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BCR-ABL Induces the Expression of Skp2 through the PI3K Pathway to Promote p27Kip1 Degradation and Proliferation of Chronic Myelogenous Leukemia Cells

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Abstract

Chronic myelogenous leukemia (CML) is characterized by the expression of the BCR-ABL tyrosine kinase, which results in increased cell proliferation and inhibition of apoptosis. In this study, we show in both BCR-ABL cells (Mo7e-p210 and Ba/F3-p210) and primary CML CD34+ cells that STI571 inhibition of BCR-ABL tyrosine kinase activity results in a G1 cell cycle arrest mediated by the PI3K pathway. This arrest is associated with a nuclear accumulation of p27Kip1 and down-regulation of p27Kip1. We also demonstrate that BCR-ABL cells show transcriptional up-regulation of Skp2 containing SFC complexes: silencing the expression of Skp2 increases its degradation by the proteasome. This degradation depends on the ubiquitinylation of p27Kip1 by Skp2. Inhibition of proliferation of BCR-ABL cells by the BCR-ABL inhibitor STI571 contributes to the pathogenesis of CML. In conclusion, these results suggest that BCR-ABL regulates cell cycle in CML cells at least in part by inducing proteasome-mediated degradation of the cell cycle inhibitor p27Kip1 and provide a rationale for the use of inhibitors of the proteasome in patients with BCR-ABL leukemias. (Cancer Res 2005; 65(8): 3264-72)

Introduction

Chronic myeloid leukemia (CML) is a hematopoietic stem cell disease characterized at the molecular level by the expression of the Philadelphia chromosome translocation that results in the rearrangement between the breakpoint-cluster region (BCR) on chromosome 22 and the Abelson leukemia gene (ABL) on chromosome 9 (1–3). BCR-ABL encodes a chimeric protein with a constitutive tyrosine kinase activity. It has been clearly shown that expression of p210BCR-ABL in hematopoietic cells is essential and sufficient for malignant transformation (4). BCR-ABL-dependent kinase activity results in the deregulation of a number of signal transduction pathways that participate in cell proliferation, differentiation, migration, adhesion, and apoptosis (3, 5–9).

Expression of BCR-ABL in hematopoietic cells results in growth factor independence and progression through the G1-S phase of the cell cycle (10). The mitogenic effects of BCR-ABL require the activation of the PI3K/Akt pathway that promotes cell survival by phosphorylation and inactivation of Bad, thus preventing apoptosis (11). The Ras/Raf/MEK/extracellular signal-regulated kinase pathway, which is involved in cell cycle regulation, is also altered in CML (12). Furthermore, we have previously shown that BCR-ABL also promotes cell survival through STAT5-mediated up-regulation of Bcl-xL (13).

The development of the BCR-ABL inhibitor STI571 has had an impact in the treatment of CML patients but has also provided a new tool for studying the effect of inhibition of the BCR-ABL kinase activity in cells harboring the endogenous BCR-ABL gene (14). Initial clinical results in patients with chronic phase CML have been extremely encouraging with complete cytogenetic remissions in >40% of patients resistant or refractory to IFN (15). Results in patients with CML in more advanced phases have not produced durable responses (16). Newer combinations of STI571 with other drugs as well as development of other kinase inhibitors are currently being tested as treatment for CML and Philadelphia positive acute lymphoblastic leukemia (17).

The cyclin-dependent kinase inhibitor p27Kip1 is a key regulator of the cell cycle in mammalian cells (18, 19). It negatively regulates cell cycle progression by directly inhibiting cyclin/Cdk2 complexes. The activity of p27Kip1 is controlled by its distribution among the different cell compartments (nucleus and cytoplasm; ref. 20). Akt directly phosphorylates p27Kip1 at T157 promoting its translocation to the cytoplasm where it is inactivated (21–23). However, the key mechanism of regulation of p27Kip1 expression is proteolysis by the ubiquitin-proteasome pathway (24), mediated by Skp2 containing SFC complexes. The ubiquitinylation by Skp2 requires the previous phosphorylation of p27Kip1 at T187 by the same cyclin E/Cdk2 complexes. The ubiquitinylation depends on the ubiquitinylation of p27Kip1 by Skp2. The ubiquitinylation of p27Kip1 by Skp2 results in inhibition of proliferation of BCR-ABL cells, indicating that the degradation of p27Kip1 contributes to the pathogenesis of CML. In conclusion, these results suggest that BCR-ABL regulates cell cycle in CML cells at least in part by inducing proteasome-mediated degradation of the cell cycle inhibitor p27Kip1 and provide a rationale for the use of inhibitors of the proteasome in patients with BCR-ABL leukemias. (Cancer Res 2005; 65(8): 3264-72)

Note: E.J. Andreu and E. Lledó contributed equally to this work and should be considered equal first authors.

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inhibitor p27Kip1 in the regulation of the cell cycle in BCR-ABL cells (27–30). In these studies, down-regulation of p27Kip1 has been shown in human and murine cell lines transfected with BCR-ABL. However, the mechanism by which BCR-ABL down-regulates p27Kip1 in primary CML cells or the role of p27Kip1 down-regulation in the pathogenesis of CML is unclear. Furthermore, analysis of CD34+ cells from patients with CML has suggested that BCR-ABL-mediated regulation of p27Kip1 depends on relocation of the cell cycle inhibitor from the nucleus to the cytoplasm in CML cells, thus preventing binding to cyclin E/Cdk2 complexes and promoting cell cycle progression (30).

In the current study, we have examined the role of p27Kip1 in the pathogenesis of CML. Our results show that BCR-ABL down-regulates p27Kip1 both by transcriptional regulation and by inducing proteasome-mediated degradation of the cell cycle inhibitor. The inhibition of BCR-ABL results in an accumulation of p27Kip1 in the nucleus and inhibition of cyclin E/Cdk2 kinase activity as well as a reduction of retinoblastoma phosphorylation. The enhanced degradation of p27Kip1 is associated with the transcriptional up-regulation of Skp2 induced by BCR-ABL. Whereas overexpression of p27Kip1 has no effect on proliferation of BCR-ABL–positive cells, a T187 p27Kip1 mutant that cannot be recognized by Skp2 induces a cell cycle arrest, providing evidence for the importance of p27Kip1 degradation in the pathogenesis of CML.

Materials and Methods

Cell lines and primary cells from chronic myeloid leukemia patients and normal donors. Human-derived Mo7e and Mo7e-p210 cells were grown in Iscove’s modified Dulbecco’s medium supplemented with 20% fetal bovine serum, l-glutamine, and penicillin-streptomycin with (Mo7e) or without (Mo7e-p210) 5 ng/mL of recombinant human interleukin-3 (IL-3). BaF/3 cells were grown in RPMI supplemented with 10% FCS, l-glutamine and penicillin-streptomycin, and 10% WEHI-conditioned medium was added to the culture as a source of murine IL-3 whereas growth of BaF/3-p210 was independent of growth factors. All media, serum and supplements were from Invitrogen Life Technologies (Paisley, United Kingdom), except for human IL-3 (R&D Systems, Minneapolis, MN).

Mobilized peripheral blood or bone marrow mononuclear cells were obtained from patients in chronic phase CML after informed consent. All patients were 100% Philadelphia chromosome–positive by direct cytogenetic analysis. CD34+ cells from bone marrow or mobilized peripheral blood were enriched using the MACS CD34+ isolation kit (Miltenyi Biotec, Cologne, Germany) and either the AutoMACS or the CliniMACS selection devices as described previously (13). CD3+ purity was always >90% after positive selection. CD34+ cells were cultured in Iscove’s modified Dulbecco’s medium supplemented with 20% FBS. IL-3 at a final concentration of 100 ng/mL was also added to the culture medium when the CD3+ cells were from healthy donors. When indicated, primary cells and/or cell lines were treated with the tyrosine kinase inhibitor STI571 at a concentration of 2 to 10 μmol/L was also added to the culture medium when the CD3+ cells were from healthy donors. When indicated, primary cells and/or cell lines were treated with the tyrosine kinase inhibitor STI571 at a concentration of 2 to 10 μmol/L. After two more washes in PBS, propidium iodide (Sigma Chemical Co., Poole, Ltd., Mamhead, Exeter, United Kingdom) at 10 μg/mL was used at a concentration of 20 μg/mL, the MEK inhibitor PD98059 (Calbiochem) at 30 μmol/L and lactacystin (AFFINITI Research Products, Ltd., Mambhead, Exeter, United Kingdom) at 10 μmol/L.

Flow cytometry analysis. For cell cycle analysis, 1 to 2 × 106 cells were stained with propidium iodide as described (26). Briefly, the cells were washed twice in cold PBS and fixed in ice-cold 50% ethanol for 30 minutes. After two more washes in PBS, propidium iodide (Sigma Chemical Co., Poole, United Kingdom), and RNase A (Sigma) were added to a final concentration of 100 ng/mL each. After incubation for 1 hour at room temperature, the cells were kept at 4°C until analysis by flow cytometry (FACScan, Becton Dickinson, Tennis, Belgium) using the CellQuest software.

Western blot analysis, immunoprecipitation, and kinase assays. For immunoblotting, cell lysates were prepared according to Kabarowski et al. (31). Protein concentrations were determined by bicinchoninic acid (Pierce, Rockford, IL). Cellular proteins (50-100 μg) were resolved on SDS-PAGE, transferred to a nitrocellulose membrane (Bio-Rad, CA), detected with specific antibodies and visualized by enhanced chemiluminescence (Tropix, Foster City, CA). Antibodies used were from Santa Cruz Biotechnology (Santa Cruz, CA; ABL, p27Kip1, cyclin E, Cdk2 and Skp2), BD Biosciences-PharMingen (San Jose, CA; cyclin D, p21[14,15], and retinoblastoma) and Zymed (San Francisco, CA; Skp2). Blots were stripped and probed with a β-tubulin antibody (Sigma) as a protein loading control. Subcellular fractionation of Mo7e-p210 cells cultured in the presence or absence of STI571 (2 μmol/L) or LY294002 (20 μmol/L) was done as previously described (32). Protein extracts were quantified with the Bio-Rad DC Protein Assay and 50 μg were used for the detection of p27Kip1 in each fraction by Western blot analysis. Lamin A (Cell Signaling, Beverly, MA) and β-tubulin (Sigma)–specific antibodies were used to assess the purity of the subcellular fractions. Skp2 was immunoprecipitated with rabbit polyclonal antibodies (sc-7164, Santa Cruz Biotechnology) and TrueBlot anti-rabbit immunoglobulin IP beads (eBioscience, San Diego, CA), from 1 mg of protein extracts from BaF/3-p210 cells overexpressing Skp2. Skp2 and p27Kip1 in the immunoprecipitates were detected with mouse monoclonal antibodies (Santa Cruz Biotechnology) and peroxidase conjugated anti-mouse IgG-Fc (Pierce).

For kinase assays, cyclin E- or Cdk2-containing complexes were immunoprecipitated from 150 μg of protein extracts with 1 μg of antibody and 30 μL of Protein A/G-Plus Agarose (Santa Cruz Biotechnology). Kinase activity assays were done as described previously using histone H1 (Boehringer Mannheim, Germany) as substrate (33). The intensity of the bands was quantified with the QuantityOne software (Bio-Rad).

Quantitative reverse transcription-PCR analysis. Mo7e-p210 cells were seeded at a density of 25 × 105 cells/mL and treated with 2 μmol/L STI571 or 20 μmol/L LY294002. Untreated controls were grown in parallel. At 24-hour intervals, total RNA was isolated with the RNeasy Mini Kit (Qiagen, Hilden, Germany), following the manufacturer’s instructions. After DNase I treatment (amplification grade, Invitrogen), 2 to 5 μg of total RNA were used as template for a reverse transcriptase reaction with the SuperScript First-Strand Synthesis System for reverse transcription-PCR (Invitrogen), using Oligo(dT) primers. For the relative quantification of the p27Kip1 and Skp2 mRNA levels, this cDNA was used as template in PCR reactions in the presence of SYBR Green I (Molecular Probes, Leiden, The Netherlands) and using the Platinum Taq DNA polymerase (Invitrogen). The PCR reactions and their analysis were done in an iCycler machine and using the iCycler iQ Optical System software (Bio-Rad). Besides p27Kip1 and Skp2, glyceraldehyde-3-phosphate dehydrogenase (GAPDH) was also utilized as an internal control. For relative quantification, a standard curve was established using serial dilutions of a known amount of a plasmid harboring the human GAPDH cDNA as template for the PCR reactions. Three serial dilutions of the cDNA from each sample and four replicates of each dilution were used. The primers used were: p27, 5′-GCACTGCAGAGACATGGAAG-3′; R5-′AGAATCGTCGGTTGCAGGTC-3′; Skp2, 5′-GCTTCACTGGGTAGGATTCTG-3′; R5-′GCAAGGGCTTCCAGGTCTATA-3′; GAPDH, 5′-ATCACCACCTCTCCAGGACC-3′; R5-′CAGGAGAACGCTGTCGCAG-3′.

Pulse-chase experiment. To examine the turnover of p27Kip1, BaF/3-p210 cells were incubated with 2 μmol/L STI571 or vehicle for 24 hours and pulse-labeled for 2 hours with 120 μCi/mL [35S]methionine in methionine-free MEM medium supplemented with 10% dialyzed FBS. Cells were then incubated in RPMI containing 10% FBS and excess methionine (chase medium) for different times. After washing with ice-cold PBS, cell lysates were prepared in radioimmunoprecipitation assay buffer (1 × PBS, 1% Nonidet P-40, 0.5% sodium deoxycholate, 0.1% SDS, 1 mmol/L phenylmethylsulfonyl fluoride, 0.1 mmol/L leupeptin, 1 mmol/L sodium orthovanadate, and 10 mmol/L sodium fluoride). Cellular debris was removed by centrifugation and the supernatant was subjected to immunoprecipitation with agaroase-conjugated anti-p27Kip1 monoclonal antibodies (Santa Cruz Biotechnology). Immune complexes were washed five times with radioimmunoprecipitation assay buffer and the eluted proteins were analyzed by SDS-gel electrophoresis on 12% acrylamide gels. The labeled p27Kip1 protein was detected by fluorography and quantified with the QuantityOne software.
(Bio-Rad). p27Kip1 degradation rates were calculated from the slope of the logarithmic transformation of the densitometry data plotted against time, as previously described (34).

**Retroviral infections.** Wild-type p27Kip1 and two different mutants, p27P- (mutated at Thr187 and therefore unable to be phosphorylated and degraded) and p27ck- (unable to interact with neither cyclin nor Cdk; ref. 35) were introduced in BaF/3-p210 cells using the LZIP-IRES-green fluorescent protein retroviral vector (36). Replication-defective retroviruses were produced by transfecting Bosc 23 producer cells with the recombinant DNAs. BaF/3-p210 cells (at a density of 2 × 10⁶ cells/mL) were incubated for 3 hours with 4 mL of filtered supernatant from producer cells in the presence of 8 μg/mL polybrene (Sigma). The day after infection, cells were seeded at 400 × 10³ cells/mL. Green fluorescent protein expression was used to detect infected cells by fluorescence microscopy.

**Adenoviral infections.** The AdEasy adenovirus system (37) was used to overexpress Skp2 in BaF/3-p210 cells. The Skp2 adenovirus was a kind gift from Dr. D. Wolf and was described previously (38). Silencing of Skp2 expression in BaF/3-p210 was achieved by infection with AdEasy-derived adenovirus harboring the H1 promoter from pSUPER (39) to generate small interfering RNA. The sequence of the Skp2 small interfering RNA was 5'-AAAGGGAGTGACAAAGACTTTG-3' (40). Cells were infected as described (41), with a multiplicity of infection of 1,000. Briefly, adenovirus produced in 293 cells were mixed with 50 × 10⁻⁷ μg Superfect (Qiagen) for 10 minutes before their addition to 1 × 10⁶ BaF/3-p210 cells. The cells were incubated with the adenovirus for 6 hours and then the medium was changed. Flow cytometry analysis of green fluorescent protein–positive cells gave an infection rate of 15% to 20%. Cell extracts were prepared 72 hours after the infection.

**Results**

**STI571 induced cell cycle arrest in BCR-ABL cells is associated with an accumulation of the cell cycle inhibitor p27Kip1.** We initially examined the effect of STI571 on the proliferation of BCR-ABL cells. Incubation with STI571 inhibited the proliferation of Mo7e-p210 and BaF/3-p210 cells, but had no effect on the proliferation of wild-type Mo7e or BaF/3 cells (Fig. 1A, top). Mo7e-p210 and BaF/3-p210 cells express the protein BCR-ABL p210, whereas only ABL can be detected in their wild-type controls by Western blotting (Fig. 1A, bottom). Cell cycle analysis indicated that STI571 induces a G₁ arrest in BCR-ABL–positive cells, with a reduction in the proliferating population (S + G₂/M phases) from 35% to 5% in Mo7e-p210 cells and from 33% to 15% in BaF/3-p210 cells (Fig. 1B). Similar results were observed in CD34+ cells obtained from patients with CML in chronic phase (34 to 6% reduction in the percentage of proliferating cells), whereas no significant changes were found in control CD34+ cells (Fig. 1B). As we have previously described (13), STI571 induced an increase in apoptosis in BCR-ABL–positive cells (Fig. 1B).

To determine potential mechanisms involved in abnormal proliferation of BCR-ABL–positive cells we examined the expression of proteins that participate in the regulation of the cell cycle. Inhibition of BCR-ABL kinase activity was associated with an increase in the protein levels of the cell cycle inhibitor p27Kip1 and a decrease in p21Cip1, cyclin E, and cyclin D protein levels in Mo7e-p210 cells, whereas there was no effect in the parental wild-type Mo7e cells (Fig. 1C). Similar changes were observed in BaF/3-p210 cells, although the reduction in the levels of the cyclins was less evident. When we examined the effect of STI571 on chronic phase CML and normal human CD34+ cells, we could show that similar to the Mo7e-p210 cells, inhibition of BCR-ABL was associated with an accumulation of p27Kip1 and a reduction of cyclin D and cyclin E proteins (Fig. 1D). We could not detect the expression of p21Cip1 in normal or CML CD34+ cells.

**STI571 inhibition of BCR-ABL results in the underphosphorylation of retinoblastoma.** The changes in the protein levels seen when we treated BCR-ABL–positive cells with STI571, specially the accumulation of p27Kip1, suggests that the blockage of the cell cycle in the G₁ phase could be the result of an inhibition in the Cdk-dependent kinase activity responsible for the phosphorylation of retinoblastoma. To test this hypothesis, we analyzed the localization of p27Kip1 in Mo7e-p210 cells treated with STI571 for 9 hours. As shown in Fig. 2A, treatment with STI571 induced a marked increase in the amount of p27Kip1 in the nuclear fraction. This accumulation of p27Kip1 was associated with a 60% decrease in the cyclin E/Cdk2 kinase activity in the presence of STI571 in Mo7e-p210 in comparison with Mo7e-wt cells (Fig. 2B). Furthermore, treatment with STI571 results in a reduction of retinoblastoma phosphorylation in Mo7e-p210 and primary CML CD34+ cells but not in Mo7e-wt or normal CD34+ cells, as shown by Western blotting (Fig. 2C). These results suggest that STI571-mediated BCR-ABL-dependent cell cycle arrest is associated with a reduction in the phosphorylation status of retinoblastoma due to the inhibition of Cdk kinase activity by p27Kip1.

**The PI3K pathway mediates the effect of BCR-ABL on the cell cycle.** BCR-ABL regulates the activity of two main signal transduction pathways involved in survival and proliferation, the PI3K/Akt and the Ras/Raf/MEK pathways. We wanted to know which of these two was the one by which the expression of p27Kip1 is regulated in BCR-ABL cells. We treated Mo7e-p210 and BaF/3-p210 cells with an inhibitor of PI3K (LY294002) or with an inhibitor of MEK (PD98059) and studied their effect on cell proliferation. As shown in Fig. 3A, inhibition of MEK with PD98059 had no effect on proliferation, whereas inhibition of PI3K with LY294002 blocked proliferation of both cell lines, suggesting that BCR-ABL-induced proliferation is mediated mainly by the PI3K/Akt pathway. Furthermore, inhibition of the PI3K pathway with LY294002 results in an accumulation of p27Kip1 in Mo7e-p210 and in BaF/3-p210 cells (Fig. 3B). Similar to the effect seen after inhibition of BCR-ABL kinase activity with STI571, the p27Kip1 protein accumulates mainly in the nuclear fraction of Mo7e-p210 cells (Fig. 3C).

**BCR-ABL regulates the levels of p27Kip1 by transcription inhibition and induced degradation.** We next studied the mechanisms by which BCR-ABL activity reduces the levels of p27Kip1. p27Kip1 expression may be regulated both at the transcriptional level by the FoxO transcription factors or by proteasome-mediated degradation following ubiquitylation. In order to determine which mechanism is altered in BCR-ABL cells, we did two types of experiments. Firstly, we treated Mo7e-p210 cells with STI571 or LY294002 and extracted the RNA at different time points. We analyzed the amount of p27Kip1 mRNA by quantitative reverse transcription-PCR using GAPDH as an internal control. As shown in Fig. 4, there was an increase in the levels of p27Kip1 mRNA when we treated the cells with either STI571 or LY294002, suggesting that BCR-ABL inhibits the transcription of the p27Kip1 gene through the PI3K pathway. Secondly, we did a pulse-chase experiment to determine the degradation rate of the p27Kip1 protein in BaF/3-p210 cells. Incubation of the cells with STI571 resulted in a time-dependent accumulation of labeled p27Kip1 in comparison with untreated BaF/3-p210 cells (Fig. 4B). Densitometric analysis of the bands (Fig. 4C) revealed that the degradation rate of p27Kip1, calculated from the slope of the logarithmic transformation of the densitometry data plotted against time, is slower when BCR-ABL kinase activity is inhibited by STI571, meaning that BCR-ABL increases the degradation of p27Kip1.
Analysis of the data with a \( t \) test revealed that the slopes of the two lines (\(-0.0328\) for the STI treatment and \(-0.0566\) for control) are significantly different from each other \((P < 0.01)\). The inhibition of the proteasome with 10 \( \mu \text{mol/L} \) lactacystin also resulted in an increment of p27Kip1 stability (data not shown), confirming that the degradation of p27Kip1 depends on the proteasome activity.

Skp2 is involved in the degradation of p27Kip1 and its expression is induced by BCR-ABL. It has been shown that the degradation of p27Kip1 in the proteasome requires its phosphorylation at T187 followed by its ubiquitinylation by the SCFSkp2 complex. We wanted to know whether Skp2 could also be the F-box protein involved in the degradation of p27Kip1 in our cell system. Silencing the expression of Skp2 with adenovirus-produced small interfering RNA resulted in an accumulation of p27Kip1 in BaF/3-p210 cells, whereas the overproduction of Skp2 resulted in a decrease of this protein (Fig. 5A, top). In Skp2
overexpressing BaF/3-p210 cells, we could coimmunoprecipitate Skp2 and p27Kip1 (Fig. 5A, bottom), showing a direct interaction between these two proteins. We then explored whether the expression of Skp2 was dependent on BCR-ABL activity. We treated Mo7e-p210 and BaF/3-p210 cells with STI571 or LY294002 and analyzed the expression of Skp2 by Western blotting. As shown in Fig. 5B, both treatments resulted in a reduction of the Skp2 protein levels 24 hours after the treatment, suggesting that BCR-ABL signals through the PI3K pathway to induce the expression of Skp2. When we examined the effect of STI571 on chronic phase CML and normal human CD34+ cells, we could show that similar to the cell lines, inhibition of BCR-ABL was associated with a decrease in the expression of Skp2 (Fig. 5C). Moreover, analysis by quantitative reverse transcription-PCR showed that there is a reduction in the Skp2 mRNA levels when Mo7e-p210 cells are treated with either STI571 or LY294002 (Fig. 5D). In summary, these results indicate that the BCR-ABL/PI3K pathway regulates the expression of Skp2 at least at the level of transcription.

Expression of a T187V p27Kip1 mutant induces a cell cycle arrest in BCR-ABL-positive cells. Thus far, our results show that the inhibition of BCR-ABL induces a cell cycle arrest that is accompanied by an increase in the p27Kip1 protein levels that results from transcriptional induction and inhibition of degradation mediated by Skp2 activity. To determine to what extent p27Kip1 degradation is responsible for the increased proliferation of BCR-ABL-positive cells, we infected BaF/3-p210 cells with LZRS-IRES-green fluorescent protein–derived retroviruses expressing wild-type p27Kip1 or the T187V mutant, which cannot be phosphorylated by Cdk-containing complexes and therefore is not ubiquitinylated by SCFSkp2 nor degraded at the proteasome (35). As shown in Fig. 6, cells expressing wild-type p27Kip1 kept proliferating as well as the uninfected cells, cells infected with the

Figure 2. STI571-treated cells accumulate p27Kip1 in the nucleus and show a decrease in cyclin E/Cdk2 kinase activity. A, Mo7e-p210 cells were incubated with 2 μmol/L STI571 or vehicle (Control) for 9 hours and processed as described in Materials and Methods to separate the nuclear (N) and cytoplasmic (C) fractions. Extracts were separated by SDS-PAGE and probed with the indicated antibodies. Lamin and β-tubulin are markers for the nuclear and cytoplasmic fractions, respectively. B, Mo7e-p210 and Mo7e-wt cells were treated with 2 μmol/L STI571 for the indicated times. Protein extracts (150 μg) were incubated with antibodies against cyclin E or Cdk2 as indicated and kinase activity of the immunoprecipitated complexes was assayed as described in Materials and Methods. Reaction products were resolved by SDS-PAGE and the phosphorylated substrate (histone H1) was detected by exposing the dried gels to X-ray films. The numbers below each band represent the intensity of the phosphorylated substrate (35). As shown in Fig. 6, cells expressing wild-type p27Kip1 kept proliferating as well as the uninfected cells, cells infected with the...
cells depends on BCR-ABL–mediated proteasome-dependent degradation of p27Kip1, which is associated with increased levels of cyclins D and E and phosphorylation of retinoblastoma. Secondly, degradation of p27Kip1 is necessary for cell cycle progression in CML cells as shown by the fact that a nondegradable mutant of p27Kip1 blocks cell cycle proliferation on BCR-ABL–positive cells. There is an inverse regulation of the levels of p27Kip1 and Skp2 in BCR-ABL cells that is mediated by the PI3K pathway. More importantly, these results are observed not only on BCR-ABL cell lines but also on samples from patients with CML in chronic phase.

Recent studies have suggested a role for p27Kip1 in cell cycle regulation in BCR-ABL–positive cells (27–30). Most of these studies have used different models of BCR-ABL cell lines and have consistently suggested that inhibition of the BCR-ABL kinase activity is associated with cell cycle inhibition, increased p27Kip1 protein levels and decreased cyclin D expression (27–29). Our results have also extended these observations in both cell lines and primary CML cells demonstrating the mechanism involved in BCR-ABL–mediated regulation of p27Kip1 and their causal relation with cell cycle deregulation in CML.

Unlike p27Kip1 levels, inhibition of BCR-ABL was associated with a decreased expression of the cell cycle inhibitor p21Cip1. Discordant expression of p27Kip1 and p21Cip1 has been previously described in other models of proliferating cells in which proliferation depends on the assembly between p21Cip1 and cyclin D-Cdk4 (42, 43), and BCR-ABL expression has also been associated with up-regulation of p21Cip1 (27).

Jiang et al. (30) have recently shown that levels of p27Kip1 are significantly higher in primary CML CD34+ cells versus normal CD34+ cells. However, p27Kip1 is not able to bind and inactivate Cdk2 kinase activity nor affect changes in cyclin E or cyclin D levels due to relocation of the protein to the cytoplasm instead of the nucleus. Differences in the in vitro models might explain some of the discrepancies between that work and our results. We compared the levels of p27Kip1 in CML cells before, 24, and 48 hours after inhibition of BCR-ABL activity with STI571, instead of normal versus CML cells. Furthermore, Jiang et al’s studies were planned to assess the effect of β1-integrin-mediated adhesion on cell cycle in CML cells in comparison with normal CD34+ cells, whereas our studies were always done using a nonadherent system. In any case, we have also observed that BCR-ABL induces an abnormal localization of p27Kip1 as treatment with STI571 induces relocalization of p27Kip1 to the nucleus.

The decrease in the p27Kip1 protein levels that we see in BCR-ABL cells is also due to a regulation at the transcriptional level. p27Kip1 gene transcription is up-regulated by the Forkhead/FoxO transcription factors (25), which in turn are phosphorylated and inactivated by Akt (44). By activating the PI3K/Akt pathway, BCR-ABL is inhibiting transcription of the p27Kip1 gene, as we see in our quantitative reverse transcription-PCR experiments using inhibitors of both BCR-ABL and PI3K. This is in agreement with results from Komatsu et al. (45) showing that BCR-ABL controls the expression of p27Kip1 through the Akt-dependent phosphorylation of FKHRL1/FoxO3a.

Several recent reports indicate that BCR-ABL participates in the regulation of the proteasome by increasing the proteasome-mediated degradation of a number of proteins (46–48). Indirect evidence also indicates that p27Kip1 is regulated by proteasome-mediated degradation in BCR-ABL–positive cells (27, 28). Our results show that BCR-ABL–mediated regulation of p27Kip1 is indeed dependent on proteasome degradation. The degradation of empty retrovirus (vector), or cells infected with a p27Kip1 mutant unable to interact with either cyclin or Cdk (p27 ck−). However, expression of the underdegradable mutant of p27Kip1 (p27 P−) inhibited proliferation of BCR-ABL cells (Fig. 6). This result confirms that the degradation of p27Kip1 is necessary for the induction of cell proliferation by BCR-ABL.

**Discussion**

The main findings of our study pertain to the mechanism of BCR-ABL–mediated regulation of the cell cycle: by inhibiting the tyrosine kinase activity of the oncogene, we show that proliferation of CML
p27\textsuperscript{Kip1} is specific and not due to an enhanced activity of the proteasome, because the levels of other cell cycle regulatory proteins (like cyclin E), which are also degraded by the proteasome, are reduced upon inhibition of BCR-ABL. p27\textsuperscript{Kip1} degradation is mediated by the F-box protein Skp2, a component of the E3 ubiquitin ligase SCF complex (49). It has been shown that the levels of Skp2 are up-regulated by PI3K (50). We have shown that BCR-ABL-induced degradation of p27\textsuperscript{Kip1} is associated with increased levels of the Skp2 protein related to activation of the PI3K pathway. This regulation is at the level of transcription, although we still do not know which transcription factor may be involved. Based on these results as well as the fact that the expression of a p27\textsuperscript{Kip1} mutant, unable of being phosphorylated in T187 and therefore unable of being recognized by Skp2 and degraded, blocks cell cycle progression, proteasome inhibitors such as PS-341 or other new molecules may be useful drugs for treatment of BCR-ABL harboring diseases (51, 52). Furthermore, it has recently been shown that resistance to STI571 can arise as a consequence of point mutations in BCR-ABL that prevents STI571 from inhibiting the kinase activity of the oncoprotein. Inhibition of the proteasome or even of the PI3K pathway by inhibitors such as LY294002 could be a means to overcome these resistances (53).

Figure 5. Interaction between Skp2 and p27\textsuperscript{Kip1} and regulation of the expression of Skp2 by STI571 or LY294002 treatment. A, functional and physical interaction between Skp2 and p27\textsuperscript{Kip1} in BCR-ABL cells. BaF3-p210 cells were infected with the empty pLZRS-IRE5-green fluorescent protein retrovirus (Vector) or derived retroviruses expressing either wild-type p27\textsuperscript{Kip1}, the T187V p27\textsuperscript{Kip1} mutant (P−) or an inactive p27\textsuperscript{Kip1} mutant (ck−). Two days after infection, cells were seeded at the same density (day 0) and infected cells (green fluorescent protein–positive cells) were counted using a fluorescence microscope for 3 more days. In each case, cell numbers were normalized using the number of green fluorescent protein–positive cells at day 0 as a reference. Points, mean; bars, SE of six independent experiments.

Figure 6. Expression of the T187V p27\textsuperscript{Kip1} mutant but not wild-type p27\textsuperscript{Kip1} blocks proliferation of BCR-ABL cells. BaF3-p210 cells were infected with the empty pLZRS-IRE5-green fluorescent protein retrovirus (Vector) or derived retroviruses expressing either wild-type p27\textsuperscript{Kip1}, the T187V p27\textsuperscript{Kip1} mutant (P−) or an inactive p27\textsuperscript{Kip1} mutant (ck−). Two days after infection, cells were seeded at the same density (day 0) and infected cells (green fluorescent protein–positive cells) were counted using a fluorescence microscope for 3 more days. In each case, cell numbers were normalized using the number of green fluorescent protein–positive cells at day 0 as a reference. Points, mean; bars, SE of six independent experiments.
Therefore, p27\textsuperscript{kip1} is a major target of BCR-ABL to promote proliferation. There are three ways in which the levels and activity of p27\textsuperscript{kip1} are regulated in CML cells; first, BCR-ABL induces a relocation of p27\textsuperscript{kip1} to the cytoplasm where it is inactive; second, BCR-ABL inhibits p27\textsuperscript{kip1} gene transcription by affecting, presumably, the activity of the transcription factors of the Forkhead/FoxO family; and third, BCR-ABL induces p27\textsuperscript{kip1} degradation by increasing the levels of Skp2 protein. All these effects are mediated by the PI3K pathway. Recently, it has been shown that this pathway regulates the localization of p27\textsuperscript{kip1} and its transcription in HL60 leukemia cells (54), but ours is the first report in which we are able to show that BCR-ABL is affecting all three mechanisms and not only in cell lines but also in primary cells from CML patients.

In conclusion, our results provide new insights into the mechanism of BCR-ABL-mediated regulation of the cell cycle and pave the way for the use of new drugs such as proteasome inhibitors in the treatment of patients with CML. Combinations of currently effective therapies such as STI571 with new compounds such as PS-341 may further improve the expectations of patients and indicate new alternatives in patients that have developed resistance to STI571.

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