Entrectinib, a Pan–TRK, ROS1, and ALK Inhibitor with Activity in Multiple Molecularly Defined Cancer Indications

Elena Ardini, Maria Menichincheri, Patrizia Banfi, Roberta Bosotti, Cristina De Ponti, Romana Pulci, Dario Ballinari, Marina Ciomei, Gemma Texido, Anna Degrassi, Nilla Avanzi, Nadia Amboldi, Maria Beatrice Saccardo, Daniele Casero, Paolo Orsini, Tiziano Bandiera, Luca Mologni, David Anderson, Ge Wei, Jason Harris, Jean-Michel Vernier, Gaël Li, Eduard Felder, Daniele Donati, Antonella Isacchi, Enrico Pesenti, Paola Magnaghi, and Arturo Galvani

Abstract

Activated ALK and ROS1 tyrosine kinases, resulting from chromosomal rearrangements, occur in a subset of non–small cell lung cancers (NSCLC) as well as other tumor types and their oncogenic relevance as actionable targets has been demonstrated by the efficacy of selective kinase inhibitors such as crizotinib, ceritinib, and alectinib. More recently, low-frequency rearrangements of TRK kinases have been described in NSCLC, colorectal carcinoma, glioblastoma, and Spitzoid melanoma. Entrectinib, whose discovery and preclinical characterization are reported herein, is a novel, potent inhibitor of ALK, ROS1, and, importantly, of TRK family kinases, which shows promise for the therapy of tumors bearing oncogenic forms of these proteins. Proliferation profiling against over 200 human tumor cell lines revealed that entrectinib is exquisitely potent in vitro against lines that are dependent on the drug’s pharmacologic targets. Oral administration of entrectinib to tumor-bearing mice induced regression in relevant human xenograft tumors, including the TRKA-dependent colorectal carcinoma KM12, ROS1-driven tumors, and several ALK-dependent models of different tissue origins, including a model of brain-localized lung cancer metastasis. Entrectinib is currently showing great promise in phase I/II clinical trials, including the first documented objective responses to a TRK inhibitor in colorectal carcinoma and in NSCLC. The drug is, thus, potentially suited to the therapy of several molecularly defined cancer settings, especially that of TRK-dependent tumors, for which no approved drugs are currently available. Mol Cancer Ther; 15(4): 628–39. ©2016 AACR.

Introduction

In 2007, two independent studies reported that the EML4 and ALK genes were rearranged in a small subset of lung cancers to produce the EML4–ALK fusion protein, bearing an activated ALK kinase domain (1,2). Even though the occurrence of this event was restricted to 3% to 7% of non–small cell lung cancer (NSCLC) patients, this finding was highly significant because it represented the first description of a recurring gene translocation leading to the generation of an oncogenic kinase fusion protein in a major epithelial malignancy. Thus ALK, whose oncogenic role in the niche indication of anaplastic large cell lymphoma (ALCL) had long been established (3) but which had been largely overlooked as a drug target, suddenly stirred strong interest within the pharmaceutical industry, spurring the clinical development of several ALK kinase inhibitors.

A similar story is also unfolding for TRKA, the high-affinity receptor for nerve growth factor (NGF) that, together with the highly related TRKB and TRKC, constitutes the TRK subfamily of receptor tyrosine kinases (RTK). Whereas the physiologic role of TRKA is relatively well elucidated (4), its involvement in neoplastic transformation and tumor progression was until very recently limited to identification of rearrangements in papillary thyroid carcinoma (PTC), a tumor type characterized by a relatively good prognosis and reports of activation due to presence of putative autocrine loops in neuroblastoma, prostate, pancreatic, and breast cancer (5–10). However, chromosomal rearrangements involving the NTRK1 gene, resulting in the expression of different TRKA fusion proteins were recently reported by Vaishnavi and colleagues (11) in NSCLC, along with robust preclinical demonstration of the oncogenic potential of the predicted chimeric proteins. In addition, we very recently reported the presence of the recurring rearrangement TPM3-NTRK1 in colorectal carcinoma patients, together with preclinical validation data supporting the role of TPM3–TRKA fusion protein as a driver for proliferation and survival of TRK-positive tumors (12).
Although an accurate estimation of the frequency of translocation events involving TRKA in either NSCLC or colorectal carcinoma is not yet available due to the low number of cases reported to date, the data available do not support the efficacy of TRKA inhibitors in these patients. However, due to the potential for new and innovative therapeutic approaches, clinical trials with selective TRKA inhibitors are underway, targeting patients with translocations involving NTRK1 as well as NTRK2 and NTRK3, the genes which respectively encode the TRKA, TRKB, and TRKC proteins, in further tumor types (14–17). These findings provide a strong rationale for the development of TRK kinase inhibitors in several distinct selected patient populations.

An additional RTK recently identified to be involved in recurring gene rearrangements in NSCLC is ROS1, an orphan receptor whose physiologic functions are still poorly understood (18). ROS1-positive patients, representing approximately 1% of NSCLC cases, tend to possess typical clinicopathologic features similar to those described for ALK-positive NSCLC patients (18,19).

The identification of recurring chromosomal rearrangements that result in the constitutive activation of ALK, TRKA, and ROS1 kinases in different clinical indications, together with the preclinical validation of the driving role of these oncogenes in the tumors, has led to the clinical exploration of inhibitors of these kinases as novel therapeutic opportunities. The clinical proof of concept that the EML4–ALK fusion protein found in NSCLC is indeed a driver oncogene in this disease was achieved in a very short time after the initial description of this aberration. A phase I/II study of crizotinib in selected ALK-positive NSCLC patients demonstrated striking clinical efficacy of the drug in this subset, with a 60% objective response rate, resulting in accelerated approval of crizotinib in 2011 by the FDA for the treatment of ALK-positive NSCLC patients (20). However, the observation that about one third of ALK-positive NSCLC patients progresses after initial clinical response to the drug due to the acquisition of secondary mutations (21–23), together with the apparently poor ability of crizotinib to reach effective concentrations beyond the blood–brain barrier (BBB; ref. 24), have prompted the clinical development of several “second-generation” ALK inhibitors, such as ceritinib (25) and alectinib (26).

Interestingly, some of the ALK inhibitors mentioned above, most notably ceritinib itself, are also active against ROS1 (27). On the basis of this cross-reactivity and supported by the preclinical activity observed in ROS1-driven tumor models, a total of 50 ROS1-positive NSCLC patients were enrolled in an expansion cohort of the phase I study of ceritinib. The results of this study showed marked antitumor activity in this patient population and prompted the FDA to assign breakthrough therapy designation for ceritinib to support its intensive clinical development in ROS1-positive NSCLC (19,28).

Although it has long been known that TRKA is of oncogenic relevance in PTC (5), there are as of today very few selective inhibitors of this kinase in clinical development. The recent description of recurring rearrangements of the NTRK1 gene, which encodes this kinase, in subsets of major indications such as NSCLC, colorectal carcinoma together with the identification of NTRK2 and NTRK3 rearrangements in gial tumors and inflammatory breast cancer, respectively, and perhaps additional tumor types (11,12,14,16,17), has highlighted the relevance of these kinases as pharmacologic targets and the clinical need for effective inhibitors.

Here, we disclose the structure and preclinical activity profile of entrectinib (RXDX-101, also formerly known as NMS-E628, NMS-0191372), a potent, orally available inhibitor of the TRK kinases invented and initially developed at NMS, and report the characterization of its biologic activity in TRKA-driven tumor models. The studies described herein provide the scientific rationale supporting the enrollment of patients harboring TRKA-dependent tumors in clinical trials of entrectinib, which are currently ongoing (EudrACT Number:2012-000148-88, NCT02097810; refs. 29–31). Being also a potent ROS1 and ALK inhibitor, entrectinib additionally possesses excellent in vitro and in vivo antitumor activity in models derived from different tumor types that are variously dependent upon ROS1 or ALK fusion proteins, supporting the rationale for exploring its clinical activity in ROS1- and ALK-dependent tumor settings.

Materials and Methods

Compound
Entrectinib was synthesized at Nerviano Medical Sciences srl as previously reported (WO2009/013126). Crizotinib was purchased from Selleck Chemicals.

Kinase biochemical profiling
Evaluation of the selectivity of inhibitors (IC_{50}) against a panel of kinases was performed using a radiometric assay format as previously described (32). All assays were performed in house, with the exception of TRKB and TRKC, for which IC_{50} were extrapolated from percentage inhibition values at 10 and 100 nmol/L of inhibitor in duplicate obtained using the SelectScreen Kinase Profiling Services from Life Technologies using the equation: IC_{50,extrap} = ([I] × 100/% inhibition) – [I], with the assumption that Hill Slope = 1. The IC_{50} value reported in Table 1 is the average of the IC_{50} calculated at each concentration.

Cell culture and cell proliferation analysis
Human cancer cell lines were obtained from the ATCC, ECACC, Interlab Cell Line Collection (ICLC) and from NCI tumor cell line repository (see Supplementary Table S1). Cells were maintained in the media recommended by the suppliers, in a humidified 37°C incubator with 5% CO_{2}. The identity of all cell lines used in this study was verified using DNA fingerprinting technology (AmpFISTR Identifier Plus PCR Amplification kit, Applied Biosystems; ref. 33). Oncogene-driven Ba/F3 cells were generated as detailed in Supplementary Data. The antiproliferative activity of test compounds and the effect of entrectinib on cell cycle were evaluated as previously described (12).

Table 1. Enzymatic profile of entrectinib against a panel of selected kinases

<table>
<thead>
<tr>
<th>IC_{50} (nmol/L)</th>
<th>TRKA</th>
<th>TRKB</th>
<th>TRKC</th>
<th>ROS1</th>
<th>ROS2</th>
<th>ALK</th>
<th>JAK2</th>
<th>AUR2</th>
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<td>IGF1R</td>
<td>FAK</td>
<td>FLT3</td>
<td>BRK</td>
<td>IR</td>
<td>AUR2</td>
<td>JAK3</td>
<td>RET</td>
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Note: IC_{50} > 1 μmol/L: FGFR1, VEGFR2, VEGFR3, LCK, KIT, AUR1, ABL, PKCβ, CDK2/CyclA, SYK.
IC_{50} > 10 μmol/L: JAK1, CDC7, CHK1, CK2, EEF2K, EGFR1, ERK2, GSK3β, IKK2, MAPKAPK2, MELK, MET, MPS1, MST4, NEK6, NIM, p53, PAK4, PDGFRB, PDK1, PERK, PIM1, PAKa, PLK1, SULU1, ZAP70.
Western blot analysis

Cellular mechanism of action of entrectinib was investigated as described (12). The following antibodies were used for Western blot analysis: Phospho-ALK-Tyr1604 (#3341), Phospho-ROS1-Tyr2274 (#3078), ROS1 (#3266), Phospho-PLCγ1-Tyr783 (#2821), PLCγ1 (#2822), Phospho-STAT3-Tyr705 (#9131), Phospho-AKT-Ser473 (#9271), AKT (#9272), Phospho-MAPK-Thr202/Tyr204 (#9101), MAPK (#9102), caspase-3 (#9662), cleaved caspase-3 (Asp175; #9661), and PARP (#9542) from Cell Signalling Technology, STAT3 (#610189), p21 (#556431) and p27 (#610242) from BD Biosciences, actin (#A4700) from SIGMA, GAPDH (#sc-25778) from Santa Cruz Biotechnology.

Efficacy studies and ex vivo target modulation in xenograft models

All procedures adopted for housing and handling of animals were in strict compliance with Italian and European guidelines for Laboratory Animal Welfare. For epithelial models, a total of 10^7 NCI-H2228 NSCLC cells or 5 x 10^6 KM-12 colorectal carcinoma cells were transplanted subcutaneously in athymic nu/nu mice (Harlan). For the ALCL model, a total of 10^7 Karpas-299 cells were transplanted subcutaneously in SCID mice (Harlan) previously pre-treated with total body irradiation of 2 Gy. For the ROS1 model, 5 x 10^5 Ba/F3-TEL-ROS1 cells were transplanted subcutaneously in SCID mice (Harlan). Mice bearing a minimal tumor mass (150–250 mm^3) were randomized into vehicle and treated groups made of 6 to 7 animals each. Oral treatments started the day after randomization, with different doses as described. Tumor dimensions were measured regularly using Vernier calipers and length (mm) x width^2 (mm^2)/2. The percentage of tumor inhibition (%TI) was calculated as follows: %TI = 100 – (mean tumor volume of treated group/mean tumor volume of control group) x 100.

Analysis of statistical significance was performed using the Student t test (P values of less than 0.05 were considered to be statistically significant).

Toxicity was evaluated on the basis of body weight reduction. At the end of the experiment, mice were reexamined by MRI.

Generation of the NPM-ALK transgenic mouse model is described in Supplementary Data.

Efficacy study in an intracranial growth model

Twenty Balb/c male nude mice, ages 6 to 8 weeks, were used for the experiment. For intracranial injection, mice were anesthetized and stereotactically implanted in the caudate nuclei region with 2 x 10^5 NCI-H2228 cells in 2 μL. With a microdrill, a small hole was done at the chosen coordinates and cells were injected at the speed of 1 μL every minute. Hole was closed using bone wax and the wound with sterile autoclips. After the end of surgery, mice were monitored for recovery until complete wakening. Two weeks after cell implantation, all mice were examined by MRI as described in Supplementary Data and randomized into four groups (n = 6 controls; n = 7 Entrectinib 120 mg/kg; n = 7 Entrectinib 60 mg/kg; n = 7 Crizotinib 100 mg/kg). At the end of treatment (day 11) all mice were reexamined by MRI.

Results

Entrectinib is a potent inhibitor of TRK, ROS1, and ALK kinase activities

A high-throughput screening (HTS) campaign of the Nerviano Medical Sciences (NMS) collection of kinase-targeted chemical libraries performed against a series of potentially cancer-related tyrosine kinases, including ALK and TRKA, resulted in the identification of several series of hit compounds belonging to different chemical classes with intriguing activity on both ALK and TRKA tyrosine kinases. Among these, subsequent medicinal chemistry efforts within the optimization program of a 3-amino-5-substituted-indazole chemical class led to the identification of entrectinib (Fig. 1A), which was found to be a highly potent inhibitor of all three members of the TRK subfamily of tyrosine kinases TRKA, TRKB, and TRKC and of ALK, as well as of ROS1 kinases and which was endowed with favorable administration/metabolism (ADME) and toxicologic properties.

In biochemical assay, entrectinib inhibits the kinase activity of TRK family members with IC_{50} values of 1, 3, and 5 nmol/L for TRKA, TRKB, and TRKC, and of ALK and ROS1 with IC_{50} values of 12 and 7 nmol/L, respectively. Steady-state kinetic experiments performed on the ALK kinase enzyme demonstrated that entrectinib is a competitive inhibitor with respect to ATP and noncompetitive with respect to peptide substrate, thus behaving as a pure ATP competitor (Fig. 1B). When profiled against the Kinase Selectivity Screen (KSS), a panel of kinases representative of the human kinome that is used internally within NMS to profile inhibitor selectivity (34), entrectinib showed limited kinase cross-reactivity with other related kinases (Table 1). To evaluate the cellular potency and selectivity of entrectinib, the in vitro antiproliferative activity of the compound was profiled against a collection of more than 200 human tumor cell lines following 72 hours of continuous exposure (Fig. 1C and Supplementary Table S1). Entrectinib was found to be exquisite active in inhibiting the proliferation of a limited number of cell lines: although mean IC_{50} of the compound across the entire panel was approximately 2 μmol/L, only seven cell lines were inhibited with IC_{50} lower than 100 nmol/L. These were: the TRKA-driven colorectal carcinoma cell line KM12 with an IC_{50} of 17 nmol/L, the ALK-dependent ALCL cell lines SU-DHL-1, Karpas-299, SUP-M2 and SR-786 which exhibited IC_{50} of 20, 31, 41, and 81 nmol/L, respectively, the ALK-dependent NSCLC cell line NCI-H2228 with an IC_{50} of 68 nmol/L and the FLT3-dependent AML cell line MV-4-11, with an IC_{50} of 81 nmol/L.

Because we also wished to explore the biologic activity of entrectinib in cellular settings dependent upon TRKB, TRKC, or ROS1 kinases, we used engineered variants of the murine pro-B cell line Ba/F3, which is normally dependent on interleukin-3 (IL3) for growth, but can be transformed to growth factor independence by a wide range of oncogenic kinases, and
therefore represents an excellent model system for the cellular assessment of kinase inhibitor potency and selectivity (35). We generated diverse Ba/F3 cell lines exogenously expressing the ALK, TRKA, TRKB, TRKC, or ROS1 intracellular domains as ETV6/TEL or EML4 fusions. Entrectinib potently blocked proliferation of Ba/F3-TEL-TRKB (IC50: 2.9 nmol/L), Ba/F3-TEL-TRKC (IC50: 3.3 nmol/L), and Ba/F3-TEL-ROS1 (IC50: 5.3 nmol/L) cells, with a high degree of selectivity versus parental Ba/F3 cells or those transformed by nontargeted kinases such as ABL and RET, which were inhibited with IC50s in the range of 2 to 3 μmol/L. As expected from the high antiproliferative activity previously observed for entrectinib in KM12 (IC50, 17 nmol/L) is related to its ability to inhibit signaling activity of TRKA, we treated cells with a range of drug concentrations and performed Western Blot analysis to assess levels of kinase domain autophosphorylation and activation status of TRKA downstream signaling components. Entrectinib abolishes autophosphorylation of TPM3-TRKA after 2 hours treatment, concomitant with complete inhibition of the phosphorylation of PLCγ1, AKT, and MAPK (Fig. 2A). Evaluation of the cell-cycle effects of entrectinib in this tumor cell line showed that a dose as low as 10 nmol/L is able to induce accumulation of cells in the G1 phase of the cell cycle at 24 hours treatment, followed by apoptosis induction at 48 hours, as assessed by subG1 DNA content and PARP cleavage (Fig. 2B and C).

The preliminary pharmacokinetic characteristics of entrectinib in the mouse (Supplementary Table S2) suggested that the drug is highly suited to oral administration and that by this route sustained plasma levels at concentrations compatible with predicted somomal rearrangement that leads to the expression of oncogenic fusion protein TPM3–TRKA (12) was selected as an in vitro and in vivo model for characterization of entrectinib preclinical activity in a TRKA-driven setting. To confirm that the high antiproliferative activity observed for entrectinib in KM12 (IC50, 17 nmol/L) is related to its ability to inhibit signaling activity of TRKA, we treated cells with a range of drug concentrations and performed Western Blot analysis to assess levels of kinase domain autophosphorylation and activation status of TRKA downstream signaling components. Entrectinib abolishes autophosphorylation of TPM3–TRKA after 2 hours treatment, concomitant with complete inhibition of the phosphorylation of PLCγ1, AKT, and MAPK (Fig. 2A). Evaluation of the cell-cycle effects of entrectinib in this tumor cell line showed that a dose as low as 10 nmol/L is able to induce accumulation of cells in the G1 phase of the cell cycle at 24 hours treatment, followed by apoptosis induction at 48 hours, as assessed by subG1 DNA content and PARP cleavage (Fig. 2B and C).

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efﬁcacy (based on in vitro activity) can be readily achieved. Thus, nude mice bearing KM12 tumor xenografts were treated twice daily by oral administration (per os twice daily) of entrectinib at the doses of 15, 30, and 60 mg/kg for 21 consecutive days. In this study, potent tumor growth inhibition was observed (Fig. 2D), with no body weight loss or other overt signs of toxicity. Ex vivo target modulation was evaluated after 3 days of treatment at the dose of 15 mg/kg, with tumors excised at different time points after the last administration of entrectinib. Complete inhibition of TPM3-TRKA phosphorylation and of the downstream transducer PLCγ1 was observed at this dose (Fig. 2E). Interestingly, inhibition was maintained for a very long time after administration and prompted us to explore intermittent scheduling in this model. Comparably strong efﬁcacy was also observed after three repeated cycles of administration of the compound at the same doses with an intermittent 4 days on/3 days off scheduling (Supplementary Fig. S1), which is one of the dosing schedules currently being adopted in the entrectinib clinical development program (29).

Additional characterization of the pharmacologic activity of entrectinib against TRKA was performed in a TRKA-driven Ba/F3 model. Consistent with that observed for KM12 cells, entrectinib inhibits proliferation and completely suppresses TRKA phosphorylation in Ba/F3-TEL-TRKA cells with low nanomolar potency (Fig. 2F) whereas in vivo, the treatment of mice bearing Ba/F3-TEL-TRKA tumors with 30 mg/kg of drug per os twice daily for 10 days induced complete tumor regression (Fig. 2G).

As mentioned above, entrectinib resulted to be well tolerated, with no signs of overt toxicity at any of the doses and regimens tested in efficacy studies. Within the context of an exploratory repeated-dose toxicity study in the mouse, the compound was administered to animals by the oral route for 14 consecutive days up to 240 mg/kg/d, which was found to be a NOAEL (No Observed Adverse Effect Level). In this study, all animals showed good general condition at the end of the treatment period at all the doses tested. No changes in blood counts or in pathology of all the organs examined were reported: these included liver, lungs, kidneys, and brain. Interestingly, in this study no neurologic effects or abnormal behavior were observed up to maximal tested dose of 240 mg/kg/d (corresponding to an entrectinib level in the brain of 1.94 μmol/L).

Efficacy of entrectinib in a ROS1-driven model

To evaluate the activity of entrectinib against ROS1-driven tumors, we generated IL3-independent Ba/F3 cells through the expression of TEL–ROS1 fusion protein, which bears constitutively active ROS1 kinase. Entrectinib potently blocks proliferation of these Ba/F3-TEL-ROS1 cells with an IC50 of 5 nmol/L, whereas crizotinib, tested in parallel, was found to be 40-fold less potent (Table 2). As expected, the inclusion of IL3 in culture medium, which allows cells to bypass reliance on TEL-ROS1, abrogates the growth inhibitory activity of entrectinib, conﬁrming that its antiproliferative activity against this line is selectively dependent on the ability of the drug to inhibit ROS1 (Table 2). The higher potency of entrectinib against ROS1 with respect to crizotinib was also conﬁrmed by Western blot analysis of target modulation in lysates of drug-treated cells (Fig. 3A). As further validation, entrectinib and crizotinib were tested in parallel also
on TEL-ALK-driven Ba/F3 cells confirming the higher potency of entrectinib also on this target (Supplementary Fig. S2). The ROS1-driven engineered model was also used for efficacy studies: in SCID mice bearing tumors generated by s.c. injection of Ba/F3-TEL-ROS1 cells, treatment with entrectinib at 60 mg/kg per os twice daily for 10 consecutive days resulted in complete tumor regression in all animals (Fig. 3B).

**In vitro and in vivo activity of entrectinib in ALK-dependent tumors**

To confirm that the high antiproliferative activity of entrectinib in ALK-dependent tumors is related to its ability to inhibit signaling activity of this kinase, we treated various ALCL cell lines for 2 hours with a range of drug concentrations and performed Western Blot analysis, as well as cell-cycle analysis by flow cytometry (Fig. 4 and Supplementary Fig. S3). In the several cellular models tested, inhibition of *in vitro* growth correlated with modulation of driver kinase activation. In Karpas-299 cells (Fig. 4A), for example, almost complete inhibition of NPM-ALK phosphorylation can be observed at 2 hours after treatment starting from the dose of 10 nmol/L, with concomitant modulation of phospho-STAT3, which is an ALK transducer in ALCL (36). At the same doses, the drug also induced a concomitant block of the cell cycle in G1 phase, as judged by flow cytometric evaluation of DNA content (Supplementary Fig. S3A). Similar results were obtained for the other ALK-dependent ALCL cell lines examined, SR-786 (Fig. 4B and Supplementary Fig. S3B), SU-DHL-1, and SUP-M2 (Supplementary Fig. S4A and S4B).
In vivo activity of entrectinib was next evaluated against Karpass-299 xenograft tumors. Tumor-bearing animals were treated with twice daily oral administration (per os twice daily) of entrectinib at the doses of 30 and 60 mg/kg for 10 consecutive days (Fig. 4C). Both dose levels were efficacious, inducing regression of all tumors to nonpalpable dimensions. During the observation period following cessation of treatment at 60 mg/kg, tumor eradication persisted in 4 of 7 mice at day 80 after end of treatment, whereas tumor regrowth was observed in all animals treated at the dose of 30 mg/kg. Excellent efficacy was also observed in SR-786 ALCI tumor xenografts, where the dose of 30 mg/kg was sufficient to induce tumor eradication in 6 out of 7 mice at the end of the observation period (Fig. 4D).

To confirm in vivo mechanism of action of entrectinib against ALK, a study was performed in which Karpass-299 tumor-bearing animals were treated with a single oral administration of entrectinib at the doses of 30 and 60 mg/kg, followed by tumor collection at 6, 12, 18, or 24 hours following treatment (Fig. 4E). Six hours after administration of 30 mg/kg entrectinib, complete inhibition of ALK and STAT3 phosphorylation was achieved, but recovery of both signals was observed within 12 hours, whereas at 60 mg/kg complete inhibition of signaling is maintained for at least 12 hours, consistent with the greater degree of activity seen at this dose over extended observation period.

To further characterize efficacy of entrectinib in the setting of ALCI, we tested the compound against a transgenic mouse model in which the NPM-ALK oncogene (a common form of oncogenic ALK in human ALCI) is expressed in T cells under the control of the T-cell-specific Lck tyrosine kinase gene promoter. This in vivo model faithfully recapitulates the human disease, with the development of thymic lymphomas as well as tumor masses at the level of peripheral lymph nodes appearing in all transgenic animals with a latency of about 20 weeks. For the study, animals were monitored by MRI and treated with entrectinib when the tumors were well established. Figure 5 depicts the MRI scans of a representative animal bearing an extensive thymic lymphoma that invades the thoracic cavity. Treatment with entrectinib at the dose of 60 mg/kg twice daily for 2 days induced complete tumor regression by day 2. Similar results were achieved in a series of additional animals, confirming that this ALK-driven tumor is highly sensitive to treatment with entrectinib.

Because ALK is a clinically validated target in a subset of NSCLC patients whose tumors harbor EML4–ALK, the in vitro and in vivo activity of entrectinib was then evaluated in NCI-H2228, a human cell line derived from a lung adenocarcinoma patient bearing this rearrangement (Fig. 6). As observed for the ALCI lines described above, strong inhibition of ALK phosphorylation is observed following 2 hours of drug exposure, with concomitant inhibition of phosphorylation of downstream signaling components AKT and p42/44MAPK (Fig. 6A). Analysis of cell cycle distribution in cells treated with entrectinib showed an accumulation of cells in G1 phase at 24 hours after treatment and increased subG1 fraction, an indicator of apoptosis induction, at 96 hours (Fig. 6B). Consistent with this observation, Western blot analysis performed in parallel with flow cytometry showed increased levels of p21 and p27 and of PARP cleavage.

We then tested the in vivo efficacy of entrectinib in NCI-H2228 tumor xenografts. NCI-H2228 cells were injected s.c. in left flanks of nude mice and, when tumors were established (volume ca. 200 mm3), entrectinib was administered orally at the dose of 60 mg/kg twice daily for 10 consecutive days. Tumors began to regress within a few days of compound administration, and complete regression was observed in all animals at the end of the treatment period. At 97 days after the end of treatment, the last observation made for the study, 3 of 7 mice remained tumor free (Fig. 6C). Analogously, crizotinib, used as reference in the same experiment and administered for 10 consecutive days at the dose of 100 mg/kg induced complete tumor regression but tumor regrowth was observed in all treated mice few weeks after the end of treatment.

To confirm in vivo mechanism of action of entrectinib in this model, biomarker analysis by Western Blot of tumor lysates was performed on tumors excised at different time points after a single oral administration of entrectinib. This analysis confirmed strong dose-dependent modulation of ALK phosphorylation as well as of the downstream signaling component AKT consistent with the efficacy observed (Fig. 6D). Additional efficacy studies were performed in NCI-H2228 tumor-bearing animals to explore dose/scheduling of the drug. Similarly, high efficacy was maintained at the doses of 15 and 30 mg/kg per os twice daily for 10
consecutive days (data not shown). Interestingly, also in this model strong efficacy was observed after repeated cycles of administration with the 4 days on/3 days off scheduling currently used in the clinical development of entrectinib (Supplementary Fig. S5).

As mentioned above, entrectinib resulted to be well tolerated, with no signs of overt toxicity at any of the doses tested in efficacy studies. Interestingly, toxicologic studies revealed that entrectinib efficiently crosses the BBB (i.e., with drug levels within the brain comparable with or exceeding plasma levels) in all three preclinical species tested (data not shown). Because metastasis to the brain represents a major problem in the clinical care of NSCLC and is the cause of relapse in many patients treated with the ALK inhibitor crizotinib (24), this finding prompted us to evaluate the efficacy of entrectinib in a murine xenograft model of brain metastasis, in which human NCI-H2228 cells were injected intracranially in nude mice, with animals subsequently monitored by MRI until tumor masses could be clearly detected in the brain. Animals were then treated with entrectinib per os twice daily for 10 consecutive days. Because in mouse the drug distributes to brain at approximately 50% of concurrent plasma concentrations (Supplementary Table S2), a dosing of 120 mg/kg/d was initially selected for this study and crizotinib was used as comparator. Treatment with entrectinib resulted in a favorable disease control rate compared with vehicle treated animals (Fig. 6E and Supplementary Fig. S6A and S6B), that translated into a significant increase in overall survival (Fig. 6F). In addition a lower dose of entrectinib corresponding to 60 mg/kg was also tested with partial but still significant activity achieved (Supplementary Fig. S6C). As expected due to its well-known low brain penetration, crizotinib was poorly active in this model (Supplementary Fig. S6D).

Clinical experience with crizotinib as well as with second-generation ALK inhibitors reveals that a frequent cause of relapse in patients after initial clinical efficacy is the acquired resistance associated with the introduction of single point mutations that impair the binding of the inhibitor to the active site of ALK kinase. Interestingly, clinical data demonstrated that patients who relapsed due to appearance of such mutations might still benefit from treatment with an ALK inhibitor with a different binding mode (22,26,37).

With the aim of testing the activity of entrectinib on different crizotinib or ceritinib-resistant mutated forms of ALK, Ba/F3 cells were made ALK-dependent upon the expression of activated EML4–ALK wt or harboring the most relevant mutations described to date. Entrectinib showed good antiproliferative activity on ALK-driven Ba/F3 cells (Table 3), which, despite a slight loss of potency with respect to wt ALK for the latter one, is maintained in the presence of C1156Y and L1196M mutations. More than 10-fold lower activity was found when Ba/F3 cells driven by G1269A-mutated form of ALK were tested. As expected, on the basis of predicted binding mode of entrectinib, very low activity was found on G1202R mutant, a feature that is common in most with the second-generation ALK inhibitors such as ceritinib and alectinib. This finding is particularly relevant as the G1202R mutation in ALK is predicted to correspond to the G2032R mutation in ROS1 kinase, the most important acquired resistance mechanism that has been described to date in ROS1-positive NSCLC, and so based on these data we would not predict significant activity of entrectinib in such clinical cases. Nevertheless, G2032 is, as of today, the only acquired resistance mutant reported for ROS1-positive patients treated with crizotinib and we cannot exclude, based on previous experience on ALK that additional, entrectinib-sensitive ROS1 mutations will be identified.

Discussion

In the present study, we disclose for the first time the structure of entrectinib and describe the preclinical characterization of this novel, orally available, small-molecule inhibitor, which is currently being investigated in two clinical trials in adult patients with TRK-positive tumors (29–31). Its preclinical activity on ROS1- and ALK-positive tumor models additionally supports the enrollment of ROS1- and ALK-positive patients in the clinical trial. In the initial characterization of the molecule, the high biochemical potency observed against TRKA, ROS1, and ALK was reflected by remarkable activity and selectivity in cellular models. When profiled on a panel of more than 200 human tumor cell lines, entrectinib selectively inhibited proliferation of tumor cells dependent upon endogenous expression of these kinases with sub 100 nmol/L activity, with negligible activity against unrelated cell lines. Subsequent studies were conducted to confirm mechanism of action of entrectinib in TRK-, ROS1- and ALK-dependent models, and to explore in vivo antitumor activity.

With regard to these distinct oncogenic events, it is fair to say that until recently, TRKA was not considered by the pharmaceutical industry as a high priority therapeutic target in the cancer field, because the best characterized oncogenic rearrangements of its gene, NTRK1, were primarily associated with a subset of PTC, a tumor type that has a good prognosis, with thyroidectomy generally being a curative surgical procedure. No TRKA inhibitors were explored in clinical trials with the possible exception of lestaurtinib (CEP-701), a staurosporine-derivative multikinase inhibitor that was investigated in clinical settings with reported TRKA overexpression, without evidence of efficacy (7,38). However, recent studies that have identified recurring oncogenic NTRK1 rearrangements in subsets of NSCLC and colorectal carcinoma patients (11,12), as well as other studies suggesting a potential role of activated TRKA in other tumor types, including glioblastoma and Spitz melanoma (14–16,39), have created much renewed interest in the identification and clinical investigation of effective TRKA inhibitors (13). In a rapidly evolving scenario, these findings indicate that TRKA inhibition may represent an innovative opportunity for the therapy of selected patients whose tumors harbor NTRK1 gene rearrangements and this has supported the enrollment of TRKA-positive patients in ongoing clinical trials of entrectinib. Here, we report that
Figure 6.
Activity of entrectinib against NCI-H2228 NSCLC tumors. A, NCI-H2228 cells were treated with entrectinib at different concentrations for 2 or 96 hours. Levels of proteins and phospho-proteins were detected by immunoblot analysis using specific antibodies. B, NCI-H2228 cells were treated with 50 nmol/L entrectinib for 24 and 96 hours and cell-cycle distribution was evaluated by PI staining and cytofluorimetric analysis (top). Induction of apoptosis was confirmed by Western Blot analysis of PARP cleavage in treated cells (bottom). C, nu/nu mice bearing established NCI-H2228 xenografts were administered entrectinib per os twice daily at 60 mg/kg or crizotinib per os die at 100 mg/kg or vehicle for 10 consecutive days. Tumor volume for each group was measured. Data are expressed as mean ± SD (n = 7). P < 0.0001 for treated versus control group at day 70. See also Supplementary Fig. S5. D, mice bearing established NCI-H2228 xenografts were administered orally a single dose of entrectinib per os and animals were sacrificed 6, 12, or 24 hours after treatment. Tumors were resected, snap frozen, and protein lysates were analyzed by Western Blot analysis with the indicated antibodies. E, mice bearing intracranial tumors were treated with vehicle or with entrectinib orally at the dose of 120 mg/kg twice daily for 10 consecutive days. Representative magnetic resonance images of vehicle or entrectinib-treated mice are shown. To gain insight into viability and perfusion of tumors, a Dynamic Contrast Enhanced (DCE)-MRI experiment was also performed by acquiring images before and after i.v. injection of a Gd-based contrast agent (see also Supplementary Figure S6). F, survival curves of vehicle- or entrectinib-treated mice used in the experiment (E) are reported (n = 6).
entrectinib is extremely effective against the human TRKA-dependent colorectal carcinoma cell line KM12, with efficacy studies showing that oral administration yields potent tumor growth inhibition at well-tolerated doses. Ex vivo target modulation analysis showed strong correlation between in vivo antitumor activity and target inhibition, as assessed by the phosphorylation status of TRKA, as well as of the downstream signaling transducer PLCγ1, thus providing strong evidence of on-target mechanism of action. These data support the rationale for clinical development of entrectinib in TRKA-dependent indications. As entrectinib was found to be also a potent inhibitor of the other members of the TRK family, the drug is currently being explored in TRKB- and TRKC-dependent clinical settings.

While being an extremely potent TRK inhibitor, we found that entrectinib also possesses excellent biochemical activity against ROS1 kinase, which translates into potent in vitro and in vivo efficacy in a ROS1-driven tumor model. Although detailed data on remarkable clinical benefit observed in ROS1-positive patient population enrolled in an expansion cohort of the phase I clinical trial with crizotinib have been recently reported (28), we believe that our report of the high in vitro and in vivo activity of entrectinib against ROS1-driven tumor models is an additional significant finding. In particular, cellular proliferation and mechanism of action data indicate that entrectinib is in the range of 10- to 100-fold more potent against ROS1 than crizotinib, and we thus propose that it holds potential for exciting clinical activity in specific subsets of NSCLC, as well as additional settings such as cholangiocarcinoma and inflammatory myofibroblastic tumors, which harbor genetic aberrancies in ROS1 (40).

Regarding the ALK-dependent tumors examined in this study, the correlation between in vitro and in vivo antitumor activity and target inhibition, as assessed by the phosphorylation status of NPM-ALK in ALCI cell lines and of EMLA-ALK in the NSCLC cell line NCI-H2228, as well as detailed pharmacokinetic/pharmaco-dynamic studies provide confirmation of target-dependent activity of entrectinib in these models. In ALK-driven xenograft models, oral treatment with entrectinib at extremely well-tolerated doses induced remarkable tumor regression with all treated animals being tumor free by the end of a 10 days treatment period and again with persistent complete tumor eradication observed in the majority of animals.

Because the development of brain metastases is a major cause of relapse after initial clinical benefit with crizotinib (24), we believe that a highly significant feature of entrectinib is its favorable BBB penetration in all preclinical species tested. To explore this feature of entrectinib's profile, the drug was tested against an intracranial growth model of NSCLC in the mouse, showing an excellent tumor growth control rate, and suggesting that the drug may be of particular clinical benefit in patients with brain metastases. This finding is particularly relevant in the perspective of potential clinical development in indications such as TRKA-positive glioblastoma and in clinical settings where brain metastases are commonly encountered, as occurs in fusion-driven NSCLC.

In conclusion, the studies described herein provide a scientific rationale supporting the development of entrectinib in TRK-, ROS1-, and ALK-dependent tumor settings. Clinical trials with the compound are currently ongoing, with promising early signs of activity (29–31). Interestingly, the active recruitment of TRKA-positive patients already in phase I trial resulted in successful treatment of a colorectal carcinoma patient and a NSCLC patient harboring TRKA-rearranged tumors, with remarkable activity observed after the first cycle of administration, including complete regression of a brain metastasis in the latter case (30,31). In addition, durable objective responses were observed in several NSCLC patients whose tumors harbored ROS1 or ALK fusions and in ALK-driven neuroblastoma (29). These exciting preliminary clinical data are fully coherent with the preclinical studies described herein, and strongly support further investigation of the drug in the patient subsets described above.

Disclosure of Potential Conflicts of Interest

D. Anderson has ownership interest (including patents) in and is a consultant/advisory board member for Ignyta. G. Li has ownership interest (including patents) in Ignyta. No potential conflicts of interest were disclosed by the other authors.

Authors' Contributions

Conception and design: E. Ardini, M. Menichincheri, M.B. Saccardo, D. Anderson, J. Harris, G. Li, A. Isacchi, P. Magnaghi, A. Galvani

Development of methodology: C. De Ponti, D. Ballinari, G. Texido, N. Amboldi, M.B. Saccardo, P. Orsini, D. Anderson, J. Harris, E. Felder, D. Donati

Acquisition of data (providing materials, acquiring and managing patients, providing facilities, etc.): P. Banfi, D. Ballinari, M. Ciompi, G. Texido, A. Degrazia, N. Avanzi, N. Amboldi, M.B. Saccardo, D. Casero, L. Mologni, G. Wei, G. Li


Writing, review, and/or revision of the manuscript: E. Ardini, R. Bosotti, R. Pulci, G. Texido, A. Degrazia, M.B. Saccardo, D. Anderson, G. Wei, J.-M. Vernier, G. Li, D. Donati, A. Isacchi, A. Galvani

Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): R. Bosotti, G. Wei

Study supervision: E. Ardini, A. Isacchi, E. Pesenti, P. Magnaghi, A. Galvani

Other (participated in the chemistry program that led to entrectinib): T. Bandiera

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Elena Ardini, Maria Menichincheri, Patrizia Banfi, et al.


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