TPX-0131, a Potent CNS-penetrant, Next-generation Inhibitor of Wild-type ALK and ALK-resistant Mutations

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ABSTRACT

Since 2011, with the approval of crizotinib and subsequent approval of four additional targeted therapies, anaplastic lymphoma kinase (ALK) inhibitors have become important treatments for a subset of patients with lung cancer. Each generation of ALK inhibitor showed improvements in terms of central nervous system (CNS) penetration and potency against wild-type (WT) ALK, yet a key continued limitation is their susceptibility to resistance from ALK active-site mutations. The solvent front mutation (G1202R) and gatekeeper mutation (L1196M) are major resistance mechanisms to the first two generations of inhibitors while patients treated with the third-generation ALK inhibitor lorlatinib often experience progressive disease with multiple mutations on the same allele (mutations in cis, compound mutations). TPX-0131 is a compact macrocyclic molecule designed to fit within the ATP-binding boundary to inhibit ALK fusion proteins. In cellular assays, TPX-0131 was more potent than all five approved ALK inhibitors against WT ALK and many types of ALK resistance mutations, e.g., G1202R, L1196M, and compound mutations. In biochemical assays, TPX-0131 potently inhibited (IC_50 <10 nmol/L) WT ALK and 26 ALK mutants (single and compound mutations). TPX-0131, but not lorlatinib, caused complete tumor regression in ALK (G1202R) and ALK compound mutation-dependent xenograft models. Following repeat oral administration of TPX-0131 to rats, brain levels of TPX-0131 were approximately 66% of those observed in plasma. Taken together, preclinical studies show that TPX-0131 is a CNS-penetrant, next-generation ALK inhibitor that has potency against WT ALK and a spectrum of acquired resistance mutations, especially the G1202R solvent front mutation and compound mutations, for which there are currently no effective therapies.

Introduction

Chromosomal rearrangements of the anaplastic lymphoma kinase (ALK) gene produce oncogenic fusion proteins, which occur in 3% to 5% of patients with non–small cell lung cancer (NSCLC; refs. 1, 2). These fusion proteins exhibit aberrant dimerization or oligomerization that results in constitutive ALK activation (3, 4). The fusion of ALK with echinoderm microtubule-associated protein-like 4 (EML4) gene to form EML4-ALK was found to be highly oncogenic in preclinical NSCLC models (4). Targeting the kinase domain of EML4-ALK with small-molecule ALK inhibitors results in clinical benefit for patients with ALK+ NSCLC (5, 6). To date, three generations of ALK inhibitors have been approved, comprising first- (crizotinib), second- (alectinib, brigatinib, ceritinib), and third-generation (lorlatinib) therapies. However, the durability of responses to these therapies can be abrogated, in part, due to the emergence of ALK mutations that interfere with drug binding (5, 6). Crizotinib was approved in 2011 for patients with ALK+ NSCLC and has a 74% objective response rate in the first-line setting (7). However, crizotinib treatment can lead to resistant mutations in the ALK active site, for example, G1269A and C1156Y, and to the gatekeeper residue L1196M (8, 9), which limit its durability of response. Second-generation ALK inhibitors (alectinib, brigatinib, ceritinib) are approved for use in patients with ALK+ NSCLC but are also susceptible to resistance from ALK mutations such as solvent front mutations (e.g., G1202R), which are found in 33% to 37% of relapsed patients, I1171 mutations in the hydrophobic regulatory spine (24%–26% of patients), and the L1196M gatekeeper mutation (17%–22% of patients; refs. 8, 10, 11). The third-generation ALK inhibitor lorlatinib is approved for patients with ALK+ NSCLC who have been previously treated with crizotinib and at least one other ALK inhibitor, or after first-line treatment with either alectinib or ceritinib (11, 12). However, ALK mutations are detected in 76% of plasma specimens from patients whose disease progressed on lorlatinib treatment: L1196M (38%), G1202R (28%), D1203N (24%), F1174C/L (14%), and I1171X (14%; ref. 11). These mutations are a mixture of single mutations and compound mutations with compound mutations found in 35% to 48% of treated patients (11, 13). The reemergence of single mutations
such as L1196M and G1202R may be due to lorlatinib’s moderate potency against these mutations (L1196M IC_{50} 18–30 mmol/L, G1202R IC_{50} 37–63 mmol/L; refs. 13, 14). Therefore, a central nervous system (CNS)-penetrant, highly potent wild-type (WT) ALK inhibitor that is not susceptible to resistance from mutations that arise from treatment with first-, second-, and third-generation ALK inhibitors is needed.

TPX-0131 is compact macrocyclic inhibitor designed to fit completely in the ATP-binding pocket with a minimal binding interface to achieve potent inhibition of WT ALK and reduce the susceptibility to a broad range of ALK drug-resistant mutations (solvent front, gatekeeper, hinge region, and compound mutations). Using a combination of biochemical, cellular, and in vivo preclinical assessments, TPX-0131 has been shown to be a CNS-penetrant molecule that potently inhibits WT ALK and a broad array of clinically relevant ALK mutants that limit the utility of previous generations of ALK inhibitors.

Materials and Methods

Reagents and chemicals

Crizotinib, ceritinib, alectinib, and lorlatinib were purchased from Selleckchem. Brigatinib was purchased from MedChem Express. Reagents and chemicals were purchased from Sigma-Aldrich and Fisher Scientific.

Preparation of (4S)-4-(difluoromethyl)-8-fluoro-13,13-dimethyl-3,4,13,14-tetrahydro-6H-1H-pyrazolo[4,3-f][1,4,8,10]benzoazatriacycloctidine-15(12H)-one (TPX-0131)

The synthetic scheme is described in Supplementary Fig. S1. Tert-butyl (1-(2-(chloromethyl)-4-(metheno)[1,4]oxazino[3,4-c]pyrazolo[4,3-f][1,4,8,10]benzoazatriacycloctidine-15(12H)-one (TPX-0131) was designed by using Prime MM-GBSA with the OPLS4 force field. The ALK crystal structure was from the PDB database (PDB 2XP2).

Biochemical kinase analysis

The biochemical kinase assays were performed at Reaction Biology Corporation following previously described procedures (15). Specific kinase/substrate pairs along with required cofactors were prepared in reaction buffer (20 mmol/L HEPES pH 7.5, 10 mmol/L MgCl2, 1 mmol/L EGTA, 0.02% Brij35, 0.02 mg/mL BSA, 0.1 mmol/L Na3VO4, 2 mmol/L dithiothreitol, 1% DMSO). Compounds were delivered into the reaction, followed about 20 minutes later by addition of a mixture of ATP (Sigma) and γ-[32P]-ATP (Perkin Elmer) to a final concentration of 10 μmol/L. Reactions were carried out at room temperature for 120 minutes, followed by spotting of the reactions onto P81 ion exchange filter paper (Whatman Inc.). Unbound phosphate was removed by extensive washing of filters in 0.75% phosphoric acid. After subtraction of background derived from control reactions containing inactive enzyme, kinase activity data was expressed as the percent remaining kinase activity in test samples compared with vehicle (DMSO) reactions. IC_{50} values and curve fits were obtained using GraphPad Prism software (GraphPad, Inc.).

Cell lines and cell culture

Ba/F3 cells (a murine IL3-dependent B cell line) were maintained in RPMI1640 supplemented with 10% FBS, 1 ng/mL of mouse IL3, and 100 U/mL of penicillin/streptomycin. Ba/F3 stable cell lines were maintained in RPMI1640 supplemented with 10% FBS, 100 U/mL of penicillin, and 0.5 μg/mL puromycin solution.

Cloning and creation of stable Ba/F3 cell lines

The WT EML4-ALK gene (variant 1) and its mutations (G1202R, L1196M, L1198F, G1269A, G1269S, I1171N, I1171S, I1171T, G1202R/L1196M, G1202R/L1198F, G1202R/C1156Y, L1196M/L1198F, L1198F/I1171N, G1202R/G1269A, G1202R/G1269A/L1204V, G1202R/G1269A/L1198F) were synthesized at GenScript and cloned into pCDH-CMV-MCS-EF1-Puro plasmid (System Biosciences, Inc.). Ba/F3 cells lines containing WT EML4-ALK or its mutations (G1202R, L1196M, L1198F, G1269A, G1269S, I1171N, I1171S, I1171T, G1202R/L1196M, G1202R/L1198F, G1202R/C1156Y, L1196M/L1198F, L1198F/I1171N, G1202R/G1269A, G1202R/G1269A/L1204V, G1202R/G1269A/L1198F) were generated by transducing Ba/F3 cells with lentivirus containing WT or mutant EML4-ALK. Stable cell lines were selected by puromycin treatment, followed by IL3 withdrawal. Briefly, 5 × 10^5 Ba/F3 cells were transduced with lentivirus supernatant in the presence of 8 μg/mL puromycin sulfate. The transduced cells were subsequently selected with 1 μg/mL puromycin in the presence of IL3-containing medium RPMI-1640 plus 10% FBS. After 10 to 12 days of selection, the surviving cells were further selected for IL3-independent growth.
Cell proliferation assays
Two-thousand Ba/F3 cells harboring EML4-ALK (WT or mutant variants) were seeded per well in 384-well white plates for 24 hours, and then treated with compounds for 72 hours (at 37°C, 5% CO2). Cell proliferation was measured using CellTiter-Glo luciferase-based ATP-detection assay (Promega) following the manufacturer’s protocol. IC50 determinations were performed using GraphPad Prism software (GraphPad, Inc.).

Immunoblotting for cellular kinase phosphorylation assays
Half a million cells (Ba/F3 EML4-ALK WT, G1202R, G1202R/ L1196M, and G1202R/L1198F) per well were seeded in 24-well plate for 24 hours, and then treated with compound for 4 hours. Cells were collected after treatment and lysed in radioimmunoprecipitation assay buffer (50 mmol/L Tris, pH 7.4, 150 mmol/L NaCl, 1% NP 40, 0.5% deoxycholate, 0.1% SDS) supplemented with 10 mmol/L EDTA, 1× Halo Protease and Phosphatase Inhibitor (Thermo Scientific). Protein lysates (approximately 20 μg) were resolved on 4%–12% Bolt Bis-Tris precast gels with MES running buffer (Life Technologies), transferred to nitrocellulose membranes using Trans-Blot Turbo Transfer System (Bio-Rad), and detected with antibodies targeting phosphorylated ALK (Y1282/1283), ALK (Y1604), total ALK, and actin (Cell Signaling Technology). Antibodies were typically incubated overnight at 4°C with gentle shaking, followed by washes and incubation with the appropriate horseradish peroxidase (HRP)–conjugated secondary antibodies. Membranes were incubated with chemiluminescent substrate for 5 minutes at room temperature (SuperSignal West Femto; Thermo Scientific). The chemiluminescent images were acquired with a C-DiGit Imaging System (LI-COR Biosciences). The relative density of the chemiluminescent bands was quantified via Image Studio Digits from LI-COR.

In vivo xenograft studies
All animal studies were conducted in accordance with the guidelines published in the Guide for the Care and Use of Laboratory Animals. Mice were maintained and used in accordance with animal protocol EB17–010 (approved by Explora BioLabs’ Institutional Animal Care and Use Committee (IACUC)). Female SCID/beige mice (5–8 weeks old) were obtained from Charles River Laboratory and were housed in Innovative IVF disposable cages on HEPA-filtered ventilated racks with ad libitum access to rodent chow and water. Five million cells in 100 μL serum-free medium supplemented with 50% Matrigel (Corning, Inc.) were implanted subcutaneously in the right flank region of each mouse. Tumor size and body weight were measured about four times per week. Tumor volume was calculated as length × width²/2. TPX-0131 was used as a control. Mice were randomized by tumor size into treatment groups when tumor volume reached about 150 to 200 mm3. TPX-0131 formulated in C‐Dex (4, 10, and 100 mg/kg) were intraperitoneally injected once daily for 28 days to male Sprague Dawley rats. Pharmacokinetic profiles using individual and mean plasma concentrations of TPX-0131 were evaluated on study Days 1 and 7 after dosing. Terminal TPX-0131 concentrations (1, 4, and 24 hours postdose on study day 7) in plasma, cerebrospinal fluid, and brain tissue samples were analyzed by LC/MS-MS to assess brain tissue distribution. A detailed description of the methods for pharmacokinetic analyses and determining rat brain penetration can be found in Supplementary Analysis.

Results

Pharmacokinetics and brain distribution properties of TPX-0131
Daily oral doses of 10 mg/kg TPX-0131 were administered to animals for 7 consecutive days to male Sprague Dawley rats. Pharmacokinetic profiles using individual and mean plasma concentrations of TPX-0131 were evaluated on study Days 1 and 7 after dosing. Terminal TPX-0131 concentrations (1, 4, and 24 hours postdose on study day 7) in plasma, cerebrospinal fluid, and brain tissue samples were analyzed by LC/MS-MS to assess brain tissue distribution. A detailed description of the methods for pharmacokinetic analyses and determining rat brain penetration can be found in Supplementary Analysis.

Enzymatic kinase activities against WT and mutant ALK variants
Biochemical characterization of TPX-0131 potency against WT and mutant ALK was assessed in a panel of enzymatic assays with recombinant ALK kinase domains performed at 10 μM ATP (Table 1). TPX-0131 potently inhibited WT ALK (IC50 = 1.4 nmol/L) and 26 ALK resistance mutations. TPX-0131 inhibited C1156Y, E1210K/ S1206C, L1198F/C1156Y, L1196F/M1198F, E1210K, L1196M, T1151M, deleted G1202, S1206R, G1202R/L1198F, F1174L, F1245C, R1275Q, and G1202R ALK mutations with IC50 values of <1 nmol/L. TPX-0131 had IC50 values of 1 to 2 nmol/L for the end of the treatment. A TGI >100% indicates tumor regression; TGI = 100% is equivalent to complete tumor regression. Statistical analyses were performed using GraphPad Prism 8 and P < 0.05 was considered a statistically significant difference. The pharmacodynamic and the corresponding free plasma concentrations of TPX-0131 were evaluated in mice bearing the Ba/F3 cell-derived xenograft tumors harboring an EML4-ALK fusion with G1202R/L1196M mutations. Samples were taken at 2 hours and 12 hours for pharmacokinetic and pharmacodynamic analyses (immunoblotting). For immunoblotting analysis of the phosphorylated ALK fusion proteins, tumor samples were collected by snap freezing in liquid nitrogen and processed in RIPA buffer. Immunoblotting analyses were performed as described above.
following ALK mutations: L1198F, L1152R, F1174S, T1151-L1152insT, V1180L, G1269A, F1174C. TPX-0131 was less active against ALK mutations including I1171N, L1152P, D1203N, D1203N/E1210K, and G1269S, with IC_{50} values of 2 to 7 nmol/L. Additionally, TPX-0131 was determined to be a selective ALK inhibitor by evaluating its potency toward a panel of 373 kinases (Supplementary Table S1). From this analysis, TPX-0131 has molecular properties (three dimensional shape, key binding interactions) that enable selective inhibition of ALK. Taken together, TPX-0131 was highly potent against a broad spectrum of ALK drug-resistant mutations.

**Cellular potency of TPX-0131**

To enable comparisons of TPX-0131 with previous generations of ALK inhibitors, a panel of matched cell lines was created that are dependent on ALK resistance mutations found in patients as well as other mutations that may arise in the clinic. Ba/F3 cells were engineered to express the oncogenic EML4-ALK variant 1 fusion protein, as well as EML4-ALK with either single mutations (G1202R, L1196M, L1198F, G1269A, G1269S, I1171N/S/T) or compound mutations (L1196M/L1198F, L1198F/C1156Y, L1198F/I1171N, G1202R/C1156Y, G1202R/L1196M, G1202R/L1198F, G1202R/G1269A, G1202R/G1269A/L1204V, G1202R/G1269A/L1198F). TPX-0131 potency was benchmarked against three generations of ALK inhibitors (crizotinib, ceritinib, alectinib, brigatinib, and lorlatinib). The initial assessment of cellular potency was in proliferation assays (Table 2). All tested ALK compounds had minimum activity (IC_{50} > 800 nmol/L) against parental Ba/F3 cells which means that proliferation potency values for Ba/F3 cells harboring EML4-ALK measure inhibition of ALK, not other aspects of the assay (Supplementary Table S2). TPX-0131 was the most potent inhibitor of cells harboring the WT EML4-ALK fusion. TPX-0131 WT potency (IC_{50} = 0.4 nmol/L) was two-fold more potent than lorlatinib (IC_{50} = 0.8 nmol/L) and significantly more potent relative to other ALK inhibitors: crizotinib (IC_{50} = 50 nmol/L), alectinib (IC_{50} = 7.4 nmol/L), brigatinib (IC_{50} = 12 nmol/L), and ceritinib (IC_{50} = 3.9 nmol/L). Toward cells harboring EML4-ALK with the G1202R solvent front mutation, TPX-0131 demonstrated the most potent activity (IC_{50} = 0.6 nmol/L) compared to other ALK inhibitors: crizotinib (IC_{50} = 2.3 nmol/L), alectinib (IC_{50} = 7.4 nmol/L), brigatinib (IC_{50} = 12 nmol/L), and ceritinib (IC_{50} = 3.9 nmol/L)

**Table 1. Evaluation of TPX-0131 in biochemical assays of WT and mutant ALK variants.**

<table>
<thead>
<tr>
<th>Kinase</th>
<th>IC_{50} (nmol/L)</th>
<th>Kinase</th>
<th>IC_{50} (nmol/L)</th>
<th>Kinase</th>
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</thead>
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<tr>
<td>WT</td>
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<td>G1202R/L1198F</td>
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<td>T1151-L1152insT</td>
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</tr>
<tr>
<td>C1156Y</td>
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<td>G1202R/L1198F</td>
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<td>T1151-L1152insT</td>
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</tr>
<tr>
<td>E1210K/S1206C</td>
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<td>G1202R/L1198F</td>
<td>0.5</td>
<td>T1151-L1152insT</td>
<td>1.2</td>
</tr>
<tr>
<td>L1198F/C1156Y</td>
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<td>G1202R/L1198F</td>
<td>0.5</td>
<td>T1151-L1152insT</td>
<td>1.2</td>
</tr>
<tr>
<td>L1196M/L1198F</td>
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<td>G1202R/L1198F</td>
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<td>T1151-L1152insT</td>
<td>1.2</td>
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<td>E1210K</td>
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<tr>
<td>L1196M</td>
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<tr>
<td>Deleted G1202</td>
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<td>G1202R/L1198F</td>
<td>0.5</td>
<td>T1151-L1152insT</td>
<td>1.2</td>
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</tbody>
</table>

Note: The biochemical kinase assays were performed in the presence of 10 μmol/L ATP following previously described procedures (15).
potent inhibition of cell proliferation (IC_{50} = 0.2 nmol/L), which was at least 260-fold more potent than any other tested ALK inhibitor. TPX-0131 was the most potent inhibitor against the L1198F mutation in the hinge region with an IC_{50} < 0.2 nmol/L and was 90- to 3,000-fold more potent than other ALK inhibitors. TPX-0131 was moderately potent against cells harboring the EML4-ALK G1202R mutation (IC_{50} = 13 nmol/L) and was less active against a serine mutation at this position (IC_{50} = 701 nmol/L). TPX-0131 was not highly potent against single I1171N/S/T mutations (IC_{50} = 189 – 516 nmol/L). Taken together, TPX-0131 potently inhibits WT EML4-ALK and EML4-ALK harboring a range of point mutations with significantly greater potency against many key resistance mutations, such as solvent front, gatekeeper, and hinge region mutations, relative to previous generations of ALK inhibitors.

In cell proliferation assays, TPX-0131 was the most potent inhibitor against a range of EML4-ALK compound mutations (Table 2). TPX-0131 inhibited six of nine compound mutations with IC_{50} < 1 nmol/L, had IC_{50} < 10 nmol/L for two mutations, and IC_{50} = 14.9 nmol/L for the ALK G1202R/G1269A/L1204V mutation. Previous generations of ALK inhibitors did not potently inhibit any of the nine EML4-ALK compound mutations tested (IC_{50} > 10,000 nmol/L). Of the 45 inhibitor/compound mutation combinations tested using previous generations of ALK inhibitors (nine assays, five ALK inhibitors), only four had an IC_{50} <100 nmol/L. In comparison with previous generations of ALK inhibitors, TPX-0131 was the only ALK inhibitor with significant potency against the entire panel of compound EML4-ALK mutations evaluated.

To confirm the results obtained from the cell proliferation assays, TPX-0131 and select other ALK inhibitors were evaluated in assays measuring pharmacodynamic modulation of ALK (autophosphorylation). TPX-0131 suppressed autophosphorylation of Tyr1604 and Tyr1282/1283 residues of ALK oncogenic fusion proteins in engineered stable cell lines expressing WT or mutant ALK fusion proteins (Fig. 2). TPX-0131 exhibited comparable activity to lorlatinib in suppressing WT EML4-ALK phosphorylation with an IC_{50} value of approximately 3 to 10 nmol/L. TPX-0131 was a potent inhibitor of ALK autophosphorylation in Ba/F3 cells expressing EML4-ALK G1202R solvent front, EML4-ALK G1202R/L1196M, or EML4-ALK G1202R/L1198F mutations, with IC_{50} values of approximately 3 to 10 nmol/L. Lorlatinib was much less potent at inhibiting ALK autophosphorylation in cells harboring G1202R, G1202R/L1196M, and G1202R/L1198F mutations, with IC_{50} values >100 nmol/L. The potency values in these in vitro pharmacodynamic assays correlated well with results from the cell proliferation assays and demonstrate potent inhibition of both single and compound EML4-ALK resistance mutations by TPX-0131.

**Evaluation of TPX-0131 in xenograft tumor models**

TGI and the pharmacodynamic modulation of ALK were performed in cell-derived xenograft (CDX) models for clinically relevant ALK mutants that limit the utility of previous generations of ALK inhibitors (e.g. SFM, compound mutations). In a Ba/F3 CDX of EML4-ALK fusion harboring the G1202R solvent front mutation, TPX-0131 treatment at 2, 5, and 10 mg/kg BID (twice daily) resulted in dose-dependent TGI of 64%, 120%, and 200% (complete regression), respectively (Fig. 3A). The mean free plasma trough concentration of TPX-0131 was 13.7 nmol/L at the dose level of 10 mg/kg twice daily. Treatment of these tumor-bearing mice with lorlatinib at 5 mg/kg twice daily resulted in 158% TGI. In a Ba/F3 CDX model harboring an EML4-ALK fusion with the G1202R/L1196M solvent front and hinge region compound mutation, treatment with 2, 5, and 10 mg/kg of TPX-0131 twice daily resulted in complete tumor regression at all dose levels (200% TGI); in contrast, lorlatinib treatment at 5 mg/kg twice daily resulted in 31% TGI (Fig. 3B). In a Ba/F3 CDX harboring an EML4-ALK fusion with the G1202R/L1196M solvent front and gatekeeper compound mutations, TPX-0131 treatment at 0.6, 2, 5, and 10 mg/kg twice daily resulted in dose-dependent efficacy with TGI of

**Table 2.** Inhibitory activity (IC_{50}) of TPX-0131 and other ALK inhibitors in Ba/F3 cell proliferation assays against single and compound EML4-ALK mutations.

<table>
<thead>
<tr>
<th>EML4-ALK</th>
<th>TPX-0131</th>
<th>Crizotinib</th>
<th>Alectinib</th>
<th>Brigatinib</th>
<th>Ceritinib</th>
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<td>I1171N</td>
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<td>G1202R</td>
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**Note:** IC_{50} values were determined from three independent replicates.
Figure 2.
The effect of TPX-0131 on phosphorylation of ALK in engineered Ba/F3 cell models containing WT or mutated EML4-ALK as measured by immunoblotting for ALK and phospho-ALK relative to a control protein (actin). TPX-0131 had similar potency to lorlatinib in suppressing WT EML4-ALK phosphorylation but significantly more potency against an EML4-ALK fusion carrying G1202R and compound mutations including G1202R/L1198F and G1202R/L1196M.

Figure 3.
Evaluation of efficacy of TPX-0131 in CDX models in SCID/beige mice administered TPX-0131 via oral gavage twice daily for seven consecutive days. A, Antitumor effect of TPX-0131 on Ba/F3 cell–derived xenograft model with an EML4-ALK WT fusion. B, Antitumor effect of TPX-0131 on Ba/F3 cell–derived xenograft model with an EML4-ALK G1202R/L1198F fusion. C, Antitumor effect of TPX-0131 on Ba/F3 cell–derived xenograft model with an EML4-ALK G1202R/L1196M fusion. Waterfall plots for each model represent the degree of xenograft response for each mouse. BID, twice daily. It should be noted that 5 mg/kg dosing of TPX-0131 andlorlatinib in mouse models result in different unbound exposures (e.g., 12 hours postdose TPX-0131, 8 nmol/L; lorlatinib, 358 nmol/L).
The pharmacokinetic/pharmacodynamic analysis of TPX-0131 in the EML4-ALK G1202R/L1196M xenograft model. Bar graph quantitates the degree of phosphorylation (Tyr1282/1283) modulation of ALK as a function of dose. The TPX-0131 unbound exposure is shown as red squares. Higher TPX-0131 exposure correlates with lower levels of ALK phosphorylation. Primary data can be found in the supplemental information (Supplementary Fig. S3).

Figure 4. Pharmacokinetic/pharmacodynamic analysis of TPX-0131 in the EML4-ALK G1202R/L1196M xenograft model. Bar graph quantitates the degree of phosphorylation (Tyr1282/1283) modulation of ALK as a function of dose. The TPX-0131 unbound exposure is shown as red squares. Higher TPX-0131 exposure correlates with lower levels of ALK phosphorylation. Primary data can be found in the supplemental information (Supplementary Fig. S3).

Figure 4. Pharmacokinetic/pharmacodynamic analysis of TPX-0131 in the EML4-ALK G1202R/L1196M xenograft model. Bar graph quantitates the degree of phosphorylation (Tyr1282/1283) modulation of ALK as a function of dose. The TPX-0131 unbound exposure is shown as red squares. Higher TPX-0131 exposure correlates with lower levels of ALK phosphorylation. Primary data can be found in the supplemental information (Supplementary Fig. S3).

The correlation of inhibition of ALK phosphorylation (Tyr1282/1283) was evaluated as a function of TPX-0131 plasma exposure analysis using the Ba/F3 CDX model harboring the EML4-ALK fusion with the G1202R/L1196M compound mutation (Fig. 4; Supplementary Fig. S3). For 2 and 5 mg/kg doses of TPX-0131, near complete suppression of phospho-ALK (92%–95%) was observed (Supplementary Fig. S3). However, 12 hours after single-dose TPX-0131 administration, the level phospho-ALK suppression was reduced (0%–63%) consistent with the use of a BID dosing regimen in mouse models (Supplementary Fig. S3). TPX-0131 exhibited more than 90% phosphorylation inhibition of EML4-ALK G1202R/L1196M fusion at a mean free plasma concentration of 19.5 nmol/L (Fig. 4). Tumor growth inhibition correlates with TPX-0131 exposure and suppression of ALK phosphorylation (Figs. 3 and 4). Taken together, TPX-0131 demonstrated marked antitumor effects in Ba/F3 CDX models of ALK resistance mutations such as the G1202R solvent front mutation, the G1202R/L1198F compound mutation, and the solvent gatekeeper/solvent front compound mutation G1202R/L1196M fusion. Furthermore, in vivo efficacy correlated with suppression of ALK phosphorylation.

Pharmacokinetics and brain distribution properties of TPX-0131

The pharmacokinetics and brain distribution of TPX-0131 were investigated in Sprague Dawley rats following repeat oral administration (Supplemental Analysis). The pharmacokinetic profile of TPX-0131 in male Sprague Dawley rats was characterized by rapid absorption and a long elimination half-life following a single oral administration. Following repeat oral administration of TPX-0131 (10 mg/kg/day) to rats for 7 consecutive days, brain levels of TPX-0131 were approximately 66% of those observed in plasma. These preclinical study results suggest that TPX-0131 has the potential to cross the blood–brain barrier in humans.

Discussion

Despite the approval of three generations of ALK inhibitors, disease progression for patients with ALK+ NSCLC often occurs due to treatment-resistant ALK mutations. The patterns of drug-resistant mutations are dependent on the molecular properties of the individual ALK inhibitors. Resistance to crizotinib arises, in part, through mutations in the ALK kinase domain such as L1196M, G1269A, and C1156Y (8). The second-generation ALK inhibitors alecinib, brigatinib, and ceritinib are effective against crizotinib resistance mutations but are susceptible to mutations in the solvent front region, which occur in approximately a third of patients that progress with ALK mutations (11). As such, clinicians use a sequence of ALK inhibitors (17). However, the sequence of ALK inhibitor administration can be complex and depends on the ALK mutant sensitivity profile. The complexity of inhibitor-specific responses is integrally connected to an inhibitor's molecular structure. TPX-0131, a compact macrocyclic molecule, was rationally designed based on the crystal structure of ALK to efficiently target the active kinase conformation and circumvent the steric interference conferred by resistance mutations, especially the solvent front and compound mutations (Fig. 1). By targeting the minimal binding interface of ATP in the ALK active site with a small, conformationally constrained macrocyclic structure, TPX-0131 is highly potent against wild-type ALK and many of the ALK mutations that limit the effectiveness of prior-generation inhibitors and, therefore, has the potential to become an important new therapy for both first-line treatment as well as for patients that progress on prior therapies.

Solvent front mutations are a frequent mechanism of resistance to both the first-generation inhibitor crizotinib and second-generation inhibitors (alecinib, brigatinib, ceritinib). The solvent front region occurs at the C-terminal end of the hinge and forms a hydrophobic interaction with the kinase β sheet. Prior generations of ALK inhibitors have substituents that extend into this region to achieve potent ALK inhibition; however, bulky mutations (e.g., G1202R) clash with these inhibitors, preventing potent inhibition (Fig. 1). Lorlatinib has a smaller group (pyrazole ring) extending into the solvent front region compared with previous generations of ALK inhibitors, but it resides directly over the G1202 residue. Although clinical responses in patients harboring solvent front mutations such as G1202R can be achieved with lorlatinib, these mutations are often detected in patients with relapsed disease, indicating that lorlatinib may not be optimally effective against this class of resistance mutations (11). In the current study, lorlatinib had moderate potency against the G1202R solvent front mutation (IC50 = 52 nmol/L), consistent with previous studies (13, 14). Lorlatinib is reported to achieve Cmax, approximately 155 nmol/L unbound exposure in patients (AUC0–24h, 5650 ng·h/mL, 66% plasma protein binding; FDA label) which is less than both EC50 and EC90 unbound exposure values reported for inhibition of ALK (G1202R) phosphorylation in a preclinical xenograft model (190 nmol/L, 682 nmol/L) as well as the unbound exposure necessary for maximum tumor efficacy in that preclinical model (624 nmol/L, 53%–86% regression; ref. 14). In comparison, TPX-0131 caused complete regression (200% TGI) of an EML4-ALK(G1202R) xenograft model at 13.7 nmol/L mean free plasma trough concentration (Fig. 3). The more complete tumor growth regression observed with TPX-0131 treatment may be due to the 260-fold greater cellular potency of TPX-0131 relative to lorlatinib (Table 2). Absolute potency – not just the potency relative to inhibitor exposure – may contribute toward overall in vivo efficacy due to time-dependent changes in target engagement in the dynamic environment of the human body where
both drug and target concentrations vary as a function of time (18–20). In addition to superior potency against the G1202R solvent front mutation, TPX-0131 is more potent than previous generations of ALK inhibitors against ALK mutations and represents a new generation of ALK inhibitor, which has the potential to cross the blood–brain barrier in humans. Based on in vitro and in vivo preclinical studies (Table 2), TPX-0131 is differentiated from previous generations of ALK inhibitors through both its breadth and degree of potency, which is a result of an active kinase conformation and overcoming a broad spectrum of compound mutations. TPX-0131 demonstrated a high level of CNS penetration in an in vivo preclinical model and therefore has the potential to cross the blood–brain barrier in humans. Based on in vitro and in vivo preclinical evaluations (Table 2), TPX-0131 is differentiated from previous generations of ALK inhibitors by both its breadth and degree of potency against a range of clinically relevant ALK resistance mutations and represents a new generation of ALK inhibitor that addresses a critical unmet medical need. A phase I/II clinical study of TPX-0131 focused on pretreated patients with ALK+ NSCLC is currently being initiated (NCT04849273).

Authors’ Disclosures

No disclosures were reported.

Authors’ Contributions

B.W. Murray: Conceptualization, data curation, formal analysis, writing—original draft, writing—review and editing. D. Zhai: Conceptualization, resources, formal analysis, writing—original draft. W. Deng: Conceptualization, formal analysis, supervision, writing—original draft. X. Zhang: Resources, data curation, formal analysis, methodology. H. Zhang: Resources, data curation, formal analysis, validation, methodology. M. Barrera: Resources, data curation, investigation, methodology. A. Parra: Resources, data curation, formal analysis, methodology. J. Cowell: Resources, data curation, supervision, investigation, methodology. D. J. Lee: Resources, data curation, investigation, methodology. H. Alosins: Conceptualization, data curation, formal analysis, investigation, methodology, writing—original draft.

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References

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