Characterization of Recombinantly Expressed Rat and Monkey Intestinal Alkaline Phosphatases: In Vitro Studies and In Vivo Correlations


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Received March 15, 2013; accepted April 30, 2013

ABSTRACT

Intestinal alkaline phosphatases (IALPs) are widely expressed in the brush border of epithelial cells of the intestinal mucosa. Although their physiologic role is unclear, they are very significant when it comes to the release of bioactive parent from orally dosed phosphate prodrugs. Such prodrugs can be resistant to cleavage by IALP, or alternatively undergo rapid cleavage leading to the release and precipitation of the less soluble parent. Because purified IALPs from preclinical species are not commercially available, and species differences have not been investigated to date, an effort was made to recombinantly express, purify, and characterize rat and cynomolgus monkey IALP (rIALP). Specifically, recombinant IALP (rIALP)-catalyzed cleavage of five prodrugs (fosphenytoin, clindamycin phosphate, dexamethasone phosphate, ritonavir phosphate, and ritonavir oxymethyl phosphate) was tested in vitro and parent exposure was assessed in vivo (rat only) following an oral dose of each prodrug. It was determined that the rate of phosphate cleavage in vitro varied widely; direct phosphates were more resistant to bioconversion, whereas faster conversion was observed with oxymethyl-linked prodrugs. Overall, the rat rIALP-derived data were qualitatively consistent with in vivo data; prodrugs that were readily cleaved in vitro rendered higher parent drug exposure in vivo. Of the five prodrugs tested, one (ritonavir phosphate) showed no conversion in vitro and no in vivo parent exposure. Finally, the apparent K_{m} values obtained for fosphenytoin and clindamycin phosphate in vitro suggest that IALP is not likely to be saturated at therapeutic doses.

Introduction

Poor aqueous solubility could be a serious barrier for the successful delivery of a therapeutic candidate. Therefore, a soluble prodrug approach is generally considered for the purpose of enhancing exposures. Phosphate prodrugs are an effective and commonly used approach to overcome solubility issues in drug delivery and have successfully been used for a number of oral and parenterally administered marketed drugs (Fleisher et al., 1996; de Jong et al., 1997; Heimbach et al., 2003a; Rautio et al., 2008; Jana et al., 2010; Stella, 2010; Huttunen et al., 2011). The advantages of phosphate prodrugs include their chemical stability, several orders of magnitude of improved solubility as compared with parent, and relative ease of synthesis in the presence of a suitable handle (Heimbach et al., 2003a). Importantly, phosphate prodrugs are cleaved in the intestine and generate a super-saturated parent solution that enhances the absorption flux (Heimbach et al., 2003a). On the other hand, poor phosphate cleavage can give rise to an unacceptable oral profile, low parent drug exposure, and a lack of improvement in clinical efficacy (de Jong et al., 1997; Heimbach et al., 2003a; Stella, 2010). Poorly soluble parents with sufficient solubility in the formulation vehicle, and dissolution times less than their gastrointestinal transit times will exhibit slow yet complete absorption and in these cases a phosphate prodrug may not be beneficial (Heimbach et al., 2003a). Therefore, the successful identification of ideal candidates for an oral phosphate prodrug strategy requires a careful analysis of the properties of the parent drug and promoiety. These include drug and prodrug solubility, dissolution, rate of bioconversion, active and passive transport characteristics, as well as the likelihood for precipitation. Multiple authoritative reviews have elaborated these properties in great detail (Heimbach et al., 2003a; Stella and Ni-Addae, 2007; Rautio et al., 2008; Jana et al., 2010; Stella, 2010; Huttunen et al., 2011).

Following oral dosing, phosphate prodrug cleavage is mediated by intestinal alkaline phosphatases (IALPs). The physiologic role of IALP is unclear since knock-out mice do not display an overt phenotype but it has been speculated that they play a role in regulating fat absorption, and in preventing the duodenum from damage due to bursts of acid from the stomach (Akiba et al., 2007; Fernandez and Kidney, 2007; Mizumori et al., 2009). IALPs are catalytically promiscuous and are abundantly expressed on intestinal epithelial membrane cells. An
orally administered phosphate prodrug must be cleaved to its parent drug before the parent drug is absorbed into the systemic circulation, since the charged phosphate moiety has very poor intrinsic passive permeability (Fleisher et al., 1996; Heimbach et al., 2003a; Rautio et al., 2008). Given the key role that IALPs play in the success of a prodrug, it is important to understand their kinetic characteristics, species differences, and in vitro-to-in vivo correlations (IVIVCs). Calf intestinal, bovine intestinal and kidney, porcine kidney and intestine, rabbit intestine, and human placental, liver, and leukocyte alkaline phosphatases (ALPs) are available commercially; however, rat and monkey IALPs, two common preclinical species in drug discovery, are not commercially available. Hence, in the present study, we have characterized rat and monkey in-house expressed recombinant IALP (rIALP). Probe phosphate prodrugs, either directly attached to a molecule or incorporated via linkers, were selected for this study. Fosphenytoin (PubChem CID 56339), dexamethasone phosphate (PubChem CID 9400), clindamycin phosphate (PubChem CID 443385), ritonavir oxymethyl phosphate (DeGoey et al., 2009), and ritonavir phosphate (DeGoey et al., 2009) were selected as model prodrugs, which are hydrolyzed to their corresponding highly permeable and poorly soluble parent drugs phenytoin (PubChem CID 657302), dexamethasone (PubChem CID 5743), clindamycin (PubChem CID 29029), and ritonavir (PubChem CID 392622), respectively (Fig. 1). It was also possible to study the bioconversion rates of the probe substrates in the presence of rat intestinal mucosal scrap (RIMS). Furthermore, the kinetic parameters describing fosphenytoin and clindamycin phosphate cleavage by rat and monkey rIALP, as well as RIMS, were determined. Finally, in vivo oral pharmacokinetic studies in rats were also conducted to understand the impact of in vitro bioconversion rate of phosphate prodrugs on in vivo exposure of their respective parent compounds. Based on the IVIVC in rat (and monkey in vitro data), and the availability of a well-characterized recombinant human IALP enzyme, it may be possible to predict whether a new phosphate prodrug will show improved exposures over parent in humans. This information can be used in support of decision-making in an early drug discovery setting.

Materials and Methods

Chemicals

Human placental ALP, bovine ALP, fosphenytoin, sodium phenytoin, clindamycin phosphate, clindamycin hydrochloride, sodium chloride, glycercol, protease inhibitor cocktail, IGEPAL (octylphenoxypolyethoxyethanol), 2-hydroxypropyl-beta-cyclodextrin, EDTA, Tris-HCl, and phenylmethylsulfonyl fluoride were purchased from Sigma-Aldrich (St. Louis, MO). Ritonavir phosphate and ritonavir oxymethyl phosphate were synthesized (>98% pure) by the Discovery Chemical Synthesis department at Biocon Bristol-Myers Squibb Research and Development center (BBRC), Bangalore, India. QuantChrom Alkaline Phosphatase Assay Kit was purchased from BioAssay Systems (Hayward, CA). The bioanalytical internal standard was an in-house proprietary compound (any suitable organic compound can be utilized as an internal standard). Liquid chromatography grade acetonitrile, dimethylsulfoxide, and ethanol were purchased from Merck Limited (Mumbai, India). MultiScreen Solventiss filter plates (0.45 µm, low binding hydrophilic polytetrafluoroethylene (PTFE)) were purchased from Millipore (Carrigtwohill, Ireland). All aqueous solutions were prepared in Milli-Q water (Millipore, Billerica, MA). All other chemicals were of analytical grade.

Expression and Purification of IALP

The cloning, expression, purification, and biochemical characterization of rat and cynomolgus rIALPs are described in brief. The IALP genes were cloned from intestinal RNA (BioChain, Newark, CA) using standard molecular biology techniques. The active forms of these enzymes were expressed in SF9 insect cell and purified from the media after secretion of the posttranslationally modified protein. The original secretion signal sequence at the N-terminus was retained and the extreme C-terminal region was replaced by a hexa-histidine tag to facilitate purification. These recombinant enzymes were found to be glycosylated and active under standard reaction conditions.

Preparation of RIMS

Immediately after excising intestines from male Sprague-Dawley rats, a segment of approximately 1 m of small intestine was placed in an ice-cold Petri dish and washed with phosphate-buffered saline (pH 7.4), containing phenylmethylsulfonyl fluoride (1 mM). Subsequently, the mucosa was scrapped off with a glass slide, minced, and homogenized with ice-cold lysis buffer using a homogenizer. The lysis buffer was composed of 50 mM, Tris-HCl (pH 7.4), 150 mM NaCl, 1 mM EDTA, 1% IGEPAL, 5% glycerol, 1 mM phenylmethylsulfonyl fluoride (PMSF) and protease inhibitor cocktail. This homogenate was used for ALP activity determination. The total protein concentration was determined by the bicinchoninic acid protein assay kit (Sigma-Aldrich).

Evaluation of ALP Activity

ALP activity of RIMS and rIALP was determined using QuantChrom Alkaline Phosphatase Assay Kit according to manufacturer’s suggested protocol. The measurement of ALP activity was based on the hydrolysis of p-nitrophenolphosphate (PNPP) to p-nitrophenol (PNP), a yellow-colored product which shows absorbance at 405 nm. The absorbance was measured using UV spectrophotometer (Tecan, Manneford, Switzerland). Activities were expressed as IU/ml (1 IU = 1 µmole of PNP metabolized per minute at 37°C, pH 9.8), and determined in triplicate.

Determination of Prodrug Cleavage Rate In Vitro

To assess the potential for generation of parent drug from the phosphate prodrug, 200 µl of rIALP or RIMS dissolved in 100 mM Tris-HCl buffer (pH 7.4) was added to 200 µl of freshly prepared prodrug solution (10 µM) prepared in the same buffer. The ALP activities ranged from 0.004 to 0.03 IU/ml. Incubations were performed in triplicate using 96-well plates (Waters, Milford, MA) at 37°C in a shaking water bath (Julabo, Allentown, PA). The prodrug and enzyme solution were prewarmed at 37°C before the reaction was initiated by addition of substrate. The incubation was performed for 120 minutes with 25-µl aliquots taken at 0, 5, 10, 15, 30, 60, 90, and 120 minutes. The assays were terminated at designated time points by the addition of 200 µl of ice-cold acetonitrile containing internal standard followed by centrifugation at 4000g for 4 minutes. The supernatant was transferred to a new 96-well plate for analysis by ultra-performance liquid chromatography combined with tandem mass spectrometry (UPLC-MS/MS). RIMS, rat rIALP, monkey rIALP, human placental ALP, and bovine ALP were tested in this assay. The t1/2 value for each prodrug/protein combination was determined from the natural logarithm of percent remaining versus time plots.

Determination of Kinetic Parameters

Incubations were performed in triplicate using 96-well plates (Waters). The reaction mixture (100 µl) contained 100 mM Tris buffer (pH 7.4), IALP protein (0.4 ng/ml protein for fosphenytoin, 12.5 ng/ml protein for clindamycin phosphate), or RIMS (500 ng/ml protein for fosphenytoin and 1250 ng/ml protein for clindamycin phosphate), and varying concentration of fosphenytoin (0.15–1000 µM) and clindamycin phosphate (19–5000 µM). Prior to reaction initiation by the addition of substrate, the incubation medium containing protein was incubated at 37°C for 10 minutes. Concentration of the organic solvent used (dimethylsulfoxide) was <0.5% of the total incubation volume. Control incubations were performed for each substrate with no protein present to account for any potential protein independent loss of prodrug over the incubation time. Incubations were performed at 37°C in a shaking water bath for 10 minutes and terminated by the addition of 200 µl of ice-cold acetonitrile containing internal standard, followed by centrifugation at 4000g for 4 minutes. The supernatant was transferred to a new 96-well plate for analysis by UPLC-MS/MS. The protein concentrations and incubation time for the kinetic reactions were selected based on preliminary assays to ensure linearity of product formation, and that the substrate consumption during the reaction was less than 20%.
Animals and Formulation. Sprague-Dawley rats weighing 260–280 g (8–10 weeks age) were obtained from Harlan Laboratories Inc. (Boxmeer, The Netherlands). All the animal experiments were conducted in the animal research facility of BBRC (Bangalore, India). Rats were housed in well-ventilated cages at room temperature (24 ± 2°C) and 40–60% relative humidity while on a regular 12-hour light-dark cycle. Animal study protocols were approved by the organizational Animal Ethics Committee. Phenytoin (sodium salt), fosphenytoin, dexamethasone, and dexamethasone phosphate formulations were prepared in water, whereas clindamycin (hydrochloride salt) and clindamycin phosphate were prepared in phosphate buffer, pH 7.4. Ritonavir, ritonavir oxymethyl phosphate, and ritonavir phosphate formulation were prepared in 10% ethanol, 36% of 2-hydroxypropyl-beta-cyclodextrin and 54% water. All the formulations were filtered through 0.22-μm filter before administration.

Oral Pharmacokinetic Study. Male Sprague-Dawley rats were fasted overnight (12–14 hour) before dosing and had free access to water throughout the experimental period. All the parent drugs and their corresponding phosphate prodrugs were administered orally as solution (5 mg/ml) to a group of three rats. All prodrugs were administered at the dose equivalent to their respective parent dose. The doses are summarized in Table 5. Animals were provided with their standard diet 4 hours after dosing, and blood samples (approximately 0.2 ml) were collected from the jugular vein into microfuge tubes containing EDTA at predetermined time points (10 minutes to 24 hours). Plasma was harvested by centrifuging the blood at 4000 g for 3 minutes on Eppendorf 5810 R (Hamburg, Germany) and stored frozen at −70 ± 10°C until analysis.

Sample Preparation. Plasma (50 μl) and internal standard in acetonitrile (200 μl) were mixed in 96-well hydrophilic Solvinert plates. The acetonitrile mixtures were vortexed and centrifuged at 4000 g for 4 minutes. Filtrates were collected in a 96-well 1-ml round collection plate and analyzed by UPLC-MS/MS.

UPLC-MS/MS Analysis

Standard curves for prodrug and parent were prepared separately by spiking a known amount of compound into blank matrix and processed according to the procedures described above. Analysis was carried out using UPLC-MS/MS consisting of a Waters Acquity Integrated System and API 4000 mass spectrometer (Applied Biosystems, MDS Sciex, Toronto, ON, Canada) equipped with an API electrospray ionization (ESI) source. Detection of the ions was performed in the multiple reaction monitoring (MRM) mode. A 4-μl aliquot of each processed sample was injected into a reverse phase column (BEH C18, 1.7 μm, 2.1 × 50 mm). The MS/MS conditions are summarized in Table 1. Chromatographic resolution of prodrugs and parents were achieved using a gradient UPLC method at a flow rate of 0.7 ml/min. Mobile phase A consisted of 0.1% ammonia for negative mode, or 0.1% formic acid in water for positive mode while mobile phase B consisted of 0.1% formic acid in acetonitrile for positive mode, or acetonitrile for negative mode MS/MS. The gradient UPLC method began with 5% B maintained for 0.8 minutes, ramped...
up to 95% from 0.8 to 1.2 minutes, maintained at 95% B up to 1.5 minutes, ramped down to 5% B from 1.5 to 1.8 minutes, and maintained at 5% B until 2.2 minutes, the total run time per injection. Lower limit of quantitation for all the analytes was 0.61 nM. The assay accuracy was found to be between 95 and 115%. The parent and prodrug were separated chromatographically and no in-source conversion was observed. Ex vivo stability in buffer was ensured prior to conduct of the all in vitro experiments.

Data Analysis

The rates of formation of the parent compound versus the prodrug concentrations were fit to the Michaelis-Menten equation (eq. 1) using GraphPad Prism 3.03 software (GraphPad Inc., San Diego, CA). Estimated kinetic parameters were: $V_{\text{max}}$, the maximal velocity of uninhibited reaction; $K_{\text{m}}$, substrate concentration at which is rate of reaction is half of $V_{\text{max}}$.

$$v = \frac{V_{\text{max}} \times [S]}{K_{\text{m}} + [S]}$$

In some cases, the data were not adequately described by eq. 1 and had to be fit to an equation which assumes two binding sites (eq. 2); one with a low $K_{\text{m}}$ and $m$, and the other with a high $V_{\text{max}}$ and $K_{\text{m}}$.

$$v = \frac{(V_{\text{max1}} \times [S]) + (C_{\text{int}} \times S^2)}{K_{\text{m1}} - S}$$

Pharmacokinetic parameters were determined based on a noncompartmental approach using Kinetic software (version 4.4.1; Thermo Electron Corporation). The area under the plasma concentration-versus-time curve up to the last quantifiable time point ($AUC_{0-\infty}$) was computed using the mixed log linear method.

Results

$p$-Nitrophenolphosphate Cleavage Rate Determination. The rate of cleavage of $p$-nitrophenolphosphate to $p$-nitrophenol was determined in the presence of rat and monkey rIALP and RIMS (Table 2).

RIMS exhibited lower activity on a per-milligram-of-total-protein basis, whereas activity was greatest with monkey rIALP versus rat rIALP. The lower activity of RIMS is unsurprising since that preparation contains multiple mucosal proteins and the result is similar to that reported previously (Wada et al., 2001).

Prodrug Cleavage Rate In Vitro. Fosphenytoin, dexamethasone phosphate, clindamycin phosphate, ritonavir oxymethyl phosphate, and ritonavir phosphate (10 μM) were used as probe substrates to assess the bioconversion of phosphate prodrugs using RIMS, rat rIALP, and monkey rIALP. The disappearance of the phosphate prodrugs and appearance of parent were monitored during the incubation.

A standard 0.03 IU/ml protein concentration was used, except for RIMS and monkey rIALP, wherein lower protein concentrations were used. This eliminates the need for any protein optimization and provides a consistent starting concentration for all $t_{1/2}$ experiments. Since the starting protein concentration will have a significant impact on the $t_{1/2}$ of the prodrug, the cleavage rates normalized to protein concentrations were also calculated (summarized in Table 3). While ritonavir phosphate showed no turnover in all of the test systems, dexamethasone phosphate and fosphenytoin showed rapid cleavage, and ritonavir oxymethyl phosphate and clindamycin phosphate showed intermediate cleavage rates. RIMS and rat rIALP showed similar rates of cleavage when the protein concentrations were expressed in international units. For three of four substrates, monkey rIALP cleavage rates were higher than rat rIALP cleavage rates (Table 3). Human placental ALP and bovine IALP were also investigated for the rate of turnover of the probe substrates. Both these enzymes showed rapid conversion of all probe substrates, including those that showed relatively slower cleavage in rIALP (clindamycin phosphate and ritonavir oxymethyl phosphate).

Kinetics of Prodrug Cleavage In Vitro. The kinetic parameters describing clindamycin phosphate and fosphenytoin cleavage are presented in Table 4. The optimal protein concentrations and incubation times are also summarized in the table. In addition, representative kinetic plots for fosphenytoin and clindamycin are presented in Figs. 2

<table>
<thead>
<tr>
<th>Enzyme Concentration</th>
<th>Enzyme Conc.</th>
<th>Dexamethasone Phosphate</th>
<th>Fosphenytoin</th>
<th>Clindamycin Phosphate</th>
<th>Ritonavir Oxymethyl Phosphate</th>
<th>Ritonavir Phosphate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rat rIALP</td>
<td>0.03</td>
<td>1.7 (13.6)</td>
<td>0.7 (33.0)</td>
<td>11.5 (2.0)</td>
<td>13.1 (1.8)</td>
<td>&gt;120 (&lt;0.19)</td>
</tr>
<tr>
<td>RIMS</td>
<td>0.0185</td>
<td>3.2 (11.7)</td>
<td>1.3 (28.8)</td>
<td>66.3 (0.56)</td>
<td>36.9 (1.0)</td>
<td>&gt;120 (&lt;0.19)</td>
</tr>
<tr>
<td>Monkey rIALP</td>
<td>0.0045</td>
<td>6.6 (23.3)</td>
<td>2.2 (70.0)</td>
<td>120 (1.3)</td>
<td>11.6 (13.3)</td>
<td>&gt;120 (&lt;0.19)</td>
</tr>
<tr>
<td>Human placental ALP</td>
<td>0.03</td>
<td>1.5 (15.4)</td>
<td>1.4 (16.5)</td>
<td>9.6 (2.4)</td>
<td>14.6 (1.6)</td>
<td>&gt;120 (&lt;0.19)</td>
</tr>
<tr>
<td>Bovine ALP</td>
<td>0.03</td>
<td>8.3 (2.8)</td>
<td>6.2 (3.7)</td>
<td>17.1 (1.4)</td>
<td>5.0 (4.6)</td>
<td>&gt;120 (&lt;0.19)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Preparation</th>
<th>Protein Conc.</th>
<th>ALP-Specific Activity</th>
<th>ALP-Specific Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mg/ml</td>
<td>IU/mg*</td>
<td>IU/mg</td>
</tr>
<tr>
<td>Monkey rIALP</td>
<td>0.67</td>
<td>203</td>
<td>303</td>
</tr>
<tr>
<td>Rat rIALP</td>
<td>1.12</td>
<td>206</td>
<td>183.9</td>
</tr>
<tr>
<td>RIMS</td>
<td>13.93</td>
<td>5.21</td>
<td>0.37</td>
</tr>
</tbody>
</table>
and 3, respectively. In general, the $K_m$ values were high suggesting a low possibility of kinetic saturation at therapeutic doses. However, high gut concentrations may still predispose to saturation in cases of high doses. For fosphenytoin, monkey rIALP had a much higher $K_m$ when compared with rat, while for clindamycin phosphate the opposite trend was noted. The $V_{\text{max}}$ values (expressed in international units) for both substrates were similar between the two species. The similarity in $V_{\text{max}}$ values were consistent with the normalized cleavage rates obtained from the half-life ($t_{1/2}$) experiment. Additionally, the $V_{\text{max}}$ for fosphenytoin was higher than clindamycin, consistent with the $t_{1/2}$ data. In the presence of RIMS, both fosphenytoin and clindamycin phosphate exhibited biphasic kinetics. Both $V_{\text{max}}$ and $K_m$ values for the low-$K_m$ binding site are reported when biphasic kinetics was observed. The rate for high-$K_m$ phosphate cleavage was higher for fosphenytoin versus clindamycin (2.4 $\mu l/min$ per nanogram of protein versus 0.38 $\mu l/min$ per nanogram of protein).

**Pharmacokinetic Study.** The results from the in vivo studies are summarized in Table 5. In the case of fosphenytoin, dexamethasone phosphate, and ritonavir oxymethyl phosphate, dosing a prodrug gave a clear improvement in oral exposure ($AUC$ increased by 2.1–2.5-fold, $C_{\text{max}}$ increased by 1.9–13.5-fold). The changes in $C_{\text{max}}$ were statistically significant for phenytoin, clindamycin and ritonavir, while the $AUC$ changes were statistically significant for ritonavir. Clindamycin phosphate cleavage was slowest in the presence of RIMS, compared with other substrates and that could explain why no $C_{\text{max}}$ improvement was observed. All produgs, except ritonavir phosphate, cleaved in vitro in rIALP and RIMS; hence the improved exposure is consistent with in vitro data. In the case of ritonavir phosphate no cleavage was observed in vitro and no exposure of ritonavir was observed upon dosing of the prodrug. The IVIVC for each prodrug is summarized in Table 6 and discussed further in the following section.

**Discussion**

To date, no previous study has characterized expressed recombinant rat and monkey IALP. Here, we report detailed kinetic characterization of rIALP from these two species, and correlation of in vitro systems to in vivo systemic exposure in rats. A previous study evaluated a rat intestinal preparation of ALP and attempted to quantify the amount of protein and its kinetics (Yuan et al., 2009). However, there were multiple issues with this study starting from the fact that a secreted human placental ALP was used to calibrate rat IALP, which assumes that rat IALP and human placental ALP have identical activities and hence the activity of human placental ALP can be used to determine the quantity of rat IALP. Additionally, the activity assays in that study employed phosphate buffer as the medium, and it has been reported (and confirmed in the authors’ laboratory, data not shown) that phosphate inhibits IALP activity (Coburn et al., 1998). Finally, the kinetic parameters determined from the intestinal preparation reported neither incubation time nor protein concentration, and there was no confirmation of linear conditions being maintained during the kinetic characterization.
The pH values to be used during in vitro incubations also require special consideration since the incubation pH of 7.4 represents neither the intestinal pH (pH range 4–6.5), nor the optimum pH of these enzymes (pH range 8–11). While IALP is present in the slightly acidic intestinal environment, it is reported that duodenal secretion of bicarbonate may provide an alkaline microclimate, via a disequilibrium unstirred boundary layer, to boost its activity (Akiba et al., 2007; Mizumori et al., 2009). The bicarbonate secretion is a part of an ecto-purinergic pH regulatory system to protect the gastric acid and may also be one of the key physiologic functions of IALP (Akiba et al., 2007; Mizumori et al., 2009). The bicarbonate secretion is an active process that depends on the generation of high-energy phosphates. In vivo, the optimal pH is 7.4, whereas at higher substrate concentrations, the optimum pH is somewhat lower. This is consistent with the observation that the pH optimum varies with substrate concentration (Akiba et al., 2007; Mizumori et al., 2009). It has also been suggested that the pH optimum varies with substrate concentration and at physiologic concentrations of phosphate esters the optimum pH is 7.4, whereas at higher substrate concentrations, the optimal pH is higher (Warnes, 1972). Hence, using a pH of 7.4 for in vitro incubations may be a reasonable compromise.

The rIALP-mediated cleavage rates were found to be in the range of ~0.5–70 ml/min per international unit for all probe phosphate prodrugs indicating the important role of the linker connecting the phosphate group to the parent (Table 3). Other authors have also reported different dephosphorylation rates depending on the prodrug (Heimbach et al., 2003a; DeGoey et al., 2009). Fosphenytoin has a methylene linker and shows the fastest turnover. Dexamethasone phosphate, although a direct prodrug, has the phosphate moiety on a flexible primary alcohol, so the enzyme is probably able to access the enzyme active site with ease and shows rapid conversion. Clindamycin is a direct prodrug and shows relatively slower turnover. Among the two ritonavir prodrugs, the candidate with a flexible oxymethyl linker cleaves while the direct phosphate shows no turnover, which could be due to the poor accessibility of the phosphate ester into the enzyme active site (DeGoey et al., 2009). The rank order (from slowest to fastest turnover) in rat rIALP was ritonavir oxymethyl phosphate, clindamycin phosphate, dexamethasone phosphate, and fosphenytoin, whereas in RIMS the rank order was clindamycin phosphate, ritonavir oxymethyl phosphate, dexamethasone phosphate, and fosphenytoin. Only the two slowest substrate rank ordered differently, probably due to the fact that both of these prodrugs had similarly slow cleavage rates. A scaling factor, calculated as the ratio of rat rIALP-normalized cleavage rate divided by RIMS-normalized cleavage rate, was between 1.1 and 3.6 suggesting that the protein concentration used in the rat rIALP assay was not too different from what could be encountered in vivo.

Complete kinetic characterization of fosphenytoin and clindamycin phosphate cleavage was carried out after compound incubation with rat and monkey rIALP and RIMS (Figs. 1 and 2; Table 4). Fosphenytoin and clindamycin phosphate were chosen for further kinetic characterization since they represented the fastest and among the slowest turned over prodrugs. The V_{max} values were found to be lower for clindamycin formation across the species in comparison with phenytoin formation. However, for a particular substrate there was not much difference between rat and monkey in V_{max} values, although the K_{m} values differed considerably between rat and monkey rIALP. Fosphenytoin had a lower K_{m} in rat as compared with monkey whereas clindamycin phosphate showed the opposite trend. RIMS for both substrates showed biphasic kinetics with a low- and high-K_{m} component. Given the K_{m} values, it appears unlikely that saturation could occur at therapeutic doses of these prodrugs. It should be noted that solubility limitations of the parent upon cleavage from the prodrug could influence the kinetic parameters.

In vivo studies were performed for four pairs of parents and prodrugs to verify if in vitro cleavage could predict in vivo exposure.

### Table 5

**Pharmacokinetic parameters after oral administration of parent and their corresponding phosphate prodrugs to rats (n = 3; mean ± S.D.)**

<table>
<thead>
<tr>
<th>Compound Administered</th>
<th>PO Dose</th>
<th>AUC_{int} (nM*h)</th>
<th>C_{max} (nM)</th>
<th>T_{max} (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenytoin</td>
<td>5</td>
<td>1738 ± 633</td>
<td>1193 ± 777</td>
<td>0.25</td>
</tr>
<tr>
<td>Fosphenytoin</td>
<td>6.5</td>
<td>3639 ± 1032</td>
<td>4439 ± 1000*</td>
<td>0.25</td>
</tr>
<tr>
<td>Clindamycin</td>
<td>50</td>
<td>13741 ± 1329</td>
<td>9371 ± 985</td>
<td>0.33 ± 0.1</td>
</tr>
<tr>
<td>Clindamycin phosphate</td>
<td>56.5</td>
<td>32968 ± 12197</td>
<td>9069 ± 1703</td>
<td>0.67 ± 0.1</td>
</tr>
<tr>
<td>Ritonavir</td>
<td>5</td>
<td>109 ± 38</td>
<td>40 ± 19</td>
<td>1.25 ± 0.8</td>
</tr>
<tr>
<td>Ritonavir phosphate</td>
<td>5.6</td>
<td>BLQ (&lt;0.6 nM)</td>
<td>BLQ (&lt;0.6 nM)</td>
<td>0.67 ± 0.1</td>
</tr>
<tr>
<td>Ritonavir oxymethyl phosphate</td>
<td>5.8</td>
<td>242 ± 97</td>
<td>77 ± 35</td>
<td>2.0</td>
</tr>
<tr>
<td>Dexamethasone</td>
<td>5</td>
<td>1529 ± 219</td>
<td>642 ± 162</td>
<td>0.25</td>
</tr>
<tr>
<td>Dexamethasone phosphate</td>
<td>6</td>
<td>3213 ± 2718</td>
<td>8670 ± 660*</td>
<td>0.25</td>
</tr>
</tbody>
</table>

* P < 0.05 in a one-way analysis of variance test.
improvement (Table 5). It was not possible to provide quantitative estimates of improvement in AUC based on in vitro cleavage rates (Table 6). Both the rapidly turned over fosphenytoin and slowly turned over clindamycin phosphate showed roughly the same increase in AUC (~2-fold). However prodrugs that cleaved in vitro provided 2-fold or higher in vivo exposures of their respective parents, whereas the one prodrug that did not cleave in vitro did not show any in vivo exposure of its parent. A better correlation was observed in fold-changes in C_{max} versus cleavage rates. For example, the two prodrugs with the slowest cleavage rates (clindamycin phosphate and ritonavir oxymethyl phosphate) showed the lowestfold increases in C_{max} (<1.9) whereas the rapidly turned over fosphenytoin and dexamethasone phosphate showed 3.7- and 13.5-fold improvements in C_{max}, respectively. An examination of parent solubilities and permeabilities could not provide an explanation for the quantitative differences in C_{max} and AUC ratio changes. Suspension dosing of parent or prodrug may have contributed some information to building an IVIVC but in these studies the parents possessed sufficient solubility for solution dosing in aqueous vehicles (except for ritonavir and its prodrugs). While it is assumed that IALPs are responsible for all dephosphorylation activity, one report suggests that phytases (which releases usable inorganic phosphate and essential metals from phytic acid) can also perform this reaction, at acidic pH values (Nakano et al., 2001). This could also lead to a potential disconnect between in vitro rIALP activity and in vivo exposure.

As previously mentioned, a number of phosphate prodrugs do not show improved in vivo exposure due to a number of reasons, since very rapid cleavage by IALP may result in super-saturated solutions of the parent and its subsequent precipitation, whereas very slow cleavage may result in insufficient parent being available for absorption. In one study, wherein multiple prodrugs with different parent solubilities and cleavage rates were synthesized, it was found that while good prodrug solubility is a prerequisite, only those prodrugs with a cleavage t_{1/2} around a narrow window of 35 minutes offered much better exposure of parent (Sohma et al., 2003). Rapid drop-offs in exposure were observed with minor deviations in the t_{1/2} away from 35 minutes. This study captures the challenge associated in balancing solubility with cleavage rate.

The rIALP in vitro experiment occurs in a static system wherein involvement of active or passive absorption, and oxidative and conjugative metabolism are absent. As such, it represents only one of several dimensions of a complex in vivo system. Reports have shown that including an absorptive component can alter the dynamic equilibrium between bioconversion, supersaturation, and absorption (Heimbach et al., 2003b; Brouwers et al., 2007; Bevernage et al., 2012). While this is a typical shortcoming of all fractional in vitro systems, the advantage of the rIALP turnover assay is that, when the right protein concentration is used, it provides a strong indication that cleavage is going to be insufficient or potentially very rapid in vivo. While, in isolation, the rate of metabolism of prodrug to parent is probably of limited value, it shows promise when correlated with increased in vivo exposure. Once a correlation between in vitro cleavage rate and in vivo exposure is established, in vitro experiments may replace more resource-intensive in vivo experiments as the cleavage rate is optimized. Another utility of rIALP is in assessing species differences/similarities. For example, if a rat IVIVC is obtained and confirmed with monkey by in vitro and in vivo experiments, then it may be possible to predict if human exposures will improve with a phosphate prodrug. This has great value in a discovery setting when a number of prodrug candidates may be under consideration.

In summary, we have elucidated the cleavage rates of five prodrugs in three matrices, determined detailed kinetics for two prodrugs and correlated in vitro data with in vivo exposures in rats. While the activity assay showed that directly linked phosphate prodrugs are resistant to cleavage, the detailed kinetics showed in general high K_m values. The in vivo improvement in AUC and C_{max} were consistent with in vitro cleavage of phosphate, although not in a quantitative sense.

Acknowledgments

The authors thank Mike Sinz, Manjunath Ramarao, Sridhar Desikan, A. Dave Rodrigues, Kimberley Lentz, and Anand Balakrishnan for guidance, support, and critical review. The authors also thank Shahe Mahammad for assistance with formulations, and Senthuran Singaram and Kumar Pabbisetty for assistance with the expression and purification or rIALP; and the in-house Discovery Chemical Synthesis department for synthesis of the ritonavir prodrugs.

Authorship Contributions

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Wrote or contributed to the writing of the manuscript: Subramanian, Singh, Pahwa, Mandlekar.

References


Recombinant Intestinal Alkaline Phosphatase Characterization

In vitro cleavage rates correlated with observed in vivo changes in exposure

<table>
<thead>
<tr>
<th>Drug</th>
<th>Normalized Rate of Metabolism</th>
<th>Fold-Increase in C_{max}</th>
<th>Fold-Increase in AUC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphate to phenytoin</td>
<td>33.00</td>
<td>3.7</td>
<td>2.1</td>
</tr>
<tr>
<td>Clindamycin phosphate to clindamycin</td>
<td>2.01</td>
<td>1.0</td>
<td>2.3</td>
</tr>
<tr>
<td>Ritonavir phosphate to ritonavir</td>
<td>&lt;0.19</td>
<td>No exposure</td>
<td></td>
</tr>
<tr>
<td>Ritonavir oxymethyl phosphate to ritonavir</td>
<td>1.76</td>
<td>1.9</td>
<td>2.5</td>
</tr>
<tr>
<td>Dexamethasone phosphate to dexamethasone</td>
<td>13.59</td>
<td>13.5</td>
<td>2.1</td>
</tr>
</tbody>
</table>


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