In vitro and In vivo Activity of SKI-606, a Novel Src-Abl Inhibitor, against Imatinib-Resistant Bcr-Abl* Neoplastic Cells

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Abstract

Resistance to imatinib represents an important scientific and clinical issue in chronic myelogenous leukemia. In the present study, the effects of the novel inhibitor SKI-606 on various models of resistance to imatinib were studied. SKI-606 proved to be an active inhibitor of Bcr-Abl in several chronic myelogenous leukemia cell lines and transfectants, with IC50 values in the low nanomolar range, 1 to 2 logs lower than those obtained with imatinib. Cells expressing activated forms of KIT or platelet-derived growth factor receptor (PDGFR), two additional targets of imatinib, were unaffected by SKI-606, whereas activity was found against PIM2. SKI-606 retained activity in cells where resistance to imatinib was caused by BCR-ABL gene amplification and in three of four Bcr-Abl point mutants tested. In vivo experiments confirmed SKI-606 activity in models where resistance was not caused by mutations as well as in cells carrying the Y253F, E255K, and D276G mutations. Modeling considerations attribute the superior activity of SKI-606 to its ability to bind a conformation of Bcr-Abl different from imatinib. (Cancer Res 2006; 66(23): 11314-22)

Introduction

The aberrantly activated tyrosine kinase Bcr-Abl, the product of the Philadelphia chromosome (Ph), is causally associated to the pathogenesis of chronic myelogenous leukemia (CML; ref. 1). This finding provided the rationale for the clinical success of the Bcr-Abl tyrosine kinase inhibitor imatinib mesylate (STI571, Gleevec/Glivec). Imatinib induces complete cytogenetic remissions (CCyR) with minimal toxicity in most patients with chronic-phase CML (2–4). However, patients in more advanced phases of CML and the majority of patients with Ph+ acute lymphoblastic leukemia (ALL) either fail to respond to imatinib or quickly relapse following an initial response (5–7).

Resistance to imatinib (reviewed in ref. 8) is usually due to the overactivation of Bcr-Abl kinase activity that can be caused by the selection of cells harboring kinase point mutations of the BCR-ABL gene or presenting BCR-ABL gene amplification (9–11). Mutations or gene amplifications are not always observed in resistant cases. Instead, other mechanisms, such as up-regulation of drug efflux transporter (12, 13), down-regulation of influx pumps (14, 15), increased activity of downstream effectors, such as the Src tyrosine kinases (16, 17), and binding of imatinib by plasma or tissue proteins (18), have been postulated as additional mechanisms of resistance.

To overcome resistance to imatinib, different strategies were developed, including dose escalation of imatinib or combination with conventional cytotoxic drugs, but their success is limited, especially against patients harboring Bcr-Abl point mutations. To improve Bcr-Abl inhibition, several inhibitors with higher potency compared with imatinib have been identified, including dasatinib (BMS-354825) and nilotinib (AMN107), which show clinical activity in patients resistant to imatinib (19–21). Whereas nilotinib is derived from imatinib and binds to the same inactive conformation of Bcr-Abl (22), dasatinib is a dual Src-Abl inhibitor, which was crystallized in complex with the active conformation of Abl (23) and was also shown to dock in different conformations of the enzyme (24).

We describe here the in vitro and in vivo characterization of a new dual Src-Abl inhibitor, SKI-606 (25), against several CML models of resistance to imatinib.

Materials and Methods

Chemical compounds and reagents. SKI-606 is a novel substituted 4-anilino-3-quinolinecarbonitrile (Fig. 64), with a molecular weight of 531 g/mol, and it was prepared as described (26). For in vitro experiments, a stock solution of SKI-606 was prepared at 1 and 10 mmol/L in DMSO (Sigma Chemical Co., St. Louis, MO), filtered, and stored at −20°C. Preparations used for animal experiments were made at the indicated doses (0.2 ml vehicle containing 0.5% methylcellulose and 0.4% polysorbate 80 (Twee 80, Sigma Chemical), and the solutions were mixed continuously at 4°C. Imatinib mesylate was provided by Novartis Pharmaceuticals (AG, Basel, Switzerland) and prepared as described previously (2). [3H]ATP was from Amer sham Biosciences, R-taigiotensin, RRRA-DDDDDDDD, RRKDLDHDEDEAMSITA, and RRASVA were kindly provided by Dr. Oriano Marin (University of Padova, Padova, Italy).

Preparation of recombinant and native protein kinases. Human FLT3 (amino acids 589-993, EntrezGene accession number NP_001110), ABL (amino acids 230-517, isoform a, NP_005148), and RET (amino acids 700-1,020, NP_066124) kinase domain cDNA sequences were cloned in pHisE baculovirus transfer vector (27), in BamHI/SalI, KpnI/XbaI, and...
Kp1/Sal1 restriction sites, respectively. Anaplastic lymphoma kinase (ALK) sequence was cloned in pBlueBacHis2C vector (Invitrogen, Groningen, The Netherlands) as described (28). The sequence of all inserts was verified by DNA sequencing. Recombinant proteins were expressed in Sf9 cells with an NH2-terminal histidine and Flavivirus-T2 hexahistidine tag to aid in purification, as described (27). Briefly, proteins from total lysate were fractionated in a DEAE-Sepharose column and positive fractions were identified by anti-HisG Western blotting, loaded on a nickel-chelate affinity column, and eluted with imidazole. The initial anion-exchange step is required to achieve homogeneity in the final preparation.

The nonreceptor tyrosine kinases Lyn, Fgr, Syk, and COOH-terminal Src kinase (Csk) were purified from rat spleen to near homogeneity as described previously (28). The serine-threonine protein kinases CK1 and CK2 were isolated from rat liver (29) and protein kinase A (PKA) was purchased from Sigma.

**Radioactive kinase assay.** Protein kinase assays were done in 30 μL of a medium containing 50 mM Tris-HCl (pH 7.5), 5 mM MgCl2, 50 μg/mL MnCl2, 10% bovine serum album (BSA), and 1% NP40. The assay contained 1 μmol phosphatase/min to either 0.1 μmol/L polyGlu/Tyr (tyrosine kinase) or casein (protein kinases CK1 and CK2) or histone IIA, under standard laboratory conditions according to the guidelines of the National Cancer Institute (NCI; Milan, Italy). This study was approved by the institutional ethics committee for laboratory animals used in experimental research of the NCI. Human KU812Bcr-Abl + cells were suspended at 10^6 cells/mL PBS and this cell suspension was injected s.c. into the left flank of each animal. Murine Ba/F3 pro-B cells expressing Bcr-Abl were suspended at 10^6 cells/mL PBS and this cell suspension was injected s.c. into the right flank of each animal. Both cell lines were maintained in RPMI 1640 with 10% FBS.

**Inhibitor specificity profiling.** Radioactive kinase assays were done at room temperature in the presence of substrate peptides, 10 μM ATP, and 0.1 μmol/L SKI-606, using recombinant kinases obtained from various expression systems. Procedures for purification and assay of 30 of the 52 kinases have been described (31, 32). Kinase assays were done using ATP concentrations close to the Km value for each kinase. All protein kinases were grouped accordingly into three categories (i.e., 5, 20, and 50 μmol/L).

**Cell lines and cell culture.** The leukemic Bcr-Abl+ cell lines (KCL22, K562, KU812, and Lama84) and the neoplastic Bcr-Abl cell line HMC-1560, harboring a point mutation in the juxtamembrane (exon 13, K642E) was obtained from Dr. J. Fletcher (Massachusetts Institute of Technology Cancer Center, Cambridge, MA; ref. 36). All cell lines were purchased from Charles River Breeding Laboratories (Calco, Italy) kept under standard laboratory conditions according to the guidelines of the National Cancer Institute (NCI, Milan, Italy). For analysis of tumor-free survival, data were compared by the log-rank test (39).

**Molecular modeling.** SKI-606 was docked into the structure of c-Abl (PDB entry: 1M52; ref. 40) in complex with PD173955 after removal of the inhibitor from the binding site. The docking was done using FlexX (42) with default variables. The docked pose was chosen because of the fact that PD173955 is a dual Src-Abl inhibitor (41) as validated by reproducing the binding mode of PD173955 in the A-chain of mouse (PDB entry: 1IEP. No further modifications to the mouse (PDB entry: 1IEP. No further modifications to the

**Statistical analysis.** Statistical analysis of tumor weights was done by Student’s t test using GraphPad software analysis program (Prism, San Diego, CA). For analysis of tumor-free survival, data were compared by the log-rank test (39). P < 0.05 was considered statistically significant and derived from two-sided statistical test.
a binding mode hypothesis. A subsequent minimization of the docked ligand and the active site 6 Å around the docking position did not lead to any major conformational changes.

Results

**SKI-606 is a potent inhibitor of Src family kinases.** SKI-606, originally identified as a Src tyrosine kinase inhibitor, was subsequently found to also inhibit Abl tyrosine kinase (25). The ability of SKI-606 to prevent the kinase activation of selected tyrosine kinases was analyzed by testing in vitro the drug against various purified enzymes (Fig. 1A). SKI-606 was a picomolar inhibitor of two Src-related kinases (i.e., Fgr and Lyn with IC₅₀ values of 0.174 and 0.850 nmol/L, respectively). It inhibits Abl kinase in a nanomolar range (IC₅₀, 2.4 nmol/L), as reported previously (25), and the Csk (IC₅₀, 314 nmol/L), which acts as endogenous inhibitor of Src family protein tyrosine kinases. The other tyrosine kinases (Syk, ALK, RET, and Flt-3) and serine-threonine kinases (PKA, CK1, and CK2) tested were inhibited only at micromolar concentrations (Fig. 1A). Data available from the literature on the inhibition of two of these kinases by dasatinib are also presented and show an activity similar to SKI-606 (43). To further enlarge the kinase specificity profile of SKI-606, a panel of 52 purified proteins belonging to serine-threonine or tyrosine kinase classes was incubated with 0.1 μmol/L inhibitor, a concentration that causes 95% of Abl kinase activity inhibition. As reported in Fig. 1B, c-Src- and Src-related Lck were fully inhibited. The serine-threonine kinase PIM2 was substantially (75%) but not completely inhibited. In addition, the serine-threonine kinase checkpoint kinase 2 was partially (52%) inhibited, whereas Csk kinase showed 58% of inhibition in this type of experiment. Thus, SKI-606 is a potent inhibitor of Src family and Abl tyrosine kinases, with lower activity against few other serine-threonine/tyrosine kinases in the panel of kinases examined.

**SKI-606 is a nanomolar inhibitor of imatinib-resistant cell lines.** SKI-606 was reported previously to reduce proliferation and survival of KU812 and K562 Bcr-Abl⁺ CML cell lines (25). As indicated in Table 1, when the antiproliferative effect of SKI-606 and imatinib was compared in several human CML-derived cell lines, SKI-606 was more active than imatinib. In fact, SKI-606 inhibited these cell lines with IC₅₀ values ranging from 1 to 20 nmol/L (Table 1) compared with 51 to 221 nmol/L for imatinib. These data agree with previously published results (33). Subsequently, we evaluated SKI-606 against two additional targets of imatinib, PDGFR and KIT. In PDGFR-transformed murine Ba/F3 cells (Table 1), a 50% inhibition was observed at 370 nmol/L. SKI-606, 2 logs higher than imatinib (3 nmol/L). In addition, a mastocytosis HMC-1 cell line and a gastrointestinal stromal tumor GIST882 cell line harboring activating mutations of c-KIT [a G560V mutation in the juxtamembrane domain (35) and a K642E in the exon 13 of c-KIT (36), respectively] were inhibited by SKI-606 only at micromolar concentrations, whereas imatinib IC₅₀ values ranged between 19 and 29.5 nmol/L (Table 1). Data available from

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Table 1.

<table>
<thead>
<tr>
<th>Kinase</th>
<th>SKI-606 IC₅₀ [nM]</th>
<th>Dasatinib IC₅₀ [nM]</th>
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<tbody>
<tr>
<td>Fgr</td>
<td>0.174 ± 0.042</td>
<td>na</td>
</tr>
<tr>
<td>Lyn</td>
<td>0.850 ± 0.247</td>
<td>2.8</td>
</tr>
<tr>
<td>Abl</td>
<td>2.400 ± 0.700</td>
<td>0.6</td>
</tr>
<tr>
<td>Csk</td>
<td>314.2 ± 78.9</td>
<td>na</td>
</tr>
<tr>
<td>Syk</td>
<td>4228 ± 900</td>
<td>na</td>
</tr>
<tr>
<td>Alk</td>
<td>5720 ± 1115</td>
<td>na</td>
</tr>
<tr>
<td>Flt-3</td>
<td>&gt;20000</td>
<td>na</td>
</tr>
<tr>
<td>Ret</td>
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<td>PKA</td>
<td>&gt;20000</td>
<td>na</td>
</tr>
<tr>
<td>CK1</td>
<td>&gt;20000</td>
<td>na</td>
</tr>
<tr>
<td>CK2</td>
<td>&gt;20000</td>
<td>na</td>
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**Figure 1.** A, effect of SKI-606 and dasatinib on different protein kinases. IC₅₀ values represent the mean of at least four separate determinations ± SD. Kinase activity was measured with a radioactive kinase assay using exogenous peptide substrates as detailed in Materials and Methods. Data on the same kinases available from literature are also reported. *, obtained from ref. 43, na, not available. B, residual activity (mean ± SD, percentage of control) of the listed protein kinases in presence of 0.1 μmol/L SKI-606. Kinase activity was measured with a radioactive kinase assay using exogenous peptide as described in Material and Methods.
the literature show that dasatinib too is active against KIT and PDGFR, with IC₅₀ values of 7 and 50 nmol/L, respectively (44, 45). These data indicated that SKI-606 was inactive or only weakly active against cells transformed by PDGFR and KIT, in contrast to imatinib and dasatinib.

The efficacy of SKI-606 was also tested against imatinib-resistant cell lines, such as Lama84R, KCL22R, and K562R human cell lines (Table 1). The molecular mechanism of imatinib resistance of Lama84R cells is due to an amplification of Bcr-Abl fusion gene (11), whereas the underlying mechanism of KCL22R and K562R resistance has not been defined. SKI-606 was more active than imatinib in reducing the proliferation rate of K562R (IC₅₀, 28 versus 3,000 nmol/L), KCL22R (IC₅₀, 150 versus 2,000 nmol/L), and Lama84R (IC₅₀, 35 versus 700 nmol/L), respectively.

SKI-606 was also tested against murine pro-B Ba/F3 cells stably transformed by p210 Bcr-Abl WT or four imatinib-resistant point mutants (D276G, Y253F, E255K, and T315I; Fig. 2; Table 1). The compound inhibited the proliferation rate of WT, D276G, and Y253F transfectants in the low nanomolar range, having IC₅₀ values ranging from 13 to 40 nmol/L (Y253F). The D276G and Y253F transfectants behaved similarly to the WT transfectant (Fig. 2A), in contrast to the results obtained with imatinib (Fig. 2B).

Table 1. Comparison of SKI-606 and imatinib on cell proliferation

<table>
<thead>
<tr>
<th>Kinase</th>
<th>SKI-606 (nmol/L)</th>
<th>Imatinib (nmol/L)</th>
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<tbody>
<tr>
<td></td>
<td>IC₅₀ ± SE (no. repeats)</td>
<td>IC₅₀ ± SE (no. repeats)</td>
</tr>
<tr>
<td>WT-Ba/F3 + IL-3</td>
<td>570 ± 350 (4)</td>
<td>5,660 ± 2,760 (3)</td>
</tr>
<tr>
<td>Bcr-Abl (K562)</td>
<td>20 ± 2 (2)</td>
<td>221 ± 20 (2)</td>
</tr>
<tr>
<td>Bcr-Abl (Lama84)</td>
<td>1 ± 0.3 (6)</td>
<td>86 ± 8 (11)</td>
</tr>
<tr>
<td>Bcr-Abl (KU812)</td>
<td>3 ± 1 (2)</td>
<td>51 ± 5 (2)</td>
</tr>
<tr>
<td>Bcr-Abl (KCI22)</td>
<td>5 ± 1 (2)</td>
<td>70.5 (1)</td>
</tr>
<tr>
<td>Bcr-Abl (K562R, imatinib resistant)</td>
<td>28 ± 3 (2)</td>
<td>3,190 (1)</td>
</tr>
<tr>
<td>Bcr-Abl (Lama84R, imatinib resistant)</td>
<td>35 (1)</td>
<td>735 ± 380 (2)</td>
</tr>
<tr>
<td>Bcr-Abl (KCI22R, imatinib resistant)</td>
<td>150 (1)</td>
<td>2,170 ± 460 (2)</td>
</tr>
<tr>
<td>p210 Bcr-Abl (Ba/F3)</td>
<td>13 ± 6 (6)</td>
<td>401 ± 70 (11)</td>
</tr>
<tr>
<td>D276G Bcr-Abl (Ba/F3)</td>
<td>25 ± 2 (2)</td>
<td>1,147 ± 231 (4)</td>
</tr>
<tr>
<td>Y253F Bcr-Abl (Ba/F3)</td>
<td>40 ± 22 (3)</td>
<td>1,888 ± 979 (4)</td>
</tr>
<tr>
<td>E255K Bcr-Abl (Ba/F3)</td>
<td>394 (1)</td>
<td>3,174 ± 1,211 (2)</td>
</tr>
<tr>
<td>T315I Bcr-Abl (Ba/F3)</td>
<td>1,800 ± 850 (2)</td>
<td>&gt;10,000 (1)</td>
</tr>
<tr>
<td>Tel-PDGFR(Ba/F3)</td>
<td>370 ± 180 (5)</td>
<td>3.4 ± 0.9 (5)</td>
</tr>
<tr>
<td>c-KIT exon 13 mutant (GIST882)</td>
<td>3,174 ± 1,211 (2)</td>
<td></td>
</tr>
<tr>
<td>c-KIT G560V (HMCL104)</td>
<td>950 ± 450 (2)</td>
<td>19 (1)</td>
</tr>
<tr>
<td>(U937)</td>
<td>3,500 ± 850 (5)</td>
<td>&gt;10,000 (4)</td>
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NOTE: Dose-response curves were used to calculate IC₅₀ values, expressed as mean ± SE. The antiproliferative activity was evaluated by [³H]thymidine uptake.

Figure 2. Effects of SKI-606 and imatinib on proliferation rate and Abl kinase activity of WT and mutant (D276G, Y253F, T315I, and E255K) Bcr-Abl–expressing Ba/F3 cells. A and B, Ba/F3 cells supplemented with IL-3, Ba/F3 cells expressing WT or mutant Bcr-Abl protein, and Bcr-Abl U937 cells were plated in quintuplicates at 10⁴ per well in 96-well plates with escalating concentrations of SKI-606 (0-20 μmol/L) or imatinib (0-20 μmol/L) for 3 days and evaluated using a [³H]thymidine uptake assay. DMSO-treated controls were set as 100%. Error bars are omitted for clarity. C, in vitro inhibition of tyrosine phosphorylation of Bcr-Abl kinase. Whole-cell lysates were prepared from Ba/F3 cells after 2 hours of incubation with SKI-606 or imatinib and subjected to Western blot analysis with antibodies against phosphorylated tyrosine or Abl as described in Materials and Methods.

ski-606 inhibits imatinib-resistant cell growth
In E255K transfectants, the IC50 for SKI-606 was substantially higher (394 nmol/L) than in WT cells but lower than imatinib (3,174 nmol/L), whereas those observed for T315I transfectants were close to control cells. Whereas SKI-606 achieved 50% inhibition of the control Bcr-Abl/C0 U937 cells at micromolar concentrations (3,500 nmol/L), the parental IL-3-dependent Ba/F3 cell line was inhibited with IC50 of 570 nmol/L, suggesting that SKI-606 could interfere with IL-3 signaling.

The inhibitory activity of SKI-606 and imatinib against WT Bcr-Abl and mutant kinases was also compared by immunoblotting analysis of total lysates derived from stable Ba/F3 transfectants, consistent with the antiproliferative activity of SKI-606 described above (Fig. 2C). Phosphorylation of Y253F was diminished at lower concentrations than observed for WT Bcr-Abl, whereas phosphorylation of the E255K and D276G mutants exhibited sensitivity to SKI-606 that was similar to WT Bcr-Abl. In contrast, whereas phosphorylation of the T315I mutant was inhibited by SKI-606, one to two order of magnitude higher concentration of SKI-606 was required to do so compared with WT Bcr-Abl.

**SKI-606 is active against human KU812 xenografts in nude mice.** It was shown previously that SKI-606 given at 75 mg/kg twice daily or 150 mg/kg once daily promoted complete regression of human K562 xenografts for up to 40 days (25). The *in vivo* efficacy of SKI-606 was tested in a KU812 human tumor xenograft model, in which we established previously the curative potential for imatinib (18). Mice bearing measurable tumors were treated with SKI-606 8 or 15 days after leukemic cell injection. In the latter condition (treatment after 15 days), imatinib is unable to eradicate the disease, whereas treatment at day 8 results in ~30% rate of relapse (18). In both models, SKI-606 led to a complete eradication of the tumors and all animals remained tumor-free for up to day 210 (Fig. 3).

Despite the therapeutic activity in this KU812 CML xenograft model, SKI-606 apparently produced a dose- and schedule-dependent weight loss. The dose of 150 mg/kg given continuously once daily for 11 days resulted in the highest toxicity, causing 25% to 30% of maximum body weight loss (BWL). The dose of 75 mg/kg twice daily had an intermediate toxicity, causing 15% to 20% of maximum BWL. The 5-day weekly regimen was better tolerated causing only a 15% of maximum BWL (data not shown).

Similar toxicity was not observed with the K562 model reported earlier (25), but these models differ from those earlier reported, and the mice used for the earlier study have a different genetic background. This likely represents a consequence of poorly understood host-tumor interactions in conjunction with aspects of inhibiting several Src family kinases in immunocompromised mice and are not good predictors of toxicity in humans.

**SKI-606 is active against syngeneic Bcr-Abl WT and mutant Ba/F3 xenografts.** In a syngeneic xenograft mouse model, pro-B murine Ba/F3 cells expressing p210 Bcr-Abl WT and three imatinib-resistant point mutants (Y253F, D276G, and T315I) were injected s.c. in nude mice. SKI-606 was given at 150 mg/kg once daily for 11 days (5 days weekly). Points, mean of the tumor growth in tumor-bearing animals; bars, SE.
when the tumors became measurable (tumor weight range, 131-375 mg). SKI-606-treated Bcr-Abl WT xenografts completely disappeared after the 1st week of treatment; however, two of four treated mice relapsed after a 14-day tumor-free window (Fig. 4A). The maximal effect of SKI-606 in D276G Ba/F3 xenografts was reached at the end of the 2nd week of treatment (day 23; Fig. 4B), when three of four mice had a complete tumor regression, but all subsequently relapsed. In Y253F xenografts (Fig. 4C), a statistically significant tumor growth inhibition of control versus SKI-606-treated animals was observed on day 23 ($P = 0.0028$) and day 29 ($P = 0.039$). SKI-606 treatment of mice bearing T315I xenografts did not inhibit tumor growth (Fig. 4D).

In other experiments, tumor-free survival and tumor growth were monitored in mice injected s.c. with Bcr-Abl+ xenografts containing WT or mutant Bcr-Abl (E255K, Y253F, and D276G) and treated with SKI-606 1 day after tumor cell injection. The T315I mutant was excluded because of its high resistance to SKI-606 treatment in the previous experiments. Figure 5 shows that SKI-606 induced a statistically significant decrease in the rate of tumor growth and prolonged event-free survival of mice injected with Ba/F3 Bcr-Abl WT or with 253, 255, or 276 mutants, as described in the figure legend.

**Modeling considerations on the activity of SKI-606.** SKI-606 was found to dock inside the intermediate (1M52) conformation of Abl [Fig. 6C, for a comparison on how the docking solution of SKI-606 compared with respect to cocrystallized ligand of 1M52 (PD179355); see Fig. 6B], at difference with imatinib, which binds to the inactive conformation (1IEP) of Abl (40). Attempts to dock the compound in 1IEP led to a binding mode at the surface of the protein, which was not considered to be meaningful and was therefore discarded. The same observation was made trying to dock SKI-606 in an active conformation (2F4J) of Abl (46).

The activity of SKI-606 against the four Bcr-Abl point mutants analyzed can be rationalized as follows. The comparison of the docked solution of SKI-606 in 1M52 with the crystal structure of imatinib in 1IEP revealed that T315I is involved in direct electrostatic interactions with both SKI-606 (Fig. 6D) and imatinib. Therefore, a decrease in activity is expected for both molecules because of the steric hindrance caused by the bulky isoleucine as well as loss of the electrostatic interaction. Unlike T315, Y253 and E255, both located in the nucleotide binding loop, do not make any polar interaction with either SKI-606 or imatinib. However, the hydroxyl group of Y253 is involved in hydrogen bonding to N322, which stabilizes the conformation of the nucleotide binding loop in both inactive and intermediate conformations. The loss of the hydrogen bond probably leads to a bigger conformational change of the nucleotide binding loop in the inactive conformation of Abl.

![Figure 5](image-url) Effects of SKI-606 on tumor-free survival of nude mice injected with Ba/F3 cells harboring different Bcr-Abl mutations. Treatment was started the day after tumor cells injection on six animals per group. Results are presented as Kaplan-Meier plots of tumor-free survival (left) and tumor growth (right; points, mean; bars, SE) of Bcr-Abl WT (A), E255K (B), Y253F (C), D276G (D) xenografts given vehicle (solid line) or SKI-606 (dashed line). SKI-606 was given at 150 mg/kg once daily (A and B) or 75 mg/kg twice daily (C and D) from day 1 to 11. Statistical analysis done using log-rank test for survival curves (left) gives the following $P$-values: 0.0047 (A), 0.016 (B), 0.0027 (C), and 0.04 (D). The $t$ test was used for tumor growth analysis. *, $P = 0.011$ to 0.05; **, $P = 0.001$ to 0.01.
compared with that of the intermediate conformation. This can be assumed because of the observation that in the inactive conformation the nucleotide binding loop is in contact with the activation loop and a conformational change of the nucleotide binding loop is likely to affect also the conformation of the activation loop. In the intermediate conformation of Abl, however, the activation loop is open and is not interacting with the nucleotide binding loop. E255 makes electrostatic interactions with K247, thereby stabilizing again the nucleotide binding loop. The loss of this interaction seems to have a more pronounced effect on the conformation of the nucleotide binding loop than for the Y253F mutation and is reflected by the higher IC50 values for both SKI-606 and imatinib (8).

D276 is close to the α-helix C and is involved in orientating the helix (37). The main effect of the D276G mutation is to destabilize the inactive conformation of Abl (37). A change in the orientation of the α-helix C is expected to affect only the binding of imatinib and not of SKI-606 because the predicted binding mode of SKI-606 suggests that it does not interact with this region.

The proposed binding mode of SKI-606 agrees with a recently published QSAR study (47) and in-house activity measurements7 on SKI-606 derivatives. Docking studies on an Abl structure, which is very similar to 1M52 but which contains another ligand (2G2H; ref. 48), lead to a nearly identical binding mode to that observed while docking SKI-606 in 1M52.

Discussion

Imatinib treatment of CML patients dramatically changed their clinical course and the prognosis of this disease (3, 49, 50) in what is considered to be one of the major breakthroughs in modern medicine. Although most patients treated in chronic-phase now enjoy durable CCyR (50), most of them remain positive for the presence of Bcr-Abl1 cells when tested by PCR (51). Under these conditions, the emergence of cells where further genetic alterations can cause resistance to imatinib represents a major potential threat. In addition, 10% to 15% of newly diagnosed patients fail to achieve CCyR and 1% to 2% of patients in CCyR lose it every year (50). Most Ph1 ALL patients also fail to obtain durable responses with imatinib. For these reasons, the availability of drugs active in cases of resistance to imatinib is highly needed.

SKI-606 is, similarly to dasatinib, a dual Src-Abl inhibitor active against Bcr-Abl1 CML cell lines (25). Our data confirm and expand the initial observation of Golas et al. (25) and investigate the activity of SKI-606 on several models of imatinib resistance. This molecule was tested in imatinib-resistant CML cell lines and Bcr-Abl transfectants. Because resistance to imatinib is not entirely explained by Bcr-Abl mutations (8, 52), we also analyzed three human CML lines with resistance to imatinib, which present no Bcr-Abl mutation. SKI-606 maintained activity in all three lines, including one (Lama84R), in which resistance is caused by BCR-ABL gene amplification, and two additional lines (K562R and KCL22R), in which no known mechanism have been identified. The IC50 value obtained (150 nmol/L) is within the concentration range that can be achieved in vivo (53).

We also selected four clinically relevant mutants of Bcr-Abl to be assayed with SKI-606. These four mutations recapitulate the different mechanisms by which mutations can cause resistance to imatinib: direct contact with the drug (T315I), P loop mutants (Y253F and E255K), and mutations that do not affect the contact with the drug, the P loop or the activation loop, but which cause resistance by shifting the equilibrium among the different
conformations of Bcr-Abl toward the active conformation (D276G; ref. 8). The latter class probably encompass the largest number of mutations identified thus far. Using these four mutants, SKI-606 activity was evident on D276G, Y253F, and partly on E255K and was absent in T315I mutants, thus confirming the T315I as the most difficult mutant to tackle. Modelling analysis also allowed us to explain this different sensitivity and to point to a further potential benefit of SKI-606 in comparison with imatinib: its ability to bind the conformational less restrictive intermediate conformation of the protein. To our knowledge, the study presented here is the first to show the different effects on SKI-606 binding of Abl mutations causing resistance to imatinib.

SKI-606 activity was also confirmed in vivo in two models. In the first one (s.c. KU812 model in nude mice), complete eradication of the tumor and cure of all animals could be obtained, even in a setting where imatinib was known to be unable to be curative (18). In the second model, Ba/F3 transfectants were injected in nude mice. In this model, some growth retardation was evident, although no leukemia eradication was achieved. The in vivo activity observed against the E255K mutants, despite the relatively high IC50 value observed in vitro, can be explained by the possibility that concentrations of SKI-606 sufficient to inhibit this mutation (0.39 μmol/L) can be reached in vivo, in contrast to imatinib, which has a higher IC50 against this mutant (>3 μmol/L). This model is particularly difficult because no animal could be cured even when using cells transformed with WT Bcr-Abl. Although the in vivo activity reported in the second model was limited against the Bcr-Abl mutations tested, the inherent limitations present in any model do not allow to conclude that the activity in patients with these mutations will be similarly limited. It is known that imatinib achieves in vivo only a partial inhibition of Bcr-Abl enzymatic activity (4, 33); it is also known that Ph+ stem cells represent the less sensitive subset of CML cells (54), probably because of a higher expression of the Bcr-Abl protein (55). It will be of interest to see if the availability of inhibitors more potent than imatinib, such as SKI-606, will allow a complete inhibition of Bcr-Abl to be obtained in vivo and will lead to greater number of patients to become PCR negative.

At difference with imatinib, no substantial inhibition of KIT and PDGFR was noted with SKI-606, thus placing this molecule in a class of its own (dual Src-Abl inhibitor devoid of activity on receptor tyrosine kinases). This different selectivity could result in fewer side effects than imatinib because many toxicities associated with imatinib (e.g., edema, muscle cramps, skin rash, pigmentations, endocrine abnormalities, and low-grade inhibition of normal hemopoiesis) can be tracked to the inhibition of PDGFR and/or KIT (56–59).

Dasatinib (BMS-354825) represents a recently registered dual Src-Abl inhibitor with a profile of activity similar to SKI-606. Dasatinib shows a slightly higher activity against Abl than SKI-606 (Fig. L4). The lack of activity against receptors tyrosine kinases differentiates SKI-606 from dasatinib; this fact could render SKI-606 less toxic than dasatinib, including some recently described side effects (19, 21). In any case, a proper comparison of dasatinib and SKI-606 will require a direct clinical comparison of the two drugs as well as the availability of longer follow-up data on safety and efficacy.

Finally, the extended profile of activity done here allows us to conclude that SKI-606 is a fairly specific inhibitor, with a very limited number of targets outside the Abl and Src families of tyrosine kinase.

In conclusion, the data presented here show that SKI-606 exerts a specific activity against imatinib-resistant Bcr-Abl models. These data indicate that the potential activity of SKI-606 in the treatment of imatinib-resistant CML/Ph+ ALL deserves the performance of dedicated phase I-II clinical trials.

**Acknowledgments**

Received 4/9/2006; revised 8/28/2006; accepted 9/12/2006.

**Grant support**: Associazione Italiana per la Ricerca sul Cancro, Min. San. Ricerca Finalizzata (2003); Centre National de la Recherche Scientifique and Minister of Education, University, and Research-COFIN and PRIN programs (2003 and 2004); European Union (Prokinase network #503467); Canadian Fund for Innovation (CFI); and NCI of Canada.

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We thank Dr. Diane Boschelli (Wyeth Research, Pearl River, NY) for kindly providing the SKI-606 compound; Protein Production and Assay Development team of the Division of Transduction Therapy at Dundee, coordinated by Hilary McLaughlan and James Hastie, for providing the protein kinases used in the specificity profile experiment; Dr. Jennifer Bain for doing the experiment; Drs. Rosaldun Gunby and Luca Mologni (University of Milano-Bicocca, Monza, Italy) for kindly providing the ALK and RET recombinant proteins, respectively; Dr. Oriano Marin for the synthesis of the peptides; Drs. G. Nilsson and J. Butterfield for kindly providing the HMC-1™ human mastocytosis cell line; and Dr. F. Fletcher for providing the human GSTR82 cell line.

**References**

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