Phase I Combination of Sorafenib and Erlotinib Therapy in Solid Tumors: Safety, Pharmacokinetic, and Pharmacodynamic Evaluation from an Expansion Cohort

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Abstract

The aims of this study were to further define the safety of sorafenib and erlotinib, given at their full approved monotherapy doses, and to correlate pharmacokinetic and pharmacodynamic markers with clinical outcome. In addition, a novel pharmacodynamic marker based on the real-time measurement of RAF signal transduction capacity (STC) is described. Sorafenib was administered alone for a 1-week run-in period, and then both drugs were given together continuously. RAF STC was assessed in peripheral blood monocytes prior to erlotinib initiation. Epidermal growth factor receptor (EGFR) expression and K-RAS mutations were measured in archival tumor samples. Changes in pERK and CD31 were determined in fresh tumor biopsies obtained pretreatment, prior to erlotinib dosing, and during the administration of both drugs. In addition, positron emission tomography–computed tomography scans and pharmacokinetic assessments were done. Eleven patients received a total of 57 cycles (median, 5; range, 1–10). Only four patients received full doses of both drugs for the entire study course, with elevation of liver enzymes being the main reason for dose reductions and delays. Among 10 patients evaluable for response, 8 experienced tumor stabilization of ≥4 cycles. Pharmacokinetic analysis revealed no significant interaction of erlotinib with sorafenib. Sorafenib-induced decrease in RAF-STC showed statistically significant correlation with time-to-progression in seven patients. Other pharmacodynamic markers did not correlate with clinical outcome. This drug combination resulted in promising clinical activity in solid tumor patients although significant toxicity warrants close monitoring. RAF-STC deserves further study as a predictive marker for sorafenib.

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Introduction

Sorafenib and erlotinib are oral kinase inhibitors with antiproliferative and antiangiogenic effects that target primarily RAF/vascular endothelial growth factor receptors 1 to 3 (VEGFR-1/3)/platelet-derived growth factor receptor-β (PDGFR-β) and epidermal growth factor receptor (EGFR) respectively (1–5). Sorafenib has been approved for the treatment of advanced renal cell and hepatocellular carcinomas; erlotinib has been approved for the treatment of advanced pancreatic and non-small cell lung cancers (6–9). The rationale for combining these two targeted agents has previously been reported; the dose escalation part of the phase I trial carried out by our group suggested that both agents could be given at their full recommended phase II dose (RP2D; ref. 10). This combination therapy is currently being studied in multiple tumor types (11–15).

The present article describes the expansion cohort of a phase I trial, treated at the RP2D, aimed at further defining the safety and tolerability of the combination and of correlating pharmacokinetic and pharmacodynamic markers with clinical outcome. A common approach taken previously to define the pharmacodynamic markers of kinase activity has been to use immunohistochemistry to assess the phosphorylation status of the target kinase’s substrate in either tumor or surrogate tissues. However, this approach has yielded only modest results and no reproducible predictive test (16–28). A major criticism of this strategy is that the dynamic nature of the
signal transduction capacity (STC) of the target cannot be evaluated in dead and fixed tissues. As shown by Nolan and colleagues, the stimulated status of a signaling network is more informative of the STC at a given moment than a static determination (29). In this context, we have developed a quantitative and reproducible pharmacodynamic test—the "phospho-shift" (pShift) for sorafenib that is based on the measurement of the dynamic RAF-STC in freshly isolated peripheral blood mononuclear cells, with exploratory aims.

Patients and Methods

Study Design and Treatment Regimen
For each patient, sorafenib alone at 400 mg p.o. bd was administered for a 1-week run-in period, followed thereafter by the addition of erlotinib at 150 mg p.o. daily. Both drugs were then given together continuously in 28-d cycles (Fig. 1A). Toxicity was graded according to the Common Terminology Criteria for Adverse Events (v.3.0). The study was approved by the local institutional

![Figure 1. Treatment and correlative study schedule. A, PK arrows, pharmacokinetic sampling; B, tumor biopsy; CT/PET, CT scan and PET scan; red dots, MEK1/2 pShift assessment. B, schematic representation of the pShift assessment. A blood sample is drawn and processed within 30 min. Whole blood is stimulated with vehicle or with IL3 which activates RAF in monocytes. RAF activation recruits and phosphorylates MEK. The difference between the degree of phosphorylation of MEK in the IL3-stimulated aliquots and the vehicle-stimulated aliquots is the pShift. As sorafenib is able to reduce the capacity of RAF to recruit and phosphorylate MEK, the changes in the pShift from day -6 to day 0 may estimate the pharmacodynamic effects of sorafenib on an individual basis.]
review board and was conducted in accordance with federal and institutional guidelines.

Inclusion criteria included histologically confirmed incurable solid tumor; age ≥18 y; Eastern Cooperative Oncology Group performance status ≤2; adequate hematologic, hepatic, and renal functions [absolute neutrophil count (ANC) ≥1.5 × 10^9/L, platelets ≥100 × 10^9/L, bilirubin ≤ upper limit of normal (ULN), aspartate aminotransferase (AST)/alanine aminotransferase (ALT) ≤2.5 × ULN, and creatinine ≤ ULN, or creatinine clearance ≥60 mL/min]. Exclusion criteria included: prior treatment with any agents targeting EGFR or RAF or VEGF/VEGFR; systolic blood pressure >140 mmHg and/or diastolic pressure >90 mmHg despite appropriate medical treatment; brain/meningeal metastases; and concurrent use of antiepileptic drugs or CYP3A4 inducers.

Patients were required to meet the following criteria before starting each cycle: ANC ≥1.0 × 10^9/L, platelets ≥100 × 10^9/L, and nonhematologic toxicity recovered to tolerable grade ≤2. Sequential dose reductions were 200 mg bd and 200 mg daily for sorafenib, and 100 mg daily and 75 mg daily for erlotinib. Patients in whom one study drug was held or discontinued could continue to receive the other. Objective responses were independently reviewed and assessed by Response Evaluation Criteria in Solid Tumors criteria (30) every other cycle.

Pharmacodynamic Analysis

**MEK1/2 pShift Assay.** The STC of RAF before starting sorafenib and before the addition of erlotinib was assessed by measuring MAP/ERK kinase 1/2 (MEK1/2) pShift. The assay is based on the following principles:
(a) standard sorafenib dose yields different toxicity/efficacy effects among different patients; (b) when RAF is stimulated, its STC increases to recruit and phosphorylate MEK1/2, resulting in an increase in phospho-MEK1/2 levels constitutes pShift which estimates RAF STC; (c) sorafenib inhibits RAF kinase activity, such that a greater inhibition results in a smaller MEK1/2 pShift; and (d) the comparison of pShift before and after sorafenib exposure reflects its pharmacodynamic effect on RAF STC. A schematic representation of the procedure is shown in Fig. 1B.

Approximately 7.5 mL of peripheral blood was obtained and aliquotted into 6 × 200 μL samples, one triplicate for measuring basal and stimulated MEK1/2 phosphorylation respectively. Samples were equilibrated at 37°C (15 min). One triplicate was stimulated with 200 ng/mL of interleukin-3 (IL3) for 5 min at 37°C and the other with vehicle. Samples were fixed and RBC were lysed simultaneously with BD-Fix-Lysis buffer (BD Biosciences), washed, permeabilized with BD-Perm buffer III for 30 min at 4°C, and washed again. The remaining leukocyte pellet was resuspended in 100 μL of PBS containing blocking antibodies (1 μg of anti-CD16/32, Cederlane labs) for 10 min at room temperature to diminish background staining. Cells were stained with mouse anti-CD16/CD32 and rabbit anti-pMEK (BD and Cell Signaling Technology) for 30 min at 4°C, washed and incubated with antirabbit Alexa488 (Invitrogen) for 45 min at 4°C to visualize pMEK1/2. Upon a final washing, cells were resuspended in PBS, sorted on a digital FACSCanto machine equipped with FACS Diva software V.5.0 (BD), and analyzed using FlowJo V.7.5.5 (Tree Star Inc.).

Preliminary evaluation of the assay in healthy volunteers is offered in Appendix A1. The evaluation of MEK1/2 pShift is depicted by flow cytometric charts in Fig. 2A and B. The target cell population for MEK1/2 pShift assessment is constituted by the monocytes. Figure 2A (left) shows a typical forward scatter/side scatter (FSC/SSC) distribution of cell size versus granularity of peripheral blood cells obtained upon RBC lysis from whole blood. Viable leukocytes are gated. The right panel of Fig. 2A shows the typical three leukocyte subpopulations: neutrophils (upper gate), monocytes (mid gate) and lymphocytes (lower gate) by plotting the viable leucocytes from the right panel in a chart of CD45 versus granularity. Monocytes are then plotted in charts (Fig. 2B) where the x-axis represents pMEK1/2 fluorescence staining intensity. The analysis of the samples from healthy volunteers revealed that a geometric mean of fluorescence intensity value of 281 segregates the one third of monocytes with highest pMEK1/2 fluorescence into the “upper gate”. Cells with increased pMEK1/2 staining intensity after stimulation with IL3 are shifted to the upper gate. pShift is calculated by subtracting the average percentage of monocyte shifts in vehicle-stimulated triplicates from that in IL3-stimulated triplicates. Figure 2B represents an example of one patient's monocytes before and after sorafenib treatment. Prior to sorafenib treatment (top), ex vivo stimulation of the patient's monocytes with IL3 resulted in an additional 25.9% of cells shifting to the upper gate, compared with stimulation with vehicle. After 7 d of sorafenib treatment (Fig. 2B, bottom), only an additional 0.7% of monocytes shifted to the upper gate when stimulated ex vivo with IL3 versus vehicle. The percent of pShift suppression as a result of sorafenib treatment for an individual patient is determined by \(\left(1 - \frac{Y}{X}\right) \times 100\%\), where X is the pre-sorafenib pShift value and Y is the on-sorafenib pShift value.

For standardization purposes, percentages were chosen as the units for quantitation of pShift suppression rather than a median fluorescence intensity value for the cell population. The individual shift values for each patient and sample are available in Supplementary Table S1.

**Other Pharmacodynamic Markers.** Three fresh tumor biopsies were obtained on time points as shown in Fig. 1. Biopsies were immediately immersed in Tissue-Tek optimal cutting temperature embedding medium, snapped frozen in liquid nitrogen, and stored in −80°C freezers. Phospho-ERK1/2 (Cell Signaling Technology) and CD31 clone JC70A (DAKO) were measured by immunofluorescence and quantified as described previously by our group (16, 31).

The relative abundance of phospho-ERK1/2 was represented by the product of mean integrated optical density and labeled region fraction. The relative abundance of blood vessels was measured by vessel count and vessel size in tumor area. Archival samples were analyzed for K-RAS mutations by PCR and sequencing of exon 2, and for EGFR expression by immunohistochemistry, with methods previously utilized by our group (32, 33). EGFR

### Table 1. Baseline characteristics of patients enrolled in the expansion cohort

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of patients</td>
<td>11</td>
</tr>
<tr>
<td>Age in years, median (range)</td>
<td>51 (38–69)</td>
</tr>
<tr>
<td>Gender (male/female)</td>
<td>10/1</td>
</tr>
<tr>
<td>ECOG performance status (0/1)</td>
<td>8/3</td>
</tr>
<tr>
<td>Smoker/nonsmoker</td>
<td>3/8</td>
</tr>
<tr>
<td>Tumor type:</td>
<td></td>
</tr>
<tr>
<td>Cholangiocarcinoma</td>
<td>5</td>
</tr>
<tr>
<td>Hepatocellular cancer</td>
<td>2</td>
</tr>
<tr>
<td>Pancreatic cancer</td>
<td>1</td>
</tr>
<tr>
<td>Neuroendocrine tumor</td>
<td>1</td>
</tr>
<tr>
<td>Germ cell tumor</td>
<td>1</td>
</tr>
<tr>
<td>Adenoid cystic carcinoma</td>
<td>1</td>
</tr>
<tr>
<td>Prior treatment:</td>
<td></td>
</tr>
<tr>
<td>Adjuvant chemotherapy</td>
<td>1</td>
</tr>
<tr>
<td>Palliative chemotherapy</td>
<td>7</td>
</tr>
<tr>
<td>Radiotherapy</td>
<td>1</td>
</tr>
<tr>
<td>No. of prior chemotherapy regimen (0/1/2/3)</td>
<td>3/4/3/1</td>
</tr>
</tbody>
</table>

Abbreviation: ECOG, Eastern Cooperative Oncology Group.
staining intensity was graded as follows: 0, none; 1, weak; 2, weak to strong; 3, strong. The proportion score is a continuous variable from 0% to 100% cells staining positive. A hybrid-score (H-score) was calculated as the product of the EGFR intensity score and the proportion score, with a possible range of results from 0 to 300.

**Positron Emission Tomography-Computed Tomography Scan.** Positron emission tomography-computed tomography (PET-CT) scans were done as listed in Fig. 1. Standardized uptake values (SUV) of target lesions were summed for each PET scan.

**Pharmacokinetic Analysis.** Blood samples for sorafenib pharmacokinetic analysis were collected during cycle 1 on day −6 before morning dosing and days −2 and +15 before morning dose and at 1, 2, 4, 6, 8, 12, and 24 h post-dose. Pharmacokinetic analysis for sorafenib was done by Bayer Healthcare Pharmaceuticals using a validated liquid chromatography-mass spectrometry method (34). The lower limit of quantification for sorafenib was 0.1 μg/mL. A noncompartmental method was used to compute pharmacokinetic variables. Minimum steady-state plasma concentrations (Css,min) for erlotinib and its metabolite OSI-420 were measured on cycle 1 days +15, 16, 22, and 29 using a high-performance liquid chromatography assay (35), with lower limits of detection of 12.5 ng/mL and 5 ng/mL, respectively.

**Statistical Considerations**

Spearman correlation was used to examine if the percentage change in on-treatment pharmacodynamic end points (pERK, SUV, pShift, and EGFR) relative to pretreatment was correlated with time to progression (TTP). For all pharmacokinetic variables of sorafenib, including area under the concentration-time curve (AUC), peak plasma concentration (Cmax), time to peak plasma concentration (Tmax), and elimination half-life, the Wilcoxon signed rank test was carried out to compare values in the presence or absence of erlotinib (day −2 versus day +15). Spearman correlation was also conducted to examine if the median sorafenib AUC value could predict the percentage change in pShift on-treatment compared with pretreatment.

### Table 2. Study course: dose delays, reductions, clinical outcome, and pharmacodynamic correlate

<table>
<thead>
<tr>
<th>Tumor type</th>
<th>No. of cycles</th>
<th>Any delay (yes/no)</th>
<th>Reason of delay</th>
<th>Length of delay*</th>
<th>No. of dose reduction</th>
<th>Timing of dose reduction</th>
<th>TTP (d)</th>
<th>MEK pShift suppression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cholangiocarcinoma</td>
<td>4</td>
<td>No</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>C2 + C3†</td>
<td>117</td>
<td>-</td>
</tr>
<tr>
<td>Neuroendocrine tumor</td>
<td>9</td>
<td>Yes</td>
<td>LFT</td>
<td>6</td>
<td>3.5</td>
<td>1</td>
<td>172</td>
<td>-</td>
</tr>
<tr>
<td>Cholangiocarcinoma</td>
<td>5</td>
<td>No</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>132</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Adenoid cystic Carcinoma</td>
<td>10</td>
<td>Yes</td>
<td>Hyponatremia</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>300</td>
<td>-</td>
</tr>
<tr>
<td>Cholangiocarcinoma</td>
<td>6</td>
<td>Yes</td>
<td>Chest pain</td>
<td>5.5</td>
<td>5</td>
<td>2</td>
<td>76</td>
<td>-</td>
</tr>
<tr>
<td>Cholangiocarcinoma</td>
<td>5</td>
<td>Yes</td>
<td>HFR</td>
<td>3.5</td>
<td>4.5</td>
<td>1</td>
<td>176</td>
<td>96%</td>
</tr>
<tr>
<td>Hepatocellular Carcinoma</td>
<td>4</td>
<td>Yes</td>
<td>LFT</td>
<td>2</td>
<td>2</td>
<td>C2 + C4</td>
<td>147</td>
<td>65%</td>
</tr>
<tr>
<td>Hepatocellular carcinoma</td>
<td>1</td>
<td>Yes</td>
<td>LFT</td>
<td>0.5</td>
<td>0.5</td>
<td>n/a</td>
<td>15</td>
<td>79%‡</td>
</tr>
<tr>
<td>Germ cell tumor</td>
<td>1</td>
<td>Yes</td>
<td>Fatigue</td>
<td>2</td>
<td>2</td>
<td>n/a</td>
<td>28</td>
<td>10%</td>
</tr>
<tr>
<td>Cholangiocarcinoma</td>
<td>2</td>
<td>Yes</td>
<td>LFT</td>
<td>4</td>
<td>6</td>
<td>C1 + C2</td>
<td>112</td>
<td>18%</td>
</tr>
<tr>
<td>Pancreatic Cancer</td>
<td>10</td>
<td>Yes</td>
<td>Hypophosphatemia</td>
<td>2</td>
<td>2</td>
<td>C1 + C3 + C2</td>
<td>287</td>
<td>91%</td>
</tr>
</tbody>
</table>

Abbreviations: S, sorafenib; E, erlotinib; n/a, not applicable; C, cycle; HFR, hand-foot reaction; LFT, liver function test abnormalities.

*Time expressed in weeks.
†Drug stopped.
‡This patient received sorafenib alone from day −6 to 0. He had a history of chronic hepatitis B infection. On day 0 he presented with a grade 4 ALT elevation and treatment was stopped. He was diagnosed with possible hepatitis B flare and never started the experimental combination. The subsequent clinical deterioration led to the diagnosis of clinical PD. As the analyzed outcome was TTP under the experimental combination treatment, and this patient never received it, he was excluded from the pharmacodynamic analysis.
Results

From July 2006 to November 2007, 11 patients were enrolled in the expansion cohort of the sorafenib and erlotinib targeted combination phase I trial. Table 1 lists the patients’ pretreatment characteristics.

Dose Delivery

In total, the 11 patients received 57 cycles of treatment (median, 5 cycles; range, 1–10 cycles). Only four patients could receive the treatment regimen without dose reductions for the entire study course (two for only one cycle; Table 2). Specifically, throughout the study, sorafenib doses were delivered in full in four patients and reduced in seven patients, whereas erlotinib doses were delivered in full in six patients, reduced in two patients, and discontinued in three patients. Nine patients needed at least one dose delay with sorafenib dosing and seven needed at least one dose delay with erlotinib dosing.

Safety

Table 3 reports adverse events (AE) that were at least possibly related to study drugs, out of 57 treatment cycles. The most commonly observed AEs (possibly related) were fatigue (11 patients) and diarrhea (8 patients). Diarrhea was usually grade 1 to 2 and manageable with loperamide; but it led to dose reduction in two patients and dose delay in one patient, respectively. Alterations in liver enzymes were common, with 10, 9, and 6 patients, respectively experiencing some degree of AST, ALT, and bilirubin increase during treatment course.

Clinically meaningful grade ≥3 AEs at least possibly related to the study drugs included AST/ALT/bilirubin increase (in 4/4/2 patients respectively), hand-foot reaction (n = 3), fatigue (n = 2), diarrhea, hypertension, and uveitis (n = 1 each). Hematologic side effects were uncommon (grade 3 lymphopenia in two patients). There were no toxic deaths on study.

Efficacy

Tumor response was assessed in 10 patients. One patient was considered nonevaluable for response due to possible flare of hepatitis B after 1 week of sorafenib treatment. Nine of 10 patients evaluable for response experienced stable disease as best response; the one remaining patient had progressive disease during cycle 1. Median TTP was 4.8 months (95% confidence interval, 3.8 months to not reached); the 6-month progression-free rate was 33% (95% confidence interval, 13–84%). Three patients remained on study treatment for 9, 10, and 10 cycles, respectively (Table 2).

Pharmacodynamic Analysis

Table 2 depicts the MEK1/2 pShift suppression induced by sorafenib treatment in the seven patients assayed. Although all patients received the same sorafenib dose within the run-in period when this parameter was measured, large interpatient variations were noted. The correlation between MEK pShift suppression and TTP is plotted in Fig. 2C; these two variables showed a direct correlation (Spearman’s ρ = 0.886) that reached statistical significance (P = 0.046).

EGFR H-score on archival tumor specimens was evaluated in 10 patients and ranged from 0 to 140 (median, 10). No correlation between EGFR H-score and TTP was found. No K-RAS mutations were identified. CD31 and pERK were assessed pretreatment and posttreatment in nine patients. pERK values decreased in 8 of 9 (88%) patients, ranging from −4% to −94% (median, −32%), whereas CD31 decreased in all patients, ranging from −20% to −84% (median, −43%). Nine patients underwent PET scans before and after treatment. Six patients had a decrease in SUV uptake, whereas three patients had an increase, ranging from −8% to +45% (median, −25%) and from +11% to +18% (median, +12%), respectively. There was no correlation between variations of pERK, CD31, and SUV with TTP (Fig. 2D). None of these parameters showed correlation with MEK1/2 pShift results.

Pharmacokinetic Analysis

All patients were eligible for pharmacokinetic analysis. Mean AUC0−12, Tmax, and Cmax values of sorafenib on day -2 and day +15 showed significant intrapatient and interpatient variability (Table 4). No statistically significant differences in any pharmacokinetic variables of...
sorafenib were detected in the presence or absence of erlotinib, suggesting a lack of effect of erlotinib on the pharmacokinetic profile of sorafenib. The availability of only trough erlotinib levels precludes any conclusion of the effects of sorafenib on erlotinib. The averageCss,min values of erlotinib and its main metabolite OSI-420 also revealed wide interindividual variability, with mean trough erlotinib concentration of around 500 ng/mL (Appendix A2). No significant effect of smoking status on the pharmacokinetic profile of sorafenib or erlotinib was detected (data not shown). Mean sorafenib AUC did not show any correlation with TTP or any of the pretreatment or posttreatment pharmacodynamic end points, including MEK1/2 pShift (data not shown).

Discussion

Our previously reported dose escalation part suggested that sorafenib and erlotinib can be combined at their full single-agent RP2D and also showed preliminary antitumor activity (10). We report here the detailed safety, pharmacokinetic, and pharmacodynamic results of the expansion cohort of patients treated with this targeted combination at the RP2D. Although over the short term this combination is safe at the RP2D, patients must be monitored carefully due to the potential for cumulative toxicity. Except for one patient who had possible flare of hepatitis B after 1 week of sorafenib treatment, all other patients tolerated the first cycle at full doses of both drugs. However, two thirds of the patients required dose reductions after one to four cycles, mainly due to liver function test abnormalities, but also as a result of fatigue, gastrointestinal or skin toxicity. This outcome is not surprising as these are overlapping toxicities of both drugs (34, 36–39). In addition, 82% of the patients required ≥1 dose delay during the study course. The toxicity profile encountered in this expansion cohort of patients was similar to that reported in the dose finding part (10). Similar targeted combinations, such as sorafenib plus gefitinib (40), and sunitinib plus erlotinib (41), have displayed comparable adverse event profiles but a lower frequency of toxicities mandating dose delays and reductions. The lower frequency of toxicities encountered with these other targeted combinations may be explained by their evaluation in selected, less-pretreated, tumor-specific patient populations. Moreover, in the case of the sorafenib plus gefitinib combination, gefitinib was administered at a lowered dose of 250 mg/d instead of 500 mg/d (41–43). A recent phase I/II trial evaluated the identical doublet of sorafenib and erlotinib in patients with recurrent glioblastoma who were not on enzyme-inducing antiepileptic agents (15). The RP2D was determined as sorafenib 200 mg bd and erlotinib 100 mg daily, which was lower than the RP2D reported in our phase I study (10). This discrepancy may be partly explained by the poorer performance status of patients with glioblastoma. Preliminary efficacy results of the sorafenib plus erlotinib doublet in this trial were disappointing, with the phase II portion failing to meet the preset criteria to proceed to the second stage. The efficacy data encountered in our current report are encouraging, with prolonged stable disease of ≥4 cycles observed in 8 of 10 patients evaluable for response, among different types of solid malignancies. However, due to the small sample size and the heterogeneity of patients in our current report, these efficacy results should be considered exploratory. Further efficacy data of this targeted combination from other tumor-specific studies are eagerly awaited.

We implemented in this study a novel, exploratory laboratory technique that proposes to measure the effect of a kinase inhibitor over its target kinase activity in real time as a potential pharmacodynamic marker. To assess STC in an otherwise quiescent pathway in a surrogate tissue (RAF-MEK-ERK in monocytes), stimulation with a specific agent (IL3) is required and the assay is designed to be done in whole blood within 15 minutes of sampling. This avoids manipulations that may affect the drug or its surrounding physiologic conditions, rendering the assay as close to in vivo testing as current techniques allow. The pharmacodynamic effects measured by this technique reflect exclusively sorafenib activity over RAF, as the change in STC of RAF is assayed during the sorafenib run-in period and prior to the initiation of erlotinib. The inability to additionally account for the pharmacodynamic effects of erlotinib is a limitation of this correlative study. There were large interindividual variations in the MEK1/2 pShift suppression in the seven patients assayed, and even though these results seem to correlate with TTP, the small sample size and the random effects of multiple comparisons preclude definitive conclusions. The lack of correlation with sorafenib pharmacokinetic parameters would suggest that the underlying molecular mechanisms are not entirely based on drug concentrations.

<table>
<thead>
<tr>
<th>Table 4. Sorafenib pharmacokinetic variables</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Day –2 mean (range)</strong></td>
</tr>
<tr>
<td>n</td>
</tr>
<tr>
<td>AUC, μg × h/mL</td>
</tr>
<tr>
<td>Cmax, μg/mL</td>
</tr>
<tr>
<td>Tmax, h</td>
</tr>
</tbody>
</table>
or exposures, but likely due to biological interactions of sorafenib with its cellular targets. Finally, the finding that non-dynamic pharmacodynamic assessments in tumor samples (e.g., pERK) did not show a concordant behavior as MEK1/2 pShift inhibition would support the proposition that these markers are likely capturing different biological profiles. In other studies, the evaluation of pERK in tumor tissues to predict for response to erlotinib has led to conflicting results (16, 42, 44, 45). In two phase II clinical trials of sorafenib (head and neck cancer and thyroid cancer), pERK was shown to decrease in a limited number of paired tumor biopsies but did not correlate with clinical outcome (31, 46). In a third phase II clinical trial with only pretreatment tissue available (hepatocellular carcinoma), the tumor staining intensity of pERK correlated positively with a longer TTP (47). Our dynamic pharmacodynamic assay, although yielding interesting results, must be further validated in tumor types where sorafenib has known antitumor activity. In fact, to date, different pharmacodynamic effects explored using variable surrogate tissues with targeted drugs have seldom been validated in a consistent manner, with a few exceptions such as the development of skin rash with EGFR inhibitors (48–50). Accordingly, further evaluations to measure the predictive effects of the MEK pShift in independent trials of sorafenib are mandatory prior to drawing definitive conclusions. Finally, the ideal platform for pharmacodynamic effects assessment would involve the utilization of tumor tissues. However, the challenges in using tumor tissues include dissociation techniques to obtain single cell suspension and washing steps that may alter cell response to drug stimulation. In addition, the presence of cell types from several different lineages present in a solid tumor sample makes it difficult to assess pShift response as compared with a single cell population in sorted peripheral blood mononuclear cells.

We explored whether changes in CD31 (an endothelial cell marker) in tumor could constitute a predictive marker for sorafenib. Despite a constant decrease in CD31 staining (Fig. 2D), the lack of correlation with TTP may be due to the analysis of a limited and nonrepresentative tissue section in each patient, or to this marker reflecting pharmacodynamic activities rather than being predictive of outcome. Reports in the literature of the predictive value of CD31 with different antiangiogenic agents have been inconsistent (31, 51, 52). Finally, in contrast to other studies involving agents that target VEGFR or EGFR pathways (53–57), we did not find a relationship between decrease in SUV and clinical outcome. Given the small sample size and the heterogeneity of our patient population, these results may have limited power to detect subtle associations even if they exist.

The pharmacokinetic parameters of sorafenib were similar to those obtained in single-agent trials (34–37), and did not vary significantly in the presence or absence of erlotinib. Although the effect of sorafenib on erlotinib could not be assessed with our trial design, in comparison with historical pharmacokinetic data of erlotinib alone, the steady-state concentration of erlotinib and OSI-420 seemed to be reduced in the presence of sorafenib. However, the small number of patients sampled renders the conclusion difficult to interpret (38, 45, 56). Data from other trials of similar combinations corroborate our findings. For instance, the phase I/II trial of sorafenib and erlotinib in glioblastoma showed a lack of accumulation of erlotinib over time, and erlotinib did not significantly affect sorafenib concentrations (15, 58). Similarly, in the phase I trial of sorafenib plus gefitinib, no pharmacokinetic effect of gefitinib on sorafenib was found, whereas the presence of sorafenib led to a decrease in gefitinib Cmax and AUC (40). As well, a slight decrease in Cmax, AUC, and steady-state-concentration of erlotinib was found when it was combined with bevacizumab (59). Although the definitive mechanism has not yet been elucidated, it has been proposed that sorafenib binding may increase the maximal velocity of CYP3A4 metabolism of erlotinib or gefitinib (58). These findings are consistent with our observations that sorafenib had to be dose reduced in more patients than erlotinib.

In summary, this targeted combination has shown promising biological activity in different tumor types, but at the expense of a high incidence of some side effects such as fatigue, gastrointestinal toxicity, and rise in liver enzymes. Our exploratory pharmacodynamic marker for RAF inhibition deserves further study in larger patient series. Sorafenib may lead to subtherapeutic erlotinib levels when given in combination; detailed analysis of this pharmacokinetic interaction should be undertaken.

Disclosure of Potential Conflicts of Interest

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