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Inhibitors of Bacterial N-Succinyl-L,L-diaminopimelic Acid Desuccinylase (DapE) and Demonstration of in vitro Antimicrobial Activity

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Abstract—The dapE-encoded N-succinyl-L,L-diaminopimelic acid desuccinylase (DapE) is a critical bacterial enzyme for the construction of the bacterial cell wall. A screen biased toward compounds containing zinc-binding groups (ZBG's) including thiols, carboxylic acids, boronic acids, phosphonates and hydroxamates has delivered a number of micromolar inhibitors of DapE from \textit{H. influenzae}, including the low micromolar inhibitor L-captopril (IC\textsubscript{50} = 3.3 µM, Ki = 1.8 µM). In vitro antimicrobial activity was demonstrated for L-captopril against \textit{E. coli}.

Bacterial infections are a significant and growing medical problem in both the United States and around the world.\textsuperscript{1} The CDC recently reported that there are now several strains of \textit{Staphylococcus aureus} that are resistant to all known antibiotics including vancomycin.\textsuperscript{2} These cases underscore the fact that limited numbers of drugs are available to prevent a simple \textit{Staph} infections from becoming deadly.\textsuperscript{3} At least four other strains of common bacterial species capable of causing life-threatening illnesses (\textit{Enterococcus faecalis}, \textit{Mycobacterium tuberculosis}, \textit{Escherichia coli} O157:H7, and \textit{Pseudomonas aeruginosa}) are already resistant to nearly all drugs in clinicians arsenal comprised of more than 100 drugs.\textsuperscript{4, 5} Thus, the search for new antibiotics that target enzymes in unexplored bacterial biosynthetic pathways is critically important, as confirmed in Supuran’s excellent review of bacterial protease inhibitors.\textsuperscript{6}

The dapE-encoded N-succinyl-L,L-diaminopimelic acid desuccinylase (DapE) enzyme is a member of the \textit{meso}-diaminopimelate (mDAP)/lysine biosynthetic pathway.\textsuperscript{7} The amino acids mDAP and/or lysine are essential components of the peptidoglycan cell wall for Gram-negative and most Gram-positive bacteria, providing a link between polysaccharide strands.\textsuperscript{7} Therefore, enzymes involved in the mDAP/lysine biosynthetic pathway, including DapE, are potential antibiotic targets. DapE's are small, dimeric enzymes (41.6 kDa/subunit) that require two Zn(II) ions per mole of polypeptide for full enzymatic activity.\textsuperscript{8, 9} On the basis of sequence alignments with other aminopeptidases\textsuperscript{10} and several DapE gene sequences, all of the residues that function as ligands in the dinuclear active site of those enzymes are strictly conserved in DapE from \textit{Haemophilus influenzae}. Studies on the E134A- and E134D- altered DapE revealed that E134 acts as the general acid/base in the hydrolysis of the substrate and is absolutely required for catalytic activity.\textsuperscript{11} Investigations on H67A- and H349A-altered enzymes together with construction of a three-dimensional homology structure of DapE from \textit{H. influenzae} (generated using the X-ray crystal structure of the Apo-DapE from \textit{Neisseria meningitidis} as a template with superposition on the structure of the aminopeptidase from \textit{Aeromonas proteolytica} (AAP)) confirmed the identification of active-site histidine zinc ligands.\textsuperscript{12} Based on this homology model, the active site of DapE contains two Zn(II) ions at a distance of \textasciitilde 3.30 Å (Figure 1).
Each of the Zn(II) ions adopts a distorted tetrahedral geometry and is coordinated by one imidazole group (H67 for Zn1 and H349 for Zn2) and one carboxylate group (E163 for Zn1 and E135 for Zn2). Both Zn(II) ions are bridged by an additional carboxylate groups (D 100) on one side and water/hydroxide on the opposite side, forming a (μ-aquo)(μ-carboxylato)dzinc(II) core with one terminal carboxylate and one histidine residue at each metal site.

In order to identify appropriate lead molecules for the inhibition of DapE, we have screened over thirty molecules representing various structural classes and containing different zinc-binding groups (ZBG’s) using N-succinyl L,L-diaminopimelic acid (L,L-SDAP) as the substrate. These ZBG’s include thiols, hydroxamates, carboxylic acids, boronic acids, and phosphates, and this fruitful initial screen has led to the identification of a number of low micromolar inhibitors (Table 1). We biased our initial screen to include bifunctional molecules that contained, in addition to the ZBG, a carboxylate moiety that could interact with the positively-charged lysine and/or arginine side chains that purportedly reside near the active site. Table 1 shows carboxylic acid-containing thiols that were found to inhibit DapE fairly potently. Even delta-mercaptopbutyric acid has an IC\(_50\) of 43 \(\mu\)M versus DapE, and meta-mercaptopbenzoic acid has a measured IC\(_50\) of 34 \(\mu\)M. L-penicillamine gave an IC\(_50\) of 13.7 \(\mu\)M, and a measured \(K_i\) of 4.6 \(\mu\)M. DapE is stereoselective with respect to recognition of inhibitors, as D-penicillamine gave an IC\(_50\) of 50 \(\mu\)M. Given the success with these carboxylic acid-containing thiols, we turned our attention to captopril, which contains the requisite ZBG and carboxylate functionalities. L-Captopril exhibited an IC\(_50\) of 3.3 \(\mu\)M and a measured \(K_i\) of 1.8 \(\mu\)M (competitive). Again, the binding is stereoselective, as D-captopril\(^{15}\) was an order of magnitude less potent, with an IC\(_50\) of 42.0 \(\mu\)M.

Table 2 shows boronic acid derivatives that were tested as inhibitors of DapE. Phenylboronic acid itself was encouraging with an IC\(_50\) of 107 \(\mu\)M and a measured \(K_i\) of 56.9 \(\mu\)M (competitive). Incorporation of a carboxylic acid along with the boronic acid was not productive, as both 4-carboxyphenylboronic acid and 3-carboxyphenylboronic acid did not inhibit DapE. It is hypothesized that geometric constraints may have precluded a productive Coulombic interaction of the carboxylate with positively charged residues in the active site. Butylboronic acid was a weak inhibitor of DapE (IC\(_50\) \(\sim\)10 \(\mu\)M). 2-Thiophenecarboxylic acid was comparable to phenylboronic acid, with an IC\(_50\) of 92 \(\mu\)M and a measured \(K_i\) of 67 \(\mu\)M, but the inhibitor was noncompetitive. Surprisingly, 1-butaneboronic is only a very weak inhibitor of DapE (IC\(_50\) \(\sim\)10,000 \(\mu\)M) even though it is a potent inhibitor of AAP (\(K_i\) = 10 \(\mu\)M).\(^{16,17}\)

Table 1. Thiols tested as inhibitors of DapE

<table>
<thead>
<tr>
<th>Compound</th>
<th>Structure</th>
<th>(IC_{50}) ((\mu)M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>delta-mercaptopbutyric acid</td>
<td><img src="" alt="Structure" /></td>
<td>43±4</td>
</tr>
<tr>
<td>3-mercaptopbenzoic acid</td>
<td><img src="" alt="Structure" /></td>
<td>34</td>
</tr>
<tr>
<td>L-penicillamine</td>
<td><img src="" alt="Structure" /></td>
<td>13.7 (K_i) = 4.6±0.6 (\mu)M (competitive)</td>
</tr>
<tr>
<td>D-penicillamine</td>
<td><img src="" alt="Structure" /></td>
<td>50</td>
</tr>
<tr>
<td>L-Captopril</td>
<td><img src="" alt="Structure" /></td>
<td>3.3 (K_i) = 1.8±0.99(\mu)M (competitive)</td>
</tr>
<tr>
<td>D-Captopril</td>
<td><img src="" alt="Structure" /></td>
<td>42.0±2.5</td>
</tr>
</tbody>
</table>

*Values are means of three experiments, standard deviation is given in parentheses.*

Table 2. Boronic acid tested as inhibitors of DapE

<table>
<thead>
<tr>
<th>Compound</th>
<th>Structure</th>
<th>(IC_{50}) ((\mu)M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>phenylboronic acid</td>
<td><img src="" alt="Structure" /></td>
<td>107/154 (\mu)M (K_i=56.9±3.6) (\mu)M (competitive)</td>
</tr>
<tr>
<td>4-carboxyphenylboronic acid</td>
<td><img src="" alt="Structure" /></td>
<td>&gt;10,000</td>
</tr>
<tr>
<td>3-carboxyphenylboronic acid</td>
<td><img src="" alt="Structure" /></td>
<td>&gt;10,000</td>
</tr>
<tr>
<td>butylboronic acid</td>
<td><img src="" alt="Structure" /></td>
<td>~10,000 (\mu)M</td>
</tr>
<tr>
<td>2-thiophenecarboxylic acid</td>
<td><img src="" alt="Structure" /></td>
<td>92 (\mu)M (K_i=67±3.8) (\mu)M (non-competitive)</td>
</tr>
</tbody>
</table>

*Values are means of three experiments, standard deviation is given in parentheses.*

Table 3 shows several other compounds that were screened versus the DapE enzyme. Given the very good potency of the ACE inhibitor L-captopril noted above (IC\(_50\) = 3.3 \(\mu\)M), the ACE inhibitor enalapril was...
screened, but did not show any potency versus DapE. Two simple hydroxamate compounds, acetohydroxamic acid and N-(benzoylcarbonyl)hydroxylamine (actually an N-hydroxy carbamate) were also screened but were too weak to measure the inhibitory potency. N-Phenylthiourea could potentially function as a zinc-binding compound and showed some inhibition of DapE, but the IC$_{50}$ is greater than 100 µM. Phosphonic acids can also inhibit metalloproteases, and (2-carboxyethyl)phosphonic acid was shown to have a very weak IC$_{50}$ of 1,620 µM.

Table 3. Other potential inhibitors explored for the DapE enzyme

<table>
<thead>
<tr>
<th>Compound</th>
<th>Structure</th>
<th>IC$_{50}$ (µM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enalapril (maleate salt)</td>
<td><img src="image1" alt="Structure" /></td>
<td>&gt;1000</td>
</tr>
<tr>
<td>Acetohydroxamic acid</td>
<td><img src="image2" alt="Structure" /></td>
<td>&gt;1000</td>
</tr>
<tr>
<td>N-(Benzoylcarbonyl)hydroxylamine</td>
<td><img src="image3" alt="Structure" /></td>
<td>&gt;1000</td>
</tr>
<tr>
<td>N-phenylthiourea</td>
<td><img src="image4" alt="Structure" /></td>
<td>&gt;100</td>
</tr>
<tr>
<td>(2-carboxyethyl)phosphonic acid</td>
<td><img src="image5" alt="Structure" /></td>
<td>1620, Ki = 800 µM</td>
</tr>
</tbody>
</table>

*Values are means of three experiments, standard deviation is given in parentheses.

Several alkyl and aryl phosphates have also been tested in addition to diaminopimelic acid amides and ornithine amides (structures not shown). In all cases, these molecules exhibited little or no inhibitory potency (IC$_{50}$ >1000 µM - >10,000 µM). Finally, (D,L)-(2-phosphonomethyl)-pentanediol acid did not inhibit DapE at concentrations up to 10 mM. 2-Carboxyethyl phosphonic acid is a significantly better inhibitor ($K_i$ = 800 µM) than phosphonoacetic acid, 3-phosphopropanoic acid, or N-(phosphonomethyl)glycine, thus presenting an optimal chain length for interactions with DapE. We expect an optimal distance between thiol and carboxylate in the thiol series as well, depending on conformational mobility of the series.

We have confirmed antibiotic activity with the DapE inhibitor, L-captopril, in an antibiotic plate assay as illustrated in the following photos (Figure 2). Application of L-captopril directly to plates cultured with E. coli showed a dose-responsive antibiotic activity for this DapE inhibitor. Very little inhibition is observed for 1 mg of L-captopril, but 5 mg demonstrates a clear positive antibiotic result, and the zone of inhibition is even greater for 20 mg of L-captopril. Furthermore, this confirms that the enzyme inhibitor is crossing the bacterial cell membrane and reaching the desired target. The positive antibiotic control ampicillin is shown as well showing its zone of inhibition.

Figure 2. Antibiotic Activity of L-Captopril Against E. coli.

In summary, a screen of compounds containing ZBG’s against DapE from Haemophilus influenzae has delivered a number of micromolar inhibitors including captopril, functioning as a competitive, reversible inhibitor with an IC$_{50}$ of 3.3 µM ($K_i$ = 1.8 µM). Furthermore, antibiotic activity has now been demonstrated for the DapE inhibitor L-captopril. Captopril is an excellent lead for medicinal chemistry optimization in consideration of its low molecular weight (217) and low measured logP of 0.34$^{18,19}$ following the rules of Lipinski$^5$ and containing few rotatable bonds,$^{21}$ consistent with its known oral bioavailability.

References and Notes


13. Inhibition studies were performed in 50 mM chelated potassium phosphate buffer pH 7.5. A 3 mM solution of DD,LL-SDAP in the same buffer was used for IC$_{50}$ determinations. $K_i$ values were determined using 0.5-4.5mM substrate concentrations and different inhibitor concentrations (depending on the inhibitor). Total volume of the mixture was 1 mL. For a more detailed summary of experimental details, see the Supporting Information.


