In vitro studies of a FLT3 inhibitor combined with chemotherapy: sequence of administration is important to achieve synergistic cytotoxic effects

Mark Levis, Rosalyn Pham, B. Douglas Smith, and Donald Small

Patients with acute myeloid leukemia (AML) harboring internal tandem duplication mutations of the FLT3 receptor (FLT3-ITD mutations) have a poor prognosis compared to patients lacking such mutations. Incorporation of FLT3 inhibitors into existing chemotherapeutic regimens has the potential to improve clinical outcomes in this high-risk group of patients. CEP-701, an indolocarbazole-derived selective FLT3 inhibitor, potently induces apoptosis in FLT3/ITD-expressing cell lines and primary leukemic blasts. We conducted a series of in vitro cytotoxicity experiments combining CEP-701 with chemotherapy using the FLT3/ITD-expressing cell lines MV4-11 and BaF3/ITD as well as a primary blast sample from a patient with AML harboring a FLT3/ITD mutation. CEP-701 induced cytotoxicity in a synergistic fashion with cytarabine, daunorubicin, mitoxantrone, or etoposide if used simultaneously or immediately following exposure to the chemotherapeutic agent. In contrast, the combination of pretreatment with CEP-701 followed by chemotherapy was generally antagonistic, particularly with the more cell cycle-dependent agents such as cytarabine. This effect appears to be due to CEP-701 causing cell cycle arrest. We conclude that in FLT3/ITD-expressing leukemia cells, CEP-701 is synergistic with standard AML chemotherapeutic agents, but only if used simultaneously with or immediately following the chemotherapy. These results should be considered when designing trials combining chemotherapy with each of the FLT3 inhibitors currently in clinical development. (Blood. 2004;104:1145-1150)

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important issue in combining FLT3 inhibitors with chemotherapy is the manner in which the agents are combined. We tested CEP-701/chemotherapy interactions in each of the 3 sequences: CEP-701 treatment before chemotherapy (“pretreatment”), CEP-701 treatment at the same time as chemotherapy (“simultaneous treat- ment”), and CEP-701 immediately following chemotherapy (“post- treatment”). Although none of these approaches can truly duplicate what occurs in an actual patient, we hoped that the data would provide guidelines for designing an effective combination regimen.

Materials and methods

Reagents

Cytarabine, daunorubicin, etoposide, and mitoxantrone were obtained from Sigma (St Louis, MO). Daunorubicin and etoposide were dissolved in dimethyl sulfoxide (DMSO) and stored frozen; cytarabine and mitoxantrone were dissolved in water and stored frozen. CEP-701, provided by Cephalon (West Chester, PA), was stored at −80°C as a 4-mM stock solution in DMSO and diluted as needed. Within any given experiment, DMSO concentration was maintained at a constant level in all samples, and in no case was it more than 0.1%. Ficoll-Hypaque was obtained from Amersham (Piscataway, NJ). Anti-FLT3 antibody was obtained from Santa Cruz Biotechnology (Santa Cruz, CA). Antiphosphotyrosine antibody (4G10) was obtained from Upstate Biotechnology (Lake Placid, NY). All other reagents were from Sigma.

Cytotoxicity assays

Cytotoxicity was assessed using a dimethyl-thiazol diphenyl tetrazolium bromide (MTT) assay. In selected cases, we also used an annexin V–binding apoptosis assay to confirm that the cytotoxic effect observed (or lack thereof) was associated with an equivalent degree of apoptosis. MTT (Roche, Indianapolis, IN) and annexin V (PharMingen, San Diego, CA) assays were performed as described previously.12

Cells

Cell lines used for these studies were all cultured at 37°C in 5% CO₂ in RPMI medium with 20% fetal bovine serum (FBS) and penicillin/streptomycin (Invitrogen, Carlsbad, CA). The BaF3/ITD cell line was generated by transfecting the interleukin 3 (IL-3)–dependent murine pro-B lymphocyte line, Ba/F3, with an expression vector containing a FLT3/ITD cDNA and has been described previously.13,24 MV4-11 is an AML cell line that expresses a naturally occurring 30 bp FLT3/ITD mutation in homozygous form.13,25 In addition, we used a primary AML sample, which was designated AML/ITD, obtained through a protocol approved by the institutional review board. The sample was obtained by Ficoll-purifying mononuclear cells from the peripheral blood of a newly diagnosed patient who presented with a white blood cell (WBC) count above 100 × 10⁹/L (100 000/mm³). The French-American-British classification was AML M0 and the cells expressed a 51–base pair (bp) FLT3/ITD mutation. The specimen was aliquoted and stored frozen for repeated use. Prior to each use, aliquots of these blasts were thawed rapidly into warm culture medium, incubated for 12 hours, and then recenterfuged over Ficoll to eliminate cells dying from the freeze-thaw process. Using this method we obtained blasts that maintained satisfactory viability (as determined by trypsin blue exclusion) and responsiveness to cytotoxic agents in culture over 48 hours. Blasts incubated for longer periods of time appeared to become quiescent (ie, poor uptake of the MTT reagent but still excluding trypan blue). We were therefore able to use these blasts only in experiments completed in 48 hours or less. This precluded our use of these cells for those experiments in which cells were pretreated with CEP-701 because this required more than 72 hours of incubation.

Cell cycle analysis

Following drug exposure, cells were fixed in 70% cold methanol, washed in IFJ buffer (150 mM NaCl, 10 mM HEPES [N-2-hydroxyethylpiperazine-N'-2-ethanesulfonic acid], pH 7.4, 4% FBS, 0.5% Tween-20) and resuspended in phosphate buffered saline (PBS) with 100 µg/mL RNAse (Roche). After incubation for 15 minutes at 37°C, propidium iodide (Sigma) in PBS was added to a final concentration of 25 µg/mL and the cells were analyzed by flow cytometry.

FLT3 phosphorylation

FLT3 expression and phosphorylation status were analyzed by incubating cells for 1 hour with and without CEP-701 followed by cell lysis in detergent buffer, immunoprecipitation, gel electrophoresis, and immunoblotting with antiphosphotyrosine antibodies as described previously.13

Median effect analysis

To characterize the interactions between CEP-701 and chemotherapy, data were analyzed using the median effect method of Chou and Talalay.26 In this method, for every combination of 2 agents tested, dose-response curves are generated for each agent individually, and these data are used to analyze the

Figure 1. CEP-701 effects on FLT3/ITD-expressing cells. (A) Cells were incubated for 1 hour in culture medium with or without 50 nM CEP-701 and then lysed in detergent buffer. Then, 500 µg of this whole-cell extract was used for immunoprecipitation and immunoblotting as described in “Materials and methods.” The upper panel shows a blot probed with antiphosphotyrosine; the lower panel is the same blot stripped and reprobed with anti-FLT3. The blot reveals the characteristic appearance of FLT3, with a larger (160-kDa) mature, glycosylated form, and a smaller (130-kDa) immature form. (B) MTT assay of cells exposed for 48 hours to increasing doses of CEP-701. Each concentration point represents the mean of quadruplicate measurements of optical density (OD). The results are plotted as percent untreated control. This experiment was performed 3 times. The graph displays a representative result. Error bars represent the SD. (C) Annexin V apoptosis assay of cells exposed to CEP-701. The y-axis represents viable (ie, non–annexin V staining) cells plotted as percent untreated control. The concentration points represent a single measurement of annexin V binding. This experiment was repeated once with essentially identical results.
results obtained from the combination treatment within the same experiment. A commonly used approach is to prepare a stock medium containing the 2 agents at a fixed ratio, and then perform serial dilutions of that original stock to test the drugs over a range of doses. This scenario mimics 2 drugs being given to a patient simultaneously, with both of them clearing from the plasma with roughly the same half-life. However, a patient treated with a FLT3 inhibitor would be maintained on a constant dose over a prolonged period of time. Therefore, we focused our efforts on studying the effects of combining a fixed dose of CEP-701 with varying doses of chemotherapy. Although a broad range (1-100 nM) of CEP-701 concentrations was used to generate the median effect analysis plots, of most interest were the interactions between chemotherapeutic agents and CEP-701 concentrations of 10 or 20 nM. These levels of CEP-701 in vitro result in FLT3 autophosphorylation inhibition to approximately 5% to 10% of baseline, which corresponds to the levels of FLT3 inhibition achieved in the recent clinical trial.20 It should be noted that to achieve this degree of FLT3 inhibition in vivo, plasma levels of CEP-701 typically needed to be in the micomolar range because CEP-701 is so highly protein-bound. Therefore, the results reported here are primarily derived from combinations of a fixed concentration of CEP-701 (10 or 20 nM) and a concentration of chemotherapeutic agent as close as possible to the IC50 value of the chemotherapeutic agent alone in these experiments, resulting in a nonfixed ratio of CEP-701 and chemotherapy.

For each CEP-701/chemotherapy drug combination experiment, a combination index (CI) number was generated using a commercially available software program (CalcuSyn; Biosoft, Manchester, United Kingdom). For each experiment, linear regression analysis of the dose-response data was used to generate a median effect value DM (corresponding to the IC50) along with a slope m and linearity coefficient r. For all data reported here, r values were more than 0.95. The CI is calculated using the formula: 

CI = (D1/Dm)/(Dm1) + (D2/Dm)/(Dm2) + (D1)(D2)/(Dm1)(Dm2)

This applies to 2 mutually exclusive drugs with independent modes of action, where (D1) and (D2), for example, represent CEP-701 and a chemotherapeutic agent, respectively, and (Dm) refers to the dose of each drug that, by itself, will generate a median effect (ie, the IC50) from the data within that experiment. As indicated, we used a nonfixed ratio of the 2 drugs to better approximate what might occur in a patient treated with continuous CEP-701. Although quantifying the degree of synergy or antagonism is of uncertain validity, this method of analysis generally defines CI values of 0.9 to 1.1 as implying additivity, 0.3 to 0.9 as synergistic, less than 0.3 as strongly synergistic, 1.1 to 3.3 as antagonistic, and more than 3.3 as strongly antagonistic.26


Table 1. Pretreatment with 10 nM CEP-701, followed by addition of chemotherapy

<table>
<thead>
<tr>
<th>Cytarabine</th>
<th>Daunorubicin</th>
<th>Etoposide</th>
<th>Mitoxantrone</th>
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<td>IC50, nM</td>
<td>CI</td>
<td>IC50, nM</td>
<td>CI</td>
</tr>
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<td>BaF3/ITD</td>
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<tr>
<td>HL60</td>
<td>875</td>
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Table 1. Pretreatment with 10 nM CEP-701, followed by addition of chemotherapy

IC50 and CI values for the combination of 10 nM CEP-701 and chemotherapeutic agents at doses corresponding to the approximate IC50. In this pretreatment scenario, triplicate samples of cells were exposed to CEP-701 for 24 hours and then transferred into medium containing both CEP-701 and the chemotherapeutic agent. MTT assays were then performed 48 hours later. Each CI value (generated by the CalcuSyn program) was obtained by conducting dose-response experiments for CEP-701 and the indicated chemotherapy individually and in combination over a range of doses for both drugs. The values shown are representative of 3 different experiments.

Although it is obviously not an AML cell line, it does offer the advantage of studying cells that are transformed exclusively because of FLT3. HL60 cells were used as an FLT3+ control line. HL60 cells are AML-derived cells that express a low level of wild-type FLT3 detectable on immunoblot only with prolonged film exposure or by fluorescence-activated cell sorting (FACS) using an anti-CD135 antibody (data not shown).27 We included such a “control” cell line to help identify non–FLT3-mediated drug interactions. Following a 1-hour exposure to 50 nM CEP-701, FLT3 autophosphorylation was inhibited in all 3 FLT3-expressing cell types. In MTT proliferation and annexin V–binding apoptosis assays, BaF3/ITD, MV4-11, and AML/ITD cells displayed dose-dependent cytotoxic responses to CEP-701 (Figures 1B-C). In contrast, HL60 cells showed no detectable FLT3 protein using even prolonged exposure of the immunoblot, and they demonstrated no apoptosis and only mildly inhibited proliferation in response to CEP-701 exposure (Figures 1A-C). These features made the use of HL60 cells an ideal control to identify chemotherapy/CEP-701 interactions that were not mediated through FLT3 inhibition.

**CYP-701 combined with chemotherapy: pretreatment with CYP-701**

The first combination we studied was the pretreatment of the leukemia cells with CYP-701 followed by the addition of individual chemotherapeutic agents. Cells were incubated with CYP-701 at various doses for 24 hours, then transferred into medium containing chemotherapy for an additional 48 hours. For any given sample, the CYP-701 concentration was maintained at a constant level throughout the 72-hour incubation. Under these conditions, 10 nM was the maximum dose of CYP-701 that could be meaningfully studied for the responsive cells because higher concentrations resulted in virtually complete cell death at 72 hours. Table 1 displays the CI values for 10 nM CYP-701 when combined with a dose of chemotherapy corresponding to the approximate

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**Results**

**Cell lines and primary samples treated with single-agent CYP-701**

BaF3/ITD, MV4-11, and AML/ITD cells all express constitutively phosphorylated FLT3, albeit at widely differing levels (Figure 1A). MV4-11 cells represent an ideal model cell line for these studies because this line harbors a naturally occurring FLT3/ITD mutation.13 The BaF3/ITD cell line was generated by transfecting the IL-3–dependent murine lymphoid line BaF3 with a FLT3/ITD construct, as described.13 Expression of the constitutively activated FLT3 construct confers factor independence to the BaF3/ITD line.
CEP-701 combined with chemotherapy: simultaneous treatment with CEP-701

The next sequence we tested was simultaneous exposure to CEP-701 and chemotherapy. Table 2 summarizes the CI values for simultaneous treatment of cells with 10 or 20 nM CEP-701 and chemotherapeutic agents at a concentration approximating the IC50 value for the chemotherapeutic agent by itself in the same experiment. All FLT3-expressing cells (including the primary AML sample) displayed a synergistic cytotoxic response when exposed to the combinations of CEP-701 and chemotherapy. Virtually identical results were obtained from combinations doses of chemotherapy corresponding to the IC50 (data not shown). In addition, we conducted a parallel experiment using the annexin V--binding apoptosis assay with MV4-11 cells exposed to cytarabine and CEP-701 and found a CI value of 0.587 for the dose of 20 nM CEP-701, confirming that the cytotoxic effect represented apoptosis.

As expected, only additive effects were seen in HL60 cells, with the interesting exception of daunorubicin. With this drug, the combination with CEP-701 was mildly synergistic, suggesting the presence of a non--FLT3-mediated interaction between the 2 agents. Because CEP-701 is highly protein-bound, we considered the possibility that the synergistic interaction we observed between daunorubicin and CEP-701 in HL60 cells was pharmacokinetic in nature. We hypothesized that competition between the 2 agents for protein-binding sites could lead to increased free levels of both, with resultant increased cytotoxicity. To test this hypothesis, we incubated BaF3/ITD cells in culture medium containing 10% FBS with a fixed concentration of CEP-701 (10 nM) plus increasing concentrations of daunorubicin, then lysed the cells, and immunoprecipitated FLT3. The results of this experiment, shown in Figure 4 (right panel), confirm that the presence of daunorubicin increases the free levels of CEP-701 in vitro, as measured by inhibition of FLT3 autophosphorylation. Daunorubicin alone showed no inhibition of FLT3 phosphorylation. We did not observe the effect when the experiment was performed using 20% FBS, nor was it observed with mitoxantrone, etoposide, or cytarabine using either 10% or 20% FBS. Although this immunoprecipitation assay does not duplicate the exact conditions of the cytotoxicity experiments shown in Table 2, the results suggest that at least part of the synergistic interaction between daunorubicin and CEP-701 may be related to this phenomenon. More importantly, these data highlight a theoretical potential for anthracycline-induced toxicity in patients treated with a combination of CEP-701 and daunorubicin. 24-30 If CEP-701 displaced daunorubicin from its cell cycle distribution of MV4-11 cells and HL60 cells with and without 10 nM CEP-701 are plotted. At every concentration of cytarabine tested, the cytotoxic effect is less pronounced, and the IC50 shifts from 2.1 μM to 4.5 μM in the presence of CEP-701. This result was highly reproducible and confirmed using an annexin V assay (CI = 1.798 for BaF3/ITD, 1.246 for MV4-11).

Examination of the CI values in Table 1 reveals that pretreatment of the FLT3-expressing cell lines (MV4-11 and BaF3/ITD) with CEP-701 followed by addition of daunorubicin or mitoxantrone led to additive cytotoxic effects, whereas pretreatment with CEP-701 appeared to antagonize the cytotoxic effects of cytarabine and etoposide. Neither synergy nor antagonism was observed between these agents in the HL60 cells, suggesting that the antagonistic interaction, when observed, was mediated through FLT3 inhibition. Because cytarabine in particular is highly cell cycle dependent, we investigated the possibility that the antagonism was due to CEP-701 influencing the cell cycle distribution of the FLT3/ITD cells. Figure 3 shows a cell cycle profile of MV4-11 and HL60 cells with and without CEP-701 treatment. CEP-701 exposure causes a decrease of S phase and G2/M phase in both MV4-11 cells and BaF3/ITD cells (not shown), with corresponding increases in G1. In contrast, the cell cycle distribution of HL60 cells was not affected. Because etoposide and cytarabine exert significant effects during S phase, the relative decrease in S phase cells pretreated with CEP-701 may account for the observed antagonism between CEP-701 and the chemotherapies.

Table 2. Simultaneous treatment with CEP-701 and chemotherapy

<table>
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<th>Cytarabine</th>
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<th>Etoposide</th>
<th>Mitoxantrone</th>
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<td>HL60</td>
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IC50 and CI values for the combination of 10 or 20 nM CEP-701 and chemotherapeutic agents at doses corresponding to the approximate IC50. Each CI value was obtained by conducting dose-response experiments for CEP-701 and the indicated chemotherapeutic agent individually and in combination over a range of doses for both drugs. The values shown are representative of 3 different experiments.
Table 3. Treatment of cells with chemotherapy followed by treatment with CEP-701

<table>
<thead>
<tr>
<th></th>
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<td>IC(_{50}), nM</td>
<td>IC(_{50}), nM</td>
<td>IC(_{50}), nM</td>
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<td>0.503</td>
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<td>AML/ITD</td>
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Table shows IC\(_{50}\) and CI values for the combination of 10 nM or 20 nM CEP-701 and chemotherapeutic agents at doses corresponding to the approximate IC\(_{50}\). In this posttreatment scenario, cells were exposed to chemotherapy for 24 hours (cytarabine only), or 1 hour (daunorubicin, etoposide, or mitoxantrone), washed, and then transferred into medium containing CEP-701. MTT assays were then performed 48 hours later. Each CI value was obtained by conducting dose-response experiments for CEP-701 and the indicated chemotherapy individually and in combination over a range of doses for both drugs. ND indicates not determined.
of FLT3/ITD AML to characterize the effects of combinations and treatment sequences on the leukemic stem cells. The data generated from such studies can be used to refine effective FLT3 inhibitor/chemotherapy regimens identified in ongoing clinical trials. We will also need to explore any potential effects of CEP-701 on recovery of marrow from chemotherapy-induced aplasia.

Cytarabine is an important component of AML therapy, with most regimens requiring that the drug be administered over several days so as to capture a higher fraction of leukemia cells as they enter S phase (the phase during which they are most susceptible to the effects of cytarabine). CEP-701 causes almost immediate FLT3 inhibition when administered to patients with AML, and although we were unable to test cytarabine and pretreatment with CEP-701 in our primary blast sample in vitro, it is reasonable to conclude that at least some leukemia blasts in vivo might respond to FLT3 inhibition with cell cycle arrest. The therapeutic efficacy of cytarabine could thus potentially be blunted by FLT3 inhibition initiated either before or simultaneously with cytarabine. These concerns favor initial exploration of a treatment regimen using cytarabine followed by FLT3 inhibitors, a treatment sequence that yielded highly synergistic cytotoxic effects in these experiments. However, it would be inappropriate to definitively conclude from these in vitro studies that this would be the only effective treatment schedule. We are planning on further exploring these different treatment sequences in mouse models.

An equally important issue concerns the potential pharmacokinetic interaction between anthracyclines and CEP-701. The in vitro data suggest that CEP-701 and daunorubicin bind to the same serum proteins in a competitive fashion. This interaction, if it occurs in human plasma, could potentially result in higher free levels of anthracyclines with subsequent increased toxicity to patients treated with both agents simultaneously. Because of this potential, and because of the observed synergistic cytotoxicity when daunorubicin or mitoxantrone was followed by CEP-701 treatment, the use of anthracycline treatment followed by FLT3 inhibitors is preferable.

Therefore, based on the clinical and correlative laboratory data from the initial trial of CEP-701 in patients with AML, along with the data from the current in vitro study, a new clinical trial has been designed. In this trial, the combination of mitoxantrone, etoposide, and cytarabine (MEC), followed by oral CEP-701 at a dose of 80 mg twice daily, will be tested in patients with relapsed AML harboring FLT3-activating mutations. This trial represents an important next step in the development of FLT3 inhibitors for clinical use, as well as an interesting test of the concept that leukemia treatment regimens incorporating targeted therapies can be successfully modeled preclinically.

Acknowledgments

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References

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