Preclinical Development

Differential Expression of Uridine Phosphorylase in Tumors Contributes to an Improved Fluoropyrimidine Therapeutic Activity

Deliang Cao1, Amy Ziemba4, James McCabe3, Ruilan Yan1, Laxiang Wan2, Bradford Kim2, Michael Gach4, Stuart Flynn3, and Giuseppe Pizzorno2,4

Abstract

Abrogation of uridine phosphorylase (UPase) leads to abnormalities in pyrimidine metabolism and host protection against 5-fluorouracil (5-FU) toxicity. We elucidated the effects on the metabolism and antitumor efficacy of 5-FU and capecitabine (N4-pentyloxycarbonyl-5′-deoxy-5-fluorocytidine) in our UPase knockout (UPase−/−) model. Treatment with 5-FU (85 mg/kg) or capecitabine (1,000 mg/kg) five days a week for four weeks caused severe toxicity and structural damage to the intestines of wild-type (WT) mice, but not in UPase−/− animals. Caepticabine treatment resulted in a 70% decrease in blood cell counts of WT animals, with only a marginal effect in UPase−/− mice. UPase expressing colon 38 tumors implanted in UPase−/− mice revealed an improved therapeutic efficacy when treated with 5-FU and capecitabine because of the higher maximum tolerated dose for fluoropyrimidines achievable in UPase−/− mice. 19F-MRS evaluation of capecitabine metabolism in tumors revealed similar activation of the prodrug in UPase−/− mice compared with WT. In WT mice, approximately 60% of capecitabine was transformed over three hours into its active metabolites, whereas 80% was transformed in tumors implanted in UPase−/− mice. In UPase−/− mice, prolonged retention of 5′dFUR allowed a proportional increase in tumor tissue. The similar presence of fluorinated catabolic species confirms that dihydropyrimidine dehydrogenase activity was not altered in UPase−/− mice. Overall, these results indicate the importance of UPase in the activation of fluoropyrimidines, the effect of uridine in protecting normal tissues, and the role for tumor-specific modulation of the phosphorolytic activity in 5-FU or capecitabine-based chemotherapy. Mol Cancer Ther; 10(12); 2330–9. © 2011 AACR.

Introduction

Uridine phosphorylase (UPase), a phosphorolytic enzyme ubiquitously expressed, has been shown to be induced in various human solid tumors compared with surrounding normal tissues (1–2). This is possibly due to frequent mutations of p53 (a suppressor of UPase gene expression; ref. 3) or higher expression of various cytokines (inducers of UPase expression) in tumor tissues (4, 5). Because of its increased expression in tumors, it is important to determine the role of UPase in the activation and antitumor activity of fluoropyrimidines, such as 5-fluorouracil (5-FU), 5′-deoxy-5-fluorouridine (5′-dFUR), and capcitabine (N4-pentyloxycarbonyl-5′-deoxy-5-fluorocytidine). UPase knockout (UPase−/−) mice provide an ideal model for this study (6).

The antitumor activity of 5-FU stems from its proximal metabolites, 5-fluoro-2′-deoxyuridine-5′-monophosphate (FdUMP), 5-fluorouridine-5′-triphosphate (FUTP), and 5-fluoro-2′-deoxyuridine-5′-triphosphate (FdUTP). These active metabolites either inhibit the activity of thymidylate synthase or incorporate into RNA or DNA, leading to nucleic acid dysfunction and cell death (7, 8). Several studies have indicated the role of UPase in fluoropyrimidine activation, including the anabolism of 5-FU into 5-fluorouridine (FUr) with subsequent phosphorylation to 5-fluorouridine monophosphate (FUMP) and the phosphorolysis of the prodrug 5′-dFUR into 5-FU (9–11). Using human and murine cancer cell lines, Peters and colleagues (12) reported that FUr synthesis was directly correlated to the intracellular UPase activity. In colon 26 tumor cells, a mixture of TNF-α, interleukin-1α (IL-1α), and IFN-γ efficiently enhanced 5-FU cytotoxicity 2.7-fold and 5′-dFUR cytotoxicity 12.4-fold due to induction of UPase activity (5). However, in most experimental models the contribution of UPase to fluoropyrimidine activity has been controversial due to the coexistence of other related metabolic enzymes, thymidine phosphorylase (TPase).
and orotate phosphoribosyltransferase (OPRTase). OPRTase participates in the de novo pyrimidine synthesis pathway, directly converting 5-FU to FUMP in the presence of 5-phosphoribosyl-1-pyrophosphate (PRPP; ref. 13), whereas TPase contributes to the formation of fluorodeoxyuridine (dFUR; ref. 14). In addition, TPase is also involved in the phosphorolysis of 5'-dFUR into 5-FU (15). We have investigated the effect of UPase on the antiproliferative activity of fluoropyrimidines using a gene-targeted cell model, UPase gene-knockout murine embryonic stem cells, and found that the abrogation of UPase in these cells resulted in an 8- and 16-fold increase in the IC_{50} values of 5-FU and 5'-dFUR, respectively (9). The unique genetic modification of UPase activity directly confirmed the role of UPase in fluoropyrimidine metabolism and activation. However, this in vitro system does not allow the investigation of the metabolic kinetics and tissue distributions of fluoropyrimidines. In addition, the cultured cells are also limited for the study of capecitabine, a prodrug of 5-FU, because its activation is precluded by the lack of carboxylesterase (16). In this article, we investigated the metabolic kinetics and tissue distributions of 5-FU in UPase^{-/-} mice and evaluated the histologic basis of host toxicity of capecitabine.

A major drawback of fluoropyrimidine-based chemotherapy are the severe dose-limiting side effects at the level of the bone marrow and gastrointestinal tract, often resulting in therapeutic failure (17, 18). Therefore, the development of prodrugs or modulatory strategies to improve the therapeutic efficacy of fluoropyrimidines using a UPase gene-targeted cell model, UPase TPase UK OPRTase DPD

Materials and Methods

**Animals and cell lines**

Wild-type (WT) and UPase^{-/-} mice were produced and maintained as previously described (6). All experiments were carried out according to Yale University and NVCI guidelines for the humane treatment of animals. Colon 38 murine adenocarcinoma cells (MC38) were originally obtained from the Southern Research Institute, Birmingham, AL (19) and authenticated by flow cytometry before implantation.

**In vivo toxicity of capecitabine**

Toxicity of capecitabine was evaluated in WT and UPase^{-/-} mice at 8 to 12 weeks. Mice were randomly grouped according to gender and body weight, 6 mice per group. Capecitabine (Xeloda) was suspended in 40 mmol/L citrate buffer (pH 6.0)/5% wt/vol of hydroxypropylmethylcellulose and administered by oral gavage at 1,000 to 1,375 mg/kg daily, 5 days a week for 4 weeks. Animal weights were measured daily to monitor the toxicity. The dose leading to 15% to 20% weight loss was defined as the maximum-tolerated dose (MTD). Observations of a given treatment group ceased when animals lost more than 20% of their body weight, or after the first mouse death occurred in the group. All the experiments were conducted at least in duplicate.

**Antitumor activity of 5-FU and capecitabine**

To observe the therapeutic efficacy of fluoropyrimidine treatment, murine colon 38 tumor suspension (200 μL) was implanted into both flanks of the mice (19). Colon 38 expresses WT UPase and its enzymatic activity was found to be similar once transplanted in WT or UPase^{-/-} mice (Table 1). When the tumors grew to an average size of 100 to 150 mg, animals were randomly assigned into groups, 6 mice in each group with comparable average body weight and tumor size. Tumor size was determined by measuring the 2 axes of the tumor (L, longest axis, and W, shortest axis) with a Vernier caliper and weight estimated according to the following formula: Tumor-weight (mg) = W^2 × L/2 (19). 5-FU was administered weekly by intraperitoneal injection at 85 and 150 mg/kg, and capecitabine was administered orally on a daily basis at 1,000 and 1,375 mg/kg, 5 days a week.

**Metabolism and tissue distribution of 5-FU**

[6-^3H]-5-FU (20 Ci/mmol, 200 mg/kg) was intravenously administered to mice through the tail vein. At the indicated time points, animals were anesthetized and

<table>
<thead>
<tr>
<th>Table 1.</th>
<th>Enzymatic activities in tissues of WT and UPase^{-/-} mice (nmol/mg/h)</th>
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<tr>
<td></td>
<td>UPase</td>
</tr>
<tr>
<td></td>
<td>WT</td>
</tr>
<tr>
<td>Liver</td>
<td>5.6 ± 1.5</td>
</tr>
<tr>
<td>Small intestine</td>
<td>696.8 ± 80.0</td>
</tr>
<tr>
<td>Colon 38</td>
<td>28.5 ± 4.7</td>
</tr>
</tbody>
</table>

Abbreviations: TPase, thymidine phosphorylase; UK, uridine kinase; OPRTase, orotate phosphoribosyltransferase. +/-, UPase WT; −/−, UPase knockout; ND, not detectable.

^a^ P < 0.05 compared with WT mice.
blood collected by retro-orbital bleeding. Plasma was separated by centrifugation at 2,000 x g, 4°C for 5 minutes, extracted with 2 volumes of 15% trichloroacetic acid (TCA) at 14,000 rpm for 10 minutes and neutralized with an equal volume of trictylamylamine-tetrafluoroethane (45:55, v:v). Aqueous phase was used for high-performance liquid chromatography (HPLC) analysis (19). Tissues frozen in liquid nitrogen were weighed and homogenized in 2 volumes of 15% TCA and the supernatant extracted for HPLC analysis as described for plasma. 5-FUrd and 5-FU were separated on a C18 reverse-phase Microsorb column (250 x 4.6 mm, Varian) using mobile phase ddH2O:10 mmol/L H3PO4:30 μmol/L heptane sulfonic acid (94:5:1, pH 3.1) at 1.0 ml/min by cooling the column at 8°C. 5-Fluorouridine nucleotides were separated by centrifugation at 2,000 rpm for 10 minutes, and subsequently for 1 hour at 37°C with RNase A/T1. To precipitate DNA, an equal volume of 2-propyl alcohol (75%–95%) was added and mixed until precipitation was complete and further with extractions with phenol/chloroform/iso-amylalcohol (49/49/1 v/v/v) and chloroform/iso-amylalcohol (49/1 v/v). DNA was precipitated with an equal volume of 2-propyl alcohol (75%–95%) and redissolved in 3 volumes of Tris-HCl buffer (pH 7.4), and 100 μmol/L [14C]-uridine, 1 mmol/L ATP, 100 μmol/L MgCl2, 50 mmol/L Tris-Cl (pH 7.6), and 100 μmol/L BAU. The resultant [14C]-UMP was separated on TLC plates and determined by scintillation counting. Dihydropyrimidine dehydrogenase (DPD) activity was measured by determining the conversion of uracil into UMP in the presence of ATP (6). The reaction was done in a 100 μL volume with 200 μmol/L [14C]-uridine, 1 mmol/L ATP, 100 μmol/L MgCl2, 50 mmol/L Tris-Cl (pH 7.6), and 100 μmol/L BAU. The resultant [14C]-UMP was separated on TLC plates and determined by scintillation counting. The assay mixture contained 200 mmol/L NADPH and 8.25 mmol/L [14C]-uracil in a solution constituted by 35 mmol/L potassium phosphate (pH 7.4), 2.5 mmol/L magnesium chloride, 10 mmol/L 2-mercaptoethanol. The formed [14C]-dihydrouracil was separated on TLC plates and radioactivity determined (22).

**MRS evaluation of capecitabine metabolism**

WT or UPase−/− mice bearing colon 38 tumors were treated orally with 1,000 mg/kg capcitabine. Animals were anesthetized with isoflurane (2%–3% induction and 1%–2% maintenance) along with 0.5 LPM O2. MRI and MRS were done with a Bruker 7T/20 Biospin MRI, equipped with a dual-tuned 7 cm ID 1H/19F volume coil (Bruker), and a 15-mm ID detunable receive-only 19F surface coil (Doty Scientific). The surface coil was placed over the region of interest (ROI) and the animal secured to minimize the effects of motion on the MR data. A 1H T2-weighted TurboRARE sequence [repeat time (TR): 2,330 milliseconds, echo time (TE): 20 milliseconds, flip angle: 90 degrees; ref. 23]. 19F spectra were acquired and averaged during 27.5 minutes blocks [3,300 free induction decays (FID), TR: 0.5 seconds, spectral width: 60 kHz, points/FID: 890, flip angle: 60 degrees, RF pulse duration: 50 micro-seconds] for 3 hours. The 19F MRS data were analyzed using Bruker’s Topspin application. The rate of capcitabine activation and build-up of the intermediate molecules were evaluated.

**Peripheral blood cells counting**

Peripheral blood samples were collected from mice treated with capcitabine at 1,000 mg/kg for 4 weeks. Number of erythrocytes per microliter and hematocrit values were determined using a Coulter counter (Model ZF, Coulter Electronics). Hemoglobin was measured by a hemoglobinometer (Coulter Electronics) using the cyanmethemoglobin method. Numbers and subtypes of white blood cells were determined on 50 μL of peripheral blood, after red blood cells were osmotically lysed, using a flow cytometer (Becton Dickinson). Total and differential white blood cell counts were determined. To determine the...
plasma 5-FU is mainly removed via the DPD-initiated
sure with an AUC of 84.5 mmol/L-min in WT compared
drug as indicated by a significantly smaller systemic expo-
clearance rate, consequently reducing exposure to the
5-FU due to UPase abrogation significantly affected its
This indicates that alterations in the anabolic pathway of
respectively, for
37.9 minutes and clearance of 29.4 versus 18.1 ml/min/kg,
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>WT</th>
<th>UPase&lt;sup&gt;−/−&lt;/sup&gt;</th>
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<tbody>
<tr>
<td>T&lt;sub&gt;max&lt;/sub&gt;</td>
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<td>5</td>
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<tr>
<td>C&lt;sub&gt;max&lt;/sub&gt;</td>
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<td>5,074.6</td>
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<td>52,385</td>
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<td>52,338</td>
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<tr>
<td>T&lt;sub&gt;1/2&lt;/sub&gt;</td>
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<td>26.3</td>
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<tr>
<td>CL</td>
<td>mL/min/kg</td>
<td>18.1</td>
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<tr>
<td>V&lt;sub&gt;ss&lt;/sub&gt;</td>
<td>mL/kg</td>
<td>633</td>
<td>595.7</td>
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NOTE: Estimated using WinNonlin V5.2, noncompartmental IV bolus model. Linear up, log down trapezoidal integration rule. AUC<sub>inf</sub> value is predicted from terminal elimination rate constant. Treated the 0 concentration at 240 min for FURD WT as

Histologic examination of small and large intestine
The intestinal tract, the small intestine, and colon were
excised from mice treated with 5-FU (85 mg/kg) or cape-
citabine (1,000 mg/kg) for 4 weeks. The isolated tissues
were then fixed in formal fixative and transverse sections (5 μm) were prepared for staining with hematoxylin and
eosin. Histologic changes of the tissues were evaluated
under light microscopy.

Results
In a previous study, we reported that the abrogation of
UPase in mice led to a decrease in 5-FU host toxicity (6).
However, it was not clear whether this host protection
resulted from a reduced activation of 5-FU through the
pyrimidine salvage pathway or from the protection of
increased uridine in the plasma and tissues, due to the
elimination of UPase activity. In this study on the
UPase<sup>−/−</sup> mouse model, we investigated metabolism and
tissue distribution of 5-FU and examined the pathologic
basis of 5-FU and capecitabine toxicity, and we evaluated
the effect of UPase abrogation on the antitumor activity of
5-FU and capecitabine.

Plasma clearance of 5-FU displayed a faster rate in
UPase<sup>−/−</sup> mice than in WT with a 1/2 of 26.3 minutes versus
37.9 minutes and clearance of 29.4 versus 18.1 ml/min/kg,
respectively, for UPase<sup>−/−</sup> and WT C57 BL6 mice (Table 2).
This indicates that alterations in the anabolic pathway of
5-FU due to UPase abrogation significantly affected its
clearance rate, consequently reducing exposure to the
drug as indicated by a significantly smaller systemic exposure with an AUC of 84.5 mmol/L-min in WT compared
with 52.3 mmol/L-min for the knockout mice. Normally,
plasma 5-FU is mainly removed via the DPD-initiated
degradation pathway (25). When the drug is administered
orally or intraperitoneally, liver represents the major site
of 5-FU metabolism, with more than 85% of a given dose
of the fluoropyrimidine eliminated through the rapid
formation of dihydrofluorouracil (26). Although the ex-
pression and the enzymatic activity of DPD in the liver
of both mice are virtually similar (Table 1), the elevated
5-FU clearance in UPase<sup>−/−</sup> mice possibly suggests a re-
duced competition of uracil for DPD, in which uracil
formation from uridine degradation is blocked because
of the lack of UPase. However, the plasma pharmaco-
kinetics of FUrD, following 5-FU delivery, displayed a
significant difference in UPase<sup>−/−</sup> mice (Table 2). In WT
mice, FUrD appeared in plasma within 5 minutes follow-
ing intraperitoneal administration of 5-FU (200 mg/kg),
reaching nearly 4 μmol/L at 10 minutes. Thereafter, FUrD
concentration quickly declined to an undetectable level
at 4 hours. Plasma FUrD in UPase<sup>−/−</sup> mice was barely
detectable at 10 minutes, and its peak appeared 1 hour
after administration of the same dose of 5-FU. The clear-
ance of plasma FUrD was significantly slower in UPase<sup>−/−</sup>
mice than in WT, and a considerable amount of FUrD was
still detected 4 hours after 5-FU administration resulting
in a significantly higher AUC (316 vs. 105 μmol/L-min;
Table 2). In WT mice, UPase rapidly catalyzed the formation
of FUrD from administered 5-FU. However, in UPase<sup>−/−</sup>
mice, plasma FUrD was possibly originated from the de-
gradation of FUMP synthesized by OPRTase-catalyzed
de novo pathway (13, 27) and eventually cleared by kidney
excretion (6). As a result, a delay occurred in plasma peak concentration of FUrD, accompanied with a prolonged
half-life in UPase<sup>−/−</sup> mice.

The liver is the major metabolic organ for 5-FU, and the
gastrointestinal system represents one of the major tox-
icty targets for fluoropyrimidines. Therefore, the 5-FU
metabolic pharmacokinetics and distribution in these
tissues were examined. Overall, 5-FU and FUrD showed
similar metabolic patterns in these tissues unlike that in
plasma (Fig. 1A and B). 5-FU was cleared slightly faster in both liver and intestines of UPase−/− mice, but with no statistical significance (P > 0.05) compared with WT animals; although the formation and metabolism of FUrd varied with UPase expression status and tissue types. In WT intestinal tissues, a high level of FUrd was detected at 10 minutes after intraperitoneal administration of 5-FU (200 mg/kg) but declined rapidly within 30 minutes and still maintained detectable levels after 4 hours. In UPase−/− intestinal tissues, however, FUrd appeared at 30 minutes and peaked at 60 minutes after 5-FU delivery. However, in UPase−/− liver tissues, FUrd was present at 10 minutes and reached a peak concentration at 30 minutes, 3-fold higher than that in the intestines, indicating an active 5-FU anabolism through pyrimidine de novo synthesis in liver. Similar to that in the intestines, the clearance of FUrd was much faster in WT liver than that in UPase−/− (Fig. 1B). Taken together, these data indicate the important role of UPase in 5-FU/FUrd metabolism in normal intestinal and liver tissues, supporting our previous observation that ribose-1-phosphate is not a rate-limiting factor in the 5-FU anabolic metabolism catalyzed by UPase (9).

The incorporation of 5-FU into RNA is important for its antiproliferative activity (28) but has also been linked to the toxic effect of fluoropyrimidines (29–30). Therefore, we included in our investigation the measurement of FUXP levels and 5-fluoro-RNA amounts in liver, gastrointestinal tract and transplanted colon 38 tumor. As shown in Fig. 1C and D, the levels of FUXP and 5-fluoro-RNA were significantly higher in WT liver and intestines than in UPase−/−; 5-FU incorporated into RNA of liver tissue started to be cleared within the first hour, although we observed a protracted accumulation in the RNA of the intestinal tissues of WT mice for more than 4 hours, providing the pharmacokinetic basis for the intestinal lesions caused by the fluoropyrimidines in the WT mice. The lower incorporation of 5-FU in the normal tissues of the UPase−/− mice, likely due to the competition of high uridine levels, confirms our previous observation of reduced in vivo host toxicity to 5-FU and a 75% higher MTD of 5-FU in this strain (6).

We observed significant differences in the concentration of uridine in plasma and normal tissues of WT mice compared with the UPase−/− (Table 3). Uridine concentration was elevated 3-fold in the intestine and kidney and up to 15-fold in spleen of UPase−/− mice compared with the corresponding WT tissues. In colon 38 tumors transplanted in both WT and UPase−/− mice, we observed a reduced uridine concentration compared with the other tissues with levels similar to plasma concentrations. The elevation in tumor uridine concentration we determined in UPase−/− was highly significant (P < 0.01) compared with the tumor in WT mice (7 vs. 1 μmol/L); however, the
A daily 1,000 mg/kg oral dose of capecitabine was administered at 1,000 mg/kg (the MTD for WT mice) and 150 mg/kg (a dose shown to be tolerated only by UPase<sup>−/−</sup> mice; ref. 7); and capcitabine was administered at 1,000 mg/kg (the MTD for WT mice) and 1,375 mg/kg (a dose shown to be tolerated only by UPase<sup>−/−</sup> mice). As presented in Fig. 2B, a higher dose of 150 mg/kg of 5-FU efficiently controlled and reduced tumor size, whereas the standard 85 mg/kg dose of 5-FU only partially slowed down tumor growth in both strains. In the capcitabine treatments, a 30% dose increase from 1,000 mg/kg to 1,300 mg/kg resulted in dramatic tumor growth inhibition in UPase<sup>−/−</sup> mice (Fig. 2C), with complete disappearance of tumors in 10 of 11 mice. These data indicate that the tumor-specific modulation of UPase activity can greatly improve the antitumor efficacy of 5-FU and capcitabine by allowing dose escalation without causing significant host toxicity. To better evaluate the activation of capcitabine and the potential differences in metabolism between colon 38

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<tr>
<th>Plasma (μmol/L)</th>
<th>Tissues (pmol/mg)</th>
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<tbody>
<tr>
<td></td>
<td>Gut</td>
</tr>
<tr>
<td><strong>WT</strong></td>
<td>1.5</td>
</tr>
<tr>
<td><strong>UPase&lt;sup&gt;−/−&lt;/sup&gt;</strong></td>
<td>7.2</td>
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Table 3. Plasma and tissue concentrations of endogenous uridine in WT and UPase<sup>−/−</sup> mice.
tumors implanted in WT mice and in UPase−/− mice, we conducted a series of in vivo 19F-MRS experiments using a 1,000 mg/kg oral dose of capecitabine administered as a bolus. The in vivo spectra (Fig. 3A) resolve 5 main fluorinated species, with the administered drug capecitabine at 7 ppm upfield from the 5-FU signal, 50-d-5-fluorocytidine at 5 ppm, 50-d-5-fluorouridine at 3.5 ppm, and the 2 main fluorinated metabolites fluorouridepropionic acid and α-fluoro-β-alanine at 17 and 19 ppm, respectively. As reported in Fig. 3A, we detected all 5 fluorinated species mentioned, starting 30 minutes after the oral administration of capecitabine, and were able to follow their presence over 3 hours of spectra acquisition.

We observed in tumors implanted in WT mice that capecitabine represented approximately 35% of the total fluorine signal, 50-dFCR corresponded to a similar percentage, whereas 50-dFUR ranged from 25% to 30% of total fluorine. The 2 catabolites, FUPA and FβAL were approximately 5% of the total (Fig. 3B). The tumors implanted in the UPase−/− mice showed that capecitabine was approximately 15% of the total fluorine signal, 50-dFCR 45%, 50-dFUR 35%, and the sum of the 2 catabolites ranged from 4% to 7% of the total (Fig. 3C).

We were unable to capture the 5-FU signal consistently, likely due to the rapid transformation of 5-FU into 5-FUrd and its fluoronucleotides in colon 38 tumors expressing WT UPase. 5-FUrd and FUXP with their signals at 3.6 and 5.1 ppm, respectively, were impossible to quantitate, given the overwhelming presence of 50-dFCR and 50-dFUR in the 3.5 to 5 ppm region.

Our data indicates that the genetically induced changes and the elevation in circulating uridine did not interfere with the carboxylesterases and cytidine deaminase in the activation of capecitabine. Also, the comparable presence of 5-FU catabolites FUPA and FβAL in liver from WT and UPase−/− mice confirms the similar DPD enzymatic activity (Table 1) and quantitative real-time RT-PCR data (WT 1.0 ± 0.1 vs. 0.8 ± 0.2 in UPase−/−) and, therefore, a similar rate of catabolic degradation for 5-FU in the 2 murine strains.

Discussion

UPase activity and expression has been shown to be elevated in many tumors including colorectal carcinomas, breast cancer, melanomas, and lung adenocarcinomas (11). Several mechanisms have been uncovered, all leading to an increased expression in human tumors. We have previously reported that the expression of UPase is induced by TNF-α through the NF-κB pathway (11). Other groups have shown that EWS/ETS fusion proteins, playing a dominant oncogenic role in cell transformation in Ewings family tumors, induce UPase gene expression through interaction with the UPase promoter (35). More
recently, PGC-1α/ERR-dependent upregulation of UPase was shown to contribute to an increased enzymatic activity in colon and breast cancer cells (36). These results show that the elevation of UPase in tumor is a key contributor to the tumor selectivity of 5-FU and capecitabine. Unlike TPase, UPase is not associated with any identified angiogenic activity because of its limited catalytic activity on deoxynucleosides. It has been shown that 2-deoxyribose-1-phosphate released from the deoxynucleoside by TPase activity can act as an endothelial cell chemoattractant and angiogenic factor (37). This feature allows for a convenient modulation of the phosphorolytic activity in tumors by UPase gene transfer or delivery of specific inducers of UPase gene expression, such as cytokines. This modulation would not be complicated by possible tumor growth stimulation due to simultaneously induced angiogenesis, as is the case with TPase (38).

The data here presented establish once more the role of uridine in protecting normal tissues from the toxicity of fluoropyrimidines. In the normal tissues of UPase−/− mice, we observed a constitutive uridine concentration above 50 μmol/L with the gut, the major target of 5-FU toxicity at 90 μmol/L. These concentrations have been found previously to be sufficient to provide adequate protection against 5-FU–based chemotherapy regimens (39–40). Similarly, the concentration of uridine in colon 38 tumors implanted in UPase−/− mice approximated the plasma uridine concentration of 7 μmol/L, indicating that the inability of some tumors to accumulate this nucleoside is likely due to the loss of the concentrative transport mechanism (41).

Several studies have shown the capacity of large doses of uridine to reduce 5-FU toxicity, without affecting its antitumor activity, if properly sequenced (42). Unfortunately, the administration of large doses of uridine, because of its rapid half-life, results in moderate to severe toxicity. Our laboratory has shown that this problem could be overcome by using inhibitors of UPase, such as BAU, to conserve endogenous uridine with consequent elevation of its concentration in plasma and tissues. A phase I clinical trial of oral BAU administered as a single agent has shown the ability of this inhibitor to elevate the...
plasma uridine concentration 2- to 3-fold without significant host toxicity (43).

The combination “rescue regimens” of 5-FU plus uridine were initially proposed to evaluate the hypothesis that the antitumor effect of 5-FU is primarily due to the inhibition of thymidylate synthase and the host toxicity mostly caused by the incorporation of the fluoropyrimidine into RNA (44). In vivo studies in a murine model and in vitro data (45, 46) have clearly indicated that the incorporation of 5-FU into RNA seems to be the major cause of gastrointestinal toxicity that uridine inhibited the incorporation and avoided the cytotoxic effect, whereas thymidine did not prevent 5-FU toxicity.

Clinical studies of 5-FU in combination with methotrexate and PALA have shown that patients tolerated combination therapy with delayed uridine up to a weekly dose of 750 mg/m² of 5-FU, with 25% experiencing moderate mucositis (grade II). In previous clinical trials without uridine, 4 of 6 patients could not tolerate a 600 mg/m² dose of 5-FU because of mucositis, diarrhea, and a decrease in performance status. Another study of high-dose 5-FU with doxorubicin, high-dose methotrexate and leucovorin, and oral uridine administration allowed for dose intensification of 5-FU and ensured rescue from 5-FU-induced hematoxicity without adverse impact on tumor response (47). As indicated in preclinical studies, properly delayed uridine rescue resulted in a faster clearance of 5-FU from RNA of bone marrow and enhancement of the rate of recovery of DNA synthesis (39).

Nucleoside transporters are expressed in a variety of cells and tissues with different substrate specificity and selectivity. Most cell types coexpress concentrative nucleoside transporters (CNT) and equilibrative nucleoside transporters (ENT) to maintain their nucleoside supply. Uridine is mainly accumulated in cells of different origin by the Na+/K+-dependent CNT1 (SLC28A1) but also by CNT3 (SLC28A3) that has broader substrate specificity. ENTs, particularly ENT1 (SLC29A1) but also by ENT2 (SLC29A2), mediate facilitated diffusion transport with broader selectivity but relatively low affinity. Recent studies have indicated that ENT1 is a sort of housekeeping transporter, and its expression is often high and is highly retained in tumors (48).

A clinical study using a tissue array on 300 paraffin-embedded gynecologic tumors (endometrium, ovary, and cervix) showed that hENT1 and hENT2 protein expression were highly retained, but a significant number of tumors were hCNT1 negative (49). A more recent breast cancer study has shown that the percentage of hCNT1-positive cells correlates positively with a reduced long-term survival in patients treated with cyclophosphamide/methotrexate/5-FU chemotherapy (50). It is reasonable to speculate that high expression of hCNT1 could be linked to high nucleotide salvage efficiency interfering with 5-FU nucleoside metabolism and, ultimately, with its antiproliferative activity.

In summary, this study determined the metabolism and tissue distribution of 5-FU in UPhase−/− mice and proved the role of UPhase in the activation and antitumor activity of 5-FU and capecitabine. This study also showed the pathologic basis for host protection by UPhase abrogation from 5-FU and capecitabine lesions, the ability of uridine to protect the normal tissues, and exhibited the effect of tumor-specific expression of UPhase on the therapeutic efficacy of these agents.

Disclosed of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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Differential Expression of Uridine Phosphorylase in Tumors Contributes to an Improved Fluoropyrimidine Therapeutic Activity

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