FLT3 Kinase Inhibitor TTT-3002 Overcomes Both Activating and Drug Resistance Mutations in FLT3 in Acute Myeloid Leukemia

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Abstract

There have been a number of clinical trials testing the efficacy of FMS-like tyrosine kinase-3 (FLT3) tyrosine kinase inhibitors (TKI) in patients with acute myeloid leukemia (AML) harboring a constitutively activating mutation in FLT3. However, there has been limited efficacy, most often because of inadequate achievement of FLT3 inhibition through a variety of mechanisms. In a previous study, TTT-3002 was identified as a novel FLT3 inhibitor with the most potent activity to date against FLT3 internal tandem duplication (FLT3/ITD) mutations. Here, the activity of TTT-3002 is demonstrated against a broad spectrum of FLT3-activating point mutations, including the most frequently occurring D835 mutations. The compound is also active against a number of point mutations selected for in FLT3/ITD alleles that confer resistance to other TKIs, including the F691L gatekeeper mutation. TTT-3002 maintains activity against patients with relapsed AML samples that are resistant to sorafenib and AC220. Studies utilizing human plasma samples from healthy donors and patients with AML indicate that TTT-3002 is only moderately protein bound compared with several other TKIs currently in clinical trials. Tumor burden of mice in a FLT3 TKI–resistant transplant model is significantly improved by oral dosing of TTT-3002. Therefore, TTT-3002 has demonstrated preclinical potential as a promising new FLT3 TKI that may overcome some of the limitations of other TKIs in the treatment of FLT3-mutant AML.

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that has demonstrated significant responses in patients with FLT3/ITD+ AML in recent trials (12, 13). However, both sorafenib and AC220 are inactive against many FLT3/PMs, including the D835Y mutation, and thus do not benefit patients harboring this mutation (14–16).

Finally, treatment failure has also been observed because of the selection for resistance-conferring point mutations that have appeared in patients with FLT3/ITD-expressing AML following TKI treatment. These mutations either occur in residues within the ATP binding pocket or to residues thought to affect protein structure in ways that also affect the binding of the drug allosterically (3). Midostaurin (PKC412) is a FLT3 TKI that demonstrated reduction of blasts in a phase II trial of patients with relapsed or refractory AML (17) and is moderately active against a number of known FLT3/PMs (14). However, in a trial of patients with relapsed or refractory AML, PKC412 selected for a mutation at residue N676K in a FLT3/ITD patient that conferred drug resistance (18). A number of initially responsive patients on AC220 and sorafenib trials were also found to have selected for additional resistance-conferring point mutations in the FLT3/ITD allele. These frequently include a F691L mutation (analogous to the T315I mutation in BCR/ABL that confers resistance to Gleevec) or D835 mutations (Y/F/V/H) in the kinase domain (19, 20). Crenolanib is a next generation FLT3 inhibitor that is currently in phase II trials of relapsed AML with FLT3/D835-activating mutations. This compound has demonstrated in vitro and in vivo activity against FLT3/D835 mutations (Y/F/V/H) and the dual FLT3-D835(Y/H)/ITD mutant receptors (21, 22). However, it is unable to target the F691L mutation, and therefore has the potential to select for this resistance mutation in trials. Currently, the most potent activity against the F691L mutation in vitro has been observed for the BCR-ABL inhibitor ponatinib. However, ponatinib still shows a nearly 20-fold shift in IC50 for the F691L mutation compared with FLT3/ITD alone, and plasma samples from patients show marginal levels of inhibition in the plasma inhibitory activity (PIA) assay against the F691L mutation and no activity against D835 mutations (23). Therefore, the search for novel FLT3 TKIs that overcome some of the mechanisms that result in persistent FLT3 activation is necessary to improve the cure rate for this disease.

We sought to explore the ability of a novel FLT3 inhibitor, TTT-3002, to overcome several mechanisms of drug resistance associated with current FLT3 TKIs. We have previously reported that TTT-3002 is the most potent FLT3 inhibitor discovered to date, with picomolar IC50 values against FLT3/ITD phosphorylation (24). Here we assess the activity of TTT-3002 against a broad spectrum of known FLT3/PMs, as well as a number of TKI resistance mutations within the FLT3/ITD allele. Finally, the protein binding characteristics of TTT-3002 in human plasma are explored to predict whether it is likely to maintain activity against FLT3/ITD and FLT3/PM in patients.

Materials and Methods

Compounds

TTT-3002 was a generous gift of Hanno Roder from Tau-Tis, Inc. CEP-701, AC220, sorafenib, and PKC412 were purchased from LC Laboratories. Compounds were dissolved in 100% DMSO and prepared as 10 μmol/L stock solutions in RPMI with 0.1% DMSO and stored at −80°C.

Immunoprecipitation and Western blotting

Cells were cultured in the presence of inhibitor for 1 hour at 37°C, and FLT3 and phospho-FLT3 expression was analyzed by performing immunoprecipitation of whole cell extracts for FLT3 (S-18), followed by SDS-PAGE and Western blotting as described previously (24). Other proteins were detected from whole cell lysates using the indicated antibodies and a horse-radish peroxidase–conjugated goat anti-rabbit secondary antibody followed by enhanced chemiluminescence.

Flow cytometry analysis

Flow cytometry analysis was performed using a BD FACS-Calibur machine (BD Biosciences). The following anti-mouse monoclonal antibodies and dyes were used for the staining of cellular markers: CD135-PE, Annexin V-APC, 7-amino-actinomycin (7-AAD; BD Biosciences). For hematopoietic stem/progenitor staining, femur, tibia, hips, and spine were isolated from Ba/F3-F691L/ITD Luc+ transplant recipient mice. BM cells were isolated by crushing and stained with anti-mouse CD135-PE (5 μL) for 40 minutes. Apoptosis was measured by incubating treated cells with Annexin V-APC antibody and 7-AAD for 10 minutes according to the manufacturer’s instructions (BD Biosciences). All data were analyzed by FlowJo analysis software (Tree Star).

Macromolecular modeling

To position TTT-3002, CEP-701, PKC412, AC220, and sorafenib on the FLT3 kinase structure (1RJB; ref. 25), the kinase domains of the VEGFR2 kinase complexed with sorafenib (4ASD; ref. 26) and the C-terminal Src kinase complexed with staurosporine (1BYG; ref. 27) were superimposed on the FLT3 kinase structure. The program COOT (28) was used to generate the N676K, F691L, and G697R substitutions by replacing the native side chain with the most common rotamer of the resistance variant.

Transplantation experiments

Transplantation of Ba/F3-F691L/ITD luciferase-expressing cells was performed as described previously (24, 29). For engraftment, 2 × 106 cells were injected by tail vein into female BALB/C mice (day 0). Starting 7 days later, engraftment was confirmed by bioluminescence imaging of luciferase-expressing cells and mice were then treated with 6 mg/kg of TTT-3002 hydrochloride suspended by brief sonication 1 hour before dosing in 1 mmol/L HCl twice daily or 10 mg/kg of sorafenib suspended in 30% (w/v) Cremorphor EL, 30% (w/v) PEG 400, 10% ethanol, and 10% glucose (all Sigma-Aldrich), as described previously, once daily by oral gavage for 2 weeks (30). Mice were imaged by injecting n-luciferin (3 mg intraperitoneally) and visualized on an IVIS Spectrum imager (Caliper LifeSciences) using Living Image software for analysis on day 7 post-inoculation in order to monitor engraftment. BM cells were harvested from the femur, tibia, and hips by crushing, and spleens were harvested by mechanically filtering through a 40-μm nylon cell strainer (BD).
**Patient samples**

Human AML BM samples were collected under an institutionally approved protocol with informed patient consent in accordance with the Declaration of Helsinki. Mononuclear cells were isolated by Ficoll centrifugation and cryopreserved until use in liquid nitrogen. All studies used freshly thawed cells. Plasma was purified by centrifugation (450 × g) and stored at −20°C.

**Statistical analysis**

Statistical analysis was performed with the Student t test by use of the GraphPad software analysis program (Prism). P values of less than 0.05 were considered to be statistically significant. All data are presented as the mean ± SD.

Additional information on Materials and Methods can be found in Supplementary Information.

**Results**

**TTT-3002 activity against FLT3-activating point mutations**

Many FLT3-activating point mutations have been observed in patients with AML and the response of each FLT3/PM to each FLT3 TKI varies widely (2, 3), (31–34). Notably, AC220 has reduced potency against many FLT3/PMs, and is thus ineffective in treating patients with these mutations. To predict the ability of TTT-3002 to inhibit FLT3/PM autophosphorylation, we generated a panel of 12 stably transfected Ba/F3 cell lines in which FLT3/PMs known to transform the cells to IL3 independence were introduced, and its activity was compared directly to the cytotoxic activity of AC220 (Supplementary Table S1). This panel included the most frequently occurring D835 mutations (Y/F/V/H) and other D835 variants, as well as I836 mutations and mutations in the juxtamembrane domain (V579A and D593A). TTT-3002 is a potent inhibitor of all 12 mutants screened, with proliferation IC_{50} values in the low nanomolar range, and is thus active against many FLT3/PMs for which AC220 is completely ineffective (Fig. 1A and Supplementary Table S1). Treatment with TTT-3002, but not AC220, results in a marked induction of apoptosis of FLT3/PM-expressing cells as determined by Annexin V binding, reaching the half maximal effective concentration (EC_{50}) by 10 nmol/L for all mutants. In contrast, activity against FLT3/ITD-expressing cells is similar for the 2 compounds (Fig. 1B). TTT-3002 inhibits FLT3/PM phosphorylation in a dose-dependent manner, achieving greater than 50% inhibition of FLT3 signaling at a concentration of 0.5 nmol/L (Fig. 1C and D). In contrast, AC220 failed to achieve thorough FLT3/ITD phosphorylation even at 10 nmol/L concentrations (Fig. 1C). Therefore, TTT-3002’s broad spectrum of activity against FLT3/PMs increases its therapeutic potential in patients with this class of non-ITD-activating FLT3 mutations.

**TTT-3002 activity against FLT3 TKI resistance mutations**

The phenomenon of drug resistance caused by selection for FLT3 point mutations is occurring at increasing frequency as higher levels of inhibition by FLT3 TKIs are achieved in clinical trials of patients with FLT3/ITD AML (19, 20, 35–37). To test the ability of TTT-3002 to successfully treat some of these resistance mutations, site-directed mutagenesis was used to generate a series of FLT3/ITD TKI-resistant Ba/F3 cell lines (29, 38). The activity of TTT-3002 was then compared with that of a number of other FLT3 TKIs currently in clinical trials. TTT-3002 is the most potent inhibitor against the 6 FLT3/ITD TKI resistance mutants screened, with proliferation IC_{50} values of approximately 1 nmol/L (with the single exception of Ba/F3-G697R/ITD, IC_{50} = 11 nmol/L; Fig. 2A and Table 1). It effectively inhibits resistance mutations, against which other TKIs are ineffective. The activities of CEP-701, sorafenib, AC220, and PKC412 against these resistance mutants is similar to what has been reported previously (21, 29). TTT-3002 inhibits FLT3 phosphorylation in a dose-dependent manner in FLT3/ITD TKI resistant cells, often with an IC_{50} of less than 250 to 500 pmol/L (Figure 2B). The extent of inhibition is also significantly greater than the other TKIs at a fixed concentration of 20 nmol/L, achieving 75% to 99% inhibition of FLT3 signaling (Fig. 2C and D). TTT-3002 also inhibits phosphorylation of downstream targets of FLT3 signaling, such as STAT5, AKT, and MAPK (Fig. 2E and Supplementary Fig. S1). Therefore, this compound’s broad spectrum of activity against FLT3/ITD TKI resistance mutations may enable it to successfully treat patients with FLT3/ITD AML who have become resistant to other FLT3 TKIs.

**Molecular modeling of the TKI-FLT3 binding interaction**

To understand the patterns of drug resistance displayed by different FLT3 TKIs in this study, the positions of staurosporine-like (TTT-3002, CEP-701, and PKC412) and sorafenib-like inhibitors (sorafenib and AC220) bound to FLT3 were modeled (Fig. 3). Although crystal structures of the FLT3 kinase bound to these inhibitors have not been determined, crystal structures of the related VEGFR2 and C-terminal Src kinases bound to sorafenib (PDB code 4ASD) and staurosporine (PDB code IBYG), respectively, have been determined (25, 26). Assuming that these drugs bind similarly to FLT3 kinase, we superimposed the kinase domains of the VEGFR2:sorafenib and C-terminal Src kinases:staurosporine complexes on the FLT3 kinase structure to generate a model for how sorafenib and staurosporine are likely to bind to FLT3. Inspecting these models to investigate the likely effects of amino-acid substitutions in FLT3 known to confer resistance to TKIs in clinical trials shows that substituting arginine for glycine at position 697 places side-chain atoms within 2.8 and 3.5 Å of atoms of staurosporine-like and sorafenib-like inhibitors, respectively, likely leading to steric clashes. Glycine 697 adopts main-chain dihedral angles (phi of 60°, psi of −170°) that are unfavorable for non-glycine amino acids, and an arginine substitution at this site would also lead to at least local changes in main-chain conformation. It has been proposed that the F691 residue forms a stabilizing π–π stacking interaction with AC220, and thus a mutation to a Leu would result in reduced TKI binding affinity (20). TTT-3002 is predicted to bind FLT3 without making direct contact with the F691 residue, and thus is unaffected by mutations at this site. Likewise, the closer proximity of F691 and N676 to sorafenib compared with...
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Figure 1. TTT-3002 is active against FLT3-activating point mutations. A, Ba/F3 cells stably transfected with the indicated FLT3-activating point mutations were treated for 48 hours, and cell proliferation was measured by MTT assay. Error bars indicate average ± SD; data are representative of three independent experiments. B, Annexin V binding at 48 hours following treatment with TTT-3002 or AC220, with error bars indicating average ± SD. The half maximal effective concentration (EC50) is indicated on the graph. C, inhibition of pFLT3 in Ba/F3-FLT3/ITD and FLT3/PM cells. Fraction of pFLT3/FLT3 relative to DMSO treatment is indicated below each blot. D, quantitation of C, represented by fraction of pFLT3/FLT3 relative to DMSO control, at 0.5 and 10 nmol/L TTT-3002. Data represent average of three independent experiments ± SD. The half maximal inhibitory concentration (IC50) is indicated on the graph.
A

Ba/F3-ITD

% OD vs. DMSO control

Ba/F3-F691L/ITD

% OD vs. DMSO control

Ba/F3-D835Y/ITD

% OD vs. DMSO control

Ba/F3-N676K/ITD

Drug conc. (nmol/L)

B

Ba/F3-F691L/ITD

0 0.25 0.5 1 2

nmol/L

pFLT3

FLT3

Ba/F3-D835Y/ITD

pFLT3

FLT3

Ba/F3-N676K/ITD

pFLT3

FLT3

C

DMSO

TTT-3002

CEP701

Sorafenib

AC220

PKC412

Ba/F3-ITD

pFLT3

FLT3

Ba/F3-F691L/ITD

pFLT3

FLT3

Ba/F3-D835Y/ITD

pFLT3

FLT3

Ba/F3-N676K/ITD

pFLT3

FLT3

D

pFLT3/FLT3 vs. DMSO control

TTT-3002

CEP701

Sorafenib

AC220

PKC412

Ba/F3-ITD

Ba/F3-F691L/ITD

Ba/F3-D835Y/ITD

Ba/F3-N676K/ITD

Ba/F3-G697R/ITD

Ba/F3-Y842C/ITD

E

Ba/F3-F691L/ITD

pSTAT5

STAT5

Ba/F3-N676K/ITD

pAkt

Akt

pMAPK

MAPK

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TTT-3002 Overcomes FLT3 TKI Limitations

Table 1. Proliferation IC50 for FLT3 TKI treatment of FLT3 mutants

<table>
<thead>
<tr>
<th>Cell line</th>
<th>TTT-3002 (nmol/L)</th>
<th>CEP701 (nmol/L)</th>
<th>Sorafenib (nmol/L)</th>
<th>AC220 (nmol/L)</th>
<th>PKC412 (nmol/L)</th>
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<tr>
<td>Ba/F3-ITD</td>
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<td>10</td>
<td>&lt;2</td>
<td>&lt;2</td>
<td>5</td>
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<tr>
<td>Ba/F3-F691L/ITD</td>
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<td>12</td>
<td>&gt;100</td>
<td>&gt;100</td>
<td>7</td>
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<tr>
<td>Ba/F3-D835Y/ITD</td>
<td>0.3</td>
<td>9</td>
<td>&gt;100</td>
<td>47</td>
<td>22</td>
</tr>
<tr>
<td>Ba/F3-N676K/ITD</td>
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<td>6</td>
<td>36</td>
<td>8</td>
<td>44</td>
</tr>
<tr>
<td>Ba/F3-N676D/ITD</td>
<td>1</td>
<td>6</td>
<td>48</td>
<td>4</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Ba/F3-Y842C/ITD</td>
<td>1.7</td>
<td>17</td>
<td>&gt;100</td>
<td>45</td>
<td>16</td>
</tr>
<tr>
<td>Ba/F3-G697R/ITD</td>
<td>11</td>
<td>55</td>
<td>&gt;100</td>
<td>&gt;100</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Ba/F3 parental</td>
<td>&gt;100</td>
<td>&gt;100</td>
<td>&gt;100</td>
<td>&gt;100</td>
<td>&gt;100</td>
</tr>
</tbody>
</table>

TTT-3002 overcomes drug resistance in vivo

To assess the ability of TTT-3002 to overcome TKI resistance in vivo, a bioluminescent mouse model of leukemia was utilized in which luciferase-expressing Ba/F3-F691L/ITD cells (Ba/F3-F691L/ITD Luc+) were transplanted into syngeneic BALB/c recipients. The Ba/F3-F691L/ITD Luc+ cell line is sensitive to TTT-3002 treatment in vitro with a proliferation IC50 of <250 pmol/L for TTT-3002 versus >50 nmol/L for sorafenib (Fig. 4A). Engraftment was confirmed on day 7 by bioluminescence imaging of luciferase-expressing cells following tail vein injection of 2 × 10^6 cells in recipient mice, which were then administered TTT-3002 and sorafenib at the maximum tolerated dose of 6 mg/kg twice a day and 10 mg/kg every day, respectively, or vehicle control (1 mmol/L HCl twice a day) for 14 days (n = 4 per group; Fig. 4B; ref. 30). There was no significant effect on hemoglobin or platelet count with this drug administration schedule, with counts in the normal range at the end of the treatment period (11.0–15.1 g/dL and 592–2972 K/μL, respectively; Fig. 4C and D). Mice treated with vehicle or sorafenib succumbed to disease at 21 days post-transplant with splenomegaly and elevated CD135+ (FLT3) leukemic cells in the BM (Fig. 4E and F). In contrast, spleen weights and the number of leukemic cells (measured by their expression of CD135) in the BM of TTT-3002 treated mice were significantly reduced (P < 0.01) and these mice seemed healthy at the time of sacrifice (Fig. 4E and F). By comparison, both TTT-3002 (24) and sorafenib are effective against Ba/F3-ITD Luc+ cells in vivo under the same dosing schedule, indicating that the presence of the F691L point mutation confers resistance to sorafenib, but not TTT-3002.

To further provide proof-of-principle that TTT-3002 is active against sorafenib-resistant cells in vivo, we utilized the Ba/F3-F691L/ITD transplant model to simulate a clinical setting in which a patient relapses while undergoing therapy with sorafenib with selection for a FLT3-F691L/ITD mutation and is treated with TTT-3002 instead. Leukemic mice that received sorafenib (10 mg/kg every day) for 2 weeks were administered a single dose of sorafenib or TTT-3002 (6 mg/kg). Leukemic Ba/F3-F691L/ITD cells from the enlarged spleens were harvested 2 hours later, and inhibition of pFLT3 was observed in vivo by TTT-3002, but not sorafenib (Fig. 4G).

TTT-3002 activity against TKI-resistant relapsed AML patient samples

Primary leukemic BM samples were obtained from patients with FLT3/ITD+ AML who had initially responded to sorafenib or AC220 on clinical trials but then had developed resistance. They had relapsed with a dual D835/ITD mutation or D835 point mutation alone while on a FLT3 TKI (relapse AML1–3; Supplementary Table S2). Leukemic blasts from these patients were evaluated for their in vitro sensitivity to TTT-3002, sorafenib, and AC220, along with a BM sample from a newly diagnosed FLT3/ITD AML patient sample (AML1) for comparison. Significant effects on proliferation, induction of apoptosis, and cell signaling were observed when each of these samples was treated with TTT-3002 (Fig. 5A–C and Supplementary Table S2). The signaling changes were especially prominent in pFLT3 (85%–99% inhibition) and pSTAT5 (71%–99% inhibition), with variable effects against pAKT (80%–86% inhibition in 2/4 samples) and pMAPK (66%–73% inhibition in 2/4 samples), dependent on their level and alternative sources of activation. The proliferation IC50 for TTT-3002 was 3 to 8 nmol/L for relapsed AML samples, and the diagnostic sample (AML1) had an IC50 of 19 nmol/L. The IC50 for AC220 against relapsed AML samples, however, ranged from 250 pmol/L for TTT-3002 versus 100–500 pmol/L for AC220 (Fig. 5D and E).

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from 19 nmol/L to greater than 50 nmol/L, compared with its low nanomolar IC50 against blasts from the newly diagnosed FLT3/ITD patient (AML1). AC220 was moderately active against blasts from AML1 and one relapsed patient sample with a D835/ITD mutation (relapse AML1) with regard to apoptosis, and was also able to inhibit FLT3 phosphorylation in AML1 and relapse AML3. Sorafenib was active against only AML1 cells and none of the three relapse samples, with proliferation IC50 values greater than 50 nmol/L, the highest concentration tested. Therefore, TTT-3002 maintains activity against patient with human AML samples that have been selected for resistance to the TKIs sorafenib and AC220 in clinical trials.

Plasma protein binding properties of TTT-3002

Only free, non-protein bound levels of TKI are available to bind to target and inhibit its kinase activity. To predict the impact of human plasma protein binding on TTT-3002 efficacy in patients, we utilized the PIA assay, which we developed previously to determine the extent of FLT3 inhibition being achieved in clinical trials of multiple FLT3 TKIs (7). The PIA assay is a valuable tool because human plasma contains the entire array of proteins capable of binding to, and thus interfering with, a TKI’s activity. Utilizing Ba/F3-ITD cells, we compared the IC50 of TTT-3002 with regard to inhibiting FLT3 phosphorylation (1-hour treatment) in media supplemented with 10% FBS (standard culture conditions) to that achieved in 100% mouse or 100% human plasma from healthy donors. We found a 4-fold and 14-fold shift in IC50 values, respectively, in mouse and human plasma (Fig. 6A and B and Supplementary Table S3). This shift corresponds to approximately 75% and 93% protein binding, which is significantly lower than the binding observed for many other TKIs (7, 39). For example, although the CEP-701 IC50 for FLT3 inhibition only shifts 6-fold from RPMI with 10% FBS to 100% mouse plasma, the IC50 shifts greater than 100-fold in 100% human plasma (from 2 to 3 nmol/L to an IC50 of 700 nmol/L), which indicates plasma protein binding of >99% (7). This was the major reason for the failure of CEP-701 to show improved CR and survival rates in a phase III clinical trial (5).

To explore the disparate plasma protein binding of TTT-3002 and CEP-701, the impact of the two major human plasma proteins known to bind many TKIs, α1-acid glycoprotein (AGP), and human serum albumin (HSA) was evaluated. AGP
is an acute phase plasma protein that is often elevated as much as 4- to 5-fold in leukemia patients (5). To ascertain whether TTT-3002 is significantly bound by this protein, we treated Ba/F3-ITD cells with TTT-3002 or CEP-701 at IC95 concentrations ascertained under typical culture conditions (5 and 20 nmol/L, respectively) in media supplemented with 0 to 2 mg/mL AGP and measured the percentage of phospho-FLT3 inhibition by Western blotting. Although CEP-701 almost completely loses TKI activity with the addition of just 0.1 mg/mL AGP, the lowest concentration tested, TTT-3002 was still strongly active at physiological AGP concentrations, achieving greater than 60% FLT3 inhibition at 2 mg/mL AGP (Fig. 6C). The other major plasma protein capable of binding many drugs is HSA. TTT-3002 and CEP-701 activities were not as greatly affected by physiological levels of HSA, the most abundant plasma protein (Supplementary Fig. 2A; ref. 40). Thus, TTT-3002 should require lower doses than CEP-701 to achieve sufficient concentrations of free drug in plasma because of lower protein binding to AGP.

TTT-3002 activity in human leukemia patient plasma

To further assess the likely activity of TTT-3002 in a clinical setting, human plasma samples were obtained from a panel of patients with adult and pediatric AML at the time of diagnosis, when AGP levels are known to often be elevated. Ba/F3-ITD cells were then cultured in these plasma samples with
addition of 0 to 10 nmol/L TTT-3002 for 1 hour (Fig. 6D). TTT-3002 potently inhibits phosphorylation of FLT3/ITD in the human AML plasma samples, with an average IC₅₀ of 6.4 ± 2.6 nmol/L (n = 5). There was no significant difference between phospho-FLT3 inhibition achieved in AML patient plasma samples relative to that achieved in normal adult plasma as determined in Fig. 6A and B (IC₅₀ = 7.0 ± 0.5 nmol/L, n = 3). 

Ba/F3-ITD cells cultured in AML plasma samples supplemented with a fixed concentration of TTT-3002 (20 nmol/L) or CEP-701 (100 nmol/L) showed that TTT-3002 achieved 75% to 85% inhibition of FLT3 phosphorylation whereas CEP-701 was inactive under these conditions (Fig. 6E and F). The CEP-701 result in plasma is in stark contrast to what was observed at the same concentrations in cell culture media with 10% FBS and remains the most likely explanation for its failure in clinical trials. We found that TTT-3002 was highly active across the AGP and HSA concentration ranges measured in the plasma samples (0.5–2 mg/mL AGP, 2.5–4.0 g/dL HSA; Supplementary Fig. S2B and S2C).

Discussion

TTT-3002 has been identified as a novel, potent small molecule inhibitor of mutant FLT3 phosphorylation (24). There are a number of mechanisms by which patients can develop resistance to FLT3 inhibition by current TKIs. One such clinical observation is the emergence of resistance mutations in FLT3/ITD-expressing cells, which render the cells insensitive to TKI treatment. Other studies indicate that activating point mutations in FLT3, which are found in 7% to
TTT-3002 Overcomes FLT3 TKI Limitations

Figure 6. TTT-3002 is active in AML patient plasma and has lower affinity for human plasma proteins compared with CEP-701. A, inhibition of phospho-FLT3 (pFLT3) by TTT-3002 or CEP-701 in Ba/F3-ITD cells cultured in RPMI-1640 with 10% FBS, 100% human plasma, or 100% BALB/C mouse plasma. B, quantitation of A; results of three independent experiments are represented as % pFLT3/FLT3 relative to DMSO control ± SD. C, inhibition of pFLT3 in Ba/F3-ITD cells cultured in RPMI-1640 supplemented with 10% FBS and AGP (0-2 μg/mL) by TTT-3002 (5 nmol/L, top) or CEP-701 (20 nmol/L, bottom). Fraction of pFLT3/FLT3 relative to DMSO control is indicated below each blot. Representative examples of adult AML 1, 2, and 3 are shown. D, inhibition of pFLT3 in Ba/F3-ITD cells cultured in 100% plasma from three adults with AML and three healthy adults by TTT-3002 (20 nmol/L) or CEP-701 (100 nmol/L) for 1 hour, and analyzed as in D. Data represented as fraction of pFLT3/FLT3 relative to DMSO control. Error bars indicate average ± SD (n = 6; ***, P < 0.0001; **, P = 0.01). E, representative examples of adult AML plasma (n = 3) from E. Fraction of pFLT3/FLT3 relative to DMSO control is indicated below each blot.

In vitro activity of TTT-3002 against a broad spectrum of FLT3/PM-activating mutations, as well as a variety of TKI resistance mutations in the FLT3/ITD sequence was demonstrated. TTT-3002 reduced cell viability and inhibited FLT3 autophosphorylation in a dose-dependent manner at low nanomolar to picomolar concentrations. Although only the D835Y variant in the FLT3/ITD allele was tested, inhibition of FLT3/D835F, D835V, D835H, and other activating FLT3 point mutations was also demonstrated. This implies that TTT-3002 would also likely target these D835 TKI-resistant variants in a FLT3/ITD allele.

Another major factor that limits the efficacy of FLT3 TKIs in clinical trials, aside from lack of activity against FLT3/PMs and selection for TKI resistance mutations in FLT3/ITD, is the extensive protein binding for many TKIs that occurs in human plasma. In the case of CEP-701, the compound is >99.9% protein bound in plasma. Similar binding properties have also been reported for PKC412 (>99%), sorafenib (99.7%), and AC220 (99%; refs. 7, 39, and 41). This large amount of protein binding limits the amount of free drug available to inhibit target, reducing the efficacy of some of these TKIs in clinical trials. TTT-3002 shows more moderate protein binding in human plasma (93%). This predicts that the shift in the dose–response curve for TTT-3002 going from cell culture conditions with 10% FBS to human patients should not be as extreme as it is for some other TKIs. Thus, achieving a total level of ≥30 nmol/L should achieve >90% FLT3 inhibition, given the average Kd of 2 nmol/L against FLT3/ITD phosphorylation by Western blotting. These are the approximate
levels that one would aim to achieve at the trough level of the drug and thus would help to determine dose and frequency of administration in a future clinical trial.

The extensive preclinical studies highlighted both here and in a previous manuscript (24) support the advancement of TTT-3002 toward human clinical trials. Further studies will be required to assess the safety and toxicity in nonrodent animal models before moving this compound into human clinical trials, where assessment of absorption, bioavailability, pharmacokinetics, and pharmacodynamics can be determined. Drug dosing schedule and tolerance in humans will also need to be determined in phase I trials before moving to trials in patients with relapsed/refractory/resistant FLT3 mutant AML.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

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