EMD 1214063 and EMD 1204831 Constitute a New Class of Potent and Highly Selective c-Met Inhibitors

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Abstract

Purpose: The mesenchymal–epithelial transition factor (c-Met) receptor, also known as hepatocyte growth factor receptor (HGFR), controls morphogenesis, a process that is physiologically required for embryonic development and tissue repair. Aberrant c-Met activation is associated with a variety of human malignancies including cancers of the lung, kidney, stomach, liver, and brain. In this study, we investigated the properties of two novel compounds developed to selectively inhibit the c-Met receptor in antitumor therapeutic interventions.

Experimental Design: The pharmacologic properties, c-Met inhibitory activity, and antitumor effects of EMD 1214063 and EMD 1204831 were investigated in vitro and in vivo, using human cancer cell lines and mouse xenograft models.

Results: EMD 1214063 and EMD 1204831 selectively suppressed the c-Met receptor tyrosine kinase activity. Their inhibitory activity was potent [inhibitory 50% concentration (IC50), 3 nmol/L and 9 nmol/L, respectively] and highly selective, when compared with their effect on a panel of 242 human kinases. Both EMD 1214063 and EMD 1204831 inhibited c-Met phosphorylation and downstream signaling in a dose-dependent fashion, but differed in the duration of their inhibitory activity. In murine xenograft models, both compounds induced regression of human tumors, regardless of whether c-Met activation was HGF dependent or independent. Both drugs were well tolerated and induced no substantial weight loss after more than 3 weeks of treatment.

Conclusions: Our results indicate selective c-Met inhibition by EMD 1214063 and EMD 1204831 and strongly support clinical testing of these compounds in the context of molecularly targeted anticancer strategies.

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Introduction

The mesenchymal–epithelial transition factor (c-Met) has emerged as a promising target in the development of anticancer therapeutics because of its low level of expression in normal tissues and its aberrant activation in many human cancers. The c-Met oncoprotein encodes a prototypic member of the receptor tyrosine kinase superfamily, which binds to the hepatocyte growth factor (HGF), identified as its only high-affinity ligand (1). c-Met engagement by HGF results in receptor dimerization and autophosphorylation, which in turn activates multiple signaling cascades involved in cell survival, motility, and proliferation (e.g., the PI3K/Akt and MAPK/ERK pathways; ref. 2).

Targeted deletion of c-Met or HGF severely compromises embryonic development, organ morphogenesis, and cell motility, resulting in early embryonic lethality (3, 4). In adult tissues, c-Met and HGF are detectable only at low levels, with epithelial and mesenchymal cells preferentially expressing c-Met and HGF, respectively. However, upon tissue damage, upregulation of both c-Met and HGF is reportedly associated with tissue regeneration and damage repair (5, 6). Interestingly, c-Met activation can induce a transdifferentiation program known as epithelial–mesenchymal transition, which results in loss of E-cadherin–mediated tight junctions, thereby conferring on epithelial cells’ mesenchymal characteristics, such as motility and invasiveness (7).

Molecular epidemiologic analyses of patient samples have revealed different types of c-Met alterations, including activating point mutations, gene amplification, and aberrant expression or overexpression (8). Notably, activating point mutations of c-Met have been identified in hereditary and sporadic papillary renal carcinoma, whereas gene
amplification has been found in lung cancers with acquired resistance to EGF receptor inhibitors (9–11). In a murine model of glioblastoma, evidence suggesting a crucial role for an autocrine c-Met–activating loop mediated by HGF, with the therapeutic efficacy of c-Met inhibition, has emerged (12, 13).

Several strategies have been used to inhibit c-Met activity, including c-Met– or HGF-specific antibodies or small-molecule inhibitors. In the generation of small-molecule inhibitors targeting the ATP-binding pockets of the c-Met protein kinase, a major obstacle has been the high degree of sequence identity within the ATP-binding clefts of canonical protein kinases (14). Indeed, all currently approved small-molecule protein kinase inhibitors exhibit promiscuous binding, targeting multiple enzymes.

Our studies define the pharmacologic and preclinical characteristics of 2 novel compounds, EMD 1214063 and EMD 1204831, which selectively inhibit c-Met. Both compounds exhibited high tolerability in vivo and effectively inhibited growth of human tumors in murine xenograft models irrespectively of whether c-Met activation resulted from HGF-dependent or -independent mechanisms.

Materials and Methods

Compounds

EMD 1214063 (3-(1-(3-((5-(1-Methylpiperidin-4-yl)oxy)-pyrimidin-2-yl)-benzyl)-1,6-dihydro-6-oxo-pyridazin-3-yl)-benzonitrile) and EMD 1204831 (4-(2-(2-(3-(1-Methyl-1H-pyrazol-4-yl)-6-oxo-1,6-dihydro-pyridazin-1-ylmethyl)-phenyl)-pyrimidin-5-yl-oxy)-ethyl)morpholine) were originally developed at Merck Serono, and were synthesized at Merck Serono.

Cell lines and antibodies

Human cancer cell lines were purchased from the American Type Culture Collection (A549, NCI-H441, U87MG, Hs746T, HT-29, LoVo, HCT-116, NCI-H1975, NCI-H1437, H460), Riken Cell Bank (EBC-1, KP-4), and "Deutsche Sammlung von Mikroorganismen und Zellkulturen" (MKN-45), and maintained according to the manufacturer's recommendations. The epitope specificity, clone designation, and commercial source of the antibodies used are indicated in Supplementary Table S1.

c-Met in vitro kinase assay

Kinase inhibition by EMD 1214063 or EMD 1204831 (1 and 10 μmol/L) was assessed in vitro using a panel of 24 different kinases. Biochemical activity was measured in a flash-plate assay. His6-tagged recombinant human c-Met kinase domain (Aa 974–end; 20 ng) and biotinylated poly-Ala-Glu-Lys-Tyr (6:2:5:1; 500 ng) were incubated with or without the test compound for 90 minutes at room temperature in 100 μL buffer containing 0.3 μCi [33P]-ATP, 2.5 μg polyethylene glycol 20,000, and 1% dimethyl sulfoxide (DMSO), as previously described (15). Radioactivity was measured with a TopCount microplate scintillation and luminescence counter (Packard BioScience BV). Inhibitory 50% concentration values (IC50) were calculated by nonlinear regression analysis using the RS/1 software program.

Phospho-c-Met-capture ELISA

Total c-Met phosphorylation was assessed by c-Met-capture ELISA in Nunc-Immuno MicroWell 96-well solid plates (Sigma-Aldrich). A549 human lung cancer cells were seeded 2 days before treatment, serum-starved for 20 hours, and treated on day 3 with different concentrations of EMD 1214063 or EMD 1204831 or 0.2% DMSO for 45 minutes at 37°C, 5% CO2. Upon stimulation with 100 ng/mL HGF for 5 minutes, cells were lysed with 70 μL per well ice-cold lysis buffer (20 mmol/L HEPES, pH 7.4; 10% (V/V) Glycerol; 150 mmol/L NaCl; 1% (V/V) Triton-X-100; 2 mmol/L EDTA) supplemented with protease and phosphatase inhibitors. In the wash-out experiments, A549 were treated with EMD 1214063 or EMD 1204831 for 45 minutes, washed, and incubated in serum-free medium for 14 hours, before stimulation with HGF (100 ng/mL).

In the ELISA, the capture antibody was specific for the c-Met extracellular domain, whereas an antiphosphotyrosine biotin-labeled antibody was used for detection. Tyrosine phosphorylation was revealed using a streptavidin peroxidase conjugate and chemiluminescence read-out.

Biochemical analysis

Phosphorylation of c-Met, Gab-1, Akt, and Erk1/2 was analyzed by Western blot analysis in EBC-1 cells. In brief, cells were seeded at a density of 3 × 106 cells per well, serum-starved for 20 hours, and lysed on day 3 after incubation with EMD 1214063. Proteins were separated by SDS-PAGE and blotted onto nitrocellulose membranes. Membranes were blocked with Tris-buffered saline and incubated in primary antibody solution (anti-pMet, anti-pAkt, anti-pERK1/2, anti-Gab1) at 4°C overnight. Proteins were detected by chemiluminescence, with VersaDoc MP 3500 imaging system (BioRad) equipped with Quantity One 1-D analysis software.
Wound healing test and proliferation assays

Wound healing tests were carried out as previously described (16). In brief, a scratch was produced with a sterile pipette tip on a monolayer of NCI-H441 lung cancer cells. The effect of EMD 1214063 and EMD 1204831 on closure of the cell gap was monitored over 24 hours in the presence or absence of 100 ng/mL HGF. All proliferation and colony formation assays were conducted in 4 replicates and included 4 DMSO vehicle controls. IC_{50} values were determined by 4PL fitting in GraphPad Prism v5.

Pharmacokinetic and pharmacodynamic studies

Plasma and tumor drug concentrations were measured using high-performance liquid chromatography (HPLC) and mass spectrometry (MS). In brief, protein precipitation was carried out in methanol for plasma samples, and in ethanol/water 80:20 (v/v) using a Precellys 24 homogenizer (Bertin Technologies) for homogenized tumor samples. The HPLC/tandem mass spectrometry (MS-MS) system consisted of an Agilent 1100 Series HPLC system with a CTC HTCL Autosampler coupled to an Applied Biosystems API4000 mass spectrometer. HPLC separation was achieved on a reversed-phase column (Chromolith SpeedRod RP-18e, 50–3 mm) using gradient elution (eluent A: formic acid 0.1%; eluent B: acetonitrile). Selectivity was achieved using multiple reaction monitoring (MRM) for the MS/MS detection of the compounds.

For the in vivo pharmacodynamic studies, all animal studies were conducted according to standard procedures approved by local animal welfare authorities. Mice were injected subcutaneously with 5 x 10^5 Hs746T cells (100 µL). Once the tumor volume had reached 600 to 1,000 mm^3, mice were randomized into different experimental groups, receiving a single oral dose of 3, 10, 30, and 100 mg/kg of EMD 1214063, EMD 1204831, or vehicle. Tumor and plasma samples were collected at 3, 6, 12, 24, 48, 72, and 96 hours after treatment. Each experimental group comprised 4 mice per dose and time point. Samples of the tumor tissue were snap-frozen for pharmacokinetic and biomarker analyses, or formalin-fixed for immunohistochemical analysis (see below).

Pharmacodynamic markers on ex vivo tumor samples

c-Met autophosphorylation was investigated by Western blot analysis on frozen ex vivo tumor samples. The tumor tissue was mechanically homogenized, lysed using Precells 24 homogenizer, or Precells lysing ceramic lysing tubes (PEQLab Ltd) according to the manufacturer’s instructions. Further preparation of lysates and protein separation by SDS-PAGE were conducted as already described for EBC-1 cells.

Histone H3 phosphorylation and biomarkers of cell-cycle arrest and apoptosis (cycin D1, p27, and cleaved, activated capase-3) were analyzed by immunohistochemistry (IHC) on formalin-fixed, paraffin-embedded sections. IHC was conducted using Discovery staining instruments (Ventana Medical Systems, Inc), with the OmniMap Kit (Ventana Medical Systems, Inc), according to the manufacturer’s instructions. Sections were counterstained with hematoxylin.

Xenograft models of antitumor efficacy

The antitumor efficacy of EMD 1214063 or EMD 1204831 was investigated in mouse xenograft models. CD-1 or BALB/c nude mice (Charles River Laboratories) were injected subcutaneously with human cancer cell lines KP-4, U87MG: 10 x 10^6 cells in 100 µL, Hs746T, EBC-1: 5 x 10^6 cells in 100 µL. As soon as the tumor reached the linear growth phase (70–150 mm^3), tumor-bearing mice (10 mice/group) were injected daily with the indicated doses of EMD 1214063 or EMD 1204831, or vehicle. Body weight and tumor size [length (L) and width (W)] were measured twice weekly. The tumor volume was calculated using the formula L x W^2/2. Statistical significance was determined by one-way ANOVA (Kruskal–Wallis, Dunn posttest). P ≤ 0.05 were considered significant.

Results

**EMD 1214063 and EMD 1204831 are competitive and selective inhibitors of c-Met kinase activity**

EMD 1214063 and EMD 1204831 were synthesized to specifically interact with c-Met and inhibit its kinase activity. The biochemical activity of these compounds was measured in a flash-plate assay using recombinant human c-Met kinase domain and a biotinylated peptide substrate. Under these conditions, EMD 1204831 inhibited c-Met kinase activity with an average IC_{50} of 9 nmol/L, whereas EMD 1214063 exhibited an average IC_{50} of 3 nmol/L.

The development of selective inhibitors of c-Met activity has been hampered by the high sequence and structural homology of the ATP-binding pocket of protein tyrosine kinases. Indeed, most of the inhibitors currently evaluated in clinical trials show a high degree of interaction with other kinases. To assess the selectivity of EMD 1214063 and 1204831 for c-Met kinase activity, these compounds were profiled against a protein kinase panel of 242 human kinases (Fig. 1A and B). At 10 µmol/L, a concentration approximately 1,000-fold above the IC_{50} of both inhibitors, only 5 of the other 241 kinases were inhibited by EMD 1214063 by more than 50%, namely IRAK4, TrkA, Axl, IRAK1, and Mer. Formal IC_{50} determinations conducted with these kinases resulted in IC_{50} values ranging from 615 to 2,272 nmol/L. Such high IC_{50} values make it unlikely that EMD 1214063 will achieve in vivo pharmacologically relevant inhibitory activity on IRAK4, TrkA, Axl, IRAK1, and Mer (proposed as IC_{90} for 24 hours).

EMD 1204831 showed an exceptionally high level of kinase selectivity toward c-Met with an inhibitory activity of more than 3,000-fold in comparison with the other 241 human kinases tested, as none of these kinases was inhibited by more than 50% at 10 µmol/L concentration of EMD 1204831. Such selectivity was reflected both in vitro and in vivo. Treatment with EMD 1214063 and EMD 1204831 resulted in a decrease in tumor cell viability in vitro (Supplementary Table S2). In in vivo mouse xenograft models,
administration of either compound induced a reduction in tumor growth of c-Met–‘addicted’ human cell lines, but only negligible effects on c-Met–independent cell lines (Supplementary Table S3). Taken together, our data show that EMD 1214063 and EMD 1204831 are highly selective, potent, and reversible inhibitors of c-Met. Interestingly, increasing concentrations of ATP suppressed inhibition of c-Met phosphorylation by EMD 1214063, indicating that this compound act via an ATP-competitive mechanism (Supplementary Fig. S1).

EMD 1214063 and EMD 1204831 inhibit c-Met phosphorylation and downstream signaling pathways

We next investigated whether EMD 1214063 and EMD 1204831 could inhibit c-Met phosphorylation induced in tumor cells by different mechanisms. To this end, we used the A549 and EBC-1 cancer cell lines, in which c-Met phosphorylation is respectively triggered by HGF binding or by c-Met gene amplification and ligand-independent activation.

Exposure of A549 cells to EMD 1214063 and EMD 1204831 resulted in inhibition of HGF-induced c-Met phosphorylation, with an average IC50 of 6 and 15 nmol/L, respectively (Fig. 2A and B).

Treatment with these compounds induced a marked reduction of c-Met–constitutive phosphorylation in EBC-1 cells with IC50 of 9 nmol/L for EMD 1214063 (Fig. 2C and Supplementary Fig. S2A and S2B) and 12 nmol/L for EMD 1204831 (Fig. 2D and Supplementary Fig. S2E and S2F), as assessed by Western blot analysis. Similarly, a strong inhibitory effect was observed in the gastric cancer cell lines MKN-45 and Hs746T (data not shown), in which c-Met is induced in a ligand-independent manner.

Upon HGF-induced or ligand-independent c-Met phosphorylation, several adapter and effector proteins, such as Grb2, Gab1, Sos, PLCγ, and phosphoinositide 3-kinase (PI3K) are recruited and ultimately orchestrate the activation of downstream signal transduction pathways, such as the Akt and the ERK/MAPK cascades (7). To assess the effect of EMD 1214063 and EMD 1204831 on the activation of signaling pathways downstream of c-Met, the phosphorylation of Gab-1, Akt, and Erk1/2 was monitored. Both inhibitors effectively blocked phosphorylation of these major downstream effectors of the c-Met enzyme in EBC-1 (EMD 1214063: Fig. 2C and Supplementary Fig. S2A–S2D; EMD 1204831: Fig. 2D and Supplementary Fig. S2E–S2H), MKN-45, and Hs746T cells in the range of 1 to 10 nmol/L (data not shown). Taken together, these data are compatible with the hypothesis that EMD 1214063 and EMD 1204831 effectively block c-Met–mediated signaling pathways involved in tumor cell growth and survival.

We next defined the efficiency of the cellular uptake and retention of EMD 1214063 and EMD 1204831. A series of wash-out studies was conducted, in which A549 cells were...
serum, resulting in average IC\textsubscript{50} values of 21.0 and 23.0 nmol/L, respectively. Higher serum concentrations could not be used in this test, as they suppressed the HGF-c-Met phosphorylation.

In contrast, in the case of EMD 1204831, incubation with the compound followed by removal and HGF stimulation led to a transient, unsustained inhibition of ligand-induced c-Met phosphorylation. Similarly to EMD 1214063, the effect of EMD 1204831 was not affected by the presence of 10% (v/v) murine or human serum, resulting in average IC\textsubscript{50} values of 26.0 and 25.0 nmol/L, respectively (Fig. 2B).

Taken together, our data show that both EMD 1214063 and EMD 1204831 have excellent cellular activity and moderate binding to serum proteins. Furthermore, they indicate that the effect of EMD 1214063 lasts longer than that of EMD 1204831.

EMD 1214063 and EMD 1204831 inhibit tumor cell proliferation and migration in vitro

c-Met can increase the proliferation rate of tumor cells and support their survival under stress conditions, particularly in the cells with c-Met gene amplification. To investigate the effect of EMD 1214063 and EMD 1204831 on tumor cell viability in vitro, MKN-45 gastric cancer cells were incubated with increasing concentrations of both inhibitors and the metabolic activity of cells was assessed. EMD 1214063 and EMD 1204831 incubation for 72 hours considerably inhibited the viability of MKN-45 cells with IC\textsubscript{50} values of less than 1 and 52 nmol/L, respectively. In contrast, other gastric cancer cells with normal c-Met gene copy number, such as SNU-16, were less sensitive to c-Met inhibitors with IC\textsubscript{50} values higher than 10 μmol/L (Supplementary Table S2 and data not shown).

The alternative name of HGF, scatter factor, indicates that HGF via c-Met activation can have a pronounced effect on cell motility, migration, and invasion. To address the effect of both c-Met inhibitors on these HGF-mediated phenomena, in vitro "wound healing" tests were conducted. Treatment with EMD 1214063 and EMD 1204831 [as low as 0.1 nmol/L] inhibited HGF-induced NCI-H441 cell migration, whereas concentrations of 100 nmol/L to 1 μmol/L almost completely prevented it (Supplementary Fig. S3).

EMD 1214063 and EMD 1204831 inhibit in vivo c-Met phosphorylation

To define the in vivo activity of different doses of EMD 1214063 and EMD 1204831, we investigated the relationship between drug exposure (pharmacokinetic) and
pharmacodynamic effects in vivo in a cancer xenograft model, using Hs746T gastric cancer cells. In line with its high volume of distribution of more than 8 L/kg in mice, EMD 1214063 concentration was higher in the tumor than in the plasma (Fig. 3A). In both matrices, concentrations and exposures seemed to increase as a function of the dose. Kinetic studies indicated that, within the tumor, the active pharmacologic range identified in vitro was reached at all time points tested (3–96 hours) upon administration of doses of EMD 1214063 of 10 mg/kg or more. EMD 1214063-treated tumors exhibited strongly reduced c-Met phosphorylation. At the lowest dose of EMD 1214063 (3 mg/kg), 90% inhibition of c-Met phosphorylation was reached at 6 hours, and decreased to 30% at 24 hours (Supplementary Fig. S4A). At doses of 10 mg/kg or more, EMD 1214063 resulted in more than 90% inhibition of c-Met phosphorylation for a period of at least 72 hours (Supplementary Fig. S4A).

For EMD 1204831, comparable drug concentrations were detected in plasma and tumor, in agreement with its volume of distribution of around 1 L/kg in this rodent species (Fig. 3B). Overall, the exposure in both matrices increased with the dose, but not in a strictly proportional fashion as in the case of EMD 1214063. Similarly to EMD 1214063, the active pharmacologic range identified in vitro was reached with doses of 10 mg/kg or more, and complete target inhibition was induced. c-Met phosphorylation was consistently reduced in all EMD 1204831-treated tumors. The lowest dose of EMD 1204831 (3 mg/kg) induced transient c-Met inhibition, which reached maximal levels (55%) at 3 hours, and subsequently returned to baseline levels (12% at 12 hours). Administration of 10 mg/kg resulted in a 90% inhibition of c-Met phosphorylation that declined after 6 hours, whereas doses of 30 mg/kg or more induced prolonged c-Met inhibition, with 58% inhibition still present at 96 hours after drug administration (Supplementary Fig. S4B).

To rule out that the reduction of c-Met phosphorylation is due to a decrease in c-Met expression, c-Met expression and phosphorylation were analyzed in vitro in U87MG cells (Supplementary Fig. S5) and ex vivo in KP4 tumors (Supplementary Fig. S6). These models were selected because the relatively moderate expression of c-Met would enable to better detect small changes upon treatment with EMD 1214063 and EMD 1204831. Our data indicate that EMD 1214063 and EMD 1204831 decrease c-Met phosphorylation (Y1234/Y1235, Y1349) in the absence of alterations in c-Met expression.

Taken together, these findings establish a correlation between the inhibitor concentration in the plasma and in the tumor, indicating the ability of these compounds to inhibit c-Met phosphorylation in vivo. Furthermore, these data provide pharmacodynamic evidence that indicate that twice daily dosing of EMD 1204831 may be required to obtain continuous and efficient target inhibition, whereas less frequent administrations may be feasible for EMD 1214063.

**EMD 1214063 and EMD 1204831 interfere with tumor cell proliferation in vivo**

To elucidate the molecular changes occurring in tumors upon in vivo administration of EMD 1214063 or EMD 1204831, we assessed c-Met phosphorylation and investigated a series of biomarkers indicative of cell-cycle arrest and apoptosis induction. The levels of phospho–c-Met were dramatically reduced upon treatment with a single dose of 30 and 100 mg/kg of EMD 1214063. While high doses (100 mg/kg) of EMD 1214063 resulted in persistent inhibition of c-Met phosphorylation, lower doses (30 mg/kg) engendered a transient inhibitory effect that returned to baseline...
after 96 hours (Fig. 4A). Further analysis revealed suppression of cyclin D1 expression, which reverted to baseline levels at 24, 48, or 96 hours, for doses of 3, 10, or 30 mg/kg, respectively. In contrast, more than 50% reduction of cyclin D1 expression persisted after 96 hours upon treatment with doses of 100 mg/kg (Fig. 4B and data not shown). A transient increase in the levels of p27 was observed upon treatment with 3, 10, 30, and 100 mg/kg of EMD 1204831. Maximal increase of p27 was detected at 12 to 24 hours, whereas baseline levels were restored after 48 to 96 hours (Fig. 4C and data not shown).

The inhibition of c-Met phosphorylation following EMD 1204831 administration did not last as long as that induced by EMD 1214063. The phosphorylation of c-Met and histone H3 as well as the levels of cyclin D1 were reduced in a dose-dependent manner (Fig. 4A and B and data not shown). A transient increase in the levels of p27 was detected upon treatment with 3, 10, 30, and 100 mg/kg of EMD 1204831. Maximal increase of p27 was detected at 12 to 24 hours, whereas baseline levels were restored after 48 to 96 hours (Fig. 4C and data not shown).

Finally, a transient increase of cleaved caspase-3 was observed in tumor samples from mice treated with a single dose of EMD 1214063 or EMD 1204831 (Supplementary

Figure 4. EMD 1214063 and EMD 1204831 effectively inhibit tumor c-Met auto-phosphorylation and cyclin D1 expression while inducing p27 expression. Mice bearing established tumors, derived from subcutaneous injection of Hs746T gastric cancer cells, received a single dose of 30 mg/kg EMD 1214063 (A–C, top) or 100 mg/kg EMD 1204831 (A–C, bottom). The levels of c-Met autophosphorylation (Y1234/Y1235; A), cyclin D1 expression (B), and p27 expression (C) were assessed by immunohistochemistry at 1 to 6, 12, 24, 48, and 96 hours after treatment. Data are representative of 4 mice per experimental group.
c-Met–driven tumors, we tested the effect of the 2 compounds on 2 sets of tumor cells: Hs746T gastric carcinoma and EBC-1 non–small cell lung cancer cell line (17, 18). To better mimic the clinical occurrence of c-Met–amplified human tumors grafted onto nude mice (Fig. 5 and Supplementary Fig. S8). To better mimic the clinical occurrence of c-Met–driven tumors, we tested the effect of the 2 compounds on 2 sets of tumor cells: the Hs746T gastric carcinoma and EBC-1 non–small cell lung cancer cell line, in which c-Met is amplified, overexpressed, and activated in a ligand-independent fashion (17, 18); on the other hand, the U87MG glioblastoma and KP-4 pancreatic carcinoma cell line in which the coexpression of HGF results in ligand-dependent c-Met activation (19, 20).

Daily administration of 5 or 15 mg/kg of EMD 1214063 to EBC-1 tumor-bearing mice resulted in effective inhibition or complete tumor regression, respectively (Fig. 5A). Similarly, EMD 1204831 administered at a dose of 25 mg/kg twice daily resulted in partial remissions in 50% of tumor-bearing mice. Interestingly, a single dose of 50 mg/kg was less effective than 2 daily doses of 25 mg/kg administered 6 to 7 hours apart, which did not induce tumor regression, but only tumor growth inhibition (Fig. 5B).

EMD 1214063 and EMD 1204831 also induced dose-dependent tumor growth inhibition in mice bearing human pancreatic carcinoma KP-4 tumors (Fig. 5C and D). Daily administration of EMD 1214063 at 200 mg/kg resulted in partial tumor regressions in 60% of tumor bearing mice, whereas twice daily administration of 200 mg/kg EMD 1214831 induced growth arrest of KP-4 tumors.

Effective tumor growth inhibition and regression of established tumors by EMD 1214063 or EMD 1204831 were also observed in mice bearing ligand-independent Hs746T and HGF-dependent U87MG tumors (Supplementary Fig. S8A–S8D).

In all studies, both inhibitors were well tolerated. Treatment-related toxic effects, as indicated by severe body weight loss or death of mice, were not observed for any of the doses studied.

Taken together, our studies indicate that EMD 1214063 and EMD 1204831 are effective in treatment of HGF–dependent and –independent tumors in vivo xenograft models.

Discussion

This report provides preclinical evidence that EMD 1214063 and EMD 1204831 effectively inhibit c-Met activation and suggests that they may be promising candidates for cancer treatment. Our data biochemically define EMD 1214063 and EMD 1204831 as ATP-competitive c-Met inhibitors, characterized by high potency, selectivity, and reversibility. Finally, EMD 1214063 and EMD 1204831 efficiently inhibited c-Met phosphorylation and downstream signaling in vivo and induced regression of established tumors in xenograft models.

Figure 5. EMD 1214063 and EMD 1204831 display antitumor activity in HGF-dependent and HGF-independent xenograft tumor models. Mice bearing subcutaneous tumors derived from the HGF-independent human lung cancer cell line EBC-1 (A and B) or the human HGF-dependent pancreatic carcinoma cell line KP-4 (C and D) were administered daily the indicated doses of EMD 1214063 (A and C), EMD 1204831 (B and D), or vehicle for the indicated treatment duration. Each data point represents the mean ± SEM of the calculated tumor volumes observed in experimental groups including 10 mice. Statistical significance was evaluated by one-way ANOVA (Kruskal–Wallis, Dunn posttest). Asterisks indicate statistically significant differences between treated and control experimental groups ($P < 0.05$). The results obtained from additional testing in other in vivo xenograft models are shown in Supplementary Fig. S8. bid, twice daily; NSCLC, non–small cell lung cancer; qd, daily.
The rationale behind developing c-Met kinase inhibitors for the treatment of cancer is based on multiple lines of preclinical evidence showing that aberrant activation of the HGF/c-Met signaling pathway plays a pivotal role in cancer progression and metastasis by promoting cell proliferation, survival, and motility (2). Dysregulation of the c-Met/HGF pathway can occur by ligand-dependent or -independent mechanisms. Indeed, overexpression of wild-type c-Met or engagement by HGF in an autocrine or paracrine fashion induces tumor transformation (21, 22). In this context, c-Met activation is dynamic, depends on altered environmental conditions, and is controlled by multiple, nonredundant signaling cross-talk. On the other hand, mutations in c-Met cytoplasmic domains can prolong the duration of activating signals, releasing inhibitory constraints, enhancing c-Met sensitivity to activating stimuli, or preventing kinase degradation. Recent studies have shown that ligand-independent c-Met activation can also occur through mutations leading to continuous c-Met endocytosis/recycling, impaired degradation, and chronic activation (23).

In this context, constitutive c-Met activity produces a phenomenon defined as "oncogene addiction," which is characterized by high steady-state signaling due to chronic receptor activation. The strong reliance of the tumor on the continued activity of c-Met makes it very sensitive to kinase deprivation, which is likely to induce strong clinical responses.

Small-molecule kinase inhibitors have a broad therapeutic efficacy and their development is becoming increasingly feasible as a result of the improved understanding of the structure and molecular mode of action of kinases. Small-molecule c-Met inhibitors impede c-Met activity irrespectively of the initial mechanism responsible for the activation. This property provides an advantage over blocking antibodies specific for HGF or c-Met, because the latter are exclusively active on ligand-dependent tumors and may not interfere with c-Met–active dimers and intracellular fusion proteins, such as TPR-Met.

EMD 1214063 and EMD 1204831 are type I small-molecule kinase inhibitors, as they bind c-Met in a U-shape geometry through interactions with both hinge and activation loop residue Y1230. Such binding interferes with ATP-binding and distinguishes these compounds from type II c-Met inhibitors (e.g., XL880 and XL184), which adopt a more extended orientation, binding protein conformations with varying degrees of "DFG-out" character. Unlike type II c-Met inhibitors, which target multiple kinases, type I c-Met inhibitors are more selective (24). Indeed, broad kinase profiling with 242 kinases highlighted the strong selectivity of EMD 1214063 and EMD 1204831 for c-Met. Such a high grade of selectivity is comparable with that of 2 other type I inhibitors, INCB28060 and JNI-38877605, which are currently under evaluation in phase I clinical trials (25).

From a therapeutic point of view, it remains controversial as to whether single- or multiple-targeted inhibitors are most advantageous. Clinical evidence suggests that multiple-targeted inhibitors may be more often associated with dose-limiting effects, whereas single-targeted kinase inhibitors can be used at maximal dosing level without causing toxic effects. Indeed, XL880 and XL184, which target multiple, non-family-related kinases including VEGF receptor, are associated with dose-limiting toxicities that may not be attributed to c-Met inhibition. On the other hand, the achievement of therapeutic effects with EMD 1204831 and EMD 1214063 may require thorough patient screening to identify a responsive subset, in which the tumor is sensitive to selective disruption of the c-Met signaling pathway.

Our preclinical data show that EMD 1204831 and EMD 1214063 block both HGF-dependent and constitutive phosphorylation of c-Met, thereby interfering with survival, anchorage-independent growth, and HGF-induced migration of susceptible tumor cells. Such observations are in agreement with reports on the effects of JNI-38877605 and INCB28060, which also belong to the category of type I c-Met inhibitors (25).

From a pharmacokinetic point of view, EMD 1214063 and EMD 1204831 have different properties. Our data show that the effect of EMD 1214063 on c-Met is sustained, whereas that of EMD 1204831 is less prolonged. In vivo pharmacokinetic/pharmacodynamics studies evaluated such differences in depth. We showed that a single dose of EMD 1214063, due to its high volume of distribution, resulted in higher drug concentrations in the tumor than in the plasma. Notably, a single dose of EMD 1214063 at 10 or 30 mg/kg resulted in a complete and long-lasting inhibition of c-Met phosphorylation in the tumors.

In contrast, a single dose of EMD 1204831 at 30 mg/kg resulted in equal drug concentrations in the tumor and plasma and in complete but transient inhibition of c-Met phosphorylation in the tumors. The reduced duration of EMD 1204831 activity on the target may have the disadvantage of requiring more frequent dosing to achieve continuous target inhibition, but may offer the advantage of a greater flexibility in the administration schedule in combination with other drugs. In light of their different properties, EMD 1214063 may be the best candidate to achieve high levels of continuous target inhibition and provide a therapeutic advantage not only over EMD 1204831, but also over other c-Met inhibitors such as JNI-38877605 (26, 27) and INCB28060 (16).

Our immunohistochemical studies indicated that treatment with EMD 1214063 and EMD 1204831 results in a substantial reduction in the levels of phospho-histone H3, in the suppression of cyclin D1 expression, and in increased levels of p27. Taken together, these findings indicate that treatment with EMD 1214063 or EMD 1204831 is effective in inducing cell-cycle arrest and inhibiting tumor cell proliferation. In vivo, both inhibitors displayed similar antitumor activity, when the dose and schedule were adjusted according to their respective pharmacokinetic properties (i.e., daily or every other day for EMD 1214063 and twice daily for EMD 1204831). Both compounds induced a marked tumor growth delay and, eventually, regression of HGF-dependent and HGF-independent c-Met–amplified tumors grafted onto nude mice. Our data are in agreement with previous
on the activity of JNJ-38877605 (26) and INCB28060 (16), but differ from those obtained with MetMab, a single-armed monoclonal antibody against c-Met, which was only active in HGF-dependent tumor models (14, 28). Evaluation of different schedules of administration revealed that continuous target inhibition is necessary to achieve maximal antitumor activity. EMD 1214063 and EMD 1204831 were well tolerated at doses as high as daily or twice-daily 200 mg/kg, as indicated by the lack of substantial weight loss in treated mice. Antitumor activity was observed at several dose levels for EMD 1214063 and EMD 1204831, at doses as low as 6 mg/kg and 10 mg/kg, respectively, indicating a large therapeutic index for both c-Met inhibitors.

In conclusion, our preclinical data show that EMD 1214063 and EMD 1204831 are selective and potent in vitro and in vivo inhibitors of the c-Met kinase, thereby supporting their clinical development as a potentially effective oral treatment for human cancers.

Disclosure of Potential Conflicts of Interest
F. Bladt is employed (other than primary affiliation; e.g., consulting) as a Director, Biomarker Discovery by Merck KGaA. C. Fittschen has ownership interest (including patents) in EMD 1214063 and EMD 1204831. D. Dorsch is employed (other than primary affiliation; e.g., consulting) as a Laboratory head by Small Molecules Platform. O. Schadt has ownership interest (including patents) in WO2009006599. No potential conflicts of interest were disclosed by the other authors.

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