

Natural Product–Guided Discovery of a Fungal Chitinase Inhibitor

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SUMMARY

Natural products are often large, synthetically intractable molecules, yet frequently offer surprising inroads into previously unexplored chemical space for enzyme inhibitors. Argifin is a cyclic pentapeptide that was originally isolated as a fungal natural product. It competitively inhibits family 18 chitinases by mimicking the chitooligosaccharide substrate of these enzymes. Interestingly, argifin is a nanomolar inhibitor of the bacterial-type subfamily of fungal chitinases that possess an extensive chitin-binding groove, but does not inhibit the much smaller, plant-type enzymes from the same family that are involved in fungal cell division and are thought to be potential drug targets. Here we show that a small, highly efficient, argifin-derived, nine-atom fragment is a micromolar inhibitor of the plant-type chitinase ChiA1 from the opportunistic pathogen *Aspergillus fumigatus*. Evaluation of the binding mode with the first crystal structure of an *A. fumigatus* plant-type chitinase reveals that the compound binds the catalytic machinery in the same manner as observed for argifin with the bacterial-type chitinases. The structure of the complex was used to guide synthesis of derivatives to explore a pocket near the catalytic machinery. This work provides synthetically tractable plant-type family 18 chitinase inhibitors from the repurposing of a natural product.

INTRODUCTION

Compounds isolated from natural sources, natural products, provide a wealth of bioactives that in some cases are directly used as drugs and/or lead to the development of potent inhibitors useful for characterization of enzymes of interest and the design of future therapeutic drugs. Argifin is a natural product that was first isolated from *Gliocladium* fungal cultures grown from a soil sample collected in Micronesia (Omura et al., 2000). The structure of argifin was shown to be an unusual arginine-

containing cyclopentapeptide (Figure 1A) (Arai et al., 2000). Initial studies of argifin found that it showed inhibition of a family 18 chitinase from *Lucilia cuprina* in a dose-dependent manner as well as inhibiting chitinases from *Streptomyces griseus* and *Vibrio alginolyticus* within the micromolar range (Omura et al., 2000).

Chitinases are enzymes that cleave the β -(1,4) glycosidic bond of chitin, a structural component in insect exoskeletons and fungal cell walls. The CAZy glycoside hydrolase family 18 (GH18), as defined by amino acid sequence similarity (Cantarel et al., 2009), contains a large number of chitinases expressed in archaea, prokaryotes, and eukaryotes. It is subdivided into two subfamilies, bacterial-type and plant-type family 18 chitinases, according to sequence similarity, active site construction, corresponding preferred activity (exo-chitinases versus endo-chitinases, respectively), and occurrence in different organisms: plants generally express plant-type GH18 enzymes, bacteria generally use bacterial-type GH18 chitinases, and members of both subfamilies have been found in fungi and vertebrates. It has been hypothesized that bacterial-type chitinases in fungi and bacteria are used to process chitin as a carbohydrate source, whereas the fungal plant-type chitinases are involved in cell wall remodeling and maintenance (Cantarel et al., 2009; Griffith and Danishefsky, 1991; Jaques et al., 2003; Takaya et al., 1998).

The fungal cell wall protects the cell from the environment; it is a dynamic structure that is continually modified by enzymes to facilitate growth (Latge, 2001). All fungal cell walls contain chitin as a major component that is broken down by chitinases during cell wall remodeling. Disrupting this process is expected to result in a decrease of fungal viability and/or virulence, making plant-type fungal chitinases potential targets for drugs against fungal pathogens. Unfortunately, although there are numerous inhibitor families targeting bacterial-type GH18 enzymes (Rao et al., 2005; Schüttelkopf et al., 2006; Vaaje-Kolstad et al., 2004) most of them perform poorly against these fungal plant-type family 18 chitinases. An exception is the natural product allosamidin isolated from *Streptomyces* species, which acts on both plant-type and bacterial-type family 18 chitinases (Sakuda et al., 1987) and competitively inhibits the plant-type chitinase CTS1 from *Saccharomyces cerevisiae* (ScCTS1, $K_i = 0.61 \mu\text{M}$; Hurtado-Guerrero and van Aalten, 2007) and hevamine ($K_i = 3.1 \mu\text{M}$; Vaaje-Kolstad et al., 2004). Unfortunately, allosamidin is a substrate analog with poor druglike properties (high

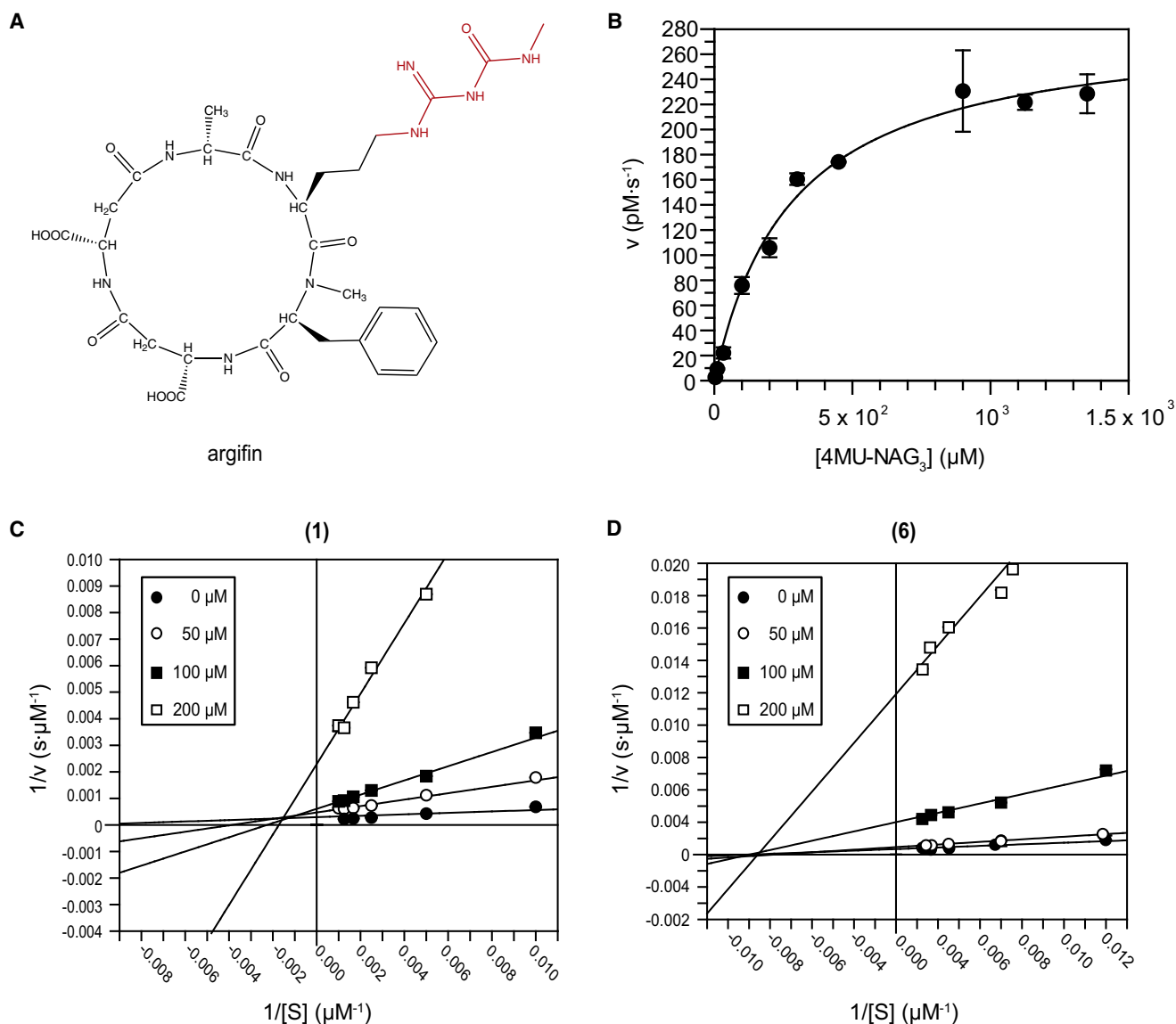


Figure 1. Chemical Structures and Inhibitory Properties

(A) Chemical structure of the cyclopentapeptide argifin with its dimethylguanylylurea moiety highlighted in red.

(B) Steady-state initial velocities measured at different substrate concentrations for *AfChiA1*. Reaction mixtures contained 200 nM of *AfChiA1*, 0.1 mg/ml BSA, and 50–800 μM of the 4MU-NAG₃ in McIlvaine buffer (100 mM citric acid and 200 mM sodium phosphate [pH 5.5]) to a final volume of 50 μl . Production of 4-methylumbelliferone was linear with time for the incubation period used (70 min at 37°C), and less than 10% of available substrate was hydrolyzed. The K_m was measured to be $300 \pm 27 \mu\text{M}$ with a k_{cat} of 3.0 s^{-1} .

(C) Lineweaver-Burk plot showing a mixed mode of inhibition for the dimethylguanylylurea fragment against *AfChiA1*. Mode of inhibition assays were set up as described previously using 50 μM –1 mM 4MU-NAG₃, and 60 μM –6 mM inhibitor.

(D) Lineweaver-Burk plot showing a noncompetitive mode of inhibition for the phenyl derivative **6** using the same reaction parameters.

molecular weight, glycosidic bonds, and a cLogP of -5.2) and its synthesis is complicated and costly (Blattner et al., 1996; Kassab and Ganem, 1999). Interestingly, a fragment identified from the large natural product argifin, dimethylguanylylurea (Figure 1A), has recently been identified as the minimal fragment necessary and sufficient for competitive inhibition of the bacterial-type chitinases (Andersen et al., 2008). Because the catalytic machinery is conserved across all GH18 family members, it can be hypothesized that the fragment molecule would also inhibit the

plant-type family 18 enzymes and provide a template for the much-needed development of potent, specific inhibitors for this class of chitinases.

Here, we report the inhibitory activity of both argifin-derived and newly synthesized dimethylguanylylurea fragments against the *Aspergillus fumigatus* plant-type chitinase ChiA1 (*AfChiA1*) as well as the crystal structure of this enzyme in complex with the most potent of these inhibitors. *A. fumigatus* is a saprotrophic fungus that is widespread in nature and is involved in carbon and

Table 1. Structures and Enzyme Inhibition of the Argifin-Derived Fragments

	R	IC ₅₀ (μM)
1	CH ₃	79 ± 8
2	CH ₃ CH ₂	310 ± 7
3	CH ₃ (CH ₂) ₂	62 ± 1
4	CH ₃ (CH ₂) ₃	38 ± 7
5		42 ± 1.3
6	Ph	112 ± 1
7	PhCH ₂	299 ± 4
		127 ± 14
	allosamidin	
	argifin	>3.8 mM

nitrogen recycling (Chazalet et al., 1998). Although the spores are not harmful to healthy individuals, *A. fumigatus* is an opportunistic pathogen that can colonize the lungs of immunocompromised individuals, frequently resulting in life-threatening invasive aspergillosis (Brakhage and Langfelder, 2002; Singh and Pateron, 2005). The deconstruction of the natural product, argifin, and the characterization of its fragments as inhibitors of AfChiA1, demonstrates the importance of combining natural product investigation with chemical deconvolution and establishes a new family of efficient and synthetically attractive leads for the development of inhibitors against medically relevant GH18 chitinases.

RESULTS AND DISCUSSION

An Argifin Fragment Inhibits Fungal Chitinases Involved in Cell Division

Argifin (Figure 1A) is a natural product that inhibits bacterial-type family 18 chitinases in the low nanomolar range by mimicking enzyme-substrate interactions (Houston et al., 2002; Rao et al., 2005). We recently reported a chemical dissection of argifin, revealing that the dimethylguanylyurea fragment (compound 1 in Table 1 and Figure 1A) still competitively inhibits the bacterial-type chitinase B1 from *A. fumigatus* (AfChiB1) (Andersen et al., 2008). This finding encouraged us to investigate inhibition of the plant-type fungal chitinases that are thought to be involved in cell wall remodelling during cell division (Selvaggini et al., 2004). We cloned the previously uncharacterized chitinase A1 from *A. fumigatus* (AfChiA1, 38% catalytic core sequence identity to the plant-type chitinase CTS1 from *S. cerevisiae*, ScCTS1) and purified the protein from a *Pichia* expression system. The enzyme hydrolyzes 4MU-NAG₃ with a *K_m* of 300 ± 27 μM and a *k_{cat}* of 3.0 s⁻¹ (Figure 1B). Strikingly, the large allosamidin pseudotriaccharide, generally a potent GH18 inhibitor, inhibits AfChiA1 with an IC₅₀ of only 127 ± 14 μM (Table 1). Similarly, the natural product argifin (Figure 1A) does not inhibit AfChiA1 (IC₅₀ > 3.8 mM). However, the nine-atom fragment 1 (Figure 1A), derived from argifin, has an IC₅₀ of 79 ± 8 μM against the enzyme (Table 1), compared to 500 ± 20 μM previously reported for AfChiB1 (Andersen et al., 2008). Mode of inhibition studies suggest that 1 is not a purely competitive inhibitor of AfChiA1 (Figure 1C). In terms of ligand efficiency (i.e., the contribution to the free energy of binding per inhibitor atom), compound 1 achieves an excellent value of -0.93 kcal·mol⁻¹·atom⁻¹, whereas allosamidin exhibits only moderate efficiency at -0.19 kcal·mol⁻¹·atom⁻¹.

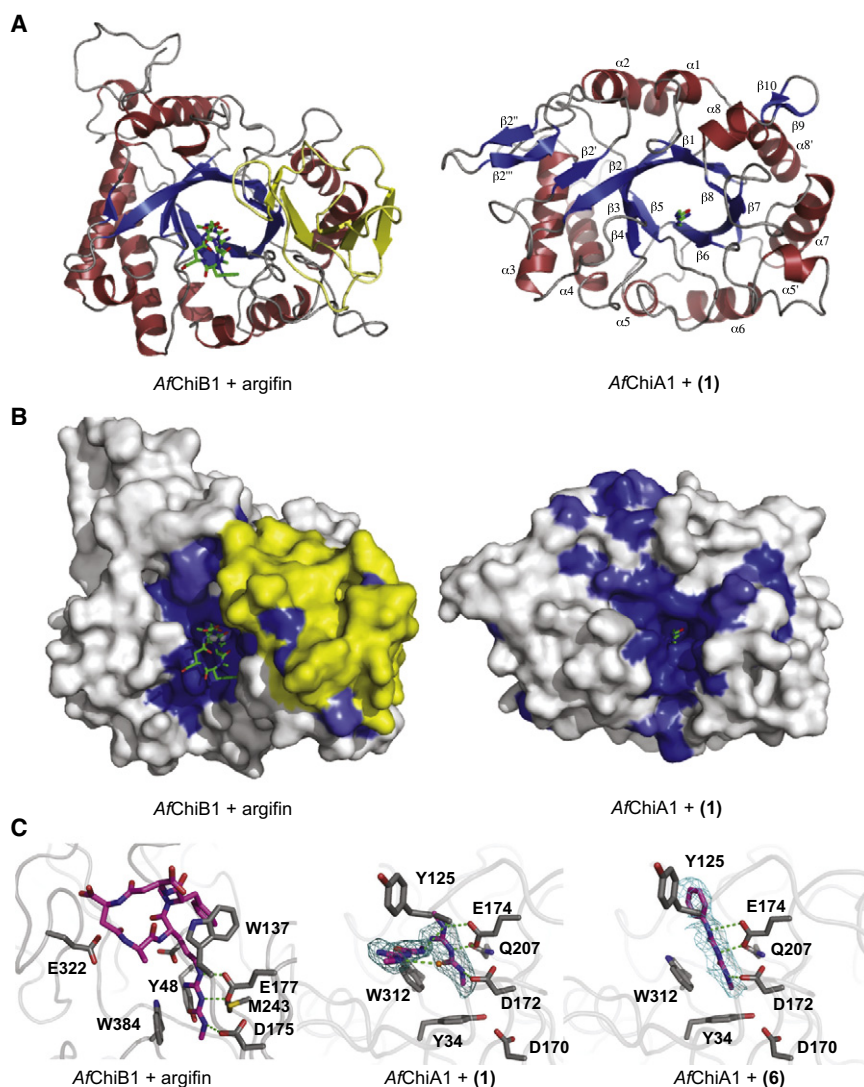
AfChiA1 Possesses a Shallow Active Site That Is Efficiently Occupied by the Argifin Fragment

To further investigate the mode of inhibition of the argifin-derived fragment 1 and to provide a platform for rational optimization, we determined the crystal structure of AfChiA1, both in its apo-form and in complex with 1 (Table 2). Data for the apo-structure were

Table 2. Summary of Data Collection and Structure Refinement Statistics

	apo-AfChiA1	AfChiA1-1	AfChiA1-6
Resolution (Å)	20.00–2.00 (2.05–2.00)	25.01–2.3	30.00–2.35
Unit cell	<i>a</i> = 76.7 Å, <i>b</i> = 126.1 Å, <i>c</i> = 213.4 Å	<i>a</i> , <i>b</i> = 100 Å, <i>c</i> = 111.2 Å	<i>a</i> , <i>b</i> = 100 Å, <i>c</i> = 111.2 Å
No. of unique reflections	69,723	55,123	51,912
Redundancy	4.1 (4.0)	4.1 (3.1)	3.0 (3.2)
R _{merge}	0.099 (0.438)	0.109 (0.58)	0.114 (0.406)
I/σ(I)	10.8 (2.6)	12.4 (5.4)	17.3 (5.2)
Completeness (%)	100.0 (99.8)	99.9 (98)	98.5 (94.1)
R, R _{free}	0.201 (0.241)	0.241 (0.285)	0.259 (0.298)
 protein (Å ²)	14.0	26.1	16.9
 ligand (Å ²)	n/a	33.1	24.4
Rmsd from ideal geometry			
Bond lengths (Å)	0.015	0.0218	0.0202
Bond angles (°)	1.38	1.912	1.837

Note values for the highest resolution shell are given in brackets.



collected to 2.0 Å resolution, solved by molecular replacement and refined to an R_{free} of 0.249 with good stereochemistry. AfChiA1 has the $(\beta/\alpha)_8$ barrel fold common to all family 18 glycoside hydrolases (Figure 1A) (Davies and Henrissat, 1995). Most of the loops connecting the helices and strands are relatively short; exceptions are the β_2 - α_2 loop, which contains three minimal β strands (labeled β_2' , β_2'' and β_2''') that, together with the C-terminal end of the extended β_2 itself, form a small four-stranded mixed β sheet, and the β_6 - α_6 loop, which includes the short α_5' helix. Helix α_8 is interrupted by a minimal β sheet comprising strands β_9 and β_{10} (Figure 1A). Comparison with existing structures of GH18 family member proteins shows that AfChiA1 is most similar to *S. cerevisiae* CTS1 (PDB id 2UY2). The agreement between the two structures is good for the core $(\beta/\alpha)_8$ barrel (overall RMSD = 1.15 Å for 265 C_α atoms), whereas some conformational differences exist in the connecting loops, many of which harbor insertions/deletions.

The AfChiA1 active site lies at the C-terminal opening of the β -barrel (Figure 2A). It is thus defined by the (mostly) very short $\beta\alpha$ -loops, which gives it the overall open, and apparently

would not have a significant effect on substrate/ligand specificity.

The exposed AfChiA1 active site contrasts with AfChiB1 (Rao et al., 2005) and other bacterial-type chitinases, which harbor larger $\beta\alpha$ -loops (including one incorporating an entire α/β domain) that form a deep active site groove (Figure 2B), lined by several solvent-exposed aromatic residues, including Trp137 (Figure 2C). It is these differences in active site construction that explain the different affinities for argifin by AfChiA1 and AfChiB1: the AfChiB1-argifin complex structure shows that the inhibitor is engulfed by the wall of the active site groove, whereas these walls are nonexistent in AfChiA1 (Figure 2B). Nonetheless, the catalytic machinery itself is relatively well-conserved among all GH18 chitinases and AfChiA1 is no exception, sporting hallmark residues of the GH18 family, including the solvent-exposed tryptophan (Trp312) that forms the bottom of the -1 sugar-binding subsite, the catalytic DxE motif (Asp172 and Glu174), and conserved tyrosines Tyr232 and Tyr34 (Figure 2C).

The structure of AfChiA1 in complex with **1** was refined against 2.3 Å synchrotron diffraction data, revealing clear density for the

Figure 2. Structural Analysis of AfChiA1 Inhibitor Complexes

(A) Comparison of the AfChiB1-argifin complex structure (left, PDB id 1W9V) and the complex of AfChiA1 with **1** (right). The proteins are shown in cartoon representation (α helices in red, β strands in blue) with the ligands drawn as sticks (green). The extra α/β domain present in the bacterial-type fungal chitinases, but lacking in the plant-type fungal chitinases, is highlighted in yellow.

(B) Surface view of the structures in (A). The AfChiB1 and AfChiA1 surfaces are shaded by sequence identity among *A. fumigatus* bacterial-type and plant-type GH18 chitinases, respectively (white = nonconserved, dark blue = completely conserved). Ligands are shown as in (A). The extra α/β domain present in the bacterial-type fungal chitinases, but lacking in the plant-type fungal chitinases, is highlighted in yellow.

(C) The active site of AfChiA1 in complex with **1/6** and AfChiB1 in complex with argifin. Side chains for important residues are shown as gray sticks and labeled. Ligands are shown as purple sticks, a water molecule is represented as an orange ball. Likely hydrogen bonds are indicated by green dashed lines. Electron density is shown contoured to 2.5 σ as a cyan mesh for AfChiA1 ligands.

featureless, architecture also seen in ScCTS1 (Hurtado-Guerrero and van Aalten, 2007) and common to plant-type family 18 chitinases (Davies and Henrissat, 1995). However, in the AfChiA1 active site the bulky Tyr125, replacing a serine in ScCTS1, appears to partially block access to the catalytic site. The ligand complexes on the other hand reveal Tyr125 to be conformationally flexible and show it pointing away from the active site, suggesting that its presence

inhibitor (Table 2 and Figure 2C). The ligand is bound in the active site in a position and orientation similar to the equivalent fragment in the AfChiB1-argifin complex (Andersen et al., 2008) (Figures 2B and 2C), where **1** forms a bidentate hydrogen bond with the side chain of Glu174 (the catalytic acid) and also donates a single hydrogen bond to the Asp172 carboxylate. Additionally, the inhibitor accepts a weak hydrogen bond from Tyr232 and stacks with the Trp312 side chain. Surprisingly, clear density for a second ligand molecule can be observed sitting in a shallow groove just outside the catalytic pocket (Figure 2C). The groove is lined by the side chains of Trp312 and Gln37 on one side and the backbone atoms of Ala124 and Tyr125 on the other side, whereas its floor is contributed by the phenyl moiety of Phe60. The ligand molecule forms one direct hydrogen bond with the protein, from the backbone amide of Ala124 to a deprotonated ligand backbone nitrogen. The ligand backbone also donates a hydrogen bond to a water molecule, which is bound in the groove through two hydrogen bonds to the backbone carbonyls of Gly122 and Tyr125. It is possible that the presence of this second inhibitor binding site explains the observed mixed inhibition pattern (Figure 1C).

Chemical Elaboration of the Argifin Fragment Identifies Additional Binding Pockets

As stated earlier, compound **1** is a highly efficient ($-0.93 \text{ kcal}\cdot\text{mol}^{-1}\cdot\text{atom}^{-1}$) plant-type chitinase inhibitor, compared to the widely studied, but less synthetically tractable, natural product pseudotrisaccharide inhibitor allosamidin ($-0.19 \text{ kcal}\cdot\text{mol}^{-1}\cdot\text{atom}^{-1}$) (Hopkins et al., 2004). Furthermore, the guanyleurea moiety would be a suitable core for high-throughput synthesis of a library of fragments, similar to what has been achieved recently for alpha-glucosidases, starting from a valienamine scaffold (Lysek et al., 2006).

To explore this, a number of analogs of **1** were synthesized using a three-step procedure, via conversion of the appropriate amine to the *N,N'*-bis(*tert*-butoxycarbonyl)guanidine derivative (Feichtinger et al., 1998), followed by treatment with methylamine to generate the desired guanyleurea (Miel and Rault, 1998) (Table 1). Compounds **2–7** were designed on the basis of the binding mode of **1** in the catalytic pocket, which suggests that only the methyl group at the guanyl end of **1** is available for derivatization (Figure 2C). Only moderately sized moieties were explored, given the relatively featureless surface beyond the immediate surroundings of the catalytic pocket and the knowledge that the full argifin molecule itself does not inhibit AfChiA1. A number of alkyl and ring extensions were explored (Table 1) and were found to inhibit AfChiA1 with IC_{50} values between $38 \mu\text{M}$ and $310 \mu\text{M}$, compared to $79 \mu\text{M}$ for the starting compound. Although some of the derivatives appeared to give modest improvements in inhibition (i.e., up to 2-fold), this is not considered to be significant given the general accuracy of IC_{50} measurements. Further examinations into the effect from substitutions of **1** on mode of inhibition and binding were focused on compound **6**. As shown in Figure 1C, the mode of inhibition is noncompetitive (Figure 1D). This compound was also a 10-fold stronger inhibitor of AfChiB1 ($\text{IC}_{50} = 210 \pm 40$) compared to the parent compound **1**.

A structure of AfChiA1 in complex with **6** was refined against 2.4 \AA synchrotron diffraction data (Table 2). The complex shows

that **6** adopts a virtually identical binding mode to the parent compound **1** (Figure 2C; maximum atomic positional shift = 0.4 \AA), with an identical hydrogen bonding pattern. The phenyl ring does not make any specific interactions with the protein and correspondingly is poorly ordered (Figure 2C). This lack of interactions in combination with the increased disorder of **6** compared to **1** explains the reduced IC_{50} observed for **6**. In contrast to the AfChiA1-**1** complex, there is no evidence for a secondary binding site, compatible with the notion that the phenyl ring of a ligand molecule bound in the secondary site would clash with the ligand occupying the catalytic pocket (Figure 2).

Conclusion

On the basis of the dissection of the natural product argifin, an inhibitor of bacterial-type GH18 chitinases (Figure 1A), we have characterized the activity of dimethylguanyleurea (**1**) and its derivatives (**2–7**) against a plant-type chitinase, ChiA1 from the fungal pathogen *Aspergillus fumigatus*. The small compounds are found to be attractive starting points for AfChiA1 inhibitors, with IC_{50} values in the micromolar range. In fact, **1** is a better inhibitor of AfChiA1 ($\text{IC}_{50} = 79 \mu\text{M}$) than it is of the bacterial-type chitinase AfChiB1 ($\text{IC}_{50} = 500 \mu\text{M}$; (Andersen et al., 2008)), reversing the relative affinities observed for its parent compound, argifin. Moreover, **1** is already a better AfChiA1 inhibitor than the broad-spectrum (and generally low nanomolar) allosamidin inhibitor. This fact is particularly striking when expressed as ligand efficiency ($-0.93 \text{ kcal}\cdot\text{mol}^{-1}\cdot\text{atom}^{-1}$ for **1** versus $-0.19 \text{ kcal}\cdot\text{mol}^{-1}\cdot\text{atom}^{-1}$ for allosamidin), taking into account the almost five-fold larger mass of allosamidin. The first structures of AfChiA1 show that **1** itself, as well as its derivative **6**, bind to the enzyme exclusively through interactions with the catalytic machinery conserved across GH18 hydrolases, explaining their ability to inhibit AfChiA1 and suggesting that they might represent a family of pan-GH18 chitinase inhibitors. The structures also reveal AfChiA1 to adopt the (minimal) TIM barrel fold typical of (plant-type) GH18 family members and shows that it is closely related to ScCTS1, the only other known fungal plant-type GH18 structure, sharing its open active site architecture, which explains the poor affinity of this enzyme for argifin and other inhibitors of bacterial-type chitinases.

According to its observed binding mode to AfChiA1, several simple derivatives of **1** were synthesized and tested against the enzyme. None of these derivatives showed significantly improved binding, which is not unexpected, given that the solvent-exposed AfChiA1 active site does not provide many functional groups to interact with. At the same time, it is encouraging that most of the derivatives were also not significantly worse binders, suggesting that it could be energetically feasible to further build up the outward-pointing side of **1** to eventually reach interactable groups on the enzyme surface. Such modifications could allow us to take this scaffold further and design bulkier compounds that retain their affinity for plant-type GH18 proteins, but lose binding to the more restricted bacterial-type GH18 active site, thus yielding inhibitors specific to plant-type chitinases that would be of interest as chemical tools to dissect the precise biological roles of different chitinases.

Intriguingly, the structure of AfChiA1 in complex with **1** reveals that, in addition to the catalytic-site bound inhibitor, a second

ligand molecule occupies a shallow groove close to the catalytic pocket. Although this second ligand makes few obviously energetically favorable interactions with the enzyme, the clear electron density observed for it suggests that it does bind with reasonable affinity. It might thus be possible to exploit its observed binding mode as a template for the further elaboration of the scaffold, possibly by simply joining two molecules of **1** into a new inhibitor able to bind in both pockets.

SIGNIFICANCE

Natural products are often large, synthetically intractable molecules, yet frequently offer surprising inroads into previously unexplored chemical space for enzyme inhibitors. This work shows how, aided by detailed structural information, the large natural product chitinase inhibitor argifin can be dissected down to a tiny nine-atom active fragment that can then be used as a scaffold to develop micromolar inhibitors for a chitinase from the opportunistic pathogen *Aspergillus fumigatus*.

EXPERIMENTAL PROCEDURES

Synthesis of Dimethylguanyleurea and Derivatives

Compounds **1–7** were synthesized by a three-step procedure as follows. Starting from the amine, R-NH₂ (R as designated in Table 1), the corresponding bis-*tert*-butoxycarbonylguanidine derivatives were generated by reaction with 1,3-di-*tert*-butoxycarbonyl-2-(trifluoromethylsulfonyl)guanidine, according to the method of Feichtinger et al. (1998). Transformation to the desired guanyleureas was then effected in two steps, by aminolysis with methylamine in tetrahydrofuran (Miel and Rault, 1998), followed by removal of the remaining *tert*-butoxycarbonyl group with trifluoroacetic acid. The final compounds were all isolated as the corresponding trifluoroacetate salts, with the exception of **7**, which was converted to the free base by neutralization with saturated aqueous sodium hydrogencarbonate. Compounds **1–7** were fully characterized by ¹H NMR (JEOL Delta at 270 MHz, or Varian Mercury-VX at 400 MHz), ¹³C NMR (JEOL Delta at 68 MHz), and high-resolution mass spectrometry (Bruker MicroTOF autospec electrospray ionisation instrument). Purities were verified by analytical RP-HPLC on a Dionex system with a Gemini 5 μ C₁₈ 110A column, 150 \times 4.6 mm (Phenomenex, UK).

Cloning and Purification

The coding sequence for residues Ser29–Leu335 of *Aspergillus fumigatus* chitinase A (AfChiA1; UniProt ID: Q873Y0) was cloned by PCR from an *A. fumigatus* cDNA library (kindly provided by Jean-Paul Latgé, Paris) using the forward primer 5'-GCGAATTCTCCAACCTTGCCACTACTGGGGTC-3' and the reverse primer 5'-CTGCGGCGCTCAAAGAATATCCTTCATGTGGTCTGCATAGGG-3', containing an EcoRI and a NotI restriction site, respectively. The PCR product was initially cloned into the PCR cloning vector pSC-B (Stratagene) and subcloned into the EcoRI and NotI sites of the *Pichia pastoris* expression vector pPICZ α A (Invitrogen). Subsequently, to obtain a soluble and crystallizable protein, we re-added the codons for residues Leu336 and His337 by site directed mutagenesis using the mutagenesis oligonucleotide pair 5'-GACCACATGAAGGATATTTCTTTGCACTGAGCGGCCGCAGCTTCTAG-3' and 5'-CTAGAAAGCTGCGGCCGCTCAGTGCAAAGAATATCCTTCATGTGGTC-3'. Site-directed mutagenesis was carried out following the QuikChange Site-Directed Mutagenesis protocol (Stratagene), using the KOD HotStart DNA polymerase (Novagene). All plasmids were verified by sequencing (DNA Sequencing Service, College of Life Sciences, University of Dundee; www.dnaseq.co.uk).

The plasmid was isolated from *E. coli* strain DH5 α , linearized with SacII, and used to transform *Pichia pastoris* strain X-33 using the LiCl method (Invitrogen) or using the *Pichia* EasyComp Transformation Kit (Invitrogen). Transformants were selected on YPD plates (1% [w/v] yeast extract, 2% [w/v] peptone, and

2% [w/v] dextrose) containing 100 mg/ml of zeocin (Invitrogen). Batch cultures were performed in a 100-ml volume of BMGY medium (1% [w/v] yeast extract, 2% [w/v] peptone, 100 mM potassium phosphate [pH 6.0], 1.34% [w/v] yeast nitrogen base, and 1% [v/v] glycerol) 50 ml were used to inoculate 500 ml of BMGY medium overnight at 30°C, and expression was induced by methanol 1% (v/v) for 72 hr at room temperature in a shaking incubator (270 rpm). Yeast cells were harvested by centrifugation at 3480 g for 30 min. The supernatants containing soluble AfChiA1 were filtered to 0.2 micron, concentrated to 50 ml using a Vivaflow 200 cassette (10,000 MWCO, PES membrane; Vivascience), and dialyzed against water.

The samples were then loaded onto a 2 \times 5 ml HiTrap Q FF column (Amersham Biosciences) that had been equilibrated with 10 column volumes of 25 mM Tris (pH 7.5) on an AKTA purifier system. Following loading, the column was washed with 10 column volumes of 25 mM Tris (pH 7.5). The protein was eluted with a salt gradient (0–500 mM NaCl) over 20 column volumes, collecting 2 ml fractions. The fractions containing the proteins were then pooled and concentrated to 5 ml. Subsequently, gel filtration was carried out using a Superdex 75 XK26/60 column in 25 mM Tris and 150 mM NaCl (pH 7.5). The concentrated AfChiA1 protein sample was used for both kinetic analysis and crystallization trials.

Crystallization and Structure Determination

The protein was concentrated to between 28 and 36 mg \cdot ml⁻¹ and was crystallized by hanging drop vapor diffusion over a reservoir containing 0.42–0.58 M NaH₂PO₄ and 0.74–0.83 M K₂HPO₄; usable crystals grew over a few days. After cryoprotection by short immersion in 2.5 M Li₂SO₄, native data were collected at 100 K in house. To obtain complex structures, AfChiA1 crystals were soaked in the presence of inhibitor from a 10 mM stock. The inhibitor was added directly to the crystal growth drop at a final concentration of 1–5 mM. After soaking for 1–10 min and cryoprotection, data were collected at 100 K on beamline ID14-EH2 (wavelength 0.953 Å) at the European Synchrotron Radiation Facility (ESRF, Grenoble, France).

AfChiA1 forms either orthorhombic crystals (crystal form I, space group I2₁2₁, unit cell dimensions $a = 76.6$ Å, $b = 125.8$ Å, $c = 211.7$ Å) with two molecules per asymmetric unit or trigonal crystals (crystal form II, space group P3₂, $a = b = 100.0$ Å, $c = 111.2$ Å) with three molecules per asymmetric unit. All data were processed and scaled using HKL software (Otwinowski et al., 2003) to resolutions of 2.0 Å (native), 2.3 Å (complex with **1**), and 2.4 Å (complex with **6**) (Table 2). The apo-data (crystal form I) were solved by molecular replacement with AMoRe (Navaza, 2001) using the *S. cerevisiae* CTS1 apo-structure (PDB id 2UY2) (Hurtado-Guerrero and van Aalten, 2007) as a search model yielding the expected two molecules per asymmetric unit, whereas the ligand complexes (crystal form II) were solved by molecular replacement with MolRep (Vagin and Teplyakov, 2010) using the refined AfChiA1 apo structure. Refinement of the AfChiA1 structures (Table 2) proceeded through rounds of minimization with REFMAC5 (Vagin et al., 2004) and model building with Coot (Emsley and Cowtan, 2004). The R-factors for the complex structures are relatively high, most likely because of disorder of the third monomer. Because of this disorder as well as the structural similarity of the first two monomers for all structures (RMSD values between 0.15 Å and 0.35 Å for ~310 C α s without NCS restraints) atoms, the further discussion will focus on the first monomer (i.e., chain A) only, unless noted otherwise. Ligand coordinates and topologies were generated with PRODRG for the complex structures (Schuttelkopf and van Aalten, 2004). In all AfChiA1 molecules built, Cys81 falls into the disallowed region of the Ramachandran plot, despite having been modeled in agreement with clear electron density. This residue participates in an intramolecular disulfide bridge, which might necessitate its strained backbone conformation.

Enzyme Assays

Michaelis-Menten parameters of AfChiA1 were determined using 4-methylumbelliferyl β -D-N,N',N''-triacetylchitotrioside (4MU-NAG₃). Standard reaction mixtures contained 200 nM of AfChiA1, 0.1 mg/ml BSA, and 50–800 μ M of the fluorogenic substrate in Mcllvaine buffer (100 mM citric acid and 200 mM sodium phosphate [pH 5.5]) to a final volume of 50 μ l. Reaction mixtures were incubated for 70 min at 37°C, after which the reaction was stopped with the addition of 25 μ M of 3 M glycine-NaOH (pH 10.3). The fluorescence of the released 4-methyl-umbelliferone was quantified using a FLx 800 microtiterplate fluorescence reader (Bio-Tek Instruments Inc.) (excitation

366 nm, emission 445 nm). Experiments were performed in triplicate. Production of 4-methylumbelliferone was linear with time for the incubation period used, and less than 10% of available substrate was hydrolyzed. The IC_{50} values of the argifin fragments against AfChiA1 were determined using the same protocol but with a constant substrate concentration of 100 μ M and 300 nM–6 mM inhibitor. Similarly, the mode of inhibition assays were set up as previously described above using 50 μ M–1 mM 4MU-NAG₃, and 60 μ M–6 mM inhibitor.

ACCESSION NUMBERS

The structure factors and models have been deposited in the Protein Data Bank under PDB ID numbers 2xvp, 2xuc, and 2xvn.

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