CHEMICAL REVIEWS

Review

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Chemical Evolution of Autotaxin Inhibitors

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1. INTRODUCTION

In 1992, autotaxin (ATX or ENPP2) was isolated as an autocrine motility factor from melanoma cells.[1] The ~120 kDa glycoprotein ATX belongs to a small family named ectonucleotide pyrophosphatase and phosphodiesterase (ENPP), which consists of seven family members.[2] ATX is the only ENPP family member with lysophospholipase D (lysoPLD) activity and is responsible for the hydrolysis of lysophosphatidylcholine (LPC) to produce the bioactive lipid lysophosphatidic acid (LPA) (Scheme 1).[3,4] LPA acts on specific G-protein-coupled receptors and thereby stimulates the migration, proliferation, and survival of many cell types.[5,6] ATX is produced in various tissues and is the major LPA-producing enzyme in the circulation. After biosynthesis by ATX, LPA is subject to degradation by membrane-bound lipid phosphate phosphatases (LPPs).[7,8]

ATX is essential for vascular development[9,10] and is found overexpressed in various human cancers.[11] Forced overexpression of ATX or individual LPA receptors promotes tumor progression in mouse models,[12−15] while LPA receptor deficiency protects from colon carcinogenesis.[16] In addition to its role in cancer, ATX−LPA signaling has been implicated in lymphocyte homing and (chronic) inflammation,[17] fibrotic diseases,[18,19] thrombosis,[20] and cholestatic pruritus.[21] Given its role in human disease, the ATX−LPA axis is an interesting target for therapy that deserves significant attention. The fact that ATX is an extracellular enzyme makes it even more attractive as a drug target.

2. ATX PROTEIN

Alternative splicing of the ATX gene (enpp2) results in three distinct isoforms (α, β, and γ) which are differentially expressed.[22,23] ATX β (863 aa) is the best studied isoform and is identical to plasma lysoPLD. ATX β is mainly expressed in peripheral tissues, whereas lower expression levels are observed in the central nervous system. In contrast, the ATX γ (889 aa) isoform is predominantly expressed in the central nervous system. ATX α (915 aa), the original melanoma-derived isoform, exhibits the lowest expression levels in both the central nervous system and peripheral tissues. The ATX α isoform contains a nonspecific protease cleavage site that is not present in the other isoforms.[22] All the three ATX isoforms exhibit similar catalytic activities in vitro.[22]

ATX is produced initially as a pre-proenzyme that has an N-terminal signal peptide required for secretion.[24] This signal peptide is removed by a signal peptidase, and ATX is subsequently cleaved by proprotein convertases (PCs) like furin.[24] The removal of an N-terminal octapeptide in ATX by PCs is associated with an enhancement of ATX activity.[24] The proteolytically processed ATX is secreted and consists of several domains. Starting from its N-terminus, ATX has two somatomedin B (SMB)-like domains, a central catalytic phosphodiesterase (PDE) domain, and an inactive nuclease-like domain, as displayed in Scheme 1. The hydrolytic activity of ATX predominantly originates from a threonine residue and two zinc ions in the ATX active site located in the PDE domain.[25] Extending from the ATX active site there is a hydrophobic pocket where the alkyl chain of its lipid substrates binds.[26]

3. NATURAL SUBSTRATES OF ATX

Next to LPC hydrolysis, ATX is also capable of hydrolyzing sphingosylphosphorylcholine (SPC, Figure 1) into sphingosine 1-phosphate (S1P).[27] S1P has signaling properties comparable to those of LPA while acting on S1P receptors.[28−30] It is however doubtful how relevant the contribution of ATX is to S1P production in vivo. S1P is thought to originate mainly from the phosphorylation of sphingosine by sphingosine kinases, rather than through SPC hydrolysis by ATX.[31]

Next to recognizing the lipids LPC and SPC as substrates, ATX can also hydrolyze nucleotides, like its family members ENPP1 and ENPP3. In vitro established nucleotide and nucleotide-derived substrates of ATX consist of adenosine-5′-triphosphate (ATP), diadenosine polyphosphates (Ap_nA), uridine diphosphate glucose (UDP-glucose), nicotinamide adenine dinucleotide (NAD^+), and 3′-phosphoadenosine-5′-

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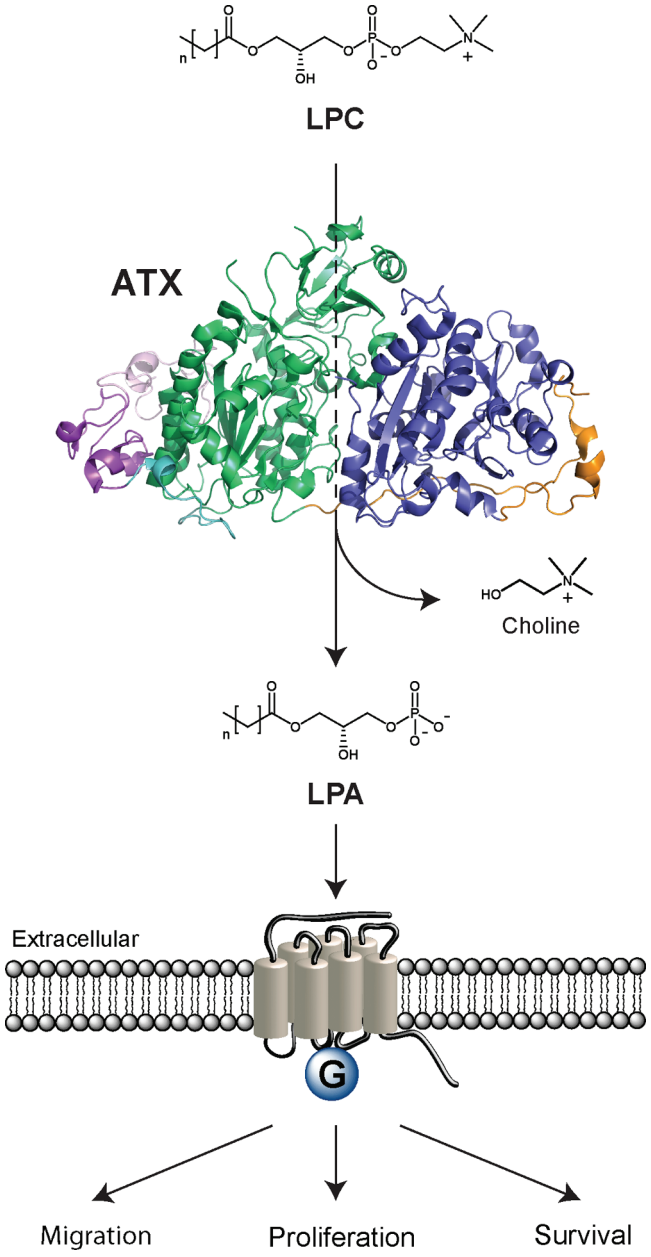
Scheme 1. ATX Is Responsible for Hydrolyzing LPC into LPA in an Extracellular Environment[a]



[a]This reaction is catalyzed by a threonine residue and two zinc ions present in the ATX active site. LPA activates specific G-protein-coupled receptors stimulating migration, proliferation, and survival of cells. ATX is displayed as a cartoon representation of an ATX crystal structure (PDB ID 2XR9) with the SMB domains in purple, the PDE domain in green, and the nuclease-like domain in blue.

phosphosulfate (Figure 1).[2] The physiological relevance of ATX-mediated hydrolysis of these nucleotide substrates is still unclear.

4. ASSAYS TO STUDY ATX ACTIVITY

In the search for inhibitors, appropriate in vitro assays are required to monitor the activity of the enzyme of interest. Over the last 10 years various assays have been developed and used to study the activity of ATX. ATX assays can roughly be divided in two classes depending on the kind of ATX substrate used for the activity measurement. The first class uses the physiological ATX substrate LPC and the second class uses unnatural ATX substrates.

4.1. LPC-Based Assays

As depicted in Table 1, ATX hydrolyzes LPC into LPA and choline. Both products can be used to measure ATX activity. When a ^{14}C label is introduced in the lipid tail of LPC, ATX activity can be measured by radiometry.[32,33] When radiolabeled LPC is hydrolyzed by ATX, the produced LPA contains this radiolabel. After lipid extraction of the ATX−LPC incubation mixture and separation of LPC and LPA using thin layer chromatography (TLC),[4] the activity of ATX can be quantified from the ^{14}C-LPA produced. Although this classical method is robust and very sensitive, it is not very suitable for high-throughput screening (HTS).

Another way to measure the formation of LPA is by using liquid chromatography−tandem mass spectrometry (LC−MS/MS).[34,35] From an ATX incubation mixture, LPC and LPA are separated by LC and detected by tandem MS. This method is very sensitive and suitable to detect naturally occurring LPA in biological fluids (i.e., plasma).[34−36]

ATX activity can also be measured by the detection of choline.[4,37] When choline is released from the ATX-mediated LPC hydrolysis, it can be converted by choline oxidase into betaine (trimethylglycine) and hydrogen peroxide. Subsequently, hydrogen peroxide is used by horseradish peroxidase (HRP) to convert a coloring substrate into its oxidized chromophoric state. Different HRP coloring substrates can be used like 2,2′-azinobis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), homovanillic acid (HVA), or Amplex red. ABTS can be detected using absorbance while HVA and Amplex red are detected by fluorescence.[36,38,39] The throughput of this assay is high and suitable for HTS screening.

A danger of the latter assay is that small molecules that do not inhibit ATX may interfere with the readout by inhibiting the enzymes (HRP or choline oxidase) used in the coloring reaction, which will result in false positives. Another possibility that could result in false positives is that reactive compounds tested in this assay can react with the coloring agent or hydrogen peroxide that is generated during that coloring reaction. Incubating molecules that are active in this assay with only choline and subsequently adding the coloring reagents should reveal if these molecules are interfering with the assay readout.[38]

4.2. Unnatural ATX Substrate-Based Assays

As a member of the ENPP family, ATX also hydrolyzes nucleotides. Therefore, the nucleotide thymidine 5′-monophosphate *p*-nitrophenyl ester (pNP-TMP) can be used as an ATX substrate (Table 1).[3,25] Upon hydrolysis of pNP-TMP by ATX, 4-nitrophenol is released, which has an absorbance at 405 nm and is detectable by colorimetry.

The same product is formed when bis(*p*-nitrophenyl) phosphate (bis-pNPP) is hydrolyzed by ATX (Table 1).[33,38] Bis-pNPP is a cheap ATX substrate that provides a direct readout.

Another artificial ATX substrate is CPF4, which has a similar core structure as bis-pNPP. In CPF4 the two nitro groups of bis-pNPP are replaced by coumarin and fluorescein (Table 1).[33,40] When the coumarin donor group in CPF4 is excited, Förster fluorescence resonance energy transfer (FRET) between coumarin and the fluorescein acceptor occurs. After hydrolysis the FRET pair is separated and FRET is lost,

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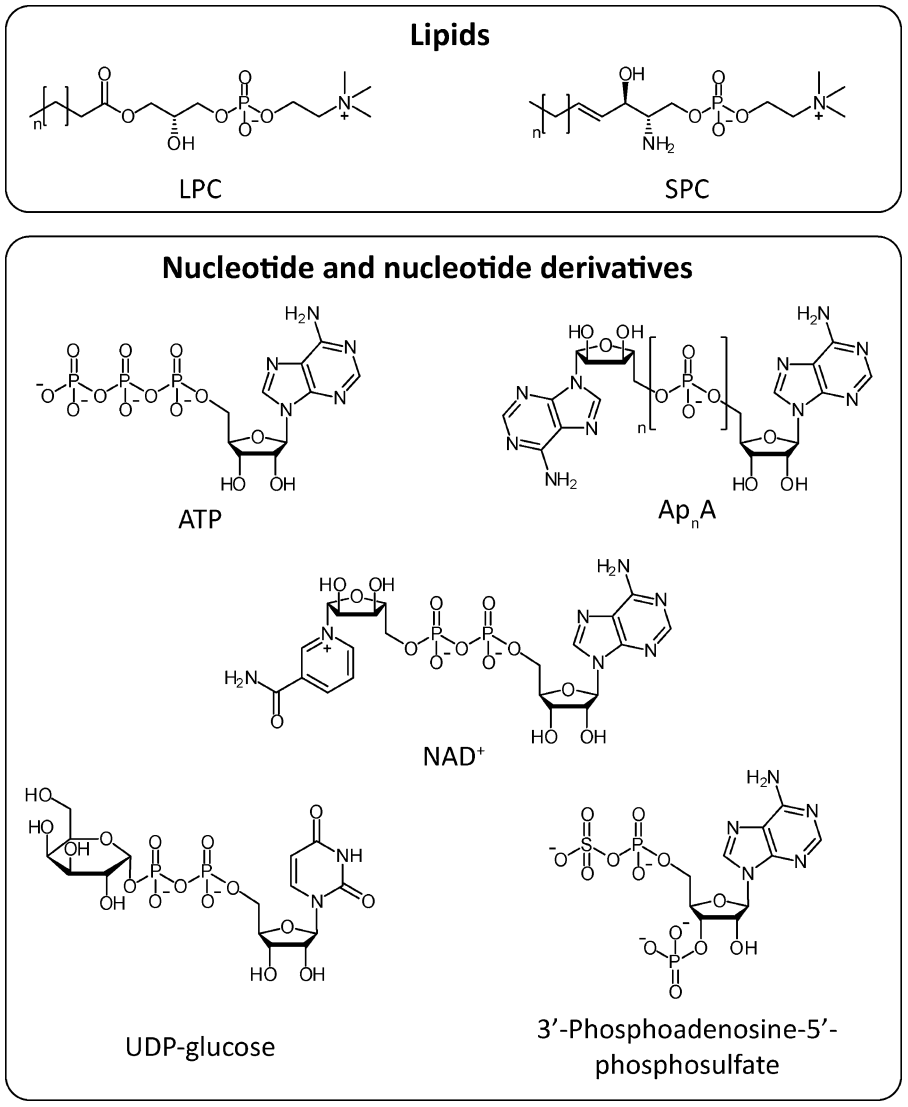

Figure 1. Identified natural substrates of ATX.

providing a very sensitive assay reagent. Although this reagent was originally developed for phosphodiesterase I,[40] it provides a very sensitive ATX activity sensor as well.[33]

FS3 is another synthetic ATX substrate that is based on LPC (Table 1).[41] In this substrate a dabcyl moiety, a quencher of fluorescein, is connected via a lipid backbone to fluorescein. The fluorescein moiety in FS3 is quenched by the dabcyl moiety and becomes fluorescent when FS3 is hydrolyzed by ATX.

A common advantage of the above-mentioned assays is that they provide a realtime readout, allowing direct kinetic studies of ATX activity.

4.3. ATX Activity-Based Probe

A first generation ATX activity-based probe (ATX-ABP) has recently been reported (Table 1).[42] This probe makes use of the activity of ATX to label ATX covalently. Upon the hydrolysis of the phosphodiester bond in ATX-ABP, the released intermediate undergoes an 1,6-elimination of a fluoride atom (Scheme 2). This generates a reactive quinone methide species that traps nearby nucleophiles in the ATX active site, resulting in covalent labeling of ATX with a fluorescent Cy5 dye in an activity-dependent manner. This ATX-ABP is able to label all the three known ATX isoforms.[42] In addition, ATX-ABP can label ATX in human plasma; however, an additional affinity-purifying step with an anti-ATX monoclonal antibody is required to make labeled ATX detectable. Further development of these types of probes could turn them into diagnostic reagents to monitor ATX activity in complex samples such as body fluids.

5. INHIBITORY EFFECT OF METAL CHELATORS ON ATX ACTIVITY

L-Histidine has been reported as the first in vitro "ATX inhibitor" with millimolar IC_{50} values for ATX using LPC or pNP-TMP as assay substrate.[43] It acts by scavenging metal ions in solution, such as zinc, which are essential for ATX activity. In addition, other metal chelating agents such as ethylenediaminetetraacetic acid (EDTA) and 1,10-phenanthroline also have an inhibitory effect on ATX activity.[43]

6. LIPID AND LIPID-BASED INHIBITORS OF ATX

A distinct class of ATX inhibitors is based on lipids. The discovery of product inhibition of ATX by LPA and S1P[33]

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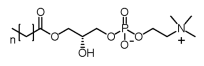
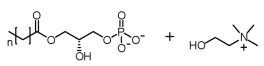
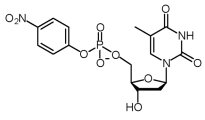
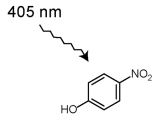
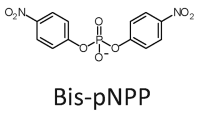
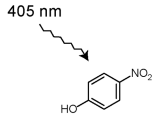
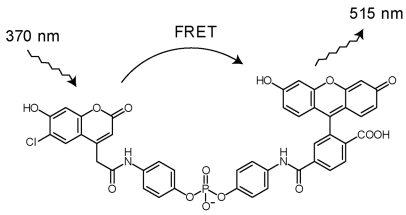
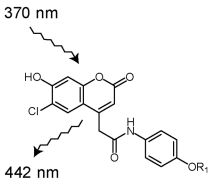
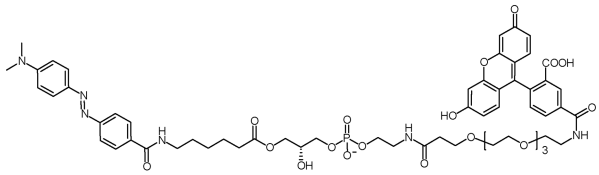
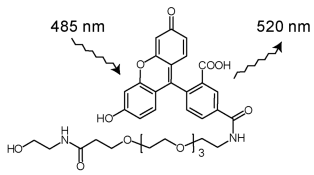
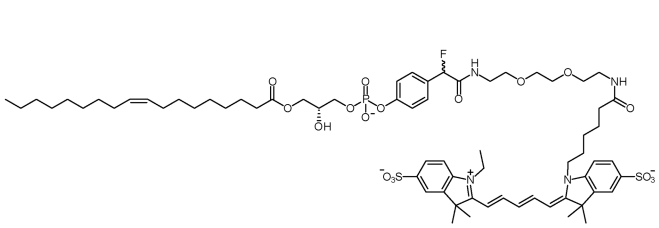
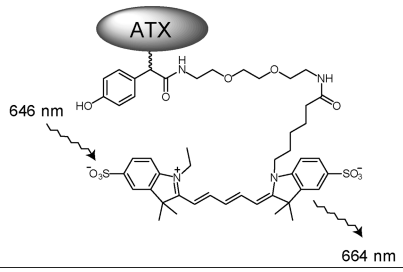
Table 1. Substrates for ATX-Activity Assays

ATX substrate	Detectable product	References
 LPC[a]		[32] [33] [34] [35] [37]
 pNP-TMP		[3] [25]
 Bis-pNPP		[33] [38]
 CPF4	 $R_1 = PO_3^{2-}$ or H	[33] [40]
 FS3		[41]
 ATX-ABP		[42]

[a]LPA can be detected by radiometry or mass spectrometry. Choline can be detected in a two-step enzymatic colorimetric reaction.

triggered the development of lipid-based ATX inhibitors (Table 2).

One class of lipid-based inhibitors includes thiophosphates.[44−46] An example of this class is thiophosphate **3** (IC_{50} = 0.6 μM, bis-pNPP) depicted in Table 2. The reported thiophosphates also act as agonists or antagonists for LPA_{1-3} receptors.[44−46] A general danger of lipid-based ATX inhibitors is that they may act on downstream LPA/S1P receptors due to their structural similarity with LPA and S1P.

There is also a class of ATX inhibitors based on cyclic phosphatidic acid (cPA) that is a naturally occurring analog of LPA where the *sn*-2 hydroxy group forms a five-membered ring with the *sn*-3 phosphate.[47,48] cPA analog **4** (Table 2, IC_{50} = 0.14 μM, bis-pNPP) has no significant agonist activity at LPA receptors. Recently, a sulfur analogue of cPA, 3-*O*-thia-cPA (**5**), has been reported as an ATX inhibitor (Table 2).[49]

Another class of lipid-based ATX inhibitors is based on α-bromomethylene phosphonates like BrP-LPA (**6**, Table 2).[50,51] In addition, phosphonate **6** acts as a pan-LPA_{1-4} receptor antagonist. α-Bromobenzyl phosphonates are well-known protein tyrosine phosphatase inhibitors that target the active site covalently.[52] Whether phosphonate **6** inhibits ATX in a covalent manner is unknown.

An inhibitor that is expected to bind ATX covalently is flouromethylphenyl phosphate **7** (Table 2).[53] The binding mechanism of **7** with ATX is postulated to be the same as for ATX-ABP, as depicted in Scheme 2. Inhibitor **7** shows time-dependent inhibition of ATX.

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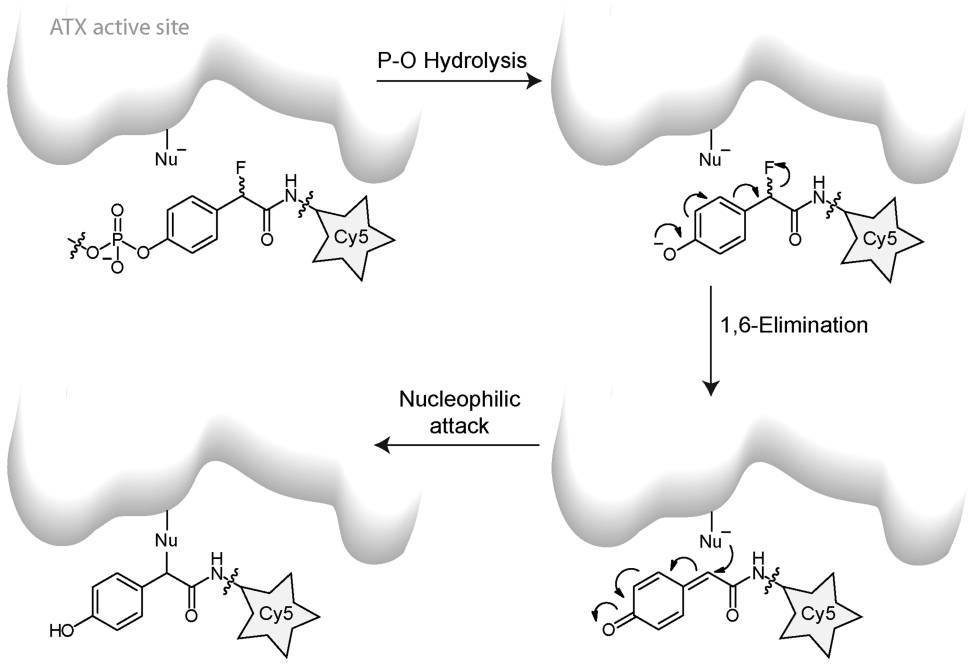
Scheme 2. Labeling Mechanism of ATX with ATX-ABP[a]



[a]Only one of the potential labeled products resulting from the labeling is shown.

Interestingly, phosphorylated FTY720 (FTY720-P, **8**, Table 2) inhibits ATX with a K_i of 0.2 μM using pNP-TMP as an ATX assay substrate.[54,55] FTY720-P is a synthetic analogue of S1P and acts as an $S1P_1$ receptor antagonist (EC_{50} = 5 nM)[55] that activates this receptor, causing its internalization and subsequent polyubiquitination, leading to proteasomal degradation of the $S1P_1$ receptor. This results in the unresponsiveness of lymphocytes to S1P.[56]

Potencies of the previously described lipid-based inhibitors all have been determined in assays using unnatural ATX substrates (bis-pNPP, pNP-TMP, CPF4, and FS3) as reporter molecules. Therefore, it is difficult to compare potencies of distinct inhibitors and their effect on LPC hydrolysis. Using assays based on LPC hydrolysis gives a better indication whether ATX inhibitors could have an in vivo effect on LPA production by ATX. The most potent (IC_{50} = 5.6 nM, LPC) lipid-based inhibitor measured in an LPC hydrolysis assay is S32826 (**9**, Table 2).[39,57,58] This phosphonate inhibitor is a result of screening 13 000 small molecules for their ability to inhibit ATX. Unfortunately, the poor in vivo stability and/or bioavailability of the compound did not permit further use in animal models.

A last lipid-like inhibitor class is based on a tyrosine building block, and an example of this class is inhibitor **10**, which has a micromolar potency (K_i = 1.0 μM, LPC, Table 2).[59−61]

A frequently observed phenomenon for ATX inhibitors is their incapability to fully inhibit ATX. Examples are inhibitors **3**, **4**, and **9** depicted in Table 2 that have residual ATX activity (RA) for ATX.

7. SMALL MOLECULE INHIBITORS OF ATX

Since 2008, many small molecule inhibitors have been reported in both academic and patent literature (Table 3). The most potent inhibitor (IC_{50} = 1.7 nM, LPC) reported to date is PF-8380 (**11**).[62,63] Interestingly, this compound reported by employees of Pfizer[62] is based on an inhibitor described in a Merck KGaA patent application.[63] Due to the high potency and favorable pharmacokinetic properties, PF-8380 is a suitable tool compound for in vivo evaluation of ATX inhibition.

Another very potent ATX inhibitor is the boronic acid HA155 (**12**, IC_{50} = 5.7 nM, LPC, Table 3).[36,38] This molecule resulted from screening ~40 000 small molecules followed by medicinal chemistry efforts on the resulting screening hit. In the original screening hit, a carboxylic acid moiety was replaced by a boronic acid moiety, designed to target the threonine oxygen nucleophile in the ATX active site. HA130,[36,38] a positional boronic acid isomer of HA155, together with PF-8380 are the only two inhibitors to date that have been demonstrated to lower LPA levels in vivo (rat or mice).

Recently, other boronic acid-based inhibitors have been reported[64] as a result of a structure-based study resulting in *E*-HA219 (**13**, Table 3), a potent inhibitor of ATX (IC_{50} = 5.3 nM, LPC).

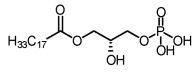
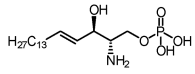
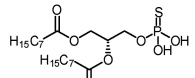
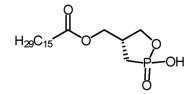
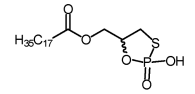
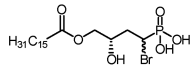
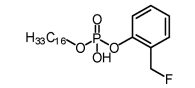
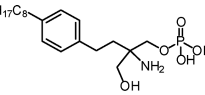
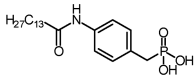
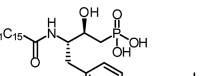
A common feature of the three most potent inhibitors reported so far (**11**−**13**, Table 3) is that they share a long linear and flexible structure, which is also reflected in the structure of LPC and LPA. Probably this structural feature helps the inhibitors to accommodate to the lipid binding site, since they bind to the ATX active site. Most of the other reported small molecules inhibitors lack this structural feature.

Several Merck KGaA patent applications claim ATX inhibitors (**15**−**18**) with in vitro potencies between 0.1 and 10 μM (LPC).[65−71] The structural diversity of these inhibitors is large, as can be judged from Table 3.

Screening a phosphodiesterase targeted inhibitor library revealed that vinpocetine (**19**, Table 3), a PDE type 1 inhibitor (IC_{50} = 8−50 μM), inhibits ATX with an IC_{50} value of 122 μM using LPC as a substrate.[72] In addition, screening a second library consisting of kinase inhibitors known to target the ATP binding site in kinases resulted in the discovery of damnacanthal (**20**, Table 3), a $p56^{lck}$ tyrosine kinase inhibitor

dx.doi.org/10.1021/cr2003213 | *Chem. Rev.* 2012, 112, 2593−2603

Table 2. Lipid and Lipid-Based Inhibitors of ATX

Entry	Inhibitor	Substrate	Activity	References [a]
1	 LPA	CPF4	K_i = 0.11 μM	[33]
2	 S1P	CPF4	K_i = 0.05 μM	[33]
3	 Thiophosphate	Bis-pNPP	IC_{50} = 0.60 μM RA = 27% [b]	[44] [45] [46]
4	 cPA-based	Bis-pNPP	IC_{50} = 0.14 μM RA = 9%	[47] [48]
5	 3-*O*-thia-cPA	FS3	PI = 55% @ 10 μM [c]	[49]
6	 BrP-LPA	FS3	PI = 94% @ 10 μM	[50] [51]
7	 Fluoromethylphenyl	FS3	PI = 95% @ 3 μM	[53]
8	 FTY720-P	pNP-TMP	K_i = 0.2 μM	[54] [55]
9	 S32826	LPC	IC_{50} = 5.6 nM RA ≈ 10%	[39] [57] [58]
10	 Tyrosine-based	LPC	K_i = 1.0 μM	[59] [60] [61]

[a]The first reference corresponds with the displayed structure and the following references refer to similar inhibitor structures. [b]RA, residual ATX activity. [c]PI, percentage inhibition.

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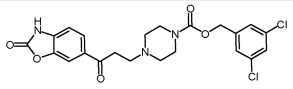
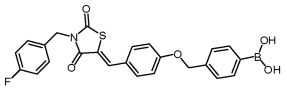
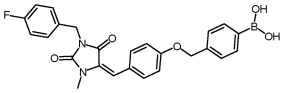
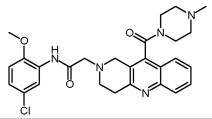
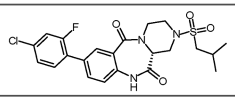
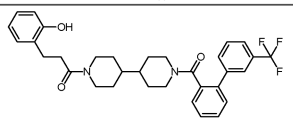
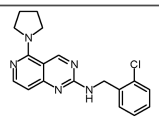
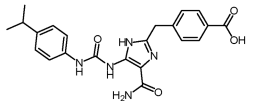
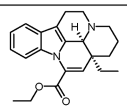
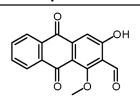
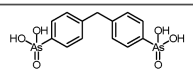
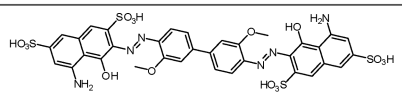
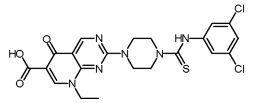
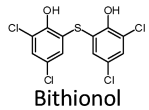
Table 3. Activities of Small Molecule Inhibitors of ATX

Entry	Inhibitor	Substrate	Activity	References [a]
11	 PF-8380	LPC	IC_{50} = 1.7 nM	[62] [63]
12	 HA155	LPC	IC_{50} = 5.7 nM	[36] [38]
13	 *E*-HA219	LPC	IC_{50} = 5.3 nM	[64]
14		LPC	IC_{50} > 0.1 μM	[65] [66]
15		LPC	IC_{50} = 0.1-1 μM	[67] [68]
16		LPC	IC_{50} > 1 μM	[69]
17		LPC	IC_{50} > 5 μM	[70]
18		LPC	IC_{50} = 1-10 μM	[71]
19	 Vinpocetin	LPC	IC_{50} = 122 μM	[72]
20	 Damnacanthal	LPC	IC_{50} = 139 μM	[72]
21	 NSC-48300	FS3	K_i = 0.240 μM	[38] [73] [74]
22	 NSC-9616	FS3	K_i = 0.271 μM	[75]
23	 H2L-7905958	FS3	K_i = 1.9 μM	[76] [77]
24	 Bithionol	FS3	K_i = 66 μM	[73] [74]

[a]The first reference corresponds with the displayed structure, and the following references refer to similar inhibitor structures.

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(IC_{50} = 17−620 nM), as ATX inhibitor (IC_{50} = 139 μM, LPC).[72]

Several ATX screening programs used libraries from the National Cancer Institute (NCI). This led for example to the discovery of arsenic acid NSC-48300 (**21**, Table 3) as ATX inhibitor, reported by two independent groups.[38,73,74] It is a competitive inhibitor that could suggest that the arsenic acid moiety in **21** acts as a nonhydrolyzable phosphate mimic. In addition, NSC-9616 (**22**, Table 3) has been identified as ATX inhibitor from screening an NCI library.[75]

The first virtual screen for ATX inhibitors led to the discovery of H2L-7905958 (**23**, Table 3).[76] This inhibitor has a K_i value of 1.9 μM (FS3) for ATX.[77] At the time of this virtual screen the ATX structure was not resolved. Therefore, the authors generated a homology model of ATX based on a *Xanthomonas axonopodis* pV. *citri* (*Xac*) ENPP structure and used this homology model for virtual screening. Recently, a follow-up study has been reported describing new analogues of **23**.[77]

Another ATX inhibitor is bithionol (**24**, Table 3),[73,74] a known metal ion chelating molecule like L-histidine and EDTA.[78] The latter two inhibit ATX by scavenging metal ions in solution, which are required for ATX activity. However, inhibitor **24** appears to act directly on ATX and not via metal chelation, since the K_i value of **24** for ATX is 2 orders of magnitude lower than the used metal ion concentration.

8. ATX STRUCTURE AND INHIBITOR DESIGN

In 2011 the crystal structure of ATX had been resolved independently by two groups.[26,79] Aside from the unliganded ATX structure, structures of ATX with different species of LPA[26] and the inhibitor HA155 liganded ATX structure[79] have been reported. Binding of HA155 to the ATX active site is predominantly driven by hydrophobic interactions and by a boronic acid moiety binding to the threonine oxygen nucleophile in the ATX active site (Figure 2B).[79] The latter binding was predicted because the boronic acid moiety in HA155 was designed and introduced to target the threonine oxygen nucleophile in the ATX active site. In addition, the ATX−HA155 structure showed that one of the boronic acid hydroxyl moieties is simultaneously tethered by the two zinc ions in the ATX active site (Figure 2B). Therefore, the boronic acid moiety not only targets the threonine oxygen nucleophile but also the two zinc ions that are essential for the catalytic activity of ATX. Another feature of HA155 binding to the ATX active site is that its 4-fluorobenzyl moiety binds to the hydrophobic lipid binding pocket of ATX (Figure 2A), preventing the alkyl chain of the lipid from binding to this pocket.[26,79]

The ATX structure liganded with HA155 triggered an ATX structure-based inhibitor design.[64] This study led to *E*-HA219 (IC_{50} = 5.3 nM, LPC, Table 3) a hydantoine analogue of HA155 (IC_{50} = 5.7 nM, LPC, Table 3). Remarkably, *E*-HA219 is an *E*-isomer while HA155 is a *Z*-isomer. To understand how *E*-HA219 binds to ATX, molecular docking experiments were performed that suggested a binding pose for *E*-HA219 different from that of the original binding pose of HA155 or from the *Z*-isomer of HA219 for ATX. This study predicted that the 4-fluorobenzyl moiety in HA155 and *E*-HA219 binds differently to the hydrophobic pocket in ATX. This finding may be used to design new inhibitors that fully exploit the hydrophobic pocket in ATX, opening further options for inhibitor design.

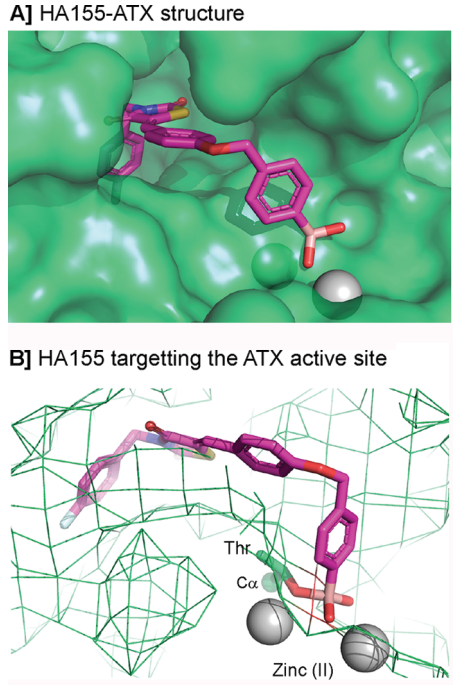

Figure 2. The inhibitor liganded ATX structure (PDB ID 2XRG). (A) Binding of HA155 with ATX. (B) Boronic acid in HA155 targeting the threonine (Thr) oxygen nucleophile and two zinc ions in the ATX active site.

9. CONCLUDING REMARKS

ATX is an attractive therapeutic target for LPA-related diseases. In the past decade, many ATX inhibitors have been discovered and developed, ranging from metal chelators to lipid and lipid-based inhibitors to small molecule inhibitors. Over the last 3 years many patents on ATX inhibitors have appeared from pharmaceutical industry and academia emphasizing the interest on ATX as drug target. Finally, the recently reported crystal structures of ATX will aid medicinal chemistry efforts to further develop ATX inhibitors into therapeutic agents.

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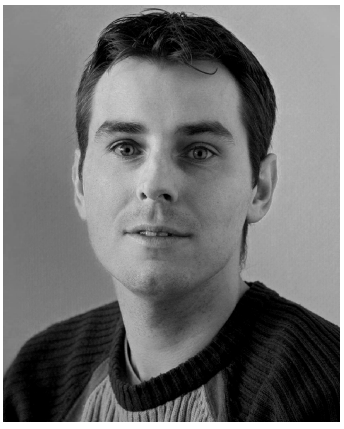

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Harald Albers obtained his M.S. degree in Chemical Engineering at Eindhoven University of Technology (TUe), The Netherlands, in 2007 with honors. During his training in organic chemistry in the laboratory of Prof. E. W. Meijer (TUe), he developed C_3-symmetrical discotics functionalized with MRI labels, which have the ability to self-assemble into a supramolecular contrast agent for MRI. In 2007, he started his graduate studies at The Netherlands Cancer Institute (NKI), which resulted in the discovery and further development of boronic acid-based inhibitors of autotaxin, a lipid phosphodiesterase that holds promise as a drug target for anticancer therapy.

Huib Ovaa received his Ph.D. degree for his work in organic synthesis in the laboratory of the late Prof. J. H. van Boom (Leiden University, The Netherlands) studying olefin metathesis reactions on sugar derivatives, in 2001. During subsequent postdoctoral work with H. L. Ploegh (Harvard Medical School, Boston, MA), chemical synthesis was used to study proteasome action and activity of deubiquitylating enzymes. This was followed by a position as an instructor of pathology at the same institute. Since 2004, he has headed a chemical biology group at The Netherlands Cancer Institute (NKI), developing inhibitors of autotaxin and studying targeted protein degradation and antigen presentation.

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NONSTANDARD ABBREVIATIONS

ABTS	2,2′-azinobis(3-ethylbenzothiazoline-6-sulfonic acid)
Ap_nA	diadenosine polyphosphates
ATP	adenosine-5′-triphosphate
ATX	autotaxin
ATX-ABP	ATX activity-based probe
bis-pNPP	bis(*p*-nitrophenyl) phosphate
cPA	cyclic phosphatidic acid
EDTA	ethylenediaminetetraacetic acid
ENPP	ectonucleotide pyrophosphatase and phosphodiesterase
FRET	Förster fluorescence resonance energy transfer
HRP	horseradish peroxidase
HTS	high-throughput screening
HVA	homovanillic acid
LC−MS/MS	liquid chromatography−tandem mass spectrometry
LPA	lysophosphatidic acid
LPC	lysophosphatidylcholine
LPP	lipid phosphate phosphatases
lysoPLD	lysophospholipase D
NAD^+	nicotinamide adenine dinucleotide
NCI	National Cancer Institute
PC	proprotein convertases
pNP-TMP	thymidine 5′-monophosphate *p*-nitrophenyl ester
S1P	sphingosine 1-phosphate
SMB	somatomedin B
SPC	sphingosylphosphorylcholine
TLC	thin layer chromatography
UDP	uridine diphosphate
Xac	*X. axonopodis* pV. *citri*

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