore, the negative charge of the aspartic residue can correctly mimic a phosphorylated tyrosine, causing the A-loop to adopt an open/active conformation as seen in the YFF mutant and WT NPM/ALK.

The ability of the DFF mutant to activate anti-apoptotic pathways (Fig. 5, B and C) was also assessed. The annexin V assay was performed on different mutants after IL-3 withdrawal. Interestingly, the DFF mutant displayed a significant (p value = 0.027) level of protection from apoptosis at 48 h compared with the kinase-dead mutant (Fig. 5B). A key mediator of NPM/ALK induced survival is the anti-apoptotic protein, Bcl-xL (32). After 48 h of IL-3 withdrawal we performed an immunoblotting analysis with the anti-Bcl-xL antibody. The DFF mutant (Fig. 5C, lane 2) displayed Bcl-xL expression levels comparable to YFF and WT NPM/ALK (Fig. 5C, lanes 3 and 1, respectively), in agreement with the annexin V results (Fig. 5B).

The FYF mutant was also used as a control of the DFF one. Kinase assay showed that FYF displayed in vitro kinase activity (Fig. 5A, panel i, lane 5 and panel iii). This is likely the result of a structural destabilization of the A-loop resulting in an open/active conformation. However, the FYF mutant was not able to be phosphorylated in cells (Fig. 5A, panel ii), did not induce Bcl-xL, and could not protect cells from apoptosis (Fig. 5, B and C).

We also assessed the ability of the DFF mutant to promote growth of BaF3 cells in the absence of IL-3 (Fig. 6A). In contrast to the YFF mutant, the DFF mutant did not support IL-3-independent growth of BaF3 cells as the FYF mutant. We observed that the DFF mutant (Fig. 6B, lane 4) was unable to phosphorylate the downstream effectors STAT3 and p70S6K similarly to the FYF and K210R mutants (Fig. 6B lanes 5 and 2, respectively). In addition, p27 was down-regulated in cells expressing NPM/ALK WT and YFF (Fig. 6B lanes 1 and 3) but not in cells expressing DFF or FYF mutants (Fig. 6B, lanes 4 and 5, respectively). Together, these results suggest that introducing a negative charge to activate the kinase is sufficient for inducing some downstream signaling such as induction of Bcl-xL, and protection from apoptosis, but not others such as STAT3 phosphorylation, which may require direct phosphorylation of this residue.

To assess if the first tyrosine is a docking site for signaling molecules involved in proliferative pathways a co-immunoprecipitation with the anti-ALKc antibody was performed (Fig. 6C). Interestingly, the DFF mutant did not co-immunoprecipitate with STAT3 (Fig. 6C, lane 3) in contrast to WT NPM/ALK and the YFF mutant, suggesting that the first tyrosine might play an important role in the interaction of NPM/ALK and STAT3.

DISCUSSION

The human genome contains 90 tyrosine kinase genes encoding 58 receptor tyrosine kinases grouped into 20 subfamilies and 32 non-receptor tyrosine kinases divided into 10 subfamilies (1, 33). Tyrosine phosphorylation is essential for the autoactivation of the majority of these kinases and the stimulation of their downstream signaling pathways. The activation of
Autoactivation Mechanisms of the ALK Catalytic Domain

**FIGURE 5. The catalytic activity and anti-apoptotic activity of the DFF NPM/ALK activation loop mutant.**

A, NPM/ALK immunoprecipitated from stably transfected BaF3 cells expressing WT (lane 1), kinase-dead (K210R, lane 2), or the DFF, YFF, and FFF A-loop mutants (lanes 3–5, respectively) was assessed for kinase activity. i, autophosphorylation was stimulated in presence of [γ-32P]ATP. Proteins were resolved by SDS-PAGE and visualized by autoradiography (first panel), NPM/ALK loading was controlled by immunoblotting with the anti-ALK#1 antibody (second panel). ii, the level of tyrosine phosphorylation inside cells was also assessed by anti-phosphotyrosine immunoblotting (first panel), NPM/ALK loading was controlled by immunoblotting with the anti-ALK#1 antibody (second panel). Arrowheads indicate NPM/ALK protein. iii, the activity of immunoprecipitated NPM/ALK mutants against exogenous substrate was assessed in the in vitro radioactive peptide kinase assay. The 32P-labeled peptide was quantified by scintillation. The graph shows the normalized versus WT cpm values (mean ± S.D.; n = 3) of a single experiment, representative of three independent repeats. B, annexin V apoptosis assay was performed on different A-loop mutants after 24, 48, and 72 h of IL-3 withdrawal. The graph shows the percentage of non-apoptotic (annexin negative) cells (mean ± S.E.; n = 3) and is representative of three independent repeats. C, activation of anti-apoptotic signaling pathways was assessed in total cell lysates. Anti-Bcl-xL immunoblotting was performed after 48 h of IL-3 withdrawal. Protein loading was controlled by anti-actin immunoblotting.

downstream pathways is important for cellular processes in both normal and pathological conditions (34–37).

Here, we assessed the role of potential autophosphorylation sites in the NPM/ALK A-loop in the autoactivation of the kinase domain. We demonstrated that the first tyrosine is necessary for triggering the kinase activity of NPM/ALK and for stimulating its downstream signaling pathways, as demonstrated by the YFF mutant. This function of the first tyrosine is likely to be mediated by its phosphorylation, considering its unique susceptibility to ALK-catalyzed phosphorylation in vitro (19) and the cellular phosphorylation of the YFF mutant (Fig. 2A), at variance with all other mutants. In addition, the introduction of a negative charge at the position of the first tyrosine in the DFF mutant led to autophosphorylation in vitro and tyrosine phosphorylation in cells similar to that of the YFF mutant (Fig. 5A). This finding suggests that the aspartic acid residue is able to mimic a phosphorylated tyrosine residue and induce conformational changes in the A-loop that stabilize an open/active conformation. In accordance with our results, phosphopeptide mapping of NPM/ALK derived from SUDHL1 and Karpas cell lines has identified four ALK phosphopeptides containing the YXXXXY motif of the A-loop: all four peptides displayed phosphorylation of the first tyrosine in the YXXXXY motif, while only one peptide was phosphorylated on the second tyrosine, and none were phosphorylated of the third tyrosine residue (38). These results suggest that for the ALK kinase the order of tyrosine phosphorylation inside the A-loop could be first, second, and third.

The presence of the first tyrosine is not a sufficient condition for activity, however, as disclosed by the failure of the mutants YFY and YFF to undergo autophosphorylation as well as phosphorylate the specific peptide substrate in vitro (Fig. 2, B and C). These findings indicate that the fully open/active conformation of the A-loop cannot be stabilized in these mutants. It is possible that the conformation of the A-loop in these mutants does not render the first tyrosine susceptible to autophosphorylation, suggesting a negative effect of the second and third residues on ALK activation. Alternatively, the inactivity of these mutants might reflect the inability of the first tyrosine, once phosphorylated in YFY and YFF contexts, to sustain an active conformation.

The FYY, FYF, and FFF mutants, whose cellular phosphorylation levels and biological function are severely impaired (Fig. 2A), are nevertheless catalytically active in vitro (Fig. 2, B and C). These findings are consistent with a partially active conformation of the A-loop in these mutants, which under in vitro experimental conditions can be pushed toward a more active conformation, whereas in the cellular context a more inactive conformation is adopted. The observation that these mutants are capable of developing tumors in vivo, albeit with delayed kinetics (Fig. 4), despite such low catalytic activity in cells, may reflect the potency of NPM/ALK as an oncogene or may possibly be attributed to the accumulation of other oncogenic mutations.

Our results suggest that ALK is characterized by a different mechanism of autoactivation from that of the IR kinase. In fact, assuming that the starting point of trans-phosphorylation is the existence for a short period of time of a non-phosphorylated protein in the active conformation, then, based on the models of ALK kinase domain and three-dimensional structure of IR kinase, it is plausible that the first tyrosine is phosphorylated and the most exposed one in the inactive conformation. The second tyrosine is more prone to cis-phosphorylation. In the active conformation, it is also conceivable, looking at the surroundings of the first tyrosine, that it can stabilize the active conformation by forming H-bonds with neighbor residues, which differ from those present in the IR kinase.
In addition to its crucial role in the autoactivation of NPM/ALK, the first tyrosine residue in the XXXXY motif might also be directly involved in the activation of downstream signaling pathways. Our data demonstrate that cells expressing the DFF mutant were partially protected from apoptosis (Fig. 5, B and C), although unable to proliferate in the absence of IL-3 (Fig. 6A). Our results also show that the first tyrosine, which remains exposed in the modeled ALK-active conformation, may be involved in the docking and activation of STAT3 (Fig. 6C).

Investigating the role of tyrosine residues of the NPM/ALK A-loop has improved our knowledge of the mechanisms regulating the autoactivation of ALK kinase domain. We have demonstrated that phosphorylation of the first tyrosine plays a crucial role during autoactivation of NPM/ALK and may also mediate the activation of downstream pathways involved in cellular proliferation.

Acknowledgments—We are grateful to Dr. Karen Pulford (Nuffield Department of Clinical Laboratory Sciences, John Radcliffe Hospital, Oxford, UK) for monoclonal anti-ALK#1 antibody and Prof. Brunangelo Falini (University of Perugia, Italy) for polyclonal anti-ALKc antibody. We also thank Dr. Oriano Marin (Dept. of Biochemistry, University of Padua, and Venetian Institute for Molecular Medicine, Padua, Italy) for the synthesis of the peptide and Dr. Loredana Cleris for in vivo experiments (Dept. of Experimental Oncology, Foundation National Cancer Institute, Milan).

REFERENCES
1. Manning, G., Whyte, D. B., Martinez, R., Hunter, T., and Sudarsanam, S. (2002) Science 298, 1912–1934
2. Hurley, S. P., Clary, D. O., Copie, V., and Lefcort, F. (2006) J. Comp. Neurol. 495, 202–212
3. Vernerossen, E., Khoo, N. K., Henriksson, M. L., Roos, G., Palmer, R. H., and Hallberg, B. (2006) Gene Expr. Patterns 6, 448–461
4. Pulford, K., Morris, S. W., and Turturro, F. (2004) J. Cell Physiol. 199, 330–358
5. Morris, S. W., Kirstein, M. N., Valentine, M. B., Dittmer, K. G., Shapiro, D. N., Saltman, D. L., and Look, A. T. (1994) Science 263, 1281–1284
6. Cook, J. R., Dehner, L. P., Collins, M. H., Ma, Z., Morris, S. W., Coffin, C. M., and Hill, D. A. (2001) Am. J. Surg. Pathol. 25, 1364–1371
7. Rudzki, Z., Rucinska, M., Jurczak, W., Skotnicki, A. B., Maramorosz-Kurianowicz, M., Mruk, A., Pirog, K., Utech, G., Bodzioch, P., Srebro-Statyczk, M., Wlodarska, I., and Stachura, J. (2005) Pol. J. Pathol. 56, 37–45
8. Cordell, J. L., Pulford, K. A. F., Bigerna, B., Roncador, G., Banham, A., Colombo, E., Pelicci, P. G., Mason, D. Y., and Falini, B. (1999) Blood 93, 632–642
9. Bischof, D., Pulford, K., Mason, D. Y., and Morris, S. W. (1997) Mol. Cell Biol. 17, 2312–2325
10. Coluccia, A. M., Gunby, R. H., Tartari, C. J., Scapozza, L., Gambacorti-Passerini, C., and Passoni, L. (2005) Expert Opin. Ther. Targets 9, 515–532
11. Pulford, K., Lamant, L., Espinos, E., Jiang, Q., Xue, L., Turturro, F., Delsol, G., and Morris, S. W. (2004) Cell Mol. Life Sci. 61, 2939–2953
12. Bai, R. Y., Ouyang, T., Miething, C., Morris, S. W., Peschel, C., and Duyster, J. (2000) Blood 96, 4319–4327
13. Bai, R. Y., Dieter, P., Peschel, C., Morris, S. W., and Duyster, J. (1998) Mol. Cell Biol. 18, 6951–6961
14. Nieborowska-Skorska, M., Slupianek, A., Xue, L., Zhang, Q., Raghunath, P. N. H., Hosier, G., Wasik, M. A., Morris, S. W., and Skorski, T. (2001) Cancer Res. 61, 6517–6523
15. Lai, R., Rassidakis, G. Z., Lin, Q., Atwell, C., Medeiros, L. J., and Amin, H. M. (2005) Hum. Pathol. 36, 939–944
16. Amin, H. M., Lin, Q., and Lai, R. (2006) Lab. Invest. 86, 417–419
17. Hubbard, S. R. (2002) Front. Biosci. 7, d330–d340
18. Zhang, B., Tavare, J. M., Ellis, L., and Roth, R. A. (1991) J. Biol. Chem. 266, 990–996
19. Donella-Deana, A., Marin, O., Cesaro, L., Gunby, R. H., Ferrarese, A., Coluccia, A. M., Tartari, C. J., Mologni, L., Scapozza, L., Gambacorti-Passerini, C., and Pinna, L. A. (2005) Biochemistry 44, 8533–8542
20. Gunby, R. H., Cazzaniga, G., Tassi, E., Le Coutre, P., Pogliani, E., Specchia, G., Biondi, A., and Gambacorti-Passerini, C. (2003) Haematologica. 88, 408–415
21. Chiarle, R., Simmons, W. J., Cai, H., Dhall, G., Zamo, A., Raz, R., Karras, J. G., Levy, D. E., and Inghirami, G. (2005) Nat. Med. 11, 623–629
22. Kasprzycka, M., Marzec, M., Liu, X., Zhang, Q., and Wasik, M. A. (2006) Proc. Natl. Acad. Sci. U. S. A. 103, 9964–9969
23. Khoury, J. D., Medeiros, L. J., Rassidakis, G. Z., Yared, M. A., Tsioli, P., Leventaki, V., Schmitt-Graeff, A., Herling, M., Amin, H. M., and Lai, R. (2003) Clin. Cancer Res. 9, 3692–3699
Autoactivation Mechanisms of the ALK Catalytic Domain

24. Lai, R., Rassidakis, G. Z., Medeiros, L. J., Ramdas, L., Goy, A. H., Cutler, C., Fujio, Y., Kunisada, K., Amin, H. M., and Gilles, F. (2004) Am. J. Pathol. 164, 2251–2258

25. Marzec, M., Kasprzycka, M., Ptasznik, A., Wlodarski, P., Zhang, Q., Odum, N., and Wasik, M. A. (2005) Lab. Invest. 85, 1544–1554

26. Zamo, A., Chiarle, R., Piva, R., Howes, J., Fan, Y., Chilosi, M., Levy, D. E., and Inghirami, G. (2002) Oncogene 21, 1038–1047

27. Zhang, Q., Raghunath, P. N., Xue, L., Majewski, M., Carpentieri, D. F., Odum, N., Morris, S., Skorski, T., and Wasik, M. A. (2002) J. Immunol. 168, 466–474

28. Chiang, G. G., and Abraham, R. T. (2005) J. Biol. Chem. 280, 25485–25490

29. Vega, F., Medeiros, L. J., Leventaki, V., Atwell, C., Cho-Vega, J. H., Tian, L., Clare, F. X., and Rassidakis, G. Z. (2006) Cancer Res. 66, 6589–6597

30. Fujimoto, J., Shiota, M., Iwahara, T., Seki, N., Satoh, H., Mori, S., and Yamamoto, T. (1996) Proc. Natl. Acad. Sci. U. S. A. 93, 4181–4186

31. Slupianek, A., Nieborska-Skorska, M., Hoser, G., Morrione, A., Majewski, M., Xue, L., Morris, S. W., Wasik, M. A., and Skorski, T. (2001) Cancer Res. 61, 2194–2199

32. Coluccia, A. M., Perego, S., Cleris, L., Gunby, R. H., Passoni, L., Marchesi, E., Formelli, F., and Gambacorti-Passerini, C. (2004) Blood 103, 2787–2794

33. Robinson, D. R., Wu, Y. M., and Lin, S. F. (2000) Oncogene 19, 5548–5557

34. Cohen, P. (2001) Eur. J. Biochem. 268, 5001–5010

35. Gunby, R. H., Sala, E., Tartari, C. J., Puttini, M., Gambacorti-Passerini, C., and Mologni, L. (2006) Anticancer Agents Med. Chem. 7, 594–611

36. Hubbard, S. R. (1999) Prog. Biophys. Mol. Biol. 71, 343–358

37. Hubbard, S. R., and Till, J. H. (2000) Annu. Rev. Biochem. 69, 373–398

38. Rush, J., Moritz, A., Lee, K. A., Guo, A., Goss, V. L., Spek, E. J., Zhang, H., Zha, X. M., Polakiewicz, R. D., and Comb, M. J. (2005) Nat. Biotechnol. 23, 94–101