Cross-class metallo-β-lactamase inhibition by bisthiazolidines reveals multiple binding modes

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Metallo-β-lactamases (MBLs) hydrolyze almost all β-lactam antibiotics and are unaffected by clinically available β-lactamase inhibitors (βLIs). Active-site architecture divides MBLs into three classes (B1, B2, and B3), complicating development of βLIs effective against all enzymes. Bisthiazolidines (BTZs) are carboxylate-containing, bicyclic compounds, considered as penicillin analogs with an additional free thiol. Here, we show both L- and D-BTZ enantiomers are micromolar competitive βLIs of all MBL classes in vitro, with K_is of 6–15 μM or 36–84 μM for subclass B1 MBLs (IMP-1 and BcII, respectively), and 10–12 μM for the B3 enzyme L1. Against the B2 MBL Sfh-I, the L-BTZ enantiomers exhibit 100-fold lower K_is (0.26–0.36 μM) than D-BTZs (26–29 μM). Importantly, cell-based time-kill assays show BTZs restore β-lactam susceptibility of *Escherichia coli*-producing MBLs (IMP-1, Sfh-1, BcII, and GOB-18) and, significantly, an extensively drug-resistant *Stenotrophomonas maltophilia* clinical isolate expressing L1. BTZs therefore inhibit the full range of MBLs and potentiate β-lactam activity against producer pathogens. X-ray crystal structures reveal insights into diverse BTZ binding modes, varying with orientation of the carboxylate and thiol moieties. BTZs bind the di-zinc centers of B1 (IMP-1; BcII) and B3 (L1) MBLs via the free thiol, but orient differently depending upon stereochemistry. In contrast, the L-BTZ carboxylate dominates interactions with the monozinc B2 MBL Sfh-I, with the thiol uninvolved. D-BTZ complexes most closely resemble β-lactam binding to B1 MBLs, but feature an unprecedented disruption of the D120–zinc interaction. Cross-class MBL inhibition therefore arises from the unexpected versatility of BTZ binding.

carbapenemase | antibiotic resistance | inhibitors | bisthiazolidines | metallo-β-lactamase

The production of metallo-β-lactamases (MBLs) by Gram-negative pathogens, such as *Escherichia coli*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, *Pseudomonas aeruginosa*, and *Stenotrophomonas maltophilia*, is a major contributor to bacterial antibiotic resistance (1, 2). MBLs are able to hydrolyze most β-lactam antibiotics, including clinically important serine β-lactamase inhibitors (βLIs, clavulanic acid and penicillanic acid sulfones) and the carbapenems, which are often used as a "last-resort" therapy for serious infections (3–6). MBLs can be divided into three subclasses—B1, B2, and B3—based on sequence, structure, and zinc ion utilization (2, 7–9). All three classes contain a similar overall αββα-fold, with the active site lying in a groove between the two β-sheets (Fig. 1). In most di-zinc B1 enzymes, such as IMP-1 (10), BcII (11), and NDM-1 (12), the Zn1 site is tetrahedrally coordinated by a water molecule (Wat1), H116, H118, and H196 [standard MBL numbering scheme (7) used throughout], whereas Zn2 is bound by Wat1, a second water molecule (Wat2), D120, C221, and H263 in a trigonal bipyrimidal coordination. A water molecule (Wat1) bridges/coordinates Zn1 and Zn2 in an arrangement that is suited to activate it as a nucleophile.

In monozinc B2 enzymes, such as CphA (13) and Sfh-I (14), binding of the zinc ion is representative of the Zn2 site in B1 enzymes, with coordination by a water molecule (Wat1), D120, C221, and H263, in a tetrahedral rather than trigonal bipyrimidal geometry. Two water molecules (Wat1 and Wat2) are present in the active site, with Wat2 hydrogen-bonded to H118 and H196, and Wat1 coordinating Zn2, lying approximately equidistant between Zn2 (2.3 Å) and Wat2 (2.6 Å). Wat2 is believed to be activated by H118, rather than a zinc ion, to act as the nucleophile during antibiotic hydrolysis (14).

Di-zinc B3 enzymes [e.g., L1 (15) and AIM-1 (16)] have similar active-site architectures to B1 MBLs, with Zn1 in tetrahedral coordination with a water molecule (Wat1), H116, H118, and H196; and the nucleophilic water (Wat1) bridging Zn1 (1.9 Å) and Zn2 (2.1 Å). Zn2, however, is coordinated by D120, H121, H263, and an additional water molecule (Wat2) in a distorted

Significance

Bacterial diseases remain a huge burden on healthcare worldwide, with the emergence and re-emergence of strains resistant to currently used antibiotics posing an increasing clinical threat. Metallo-β-lactamases (MBLs) are key determinants of antibiotic resistance because they hydrolyze almost all β-lactam antibiotics and are unaffected by currently available β-lactamase inhibitors (βLIs). The structural diversity between MBLs has proved problematic when designing βLIs effective against all MBL targets. Here we show a series of small compounds, bisthiazolidines, which act as inhibitors of all MBL types, restoring the efficacy of currently used antibiotics against resistant bacterial strains producing different MBLs. High-resolution crystal structures reveal how diverse MBLs are inhibited by the unexpected versatility of bisthiazolidine binding, raising implications for future βLI design.

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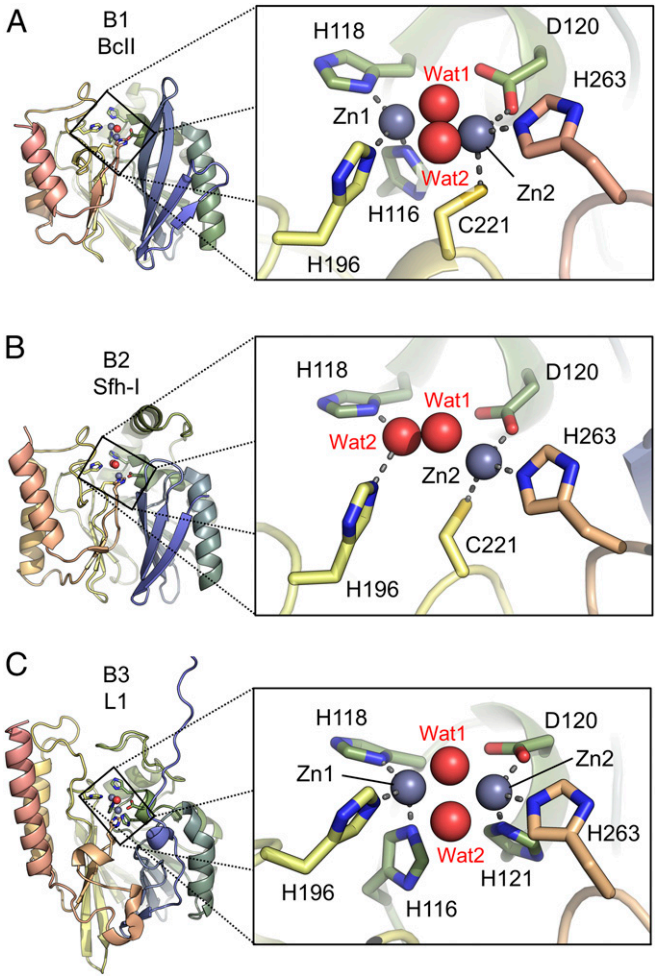

Fig. 1. Architecture of B1, B2, and B3 metallo-β-lactamases. The common αββα-fold of representative MBLs is colored from the N (light blue) to C terminus (light red), and is shown alongside a close up view of the active-site (boxed). Zinc ions (gray) and water molecules (red) are represented as spheres. Zinc coordination bonds are shown as gray dashes, with the corresponding residues (labeled) shown as sticks. (*A*) B1 BcII (PDB ID code 4C09), (*B*) B2 Sfh-I (PDB ID code 3SD9), and (*C*) B3 L1 (PDB ID code 1SML).

trigonal bipyramidal geometry. To date, clinically useful βLIs of any of the three MBL classes have not been identified, and the aforementioned structural differences have complicated development of βLIs with cross-class (B1, B2, and B3) activity.

In response to this urgent medical need, we have developed and synthesized four bisthiazolidine (BTZ) compounds, L-CS319 (**1a**), D-CS319 (**1b**), L-VC26 (**2a**), and D-VC26 (**2b**) (blue, gray, orange, and cyan, respectively, in Fig. 2) (17, 18). These βLIs contain both a free thiol, which is a high-affinity zinc-binding group, and two defining properties of β-lactam substrates, a feature hitherto overlooked in MBL inhibitor design. These are, first, a carboxylate moiety that in penicillins and carbapenems is able to bind Zn2 and interact with conserved residues on the protein main chain (19, 20); and, second, a tetrahedral bridgehead nitrogen that interacts with Zn2 as hydrolysis of bicyclic β-lactam antibiotics proceeds (21, 22). The absence of structural information on how a single compound can bind and inhibit all three classes of MBLs hinders further development of any potent cross-class inhibitors. We therefore characterized cross-class MBL inhibition in vitro, and in MBL-producing bacteria, by the four previously synthesized BTZs, and obtained crystal structures for B1 (IMP-1 and BcII), B2 (Sfh-I), and B3 (L1) MBLs complexed with the novel scaffold, including one compound (**1a**) now structurally characterized in all three classes. These data demonstrate how a single compound class can use multiple modes of binding to inhibit, in vitro and in producer organisms, MBLs of different classes and active-site architectures, and identify routes to further improve potency against the range of target enzymes.

Results

BTZs Are Cross-Class MBL Inhibitors in Vitro. Previous kinetic characterization of BTZ inhibition of selected MBL targets demonstrated them to be micromolar competitive inhibitors of carbapenem (imipenem) or cephalosporin (nitrocefin) hydrolysis by the B1 MBLs, VIM-2 and NDM-1, with K_is varying between 3.7 ± 0.3 and 19 ± 3 μM (17, 18) (Table 1). Here, we evaluate their cross-class inhibition potential by measuring the in vitro effect of BTZs on imipenem hydrolysis by VIM-2 and other MBLs of subclasses B1 [*Bacillus cereus* BcII (11, 23, 24) and *Serratia marsescens* IMP-1 (10)], B2 [*Serratia fonticola* Sfh-I (14, 25)], and B3 [*S. maltophilia* L1 (15, 26)]. To ensure coverage of diverse MBLs, we also assayed activity against the structurally uncharacterized, atypical *Elizabethkingia meningoseptica* GOB-18, reconstituted in its fully active monozinc form (27).

These data reveal the compounds to be competitive, micromolar inhibitors of all MBL classes (Figs. S1 and S2), with K_is between 0.26 ± 0.03 μM and 84 ± 6 μM (Table 1). The inhibition of B1 MBLs is little affected by the stereochemistry on the BTZs [D- (**1b**, **2b**) or L- (**1a**, **2a**) BTZs], or by the presence of a *gem*-dimethyl group (**2a**, **2b**), with K_i values varying by 2- and 2.5-fold (IMP-1 and BcII, respectively). In particular, BTZ potency against IMP-1 or VIM-2 is the same for both enantiomers, whereas the addition of a *gem*-dimethyl group (**2a**/**2b**) resulted in a two- to threefold increase in K_i. In contrast, against BcII, D-BTZs were 1.5- to 2.5-fold less potent than the L-BTZs, whereas the *gem*-dimethyl group had little effect on potency (**2a**/**2b** K_i is up to 1.5-fold greater than **1a**/**1b**). Against the B3 MBL L1, all compounds exhibit near identical K_i values, between 10 and 12 μM ± 1–2, whereas only **2b** exhibits similar potency against the B3 MBL GOB-18 (10 μM), with the three other BTZs three- to fourfold less potent (30–41 μM ± 1–4). The unusual GOB-18 active site, in which the Zn1 ligand H116 is replaced by Q and only the Zn2 site is occupied in vitro (27), likely accounts for these small differences we observe in potency against B3 enzymes. Although it is possible periplasmic GOB-18 is di-zinc, as GOB-1 (28), importantly these data show the BTZ scaffold inhibits MBLs with even highly atypical active-site architectures. Only against B2 Sfh-I is there strong stereochemical preference, with L-BTZs (**1a**, **2a**) greater than 100-fold more potent than their corresponding D-enantiomers (**1b**, **2b**). As is the case for the B1 and B3 enzymes, there is little change in BTZ potency on addition of a *gem*-dimethyl group, with **1a** and **2a** exhibiting similar, submicromolar K_i values (0.26 ± 0.03 μM and 0.36 ± 0.04 μM, respectively).

BTZs Restore β-Lactam Efficacy Toward MBL-Producing Isolates. To assess the clinical potential of BTZs, time-kill assays were performed using *E. coli* cells expressing the B1 MBLs IMP-1 and BcII, B2 Sfh-I,

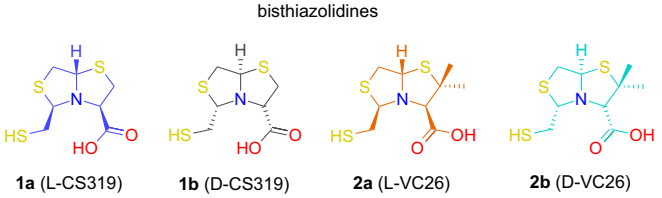

Fig. 2. Chemical structures of bisthiazolidine inhibitors. Bisthiazolidines **1a** (L-CS319, blue), **1b** (D-CS319, gray), **2a** (L-VC26, orange), and **2b** (D-VC26, cyan).

Table 1. In vitro competitive inhibition of MBLs by bisthiazolidines

MBL subclass	Enzyme	Substrate	Inhibition constants (K_i/μM) 1a	1b	2a	2b	Source
B1	NDM-1	Imipenem	7 ± 1	19 ± 3	18 ± 3	12 ± 1	(17)
	VIM-2	Imipenem	2.9 ± 0.4	3.2 ± 0.4	6 ± 1	10 ± 2	—
	IMP-1	Imipenem	8 ± 2	6 ± 1	15 ± 3	14 ± 3	—
	BcII	Imipenem	36 ± 2	53 ± 5	32 ± 3	84 ± 6	—
B2	Sfh-I	Imipenem	0.26 ± 0.03	26 ± 3	0.36 ± 0.04	29 ± 3	—
B3	L1	Imipenem	12 ± 1	10 ± 1	11 ± 2	10 ± 1	—
	GOB-18	Imipenem	41 ± 4	30 ± 2	31 ± 2	10 ± 1	—

and the B3 enzyme GOB-18 (Fig. S3). Additionally, a multidrug-resistant *S. maltophilia* clinical isolate producing both the B3 MBL L1 and the serine β-lactamase L2 was also studied (Fig. 3 and Fig. S4). The βLIs do not have any antimicrobial effect on their own, as differences could not be detected in viable cell number between cells exposed to BTZs and broth-only controls. Viable cell counts following exposure to sublethal concentrations of β-lactams (imipenem and ticarcillin-clavulanate for the *E. coli* and *S. maltophilia* isolates, respectively) in the presence of BTZs demonstrated that BTZs are able to inactivate the MBLs in clinically relevant strains, as evidenced by the significant reductions in bacterial count ($>10^3$). Potentiation of antibiotic activity against *S. maltophilia* is particularly significant because strains of this Gram-negative pathogen tend to be extensively multidrug-resistant, particularly because of the expression of two distinct β-lactamases and several membrane-spanning multidrug efflux pumps (29).

Structure Determination of BTZ Complexes with B1, B2, and B3 MBLs. An understanding of how BTZs inhibit all three classes of MBL requires structural information for representative BTZ:MBL complexes to complement our previously obtained structures of **1a** bound to the B1 MBLs VIM-2 and NDM-1 (17, 18). We therefore crystallized the MBLs IMP-1 and BcII (subclass B1), Sfh-I (B2), and L1 (B3) and soaked the crystals in the four BTZs. Cocomplex structures were solved for IMP-1 with **1b** (2.30 Å resolution) and **2a** (2.30 Å); BcII with **1b** (1.80 Å); Sfh-I with **1a** (1.30 Å); and L1 with **1a** (1.63 Å), **1b** (1.84 Å), and **2b** (1.80 Å) (Table S1). For B2 Sfh-I we were unable to obtain a cocomplex with both BTZ stereoisomers, consistent with the in vitro observation that D-BTZs were at least 100-fold less-potent Sfh-I inhibitors than L-BTZs. In all seven cases there was clear F_o–F_c density in the MBL active site into which the corresponding ligand could be modeled (Fig. S5). Further ligand validation statistics (real-space *R* value, local ligand density fit, and real-space correlation coefficient) are presented in Table S2.

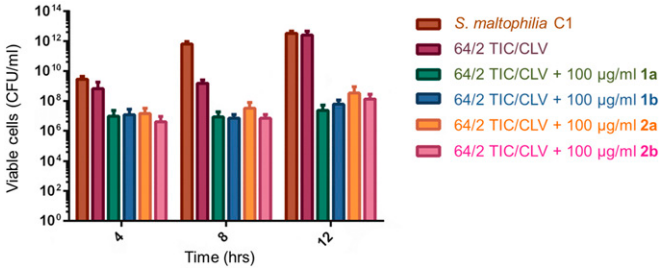

Fig. 3. Bisthiazolidines restore the in vitro activity of ticarcillin-clavulanate against a *S. maltophilia* clinical isolate. Bacteria were grown at sublethal concentrations of a mixture of ticarcillin (TIC, 64 μg/mL) and clavulanate (CLV, 2 μg/mL), or in combination with 100 μg/mL of each compound. Viable cells were recovered at 4, 8, and 12 h. Results shown are the mean of three biological replicates ± SD.

IMP-1 crystallized in the space group $P2_12_12_1$, with four molecules in the asymmetric unit (ASU), not previously described. Electron density consistent with bound **2a** was observed in three of the four subunits (average B-factor 1.8 times greater than the protein main chain), whereas **1b** could be confidently modeled in all four molecules of the ASU (B-factors 1.1 times greater than the main chain). For comparison, we have also solved, to 1.98 Å resolution, the structure of uncomplexed dizinc IMP-1, also in the space group $P2_12_12_1$ (*SI Results*). BcII crystallized in the previously described space group C2 (30), with one molecule in the ASU and one molecule of **1b** identified in the active site (B-factor 1.6 times greater than the main chain). Sfh-I crystallized in space group $P2_1$ (14), with **1a** clearly defined in both monomers of the ASU (B-factors 1.2 times greater than the protein main chain). L1 crystallized in space group $P6_422$ (15), with one molecule in the ASU, into which **1a**, **1b**, and **2b** were modeled into clearly defined density (B-factors 2.1, 1.8, and 1.7 above the main chain). Ligands were refined at full occupancy for all but L1:**1b** (ligand occupancy 0.76) and L1:**2b** (0.81).

A Dual-Mode of Binding for L-BTZs to MBLs. The IMP-1:**2a** (Fig. 4*A*) and L1:**1a** (Fig. 4*B*) structures reveal similar binding modes for L-BTZs to IMP-1 (B1) and L1 (B3) (Fig. 4*C*). These modes also resemble the previously observed binding mode of **1a** to both VIM-2 (18) and NDM-1 (17) (Fig. S6). In all these structures, the thiol of the BTZ mercaptomethyl group is positioned nearly equidistant between the two zinc ions (between 2.22 and 2.43 Å ± 0.14 and 0.23 Å) (see Table S1 for coordinate errors and Table S3 for detailed distances). BTZ binding displaces the zinc-bridging nucleophilic water/hydroxide (Wat1) that is observed in the native MBL active site (Fig. S7), with a concomitant small increase in the Zn1–Zn2 distance of approximately 0.3/0.4 Å (±0.14/0.23 Å), compared with uncomplexed enzymes (Table S3). L-BTZ binding is further stabilized by direct interaction of its carboxylate with structurally equivalent side chains that are implicated in substrate binding (19, 20, 31), K224 in IMP-1 and S223 in L1. **1a** also makes hydrophobic interactions with two residues on L1 (W38 and P226), and **2a** contacts two (W64 and V67) on the flexible L3 loop (32) positioned above the IMP-1 active site (gray side chains in Fig. 4 *A* and *B*). Despite these similarities, BTZ binding results in a larger ligand:protein buried surface area in the IMP-1:**2a** (330 $Å^2$) complex compared with L1:**1a** (264 $Å^2$), largely because of the L3 loop which is present in IMP-1 but not L1 (Fig. 4).

In contrast, L-BTZ binding to the monozinc B2 MBL Sfh-I differs substantially from that to B1 or B3 enzymes. In the complex with **1a**, the **1a**-carboxylate group interacts with the active-site zinc (1.84 ± 0.03 Å), and is within hydrogen-bonding distance of two protein side chains, N233 (2.97 ± 0.03 Å) and H196 (2.96 ± 0.03 Å) (Fig. 5*A*). Binding to Sfh-I results in approximately 265 $Å^2$ of buried surface area, and is stabilized by interactions with four hydrophobic residues (W87, F156, I153, F236) (Fig. 5*A*, gray). In addition, although BTZ binding has little effect on the overall Sfh-I structure [rmsd 0.33 Å over 228 Cα atoms, compared with native Sfh-I (14)], there are significant

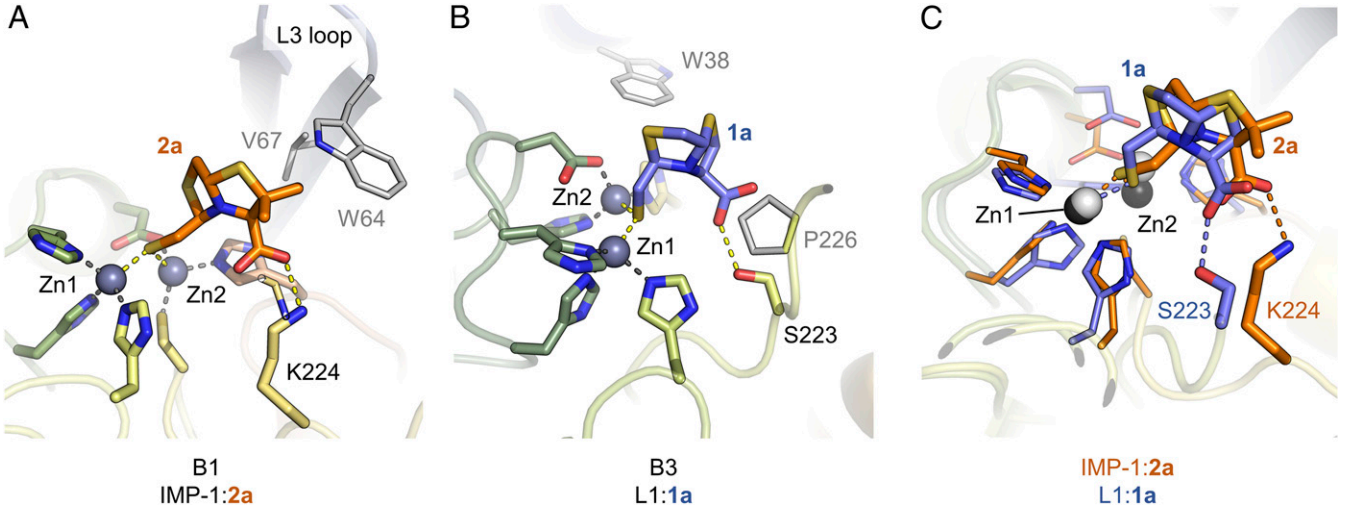

Fig. 4. L-bisthiazolidine binding to B1 (IMP-1) and B3 (L1) metallo-β-lactamases. Close-up view of IMP-1 and L1 active sites with bound L-BTZ (sticks, colored as in Fig. 2). Protein main chain is colored from the N (light blue) to C terminus (light red). Residues that interact with the zinc ions (Zn1 and Zn2, gray spheres) are shown as sticks (colored as main chain), whereas hydrophobic residues that stabilize BTZ binding are shown as gray sticks. IMP-1 K224 and L1 S223 (labeled) interact with the BTZ carboxylate. (*A*) **2a** bound to B1 IMP-1. Protein–zinc interactions are shown as gray dashes and BTZ–protein or BTZ–zinc interactions are shown as yellow dashes. (*B*) **1a** bound to B3 L1. Interactions shown as in *A*. (*C*) Superposition of IMP-1:**2a** (orange) and L1:**1a** (blue). BTZ–protein or BTZ–zinc interactions are shown as dashes colored orange (IMP-1:**2a**) or blue (L1:**1a**).

rearrangements within the active site (Fig. 5*B*). The BTZ carboxylate displaces the water zinc ligand (Wat1), maintaining the tetrahedral zinc geometry, and causing a flip and approximately 0.6 Å (± 0.03 Å) movement of the H196 side chain. This movement results in a loss of interaction of H196-Nε2 with the nucleophilic water (Wat2), which moves 0.9 Å deeper into the active site and closer to Zn2 (3.0 Å compared with 3.5 Å in uncomplexed Sfh-I, ± 0.03 Å). Notably, and in direct contrast to the structures obtained for complexes with IMP-1 and L1, the BTZ thiol is not involved in interactions with the Sfh-I zinc site.

A Distinct Mode of D-BTZ Binding to L1. We next investigated binding of D-BTZ inhibitors to our chosen MBL targets. Surprisingly, structural analysis of D-BTZs bound to the B3 enzyme L1 revealed a third mode of binding. Similar to the L1:**1a** complex, the **1b**-mercaptomethyl group dominates L1 active-site interactions, with the thiol bridging the two zinc ions, again resulting in a small (0.4 ± 0.17 Å) increase in the Zn1–Zn2 distance (Table S3). However, the carboxylate group is no longer bound to S223, but instead interacts, via a water molecule, with Y32 on the nonconserved N-terminal extension of L1 (2.74 Å BTZ–water, 2.40 Å water–Y32, ± 0.17 Å) (Fig. 6*A*). This interaction causes an approximate 90° rotation of D-BTZ around the thiol compared with L-BTZ, orientating the BTZ to make hydrophobic interactions with three residues (P226, F156, I162) (Fig. 6*B*) of which only P226 is involved in binding **1a**. Despite this, the buried surface area on ligand binding is similar in both the L1:**1a** and L1:**1b** complexes (264 $Å^2$ and 268 $Å^2$, respectively). The structure of L1:**2b** indicates that the presence of a dimethyl group does not affect this mode of binding, although unsurprisingly there is a slight increase in the buried surface area (279 $Å^2$). **2b** makes the same hydrophobic interactions as **1b** (Fig. 6*C*) and is bound with similar thiol–zinc and Zn1–Zn2 distances (Table S3). As in the L1:**1b** structure, interaction of the **2b** carboxylate with Y32 is also mediated by a water molecule (2.81 Å **2b**–water, 2.53 Å water–Y32, ± 0.18 Å).

Binding of 1b to B1 MBLs Involves Multiple Ligand–Zinc Interactions. Structures of **1b** bound to the B1 enzymes BcII and IMP-1 reveal multiple interactions of the inhibitor with both zinc ions in the active site (Fig. 7). However, BTZ binding does not result in global conformational changes for either IMP-1 (IMP:**1b** compared with

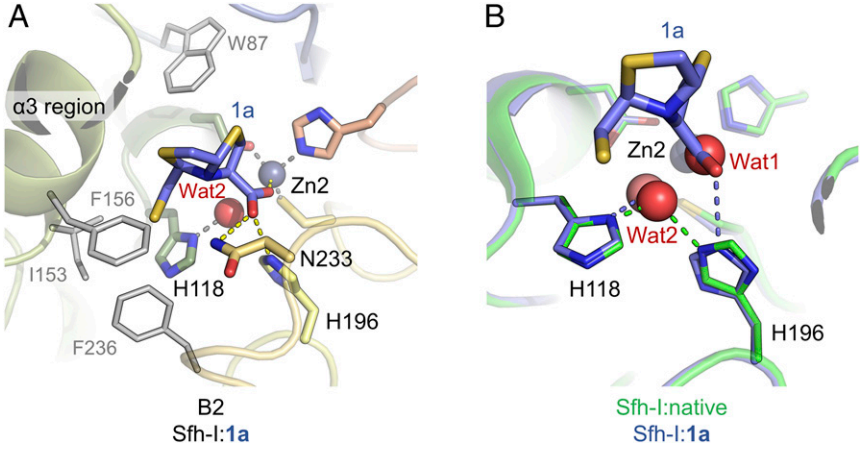

Fig. 5. **1a** binding to Sfh-I and concomitant active-site conformational changes. Active-site zinc ions (gray spheres) and water molecules (red spheres) are labeled. (*A*) **1a** (blue) bound in the active site of B2 Sfh-I (main chain colored as in Fig. 1). Hydrophobic residues, on the α3 region and within the active site, involved in binding **1a** are shown as gray sticks. The **1a** carboxylate bridges N233 and H196 (sticks). Residues involved in binding the active-site zinc ion (Zn2, gray sphere) and water (Wat2, red sphere) are represented as sticks. Interactions of **1a** with the protein main chain or Zn2 are shown as yellow dashes. Protein–zinc and protein–water interactions are shown as gray dashes. (*B*) Superposition of Sfh-I:**1a** (blue) with unliganded, native Sfh-I (PDB ID code 3SD9, green). Interactions of H118 and H196 with the BTZ or Wat2 are shown as dashes.

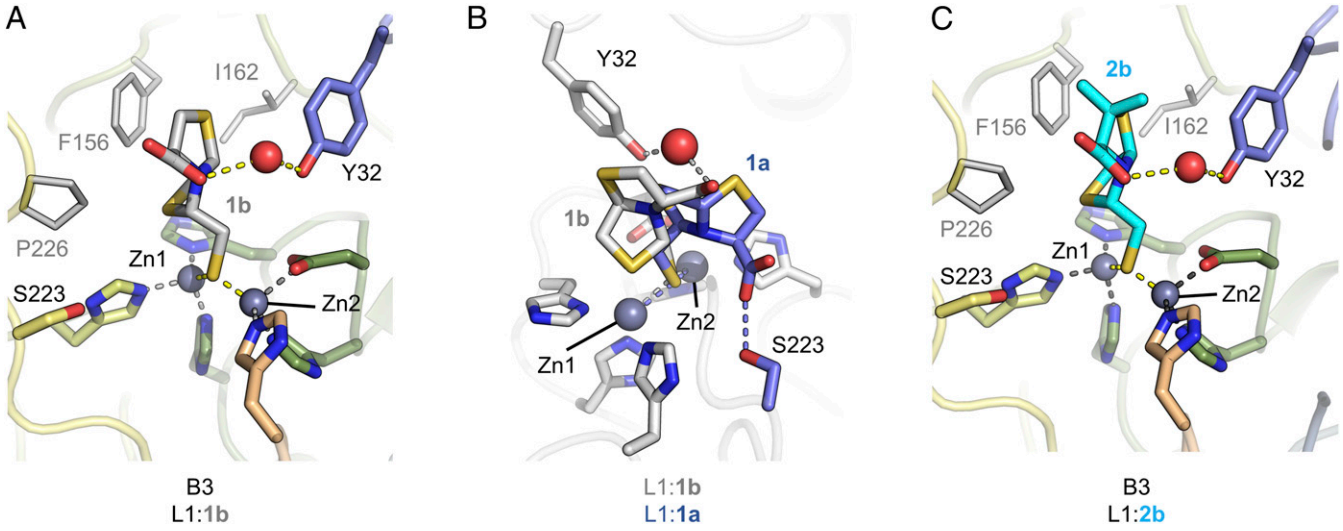

Fig. 6. **1b** binding to B3 MBL L1. A water molecule (red sphere) mediates the interaction of Y32 (sticks, labeled) with the D-BTZ carboxylate, but S223 (sticks, labeled), which binds **1a**, is not involved. Hydrophobic and zinc-binding residues represented as Fig. 4. (*A*) **1b** (gray) bound in the active site of B3 L1 (colored as in Fig. 4). Interactions shown as in Fig. 4. (*B*) Superposition of L1:**1b** (gray) with L1:**1a** (blue). Interactions between the BTZ and protein are shown as gray or blue dashes, according to their respective structures. (*C*) **2b** (cyan) bound to B3 L1, represented as in *B*.

uncomplexed IMP-1, rmsd = 0.28 Å over 222 Cα atoms) or BcII (BcII:**1b** compared with uncomplexed BcII, rmsd = 0.41 Å over 223 Cα atoms). **1b** binding to IMP-1 (buried surface area 292 Å^2) features four ligand–zinc interactions (Fig. 7*A*), the carboxylate (2.1 ± 0.26 Å) and bridging nitrogen (2.8 ± 0.26 Å) with Zn2, and the thiol bridging Zn1 (2.0 ± 0.26 Å) and Zn2 (2.2 ± 0.26 Å), with the Zn1–Zn2 distance increasing by 0.2–0.3 Å (± 0.26 Å). Binding is further favored by interaction of the carboxylate with Lys224, as is the case with **2a** binding to IMP-1.

As in the IMP-1:**2a** complex, residues W64 and V67 in the L3 loop are involved in hydrophobic interactions with the inhibitor, with W64 in particular forming π-stacking interactions with the BTZ bicyclic ring. Despite previous observations that the NDM-1 L3 loop may "close" on **1a** binding (17), the position of the IMP-1 L3 loop is more stable, with no substantial conformational shifts evident on BTZ binding compared with the native structure. **1b** makes very similar interactions (Fig. 7*B*) on binding BcII (buried surface area 287 Å^2): that is, the carboxylate (2.0 ± 0.13 Å) and bridging nitrogen (2.7 ± 0.13 Å) with Zn2, the carboxylate with K224 (2.9 ± 0.13 Å), and the thiol equidistant between active-site zincs (2.2 ± 0.13 Å), with the Zn1–Zn2 distance increasing by 0.3 ± 0.13 Å compared with uncomplexed BcII (PDB ID code 4C09). Three hydrophobic interactions are formed, one with W87 and two with residues F61 and V67 in the L3 loop, which form after the L3 loop closes by ∼3.0–4.6 ± 0.13 Å compared with its position in the native structure (Fig. S8). As observed in the **1a**:Sfh-I complex, there are also important rearrangements within the IMP-1 and BcII active sites on **1b** binding (Fig. 7 *C* and *D*). Remarkably, the electron density clearly defines a displacement of the Zn2 ligand D120 and consequent loss of the D120–Zn2 coordination interaction (Fig. S9). Instead, D120 reorients to form hydrogen bonds with either E59 (IMP-1) or S69 (BcII), which results in an irregular five-coordinate geometry for Zn2 and a 1.0 ± 0.26 Å (IMP-1) or 0.7 ± 0.13 Å (BcII) movement of Zn2 away from D120.

Discussion

Here we show the structural basis for micromolar competitive inhibition of all three MBL classes by BTZs, including of clinically relevant enzymes from opportunist bacterial pathogens, such as *E. coli*, *P. aeruginosa*, or *S. maltophilia*, which can cause severe or even life-threatening infections. BTZs are able to cross the outer membrane of Gram-negative bacteria and enter the periplasm, inhibiting MBL activity in vivo and potentiating the activity of carbapenems and other β-lactams against MBL-producing clinical isolates. Our data demonstrate this simple scaffold, which in several aspects resembles the architecture of the bicyclic β-lactam substrate, is able to overcome the variations in MBL active-site architecture across subclasses to achieve roughly equipotent inhibition of all MBLs tested. Such variations, which encompass differences in zinc ligands, interaction partners for the carboxylate group at C2/C3 of β-lactams and the positions and locations of hydrophobic surfaces and conformationally flexible surface loops adjacent to the active site, have manifest as substantial differences in potency against different MBL targets for some other inhibitor classes. Unexpectedly our structural data reveal that BTZ inhibition of different MBLs is unique and characterized by multiple binding modes that vary both with target enzyme and with the BTZ enantiomer used.

The crystal structures of MBL:BTZ complexes presented here and in previous publications (17, 18) identify that BTZs use four distinct modes of binding to the range of MBL targets. L-BTZs adopt similar binding modes to the B1 and B3 binuclear enzymes, with overall BTZ orientation retained across enzymes that use different side chains [K224 (BcII, IMP-1, NDM-1); R228 (VIM-2) and S223 (L1)] in interactions with the BTZ carboxylate group that may or may not involve the intermediacy of bound water molecules. This binding mode is also robust to differences in the composition (particularly with respect to the positions of aromatic residues) and orientation of the mobile L3 loop that is a feature of most B1 MBLs, but absent in B3 enzymes such as L1.

In contrast, D-BTZ binding differs profoundly between complex structures for B1 (BcII, IMP-1) and B3 (L1) enzymes, with interactions involving the carboxylate group (with Zn2 and the K224 side chain) a feature of the BcII and IMP-1 complexes but absent from those with L1. The differing L1 active-site architecture, which compared with B1 MBLs lacks an extended L3 loop and instead features elongated linkers between other secondary structural elements adjacent to the active site and hydrophobic residues at different positions, likely imposes a different orientation upon the bound D-BTZ ligand. The fourth binding mode is observed in B2 MBL Sfh-I complexed with **1a**. In B2 enzymes conserved hydrophobic residues on the long α3 helix adjacent to the active site form a "hydrophobic wall" proposed

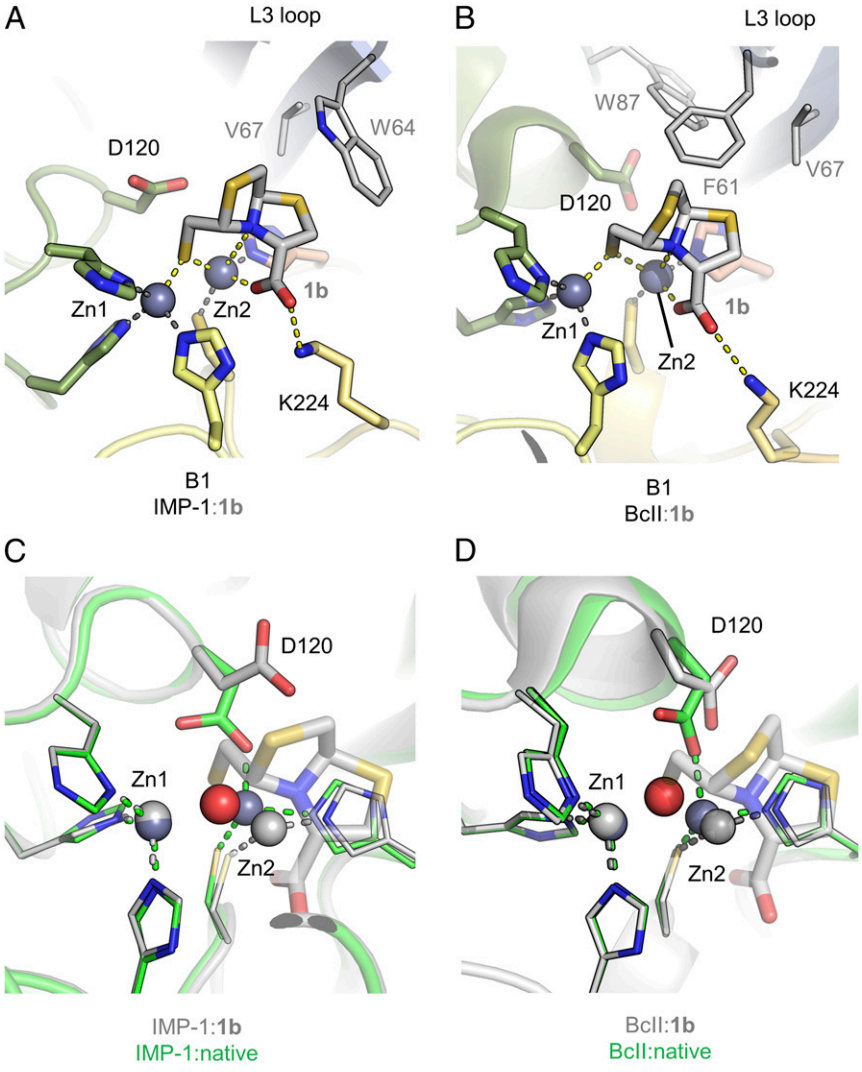

Fig. 7. **1b** binding to B1 MBLs BcII and IMP-1. **1b** bound in the active of B1 MBLs (*A*) IMP-1 and (*B*) BcII (colors and interactions as in Fig. 4). In both *A* and *B*, K224 binds the **1b** carboxylate and the D120–Zn2 coordination is disrupted. (*C*) Superposition of IMP-1:**1b** (gray; zinc ions, light gray) with unliganded, native IMP-1 (green; zinc ions, dark gray). Binding causes movement of Zn2, and loss of the D120–Zn2 interaction. (*D*) Superposition of BcII:**1b** (gray; zinc ions, light gray) with unliganded, native BcII (PDB ID code 4C09 green; zinc ions, dark gray). Binding is similar to *C*, causing the same rearrangements within the active site.

to contribute to selective carbapenem binding (33, 34). In the Sfh-I:**1a** structure, the BTZ thiol was observed buried deep into the hydrophobic cavity formed by residues W87, I153, F236, and F156, rather than, as anticipated, involved in interactions with the zinc center. We consider it likely that positioning of the thiol moiety in this cavity by the unique hydrophobic wall of B2 MBLs also explains the high selectivity of Sfh-I for L- over D-BTZs, which is not observed in the B1 and B3 family members studied in this work. In addition, the carboxylate of bound D-BTZ would be positioned differently at the Zn site, requiring different ancillary interactions with the protein main chain. In Sfh-I, unlike our observations of BTZ binding to L1 and IMP-1, the more constrained active site provides little room for a second BTZ binding mode. It is likely that significant conformational changes within the active site would be required to bind D-BTZs, resulting in higher K_is in vitro, whereas in the crystalline state these are prevented by packing interactions. Taken together, these data clearly indicate that the variation in active-site architecture between different MBLs is such that the ability to support more than one mode of binding may be necessary to achieve activity toward the full range of targets for even simple inhibitor scaffolds.

Investigation of the activity of BTZs as potential MBL inhibitors was in part prompted by their structural similarities to β-lactam substrates. Comparison of L-BTZ:MBL and hydrolyzed substrate:MBL structures highlights both differences and similarities in the modes of ligand binding (Fig. 8). B1 and B3 MBLs bind antibiotic similarly, exemplified by the NDM-1:ampicillin (19) (Fig. 8*A*, green) and L1:moxalactam (20) (Fig. 8*B*, green) structures, respectively. In particular, in binuclear MBLs K224 (B1) or S223 (B3) interact with the carboxylate at C2/C3 of the hydrolyzed β-lactam. However, in both cases β-lactam binding is also characterized by interactions of Zn2 with the β-lactam nitrogen and carboxylate, whereas equivalent interactions are not observed in the **1a**:MBL complexes. The absence of an interaction between the BTZ nitrogen (a component of the bicyclic ring structure) and Zn2 is, however, consistent with several models of MBL-catalyzed antibiotic hydrolysis that feature Zn2-coordination by the β-lactam nitrogen only after the amide bond has been cleaved and the β-lactam ring opened (21, 22). On the other hand, BTZ binding involves the thiol group bridging Zn1 and Zn2, and displacement of the nucleophilic water (Wat1), whereas in complexes with hydrolyzed antibiotics Wat1 is present (19, 20), albeit with differences in zinc geometry. These differences are particularly evident in the NDM-1:ampicillin structure [PDB ID code 3Q6X (19)] where Wat1 is more tightly bound to a trigonal byprimidal Zn1 (2.1 Å) than Zn2 (2.7 A). In comparison, in the native NDM-1 structure [PDB ID code 3SPU (12)], Wat1 is more consistently (between the five chains in the ASU) equidistant between Zn1 (tetrahedral geometry) and Zn2. **1b** binding to L1 also involves fewer interactions with Zn2 than

hydrolyzed antibiotic (Fig. 8*C*), although it is notable that Y32, which helps to stabilize inhibitor binding by interaction with the BTZ carboxylate, also stabilizes antibiotic binding through interaction with the moxalactam carbonyl oxygen (20).

In comparison with MBL:L-BTZ complexes, (or binding of D-BTZs to L1), **1b** binding to the B1 MBLs IMP-1 and BcII more closely represents that of hydrolyzed β-lactams. This is most evident with respect to interactions involving Zn2 and Lys224, as highlighted by comparison of IMP-1:**1b** and BcII:**1b** complexes with that of hydrolyzed ampicillin bound to NDM-1 (19) (Fig. 9 *A* and *B*, respectively). In particular, both the BTZ and ampicillin carboxylate groups interact with Zn2 (2.0–2.2 Å) and hydrogen bond to Lys224 Nε (2.5–2.9Å). Furthermore, the bridgehead nitrogen of D-BTZs lies within coordination distance of Zn2 (2.7–2.8 ± 0.13/0.26 Å), although this interaction is not as strong as the equivalent in the NDM-1:ampicillin complex involving the β-lactam nitrogen (2.2 Å) (Fig. 9 *C*–*E*). However, despite the closer resemblance of their binding to that of antibiotic substrates, comparison of K_i values shows D-BTZs to be no more effective B1 MBL inhibitors than the L-BTZs that exhibit different binding modes (Table 1). This difference may arise from D-BTZ binding causing the energetically unfavorable disruption of the D120–Zn2 interaction. This D120 rearrangement may be necessary to relieve conformational strain about the Zn2 site arising from interaction with bound D-BTZ, or may be a means of relieving steric clashes because of the orientation of D-BTZ in the active site imposed by interactions involving the carboxylate group and, in particular, positioning of the sulfur atom as a bridging ligand to both zinc ions.

Similar to B1 and B3 enzymes, structural characterization of hydrolyzed biapenem binding to the B2 MBL CphA (34) (Fig. 8*D*, green) reveals the antibiotic to interact with Zn2 via its β-lactam nitrogen atom and carboxylate group, and by hydrogen bonds to Lys224, Thr157, and T119. In comparison, in Sfh-I:**1a**, the BTZ carboxylate group, and not the nitrogen atom, interacts with the Sfh-I zinc ion, as well as two residues that are not involved in antibiotic binding to CphA, H196, and N233 (Fig. 8*D*, blue). Binding of hydrolyzed biapenem also involves residues W87, I153, F236, and F156 of the hydrophobic wall, a unique structural feature of B2 MBLs. These residues also stabilize binding of **1a**, specifically the thiol moiety, indicating that the hydrophobic wall is also important in BTZ binding by B2 MBLs (34). However, although thiol compounds have been shown as high-affinity MBL ligands (35), giving rise to the identification of a variety of thiol-based inhibitors, the absence of thiol:Zn2 interactions in our Sfh-I:BTZ crystal structure supports consideration of other metal binding groups, such as carboxylates or phosphonates, in searches for broad-spectrum MBL inhibitors.

Numerous chemical scaffolds have been explored as candidate MBL inhibitors, in a search that is given added impetus by the increasing dissemination of MBLs on mobile genetic elements and in clinically significant pathogens. However, studies to date have focused upon relatively restricted numbers of target enzymes, and characterization, particularly at structural level, has not in most cases extended to all three enzyme subclasses. Captopril (an angiotensin-converting enzyme and MBL inhibitor) is the most studied MBL inhibitor, with complexes of one or both of its enantiomers described for B1 (BcII [PDB ID codes 4C1H (36) and 4C1C (36)], BlaB (37), IMP-1 [PDB ID codes 4C1G and 4C1F (36)], NDM-1 (38) and VIM-2 [PDB ID codes 4C1D and 4C1E (36)]), B2 [CphA (35)] and B3 [L1 (39)] MBLs. Hence we compared the BTZ binding modes described here to those of L- and D-captopril, which, like BTZs, feature a carboxylate group attached to a ring system and a free thiol group, but lack the bicyclic organization and bridgehead nitrogen of the BTZ scaffold. Similar to BTZ complexes, the free thiol of D- or L-captopril bridges the

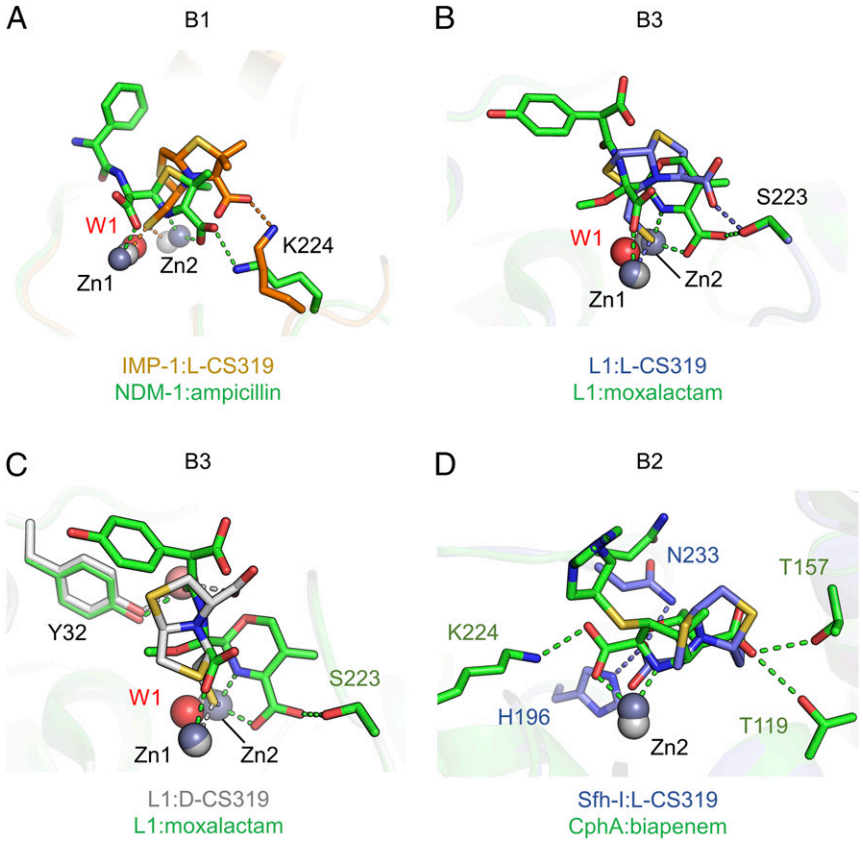

Fig. 8. Comparisons of the mode of binding between bisthizolidines and hydrolyzed antibiotics. Superpositions of (*A*) IMP-1:**1a** (orange; zinc ions, light gray) with NDM-1:hydrolyzed ampicillin (PDB ID code 3Q6X, green; zinc ions, dark gray); (*B*) L1:**1a** (blue; zinc ions, light gray) with L1:moxalactam (PDB 2AIO, green; zinc ions, dark gray); (*C*) L1:**1b** (gray; zinc ions, light gray) with L1:moxalactam (as in *B*); (*D*) Sfh-I:**1a** (gray; zinc ions, light gray) with CphA:biapenem (PDB ID code 1X8I, green; zinc ions, dark gray).

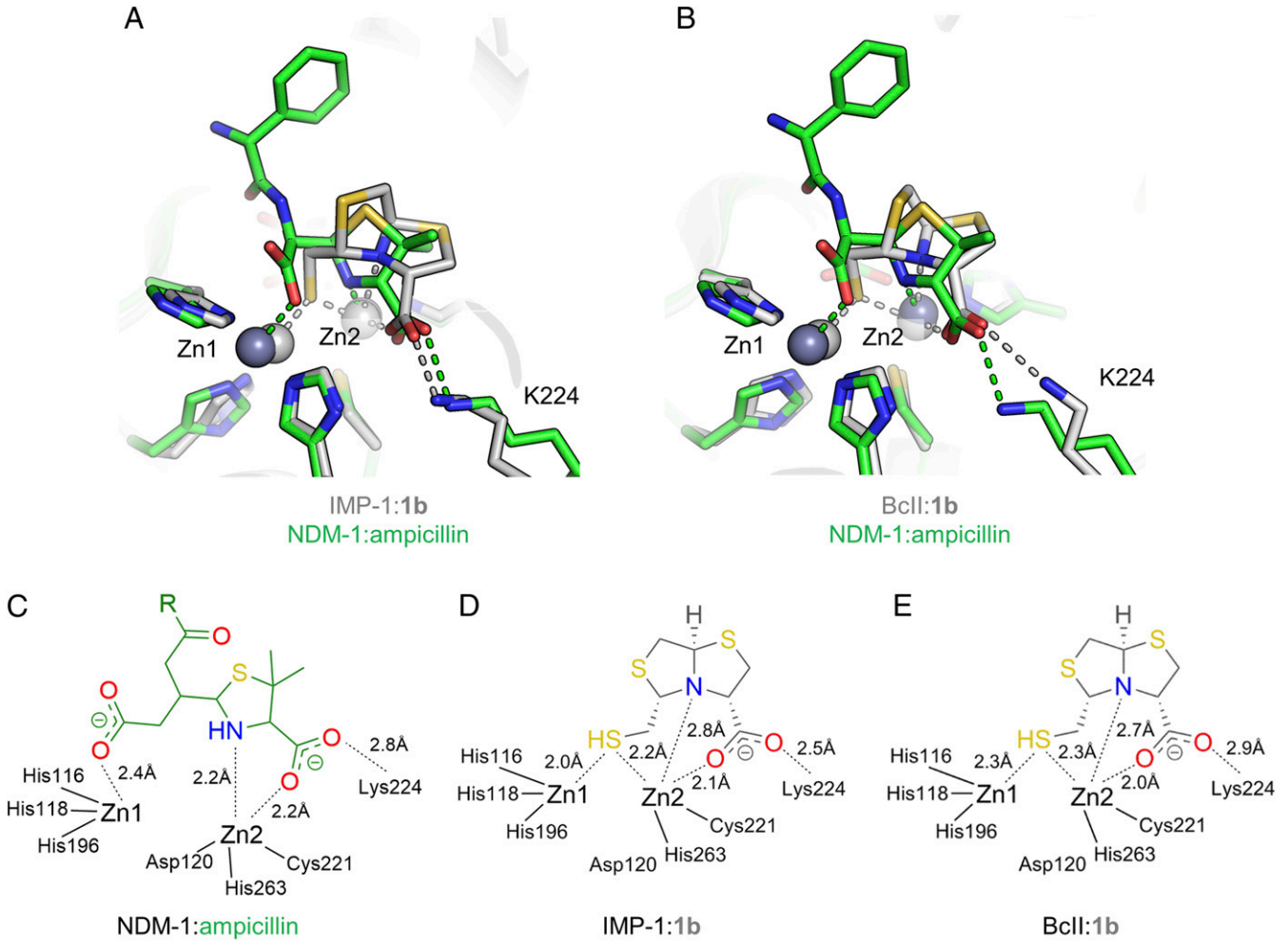

Fig. 9. **1b** binding to B1 MBLs IMP-1 and BcII closely resembles binding of hydrolyzed antibiotic. Superpositions of NDM-1:ampicillin (green) with (*A*) IMP:**1b** and (*B*) BcII:**1b** (gray; zinc ions, light gray). The modes of binding and ligand-protein/zinc interaction distances are shown in schematic representation for (*C*) NDM-1: hydrolyzed ampicillin, (*D*) IMP-1:**1b**, and (*E*) BcII:**1b**.

active-site zinc ions of both B1 (IMP-1 and BcII) and B3 (L1) MBLs (Fig. S10 *A–E*), whereas the carboxylate interacts with K224 (B1), S223 (B3), or R228 (B1 VIM-2). However, D-captopril binding to L1 does not involve Y32, as in the L1:**1b** structure (Fig. S10*D*), and unlike **1b** binding to BcII and IMP-1 (Fig. S10 *B* and *C*), D-captopril binding to these targets does not feature Zn2–nitrogen or Zn2–carboxylate interactions.

Some other thiol-based inhibitors, such as the thioenolate ML302F (30), or mercaptoacetic acids (40), have been noted to make additional interactions with Zn2 through their carboxylate groups. Resemblance of D-captopril and BTZ binding is most apparent for the B2 enzymes, where D-captopril binds to the active site of CphA through interaction of its carboxylate group with the zinc ion (35), as observed in the Sfh-I:**1a** structure (Fig. S10*F*). However, thiol-binding to the Zn2 site of B2 enzymes is possible, as observed previously in a CphA:inhibitor cocrystal structure (PDB ID code 3IOF) (41). These data may indicate that, when both a thiol and carboxylate are present, the carboxylate–Zn2 interaction may be preferable, possibly as a result of the ability of the carboxylate group to make ancillary interactions with the protein main chain.

A major hurdle in the development of small molecules as effective countermeasures for infections by opportunistic Gram-negative bacteria is the requirement to penetrate the outer envelope of the bacterial cell. Many Enterobacteriaceae, and in addition nonfermenting species such as *A. baumannii* or *P. aeruginosa*, have limited permeability toward many small molecule solutes. In a previous investigation we established that BTZs can penetrate Gram-negative bacteria that express the NDM-1 MBL (17). The present work extends these results significantly by demonstrating BTZ inhibition (as evidenced by potentiation of carbapenem antimicrobial activity) of MBL activity for enzymes of all three subclasses expressed in *E. coli*. However, to investigate the ability of BTZs to penetrate more challenging organisms, we also assessed MBL inhibition in clinical *S. maltophilia* isolates. *S. maltophilia* is a versatile opportunist pathogen of compromised patients (42), and is attracting increasing attention as a pathogen of note in the biology of cystic fibrosis lung disease, with chronic infection identified as a risk factor for pulmonary exacerbations (43). *S. maltophilia* is a notoriously resistant organism with increased efflux pump activity, porin reduction, and two inducible β-lactamases (L1 and L2), that collectively confer resistance to most β-lactams (29). Ticarcillin–clavulanate is a combination shown to be effective against some *S. maltophilia* infections (44), but may be compromised by β-lactamase production (45). Therefore, the ability of BTZs to restore β-lactam efficacy against a nosocomial *S. maltophilia* isolate indicates potential effectiveness in clinically relevant situations, where cross-class inhibition must extend to extensively drug-resistant physiological strains.

In closing, we report BTZs achieve cross-class MBL inhibition despite the structural diversity and zinc requirements of the different enzyme targets. The ability of the unique BTZ scaffold to bind in multiple orientations is likely a result of the substrate-like design that is decorated with two strong metal-binding groups (-SH and -COOH). Indeed, the multiple binding modes possible for B1 and B3 enzymes accord with the broad substrate spectrum of these enzymes, whereas the B2 MBL, which shows preference for carbapenem substrates, shows some stereochemical preference. BTZs therefore provide a novel, efficient strategy for cross-class MBL inhibition, show activity against target bacterial pathogens as well as in vitro, and thus justify efforts at further improvement to enhance potency and clinical applicability.

Materials and Methods

Synthesis of Bisthiazolidines. 1a (L-CS319; (2R,5S,8R)-8-carboxylate-2-mercaptomethyl-1-aza-3,6-dithiobicyclo[3.3.0] octane); **1b** (D-CS319; (2S,5R,8S)-8-carboxylate-2-mercaptomethyl-1-aza-3,6-dithiobicyclo[3.3.0] octane); **2a** (L-VC26; (2R,5S,8R)-2-mercaptomethyl-7-dimethyl-8-carboxylate-1-aza-3,6-dithiobicyclo[3.3.0] octane); and **2b** (D-VC26; (2S,5R,8S)-2-mercaptomethyl-7-dimethyl-8-carboxylate-1-aza-3,6-dithiobicyclo[3.3.0] octane) were synthesized as previously described (18). The L- and D- notation thus refers to the 2R,5S,8R and 2S,5R,8S chiralities of the BTZs, respectively.

Purification of Soluble MBLs. IMP-1, L1, and Sfh-I lacking the first 21 amino acids were cloned into pOPINF vectors (46) resulting in a N-terminally His_6-tagged protein cleavable with 3C protease. BcII was cloned into the pET28a vector (Novagen) using NdeI and SalI restriction sites, resulting in a N-terminally His_6-tagged protein cleavable with thrombin. For IMP-1, L1, and Sfh-I production, *E. coli* SoluBL21 (DE3) cells (Genlantis) bearing pOPINF were grown at 37 °C in auto-induction terrific broth media (Formedium) for 8 h, then left overnight at 20 °C. BcII was overexpressed in *E. coli* BL21(DE3), grown at 37 °C in LB medium to A_{600} 0.6, when 0.5 mM IPTG and 0.5 mM $ZnSO_4$ were added (16 h, 18 °C). Cells were harvested by centrifugation (6,500 × *g*, 10 min).

For L1, cells were resuspended in 50 mM Hepes pH 8.0, 400 mM NaCl, Complete EDTA-free protease inhibitor mixture (Roche), 10 μM $ZnCl_2$, and broken by two passages through a cell disruptor (30,000 psi). After centrifugation (100,000 × *g*, 1 h), supernatant (plus 8 mM imidazole) was incubated 2 h with Ni-NTA resin (Qiagen); 1 mM β-mercaptoethanol was included in all subsequent buffers. Protein-bound resin was washed in Buffer A (50 mM Tris pH 7.5, 400 mM NaCl, 10 μM $ZnCl_2$) plus 10 mM imidazole, then with the same buffer plus 0.1% Triton X-100. Resin was further washed in Buffer A plus 20 mM imidazole and protein eluted in 50 mM Tris pH 7.5, 200 mM NaCl, 10 μM $ZnCl_2$, 400 mM imidazole. Imidazole was reduced to 10 mM in an Amicon 10-kDa centrifugal filter. The tag was removed by 3C protease cleavage (4 °C, overnight) and capture on Ni-NTA resin. L1 was subsequently loaded onto a Superdex S200 column equilibrated in 10 mM Tris pH 7.0, 100 mM NaCl, 100 μM $ZnSO_4$. Peak fractions were concentrated to 23 mg/mL. For crystallization, L1 protein was supplemented with 5 mM $ZnSO_4$. IMP-1 was purified similar to L1, except 1 mM TCEP (rather than β-mercaptoethanol) was included in all buffers, and protein loaded onto a Superdex S75 column equilibrated in 50 mM Tris pH 7.5, 150 mM NaCl, 100 μM $ZnCl_2$, 1 mM TCEP, and concentrated to 25 mg/mL Sfh-I was purified as L1, except protein was loaded on to a Superdex S75 column equilibrated in 50 mM Hepes pH 7.0 and concentrated to 15 mg/mL. For BcII, cells were resuspended in Buffer B (50 mM Tris pH 8.0, 200 mM NaCl) supplemented with 10 μg/mL DNase, 4 mM $MgCl_2$, and 2 mM phenylmethylsulfonyl fluoride and disrupted by sonication. After centrifugation (60 min, 15,000 × *g*) and supernatant loaded on to Ni-Sepharose resin equilibrated with Buffer A. The column was washed with 100 mL of Buffer B and BcII was eluted with Buffer B plus 500 mM imidazole using a linear gradient (0–100% Buffer B, over 100 mL). The his-tag was removed with thrombin and capture on Ni-Sepharose resin. Flow-through (cleaved BcII) was diluted (1:5) in Buffer C (100 mM Hepes pH 7.0, 1 mM $ZnSO_4$) and loaded on to CM-Sepharose resin equilibrated with Buffer C. The column was washed with 100 mL of Buffer C and BcII was eluted with Buffer C plus 400 mM NaCl, with a purity >95%, as determined by SDS/PAGE. Protein was concentrated to 15 mg/mL using Centricon ultrafiltration devices (Millipore) and exchanged into 10 mM Tris·HCl pH 7, 50 mM NaCl, 1 mM DTT, and 1 mM $ZnSO_4$.

GOB-18 was purified cytoplasmically, and reconstituted in its fully active monozinc form, as previously described (27).

Enzyme Assays. Inhibition constants (K_i) were determined by following imipenem hydrolysis at 300-nm absorbance (JascoV-670 spectrophotometer) in Buffer C (10 mM Hepes pH 7.5, 0.2 M NaCl, 50 μg/mL BSA; B1 and B3 enzymes) or Buffer C plus 20 μM $ZnSO_4$ (B2 Sfh-I). BTZs were dissolved in DMSO (30 mM) and diluted in reaction buffer to the desired concentration. The presence of 1% DMSO did not alter the enzyme activity. Assays were initiated by enzyme addition to the substrate and inhibitor mixture. K_is were determined by data fitting to the Competitive Inhibition Model implemented in GraphPad Prism 5.0.

In Vitro Time-Kill Study. *E. coli* DH5α carrying the pMBLe plasmid (17) expressing MBLs BcII, IMP-1, Sfh-I, and GOB-18 were cultured overnight at 37 °C in Mueller Hinton Broth (MHB) supplemented with 25 mg/L gentamycin. Next, 1.5 μL of the overnight cultures were inoculated in 1 mL MHB supplemented with 100 μM isfopropyl-β-D-thiogalactopyranoside (IPTG) to obtain a bacterial suspension of ∼10^6 CFU/mL To examine the effects of the novel BTZs compounds on bacterial growth, bacterial suspensions were grown at 37 °C under different conditions: MHB alone (growth control) or supplemented with 0.4% DMSO (growth control), sublethal imipenem concentrations, 100 mg/L of each inhibitor, or a combination of imipenem and inhibitor. Samples (10 μL) were removed at intervals of 100, 300, and 500 min of exposure, and serial dilutions performed on MHB. Viable cell numbers were determined by spotting 20 μL of each dilution on Muller Hinton Agar (MHA). Plates were incubated (37 °C overnight), and colonies counted. Results are the mean of three biological replicates. Assays using a clinical isolate of *S. maltophilia* (strain C1: L1 and L2 producer) were performed similarly except samples were taken after 4, 8, and 12 h of treatment.

Crystallization and Structure Determination. L1 and Sfh-I were crystallized as previously described (14, 15). IMP-1 was crystallized using sitting-drop vapor diffusion in CrysChem24 well plates (Hampton Research) at 18 °C. Drops were formed by mixing 1-μL protein solution with 1-μL crystallization reagent [0.1 M sodium cacodylate pH 6.0, 0.2 M sodium acetate, 25% (wt/vol) PEG8000] and equilibrated against 500 μL. Crystals grew to maximum size in 7 d. BcII was crystallized using hanging-drop vapor diffusion in 24-well plates (Hampton Research) at 20 °C. Drops were formed by mixing 1-μL protein solution with 1-μL crystallization reagent [180 mM K_2SO_4, 20% (wt/vol) PEG 3350, 1 mM DTT, and 1 mM $ZnSO_4$] and equilibrated against 1 mL. Crystals grew to maximum size within 3–5 d.

Inhibitor bound complexes were obtained by soaking crystals for 15–60 min in 2- to 5-mM inhibitor dissolved in cryoprotectant [L1: 0.05 M Hepes pH 7.5, 1.75 M $(NH_4)_2SO_4$, 1.25% (vol/vol) PEG400, 25% (vol/vol) glycerol, 2 mM TCEP; IMP-1: 0.1 M sodium cacodylate, 0.15 M sodium acetate, 25% (vol/vol) ethylene glycol, 15% (wt/vol) PEG8000, 2 mM TCEP, 50 μM $ZnCl_2$; Sfh-I: 0.02 M Hepes pH7.5, 0.12 M sodium acetate, 14% (wt/vol) PEG3350, 20% (vol/vol) glycerol, 2 mM TCEP; BcII: reservoir plus 20% (vol/vol) glycerol]. IMP-1 native crystals were cryoprotected by soaking (1 min) in IMP-1 cryoprotectant. Crystals were looped and flash-frozen in liquid nitrogen. Diffraction data were collected at 100K on beamlines I02, I03, I04, I04-1, or I24 (Diamond Light Source, United Kingdom) or on a high-flux Rigaku RAXIS IV++ in-house X-ray generator (BcII, Los Alamos National Laboratory). Datasets were indexed and integrated using XDS (47), iMosflm (48), or HKL2000 (49) and scaled using Aimless in CCP4 (50) or HKL2000 (49). Crystals were not prone to radiation damage in all cases and relatively high R_{merge} values, compared with high I/σI values, are a result of the high redundancy of the data, or in the case of BcII:**1b** because of the collection of data on a home source. Structures were phased by molecular replacement with Phaser (51) using as starting models PDB ID codes 3I13 (52) (BcII), 1SML (15) (L1), 1DD6 (10) (IMP-1), or 3SD9 (14) (Sfh-I). Structures were completed by iterative rounds of manual model building in Coot (53) and refinement in Phenix (54) or Refmac5 (55). Sfh-I crystals were pseudomerohedrally twinned [twin law h,-k,-l, determined by Xtriage (54)], so the Sfh-I model was completed with twin refinement in Refmac5. Omit maps were calculated from the final model after removal of the ligand and refinement in Phenix (L1, IMP-1, BcII) or Refmac (Sfh-I). Ligand structures and geometric restraints were calculated with PRODRG (56) or Phenix eLBOW (57). Structure validation was assisted by Molprobity (58), SFCHECK (59), and Phenix. Figures were prepared using PyMol (60). The rmsds were calculated over Cα atoms aligned using PDBeFold (61). Ligand buried surface areas were calculated using PDBePisa (62).

See *SI Results* and Fig. S11 for a discussion of the movement of the uncomplexed di-zinc IMP-1 L3 loop between chains in the asymmetric unit.

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