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Synthesis, conformational analysis and glycosidase inhibition of bicyclic nojirimycin C-glycosides based on an octahydrofuro[3,2-b]pyridine motif

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Abstract: A set of bicyclic iminosugar C-glycosides, based on a octahydrofuro[3,2-b]pyridine motif, has been synthesized from a C-allyl iminosugar exploiting a debenzylative iodocycloetherification and a iodine nucleophilic displacement as the key steps. The halogen allowed the introduction of a range of aglycon moieties of different sizes bearing several functionalities such as alcohol, amine, amide and triazole. In these carbohydrate mimics the fused THF ring forces the piperidine to adopt a flattened ¹C₄ conformation according to NMR and DFT calculations studies. In their deprotected form, these bicycles were assayed on a panel of 23 glycosidases. The iminosugars displaying hydrophobic aglycon moieties proved to be superior glycosidase inhibitors, leading to a low micromolar inhibition of human lysosome β-glucosidase (compound **11**; IC₅₀ = 2.7 μM) and rice α-glucosidase (compound **10**; IC₅₀ = 7.7 μM). Finally, the loose structural analogy of these derivatives with Thiamet G, a potent OGA bicyclic inhibitor, was illustrated by the weak OGA inhibitory activity (K_i = 140 μM) of iminosugar **5**.

Keywords: iminosugar; glycosidase; conformation; inhibition; bicycle, hexosaminidase.

1. Introduction

Carbohydrate-processing enzymes represent an important class of proteins found in nature that are involved in a vast array of biological processes including cell signalling, inflammation and protein quality control [1]. One sub-class of glycosidases of significant interest is constituted by the exo-N-acetyl-D-hexosaminidases (HexNAcase) that process N-acetylglucosamine and N-acetylgalactosamine residues from glycoconjugates. These enzymes are ubiquitous in all domains of life where, for example, they play roles in peptidoglycan recycling [2], bacterial virulence [3], as well as diverse roles in eukaryotic cell physiology [4]. Notably, N-acetylhexosaminidases have attracted considerable interest, due to their involvement in diseases such as osteoarthritis [5], allergy [6], as well as Alzheimer's disease [7]. In addition, catalytically inactive and misfolded mutant forms of N-acetylhexosaminidases are responsible for hereditary lysosomal disorders [8] and inhibitors of this class of glycosidases have been suggested as pharmacological chaperone therapeutics for Tay-Sachs' as well as Sandhoff's diseases [9]. Lysosomal HexNAcases are among the glycosidases secreted into extra cellular space by cancer cells to remodel and degrade the extra cellular matrix (ECM), allowing the cancer to spread to secondary locations in a process known as

metastasis formation [10]. Regarding the enzymatic mechanism, as seen for glycosidases in general, N-acetylhexosaminidases from GH3 family [11] carry out glycosidic bond cleavage in which an enzymic catalytic nucleophile attacks the anomeric center to generate a glycosyl enzyme intermediate, which is subsequently broken down by attack of water at the anomeric center. Both steps of this reaction proceed through oxocarbenium ion-like transition states (TS), which are characterized by the development of positive charge at the anomeric carbon and extending to the endocyclic oxygen through lone pair conjugation [12]. However, hydrolysis by N-acetylhexosaminidases from GH84 [13] and from GH20 [14] harnesses a mechanism that differs in the nature of the catalytic nucleophile. For enzymes from these families, the 2-acetamido group provides neighboring group participation and attacks the anomeric carbon to give rise to an oxazoline or oxazolinium ion intermediate (Figure 1B) [12]. Inspired by this distinctive mechanism and of the biological importance of the related enzymes, a vast array of compounds has been designed and tested especially as O-GlcNAcase inhibitors [15]. Amongst them, a set of synthetic bicyclic sugar-derived inhibitors, that are easily accessible by synthesis, have been reported as having down to picomolar K_i values and impressive selectivity toward OGA. The most representative molecules include NAG-thiazoline **1** [16], NButGT **2** [17], commercially available Thiamet G **3** [18], and the recently described MK-8719 **4** [19] that entered Phase I clinical trials with the goal of being developed to treat the neurodegenerative disease progressive supra-nuclear palsy (Figure 1A). In these derivatives, the transient enzyme-bound oxazoline intermediate is efficiently mimicked by the thiazoline or aminothiazoline moiety but the glycosyl oxocarbenium ion like character of the TS, namely the positive charge localized on the endocyclic oxygen of the sugar ring, is not mimicked. In this work, we set out to explore this aspect by reporting the synthesis, conformational examination, and biological evaluation of a series of bicyclic iminosugars **5-11** (Figure 1C). In these sugar analogs the ring oxygen has been replaced by a nitrogen atom, designed to emulate the glycosyl cation-like character of the TS of hexosaminidases, and to enable this the oxazolidine ring has been replaced by a THF ring.

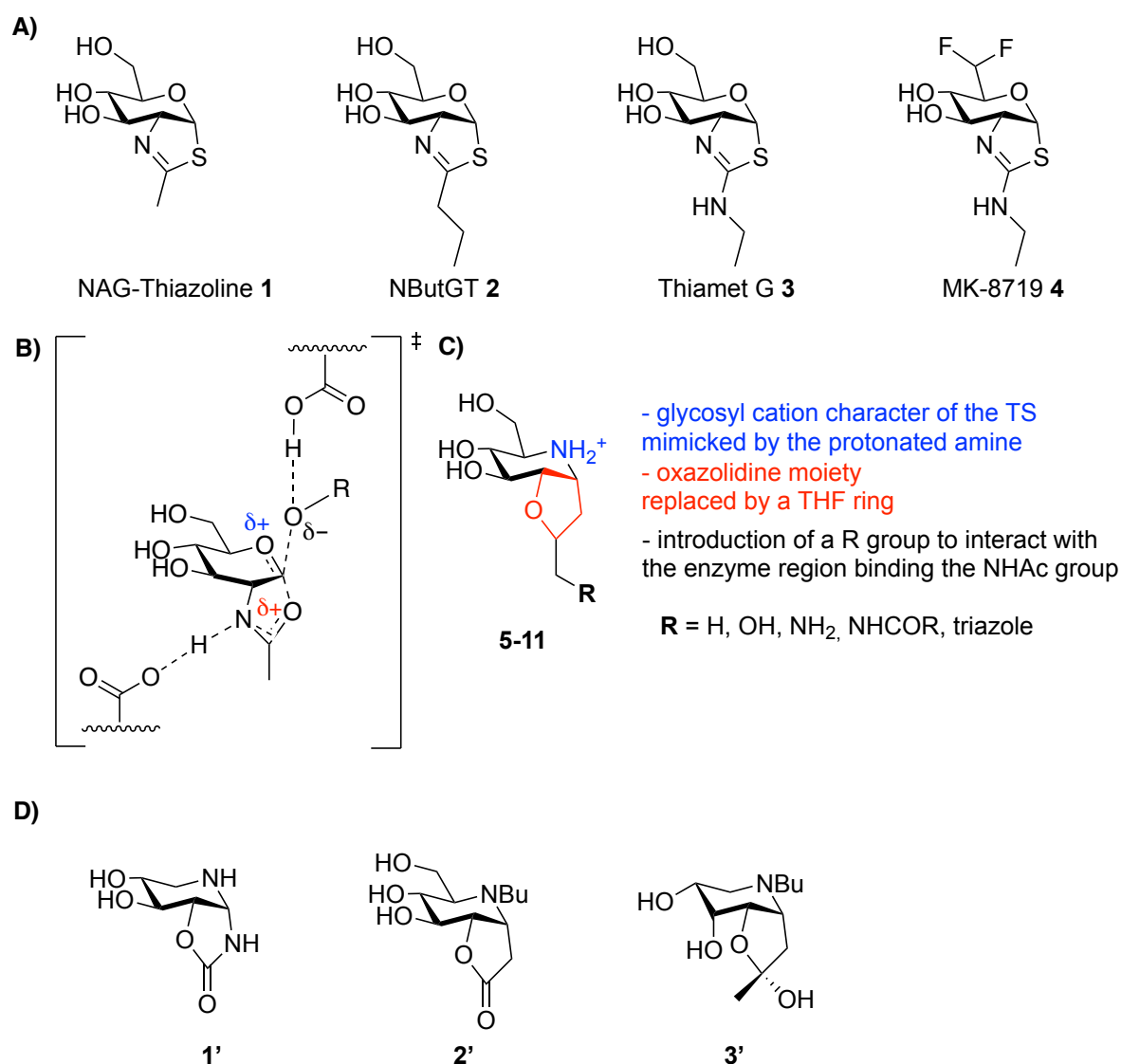


Figure 1. (A) Structure of known OGA bicyclic inhibitors **1-4**; B) Proposed transition state (TS) for formation of the oxazoline intermediate; C) Structure of new bicyclic iminosugars **5-11** reported in this study and the rationale for their design; D) Structure of related iminosugars **1'-3'** in the literature.

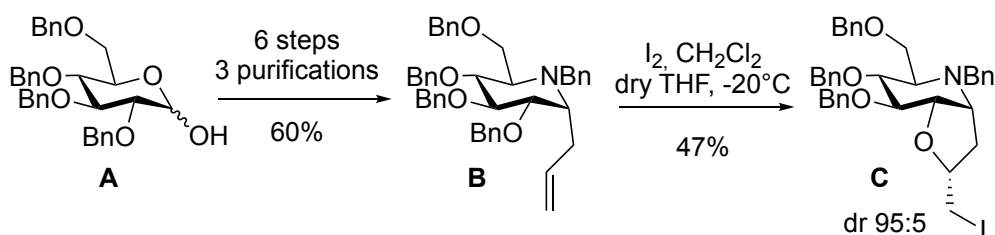
Addition of a fused five-membered ring to a core monosaccharide motif or analog is a strategy often seen within nature, and exploited by researchers, to generate bicyclic constrained structures that have limited conformational flexibility.[20] Indeed, naturally occurring swainsonine [21] as well as sp² iminosugars [22], in which the nitrogen atom is at the junction of the two rings, are well established as valuable tools to study glycoside processing enzymes. Apart from compounds **1-4** reported above, other sugar derivatives that display an extra ring fused to the C1-C2 bond have been synthesized [23] for different purposes ranging from serving as peptide mimics to Tn antigen constrained analogs. Introduction of such structural modification in iminosugars as illustrated by compounds **1'-3'** is scarce (Figure 1D). [24]

2. Results

2.1. Chemistry

2.1.1. Preparation of the bicyclic iminosugar C-glycoside scaffold

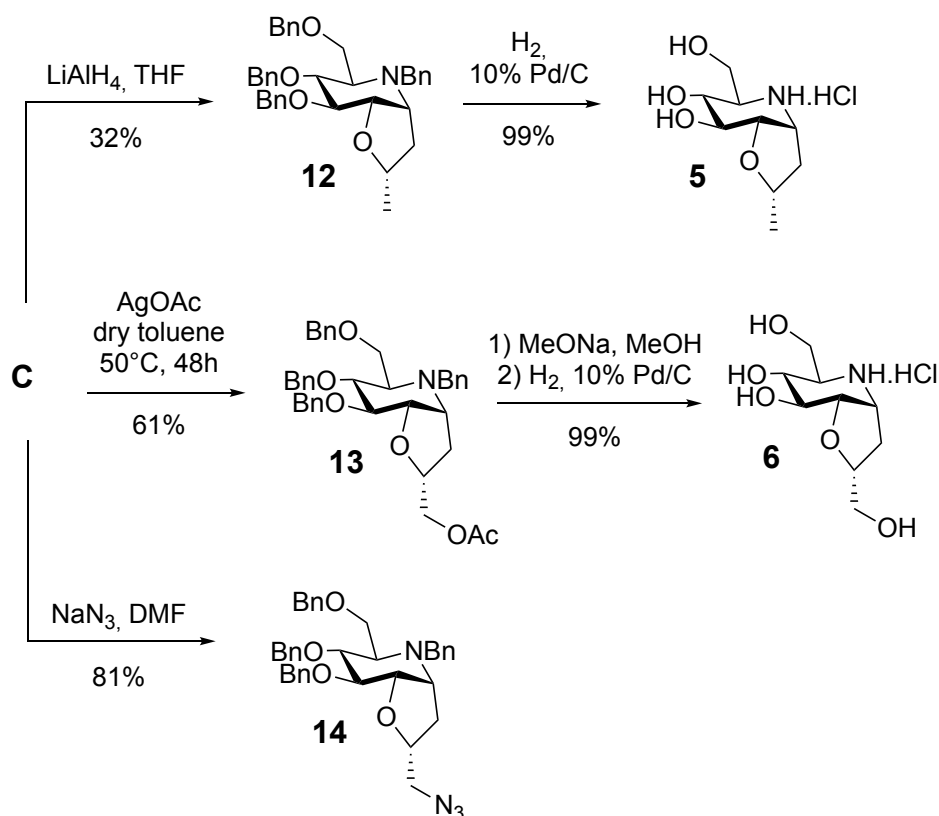
Two decades ago, the group of Nicotra reported the debenzylative iodocycloetherification [25] of various C-allyl glycosides [26]. This transformation, recently used in the total synthesis of herbicidin C [27], allowed access to bicyclic carbohydrate scaffolds in which their rigidity and the ease by which structural elements can be appended to them were notably exploited in the context of generating peptide mimetics [28] and exploring chemical diversity [29]. Applied to the corresponding C-allyl iminosugar **B** [30-32] obtained in 60% and six steps from commercially available tetrabenzyl glucose **A**, this reaction yielded the expected bicycle **C** in 47% yield and excellent stereocontrol (Scheme 1).



Scheme 1. Synthesis of iodocycloether **C** from commercially available tetrabenzyl glucose **A**.

2.1.2. Synthesis of bicyclic iminosugar C-glycosides bearing a methyl or hydroxymethyl appendage

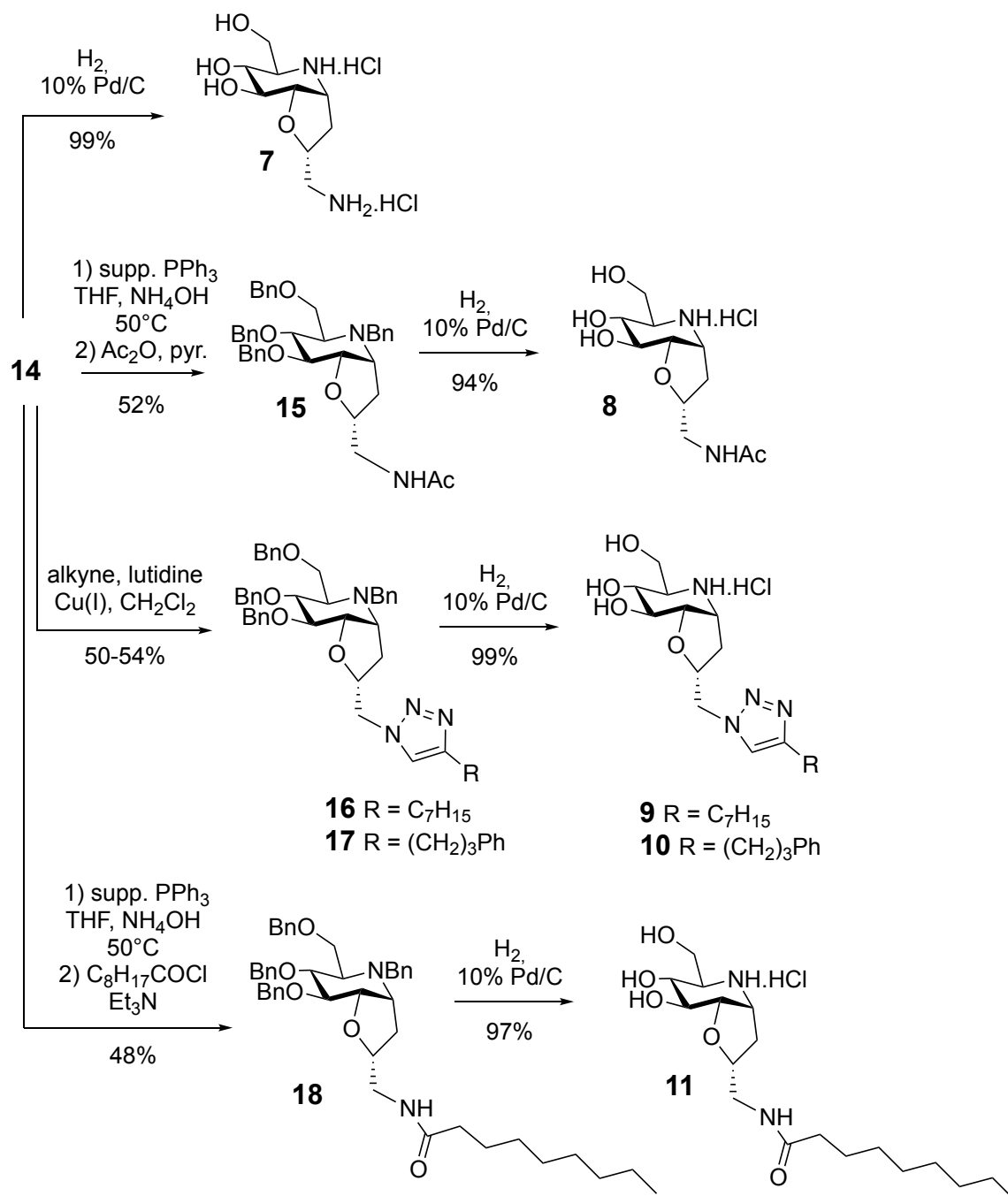
Bicycle **C** is a useful scaffold to generate a small library of bicyclic iminosugars encompassing the suitable hydroxyl pattern and the required positive charge of the TS, as well as a five-membered THF ring. Importantly, tuning of the pK_a of the appendage in the aminothiazoline moiety of Thiamet G **3**, that interact with the enzymatic region that serves to position the 2-acetamido group of the substrate, has been shown to be important to improve the inhibitor potency and selectivity [33]. In this context, the iodine atom in scaffold **C**, through its nucleophilic displacement, should allow the introduction of functional diversity that enables installing groups with a desirable pK_a value. To this end, the iodocycloether **C** was synthesized on a multigram scale. To test its chemical stability and reactivity, it was first treated with $LiAlH_4$ (4 eq.) in THF at room temperature to furnish the methyl derivative **12** in an unoptimized 32% yield. Its subsequent hydrogenolysis quantitatively yielded the bicyclic iminosugar **5** demonstrating the relative chemical robustness of this bicycle. Introduction of an OH group was achieved by treating **C** with $AgOAc$ (10 eq.) in dry toluene at $50^\circ C$ for 48 h that furnished the expected ester **13** in 61% yield. Deacetylation with $NaOMe$ in dry MeOH overnight provided the corresponding alcohol that was directly engaged in a hydrogenolysis step to afford the tetrahydroxylated iminosugar **6**. In order to build up a small library of compounds with various aglycon moieties, we relied on the introduction of an azide function that could be then exploited to connect amines and amides but also others functionalities and substituents through the use of click chemistry. Displacement of the iodine atom with NaN_3 at room temperature furnished the key azide **14** in 81% yield (Scheme 2).



Scheme 2. Synthesis of bicyclic iminosugars **5**, **6** and **14**

2.1.3. Synthesis of bicyclic iminosugar C-glycosides bearing amine, amide and triazole appendages

Introduction of an amine and acetamide function was investigated first as these groups could mimic the exocyclic amine found in Thiamet G **3** and MK-8719 **4**. Hydrogenolysis of azide **14** uneventfully yielded the diamine **7**, while its reduction with supported PPh_3 in $\text{NH}_4\text{OH}/\text{THF}$ provided the corresponding crude amine that was directly acetylated with Ac_2O in pyridine to obtain the acetamide **15**, which, upon hydrogenolysis, furnished the iminosugar **8**. Introduction at the C-2 position of amides differing in shape and size has been used in hexosaminidase inhibitors to improve their potency and selectivity by exploiting enzymatic plasticity [34-37]. Thus, reaction of azide **14** respectively with nonyne and 5-phenylpentyne in the presence of 2,6-lutidine and tetrakis(acetonitrile) copper(I) hexafluorophosphate complex furnished the corresponding triazoles **16** and **17** in 50% and 54% yield respectively. Their hydrogenolysis quantitatively yielded the iminosugars **9** and **10**. As these molecules proved to be potent glucosidase inhibitors (*vide infra*), a derivative bearing a long alkyl chain connected by an amide bond to the bicyclic iminosugar was prepared to check whether the triazole had an influence on the potency of these molecules. Azide **14** was therefore reduced to the crude amine and acylated with nonanoyl chloride in the presence of triethylamine to produce acetamide **18**, which upon deprotection, furnished the iminosugar **11** (Scheme 3).



Scheme 3. Synthesis of bicyclic iminosugars 7-11

2.2. Conformation analysis by NMR and DFT calculations

In order to gain insights into the conformation of the bicyclic iminosugars, including the orientation of the substituent on the THF ring, bicyclic iminosugars **9** and **11** were chosen as representatives of the set of compounds depicted in this study. Conformational analysis of iminosugar **9** by NMR and DFT calculations demonstrated that the iminosugar ring adopt a flattened ${}^4\text{C}_1$ conformation that was, according to NMR data (${}^3J_{5,6} = 7.9$ Hz, ${}^3J_{6,7} = 7.7$ Hz, ${}^3J_{7,7a} = 6.2$ Hz), close to the slightly distorted ${}^4\text{C}_1$ chair conformation observed for NAG thiazoline in complex with BtGH84 [38] (Figure 2A). Similarly, conformational analysis of iminosugar **11** also demonstrated a chair-like conformation that was somewhat flattened (${}^3J_{5,6} = 8.4$ Hz, ${}^3J_{6,7} = 7.7$ Hz, ${}^3J_{7,7a} = 6.2$ Hz). The coupling constant (${}^3J_{3a,7a} =$

6.3 Hz) between the protons in the fused ring position is consistent with an eclipsed arrangement of these protons. Typical NOEs crosspeaks between H7 and H5 (equivalent to H3 and H5 in Glc) and between H7a and H6 (similar to H2 and H4 in Glc) are also consistent with a flattened 4C_1 chair conformation. Analysis of HSQC and HMBC spectra for compounds **9** and **11** showed a high degree of similarity, indicating that the carbon skeleton is comparable in both molecules (see SI).

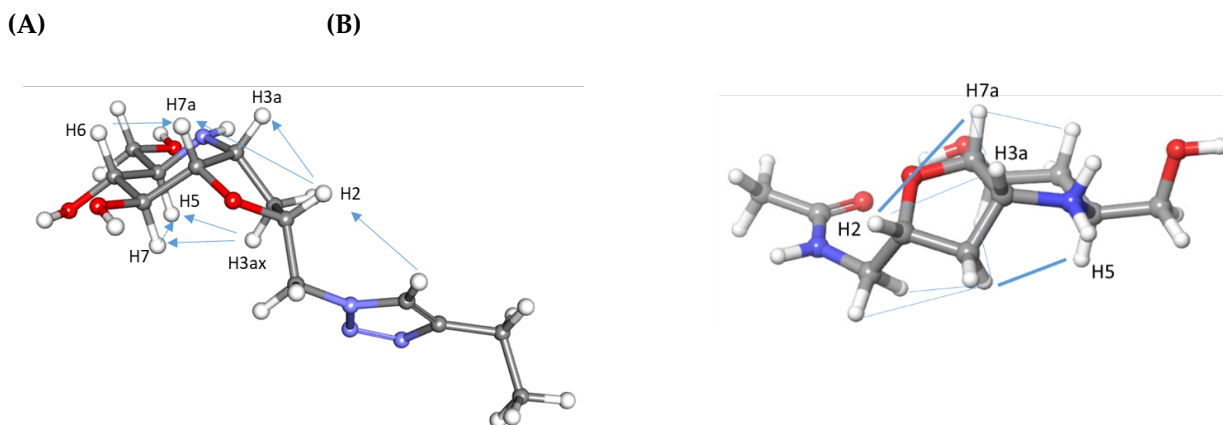


Figure 2. Proposed model for the conformation of iminosugar **9** (A) and iminosugar **11** conformation (B) from DFT calculations in full agreement with the NMR experimental data.

2.3. Glycosidase inhibition by bicyclic nojirimycin C-glycosides

The glycosidase inhibitory potency of these 7 newly synthesized nojirimycin C-glycosides **5-11** were first assayed on a panel of nineteen glycosidases (Table 1). The D-gluco stereochemistry of these molecules was seen to translate into their potent inhibition of α -glucosidase from rice and β -glucosidases from bovine liver and human lysosome. It seems that the incorporation of the 2-OH group of the parent iminosugar in the THF ring conformation is well tolerated by the assayed glycosidases. The simplest bicycle **5** showed moderate inhibition against rice α -glucosidase (IC_{50} 36 μ M). Usually, inhibitory potency of both rice α -glucosidase and rat intestinal maltase is closely related and parallel. However, here, the bicyclic molecules show some interesting selectivity toward the rice enzyme. Introduction of an OH function on the methyl group of **5** as in **6** did not significantly modify the inhibition profile. Replacement of the OH group by an amine as in **7** reduced the potency toward rice α -glucosidase (IC_{50} 109 μ M). Switching from an amine to an acetamide group as in **8** has no effect on the overall potency. Nevertheless, introduction of bulkier/lipophilic groups as in compounds **9-11** had a significant impact of the inhibition profile of these derivatives. First, replacing the triazole linker present in **9** and **10** by an amide bond as seen in **11** seems to have no effect on the inhibition profile of these molecules. Compounds **9-11** showed increased potency toward rice α -glucosidase (IC_{50} 7.7 μ M for compound **10**), but they also displayed significant inhibition of bovine liver β -glucosidase (IC_{50} 4.6 μ M for compound **9**) and more importantly of human lysosome β -glucosidase (IC_{50} 2.7 μ M for compound **11**), the enzyme whose deficiency is responsible for Gaucher disease [39]. As expected, all compounds showed some inhibition of bovine liver β -galactosidase, culminating in compound **9** (IC_{50} 0.39 μ M), an enzyme that is usually strongly inhibited by a range of sugar mimics [40]. Altogether, these preliminary results indicate that fine tuning of the lipophilic moiety in these derivatives might lead to potent and selective β -glucosidase inhibitors. Disappointingly, none of these compounds showed significant inhibition of β -N-acetyl-D-glucosaminidases from bovine kidney, HL60, jack bean, and human recombinant α -N-acetyl-D-glucosaminidase at even a 1 mM concentration.

Table 1. Concentration of iminosugars giving 50% inhibition of various glycosidases

Enzyme	IC ₅₀ (μM)						
	5	6	7	8	9	10	11
α-Glucosidase							
Yeast	^a NI ^b (23.1%)	540	NI (29.7%)	NI (16.1%)	NI (31.9%)	310	NI (37.8%)
Rice	36	57	109	82	13	7.7	16.0
Rat intestinal maltase	193	372	155	488	279	154	187
β-Glucosidase							
Almond	NI (22.3%)	NI (21.6%)	NI (15.1%)	NI (19.7%)	NI (31%)	NI (7.9%)	NI (15.7%)
Bovine liver	438	255	310	NI (46.6%)	4.6	7.6	10
Human lysosome	127	15.9	42.4	NI (0%)	63.1	6.0	2.7
α-Galactosidase							
Coffee beans	136	NI (3.6%)	NI (24.5%)	NI (4.6%)	NI (1.0%)	NI (5.0%)	NI (0%)
β-Galactosidase							
Bovine liver	117	83	292	166	0.39	1.1	3.0
α-Mannosidase							
Jack bean	NI (0%)	NI (0%)	NI (2.5%)	NI (0%)	NI (0%)	NI (3.2%)	NI (0%)
β-Mannosidase							
Snail	ND	NI (0%)	NI (0%)	NI (6%)	NI (25.7%)	NI (35.1%)	NI (12.4%)
α-L-Fucosidase							
Bovine kidney	NI (0%)	NI (20.1%)	NI (30.6%)	NI (0%)	NI (0%)	NI (0%)	NI (0%)
α,α-Trehalase							
Porcine kidney	NI (4.0%)	NI (8.8%)	NI (10.7%)	NI (4.0%)	NI (9.1%)	NI (3.6%)	NI (0%)
Amyloglucosidase							
<i>Aspergillus niger</i>	NI (6.7%)	NI (34.6%)	NI (10.7%)	NI (0%)	NI (27.8%)	NI (23.7%)	NI (29.2%)
α-L-Rhamnosidase							
<i>Penicillium decumbens</i>	ND	NI (5.1%)	NI (7.0%)	NI (5.7%)	NI (26.4%)	NI (8.3%)	544
β-Glucuronidase							
<i>E.coli</i>	NI (22.9%)	NI (43.4%)	728	NI (1.2%)	813	660	424
Bovine liver	ND	NI (4.4%)	NI (8.1%)	NI (0%)	NI (0%)	NI (0%)	NI (12.5%)
β-N-Acetylglucosaminidase							
Bovine kidney	NI (18.0%)	NI (0%)	NI (3.1%)	NI (0%)	NI (10%)	NI (0%)	NI (5.5%)
HL60	NI (4.0%)	NI (0%)	NI (0%)	NI (4.4%)	NI (12.4%)	NI (0%)	NI (2.6%)
Jack bean	NI (25.5%)	NI (0%)	NI (25%)	NI (30%)	NI (31.7%)	NI (15.2%)	NI (34.4%)
α-N-Acetylglucosaminidase							
Human recombinant	NI (31.0%)	NI (34.9%)	NI (13.2%)	NI (0%)	NI (20.8%)	NI (0%)	NI (0%)

^a NI: No inhibition (less than 50% inhibition at 1000 μM).^b (): inhibition % at 1000 μM.**Table 1.** Concentration of iminosugars giving 50% inhibition of various glycosidases.

2.4. Human and bacterial N-acetyl-D-glucosaminidase inhibition by bicyclic nojirimycin C-glycosides

While nojirimycin C-glycosides **5-11** showed no significant inhibition of plant and mammalian hexosaminidases, we have previously observed that poor inhibitors of these enzymes can nevertheless be more potent inhibitors of human and bacterial hexosaminidases [41]. Thus a selection of the nojirimycin C-glycosides was assayed as inhibitors of OGA, NagZ, Hex A and HexB enzymes.

Table 2. Concentration of iminosugars giving 50% inhibition

Enzyme/compound	5	7	8	9	10	11
OGA	140	ND	NI	204	NI	488
NagZ	N	NI	NI	NI	405	ND
HexA	NI	NI	NI	NI	NI	ND
HexB	ND	362	459	298	134	NI

The weak inhibitory activity of these compounds reveals certain constraints with regard to the active sites of these enzymes. In particular, OGA, HexA, and HexB all have tightly constrained

active sites in which the acetamido group is carefully packed within a tightly defined pocket, and polarized by an important enzymic catalytic carboxylate that hydrogen bonds with the amide nitrogen of the acetamido group of natural substrates. The THF derivatives (**5**, **7-11**) described here do not enable this hydrogen bond, supporting the importance of this interaction. Moreover, the elaboration of these derivatives with larger substituents is clearly not well tolerated by these enzymes because of the constrained active site pocket. The weak inhibition against NagZ can also be understood in the context of the catalytic mechanism and is also consistent with NAG-Thiazoline being a poor inhibitor of this enzyme [42]. For NagZ enzymes the 2-acetamido group acts as a spectator and larger N-acyl groups are generally well tolerated by a much larger active site that allows substituents to project out into bulk water. The amide moiety, however, hydrogen bonds with a conserved arginine that drive the N-acyl substituent into an orientation that is in plane with the carbohydrate-derived ring [43]. This orientation also enables the enzyme catalytic carboxylate to be positioned below the plane of the sugar ring, directly beneath the anomeric center. Accordingly, the compounds evaluated here, in which the THF ring occupies a space below the piperidine ring and the substituent is oriented in a more downward manner, are likely weak inhibitors because they cannot conform to the requirements of the active site of NagZ. Whilst these compounds are weak inhibitors, their failure to inhibit provides insight into key design features and suggests structures that could be much more potent – in particular we reason that installation of a cyclic amidine in place of the THF moiety could yield very potent inhibition of GH20 and GH84 enzymes and that small N-alkyl substituents on the exocyclic nitrogen could confer selectivity for GH84 enzymes over GH20 enzymes, in keeping with previous reports where such subtle differences have delivered excellent selectivities [17, 19, 33]

3. Conclusion

A small set of constrained nojirimycin C-glycosides **5-11** has been synthesized and evaluated for glycosidase inhibition. The incorporation of the 2-OH group of the nojirimycin scaffold into a fused THF ring still maintains the inhibitory potency of these molecules, some demonstrating low micromolar inhibition toward rice α - and human lysosome β -glucosidase in agreement with their D-gluco like stereochemistry. The initial hypothesis that such bicycles, lacking the key NHAc group or oxazolidine ring, could mimic the overall charge and shape of the OGA TS was supported to some extent as compound **5** proved to be a weak OGA inhibitor. Nevertheless, this poor inhibitor compared to known potent OGA inhibitors emphasizes the necessity to incorporate a NHAc or oxazolidine surrogate in these molecules to reach high potency. All told, the straightforward access to iminosugar C-glycoside scaffold **C** depicted herein is likely to offer opportunities for the preparation of a larger range of iminosugar-derived bicycles displaying other stereochemistries and substitution pattern [32a] that could be of further therapeutic interest [44]. In addition, the iodine atom should be useful to explore other coupling reactions to increase the scope of aglycons to be introduced. Replacement of the THF ring in these derivatives by a pyrrolidine ring is also worth investigating. Work in this direction is in progress in the laboratory.

4. Experimental

General methods: All commercial reagents were used as supplied. TLC plates were visualized under 254 nm UV light and/or by dipping the TLC plate into a solution of phosphomolybdic acid in

ethanol (3 g/100 mL) followed by heating with a heat gun. Flash column chromatography was performed using silica gel 60 (15-40 μm) or carried on a Combiflash® Rf automated apparatus (Teledyne-Isco) using columns specified in each protocol. NMR experiments were recorded with a 400 or 500 Bruker spectrometer at 400 or 500 MHz for ^1H and 100 or 125 MHz for ^{13}C nuclei. The chemical shifts are expressed in part per million (ppm) relative to TMS ($\delta = 0$ ppm) and the coupling constant J in hertz (Hz). NMR multiplicities are reported using the following abbreviations: b = broad, s = singulet, d = doublet, t = triplet, q = quadruplet, m = multiplet. HRMS were obtained with a Q-TOF spectrometer from the Mass Spectrometry Service (IC2MP, UMR CNRS 7285-Poitiers University, France). Optical rotations were measured using a Modular Circular Polarimeter MCP100 (Anton Paar).

Conformational analysis: Structural models for compounds **9** and **11** (see supplementary material) were calculated with the MacroModel application within the Maestro software (version 12.3). An initial structure was minimized using conjugate gradients with the OPLS3* force field. A maximum number of 5000 iterations were employed with the PRCG scheme, until the convergence energy threshold was 0.05. The minimized structure was submitted to a conformational search protocol, using a Monte Carlo torsional sampling method (MCMC) with automatic setup during the calculation, energy window of 50 kJ mol⁻¹, 1000 maximum number of steps, and 100 steps per torsion of the bond to be rotated.

Glycosidase assays: Glycosidase inhibition profiling was performed using appropriate *p*-nitrophenyl glycosides as substrates at the optimum pH of each enzyme. The reaction was stopped by adding 400 mM of Na₂CO₃. The released *p*-nitrophenol was measured spectrometrically at 400 nm.

Hexosaminidases assays:

HEXA: IC₅₀ values for compounds against Recombinant Human Hexosaminidase A (HexA) enzyme, purchased from R&D Systems (cat# 6237-GH-020), were determined by measuring the fluorescent signal corresponding to the rate of hydrolytic activity against the commercially available artificial substrate, 4-Methylumbelliferone-N-acetyl- β -D-glucosaminide. HexA inhibition assays were performed in a buffer of 100mM sodium citrate, 250 NaCl, pH 4.5 and 1.0nM [HexA], then stopped after 20 minutes with a solution of 1.0M Tris, pH 9.5 to enhance fluorescent signal. Preliminary experiments have shown that reaction rates are linear for 20 minutes after substrate addition, and that 1.0M Tris at pH 9.5 is sufficient for stopping enzyme activity, as the signal is stable for 24 hours after stopping. Inhibition assays were run in the presence or absence of various concentrations of compounds and at a fixed substrate concentration of 100 μM and 1% DMSO. First, compounds were serially diluted to the desired range of concentrations in 2% DMSO buffer. Next, 25 μL of compound solutions at various concentrations in 2% DMSO Buffer was added to 25 μL of 4.0nM enzyme and allowed to incubate at 25°C for 5 minutes. 50 μL of 200 μM and 1% DMSO substrate was then added and allowed to react for 20 minutes. 100 μL of stop solution was added to reaction mixture, and immediately mixed and aliquoted in 45 μL triplicates to a CORNING 384 well black plate. Fluorescence signal was measured in a BioTek Neo 2 Plate reader set at excitation and emission wavelengths of 355 and 450nm, respectively. %Activity was subsequently calculated for each compound concentration against the fluorescence signal of HexA without any compound. GraphPad Prism 2016 was used to calculate IC₅₀ values for each compound.

HEXB: IC₅₀ values for compounds against Recombinant Human Hexosaminidase B (HexB) enzyme, purchased from R&D Systems (cat# 8907-GH-020) were determined by measuring the change in fluorescent signal corresponding to the rate of hydrolytic activity against the commercially available artificial substrate, 4-Methylumbelliferone N-acetyl- β -D-galactosaminide. HexB inhibition assays were performed in a buffer of 100mM MES at pH 5.5 and 5.0nM [HexB], in the presence or absence of various concentrations of compounds and at a fixed substrate concentration of 150 μM and 5% DMSO. First, compounds were serially diluted to the desired range

of concentrations in 10% DMSO buffer. Next, 50 μ L of compound solutions at various concentrations in 10% DMSO Buffer was added to 50 μ L of 20nM enzyme and allowed to incubate at 25°C for 5 minutes. 100 μ L of 300 μ M and 5% DMSO substrate was then added and reaction mixture was immediately mixed and aliquoted in 45 μ L triplicates to a CORNING 384 well black plate. Fluorescence signal was measured continuously for 20 minutes at 25°C in a BioTek Neo 2 Plate reader set at excitation and emission wavelengths of 355 and 450nm, respectively. Max reaction rates for all compound concentrations were calculated within Gen5 BioTek reader software. %Activity was subsequently calculated for each compound concentration against the max reaction rate of HexB without any compound. GraphPad Prism 2016 was used to calculate the IC50 values for each compound.

NAGZ: IC50 values for compounds against the NagZ enzyme were determined by measuring the change in fluorescent signal corresponding to the rate of hydrolytic activity against the commercially available artificial substrate, 4-Methylumbelliferone N-acetyl- β -D-glucosaminide. NagZ inhibition assays were performed in a buffer of phosphate-buffered saline at pH 7.4 and 2.0nM [NagZ], in the presence or absence of various concentrations of compounds and at a fixed substrate concentration of 60 μ M and 5% DMSO. First, compounds were serially diluted to the desired range of concentrations in 10% DMSO buffer. Next, 50 μ L of compound solutions at various concentrations in 10% DMSO Buffer was added to 50 μ L of 8nM enzyme and allowed to incubate at 25°C for 5 minutes. 100 μ L of 120 μ M and 5% DMSO substrate was then added and reaction mixture was immediately mixed and aliquoted in 45 μ L triplicates to a CORNING 384 well black plate. Fluorescence signal was measured continuously for 20 minutes at 25°C in a BioTek Neo 2 Plate reader set at excitation and emission wavelengths of 355 and 450nm, respectively. Max reaction rates for all compound concentrations were calculated within Gen5 BioTek reader software. %Activity was subsequently calculated for each compound concentration against the max reaction rate of NagZ without any compound. GraphPad Prism 2016 was used to calculate the IC50 values for each compound.

hOGA: IC50 values for compounds against the human Protein O-GlcNAcase (hOGA) enzyme, were determined by measuring the change in fluorescent signal corresponding to the rate of hydrolytic activity against the artificial substrate, Resorufin-N-acetyl- β -D-glucosaminide (synthesized by Sandeep Bhosale of the Vocadlo Lab). hOGA inhibition assays were performed in a buffer of 20mM HEPES, 5mM EDTA, 150mM KCl, pH 7.1 and 0.2nM [hOGA], in the presence or absence of various concentrations of compounds and at a fixed substrate concentration of 25 μ M and 1% DMSO. First, compounds were serially diluted to the desired range of concentrations in 2% DMSO buffer. Next, 50 μ L of compound solutions at various concentrations in 2% DMSO Buffer was added to 50 μ L of 0.8nM enzyme and allowed to incubate at 25°C for 5 minutes. 100 μ L of 50 μ M and 1% DMSO substrate was then added and the reaction mixture was immediately mixed and aliquoted in 45 μ L triplicates to a CORNING 384 well black plate. Fluorescence signal was measured continuously for 20 minutes at 37°C in a BioTek Neo 2 Plate reader set at excitation and emission wavelengths of 572 and 610nm, respectively. Max reaction rates for all compound concentrations were calculated within Gen5 BioTek reader software. %Activity was subsequently calculated for each compound concentration against the max reaction rate of hOGA without any compound. GraphPad Prism 2016 was used to calculate the IC50 values for each compound.

General Procedure A for deprotection by hydrogenolysis: The benzylated compound was dissolved in a mixture THF/*i*-PrOH (0.05 M - 1/1, v/v) then a solution of HCl (1N, 3 eq.), Pd/C (0.5 mass eq.) and black Pd (0.5 mass eq.) were added. The mixture was stirred overnight under H₂ atmosphere, filtrated through a pad of Celite® (previously washed with 1N HCl and water) and concentrated to give the deprotected compound as its hydrochloride salt.

(2*R*,3*aR*,5*R*,6*R*,7*S*,7*aR*)-4-benzyl-6,7-bis(benzyloxy)-5-[(benzyloxy)methyl]-2-(iodomethyl)octa hydrofuro[3,2-*b*]pyridine **C**

I₂ (3.88 g, 15.29 mmol) was added to a solution of **B** (5.00 g, 7.65 mmol) in anhydrous THF (153 ml) under argon at -20 ° C. The mixture was then stirred at -20 ° C for 24 h. A saturated solution of Na₂S₂O₃ (100 mL) was added and the mixture was stirred for 10 min. at rt. The aqueous layer was extracted with Et₂O (3 x 50 mL), the combined organic layers dried over MgSO₄ and concentrated. The crude was purified by flash chromatography (RediSep® 80 g, PE / EtOAc 95 : 5 to 90 : 10) to give **C** as a yellow oil (2.48 g, 47%). R_f = 0.39 (PE/EtOAc 90 : 10); [α]_D = - 13.0 (c 1.0, CHCl₃); ¹H NMR (400 MHz, CDCl₃): δ 7.47-7.10 (m, 20H, CH-Ar), 5.01 (d, J = 11.5 Hz, 1H, OCHH-Ph), 4.83 (d, J = 11.5 Hz, 1H, OCHH-Ph), 4.66 (d, J = 11.2 Hz, OCHH-Ph), 4.50-4.41 (m, 3H, OCH₂-Ph), 4.19 (t, J = 8.4 Hz, 1H, H-7a), 4.01-3.92 (m, 2H, NCHH-Ph, H-2), 3.89 (t, J = 8.5 Hz, 1H, H-7), 3.73-3.56 (m, 5H, NCHH-Ph, CH₂-OBn, H-6, H-3a), 3.33 (dd, J = 10.0 Hz, J = 4.8 Hz, 1H, CHH-I), 3.25 (dd, J = 10.0 Hz, J = 6.7 Hz, 1H, CHH-I), 3.03 (q, J = 4.6 Hz, 1H, H-5), 2.30-2.24 (m, 1H, H-3), 1.68 (br, q, J = 10.5 Hz, 1H, H-3); ¹³C NMR (100 MHz, CDCl₃): δ 139.3, 139.1, 138.6, 138.1 (C^{iv}-Ar), 128.5-127.1 (CH-Ar), 84.4 (C-7), 80.9 (C-7a), 80.0 (C-6), 77.8 (C-2), 74.3, 73.4, 73.1 (OCH₂-Ph), 67.1 (CH₂-OBn), 61.0 (C-3a), 59.4 (C-5), 54.9 (NCH₂-Ph), 36.2 (C-3), 10.3 (CH₂-I); HRMS (ESI⁺) m/z calcd for C₃₇H₄₁INO₄ [M+H]⁺: 690.2075, found: 690.2107.

(2*S*,3*aR*,5*R*,6*R*,7*S*,7*aS*)-4-benzyl-6,7-bis(benzyloxy)-5-((benzyloxy)methyl)-2-methyloctahydrofuro[3,2-*b*]pyridine **12**

To a solution of **C** (235 mg, 0.34 mmol) in anhydrous THF (40 mL) was added LiAlH₄ (52 mg, 1.36 mmol, 4 eq.), then the mixture was stirred at rt for 4 h, neutralized with EtOAc (20 mL) and washed with water H₂O (20 mL). The organic layer was dried over MgSO₄, concentrated and the crude was purified by flash chromatography (PE/EtOAc 100 : 0 to 95 : 5) to give **12** (61 mg, 32%) as a colorless oil. R_f (PE/EtOAc 95 : 5); [α]_D = + 11.0 (c 1.0, CHCl₃); ¹H NMR (400 MHz, CDCl₃): δ 7.45-7.19 (m, 20H, CH-Ar), 5.01 (d, J = 11.6 Hz, 1H, OCHH-Ph), 4.82 (d, J = 11.6 Hz, 1H, OCHH-Ph), 4.61 (d, J = 11.2 Hz, 1H, OCHH-Ph), 4.49-4.43 (m, 3H, OCH₂-Ph), 4.08-4.00 (m, 2H, H-7a, H-2), 3.96 (d, J = 14.0 Hz, 1H, NCHH-Ph), 3.88 (t, J = 8.4 Hz, 1H, H-7), 3.70-3.63 (m, 3H, NCHH-Ph, CHH-OBn, H-3a), 3.63-3.57 (m, 2H, CHH-OBn, H-6), 3.06 (like dd, J = 9.2 Hz, J = 4.6 Hz, 1H, H-5), 2.19-2.13 (m, 1H, H-3), 1.52 (like dd, J = 22.0 Hz, J = 10.9 Hz, 1H, H-3), 1.33 (d, J = 6.0 Hz, 3H, CH₃); ¹³C NMR (100 MHz, CDCl₃): δ 139.5, 138.7, 138.2 (C^{iv}-Ar), 128.5-127.0 (CH-Ar), 84.8 (C-7), 80.4 (C-6) 80.0 (C-7a), 74.6 (C-2), 74.2, 73.4, 72.7 (OCH₂-Ph), 67.2 (CH₂-OBn), 61.4 (C-3a), 59.6 (C-5), 55.0 (NCH₂-Ph), 38.6 (C-3), 21.6 (CH₃); HRMS (ESI⁺) m/z calcd for C₃₇H₄₂NO₄ [M+H]⁺: 564.3114, found: 564.3110.

((2*R*,3*aR*,5*R*,6*R*,7*S*,7*aS*)-4-benzyl-6,7-bis(benzyloxy)-5-((benzyloxy)methyl)octahydrofuro[3,2-*b*]pyridin-2-yl)methyl acetate **13**

AgOAc (242 mg, 1.45 mmol) was added to a solution of **C** (100 mg, 0.145 mmol) in dry toluene (2.2 mL) at rt under argon, then the mixture was stirred at 50 ° C for 48 h. After filtration through a pad of Celite® and concentration, the crude was purified by flash chromatography (PE/EtOAc 80:20) to give **13** (55 mg, 61%) as a colorless oil. R_f = 0.16 (PE/EtOAc 85 : 15); [α]_D = + 5.1 (c 1.0, CHCl₃); ¹H NMR (400 MHz, CDCl₃) δ 7.35-7.28 (m, 20H, CH-Ar), 4.96 (d, J = 11.5 Hz, 1H, OCHH-Ph), 4.80 (d, J = 11.5 Hz, 1H, OCHH-Ph), 4.66 (d, J = 11.5 Hz, 1H, OCHH-Ph), 4.49-4.45 (m, 3H, OCH₂-Ph), 4.26 (dd, J = 3.4 Hz, J = 11.4, 1H, CHH-OAc), 4.15-4.08 (m, 3H, H-2, H-7a, CHH-OAc), 4.00 (d, J = 13.7 Hz, 1H, NCHH-Ph), 3.82 (t, J_{H-7/H-7a} = 8.4 Hz, 1H, H-7), 3.70-3.59 (m, 5H, NCHH-Ph, CH₂-OBn, H-6, H-3a), 3.05 (q, J = 4.7 Hz, 1H, H-5), 2.11 (m, 4H, CH₃, H-3), 1.70 (q, J = 10.9 Hz, 1H, H-3); ¹³C NMR (100 MHz, CDCl₃) δ 170.9 (C=O), δ 139.1, 139.1, 138.4, 137.9 (C^{iv}-Ar), 128.3-127.0 (CH-Ar), 84.2 (C-7), 80.1 (C-7a), 79.8 (C-6), 76.0 (C-2), 73.9, 73.3, 72.9 (OCH₂-Ph), 67.0 (CH₂-OBn), 66.4 (CH₂-OAc), 60.5 (C-3a), 59.4 (C-5), 54.9 (NCH₂-Ph), 31.5 (C-3), 20.9 (CH₃); HRMS (ESI⁺) m/z calcd for C₃₉H₄₄NO₆ [M+H]⁺: 622.3178, found: 622.3163.

(2*R*,3*aR*,5*R*,6*R*,7*S*,7*aS*)-2-(azidomethyl)-4-benzyl-6,7-bis(benzyloxy)-5-((benzyloxy)methyl)octahydrofuro[3,2-*b*]pyridine **14**

NaN₃ (57 mg, 0.88 mmol) was added to a solution of **C** (300 mg, 0.43 mmol) in dry DMF (5.5 mL), then the mixture was stirred under Ar at rt for 27 h. After concentration, the crude was purified by flash chromatography (RediSep® 4 g, PE / EtOAc 95 : 5 to 85 : 15) to give **14** as a yellow oil (115 mg, 40%). R_f = 0.35 (PE/EtOAc 85 : 15); [α]_D = - 17.3 (c 1.0, CHCl₃); ¹H NMR (400 MHz, CDCl₃) δ 7.40-7.17 (m, 20H, CH-Ar), 4.96 (d, J = 11.4 Hz, 1H, OCHH-Ph), 4.79 (d, J = 11.4 Hz, 1H, OCHH-Ph), 4.61 (d, J = 11.2 Hz, 1H, OCHH-Ph), 4.46-4.44 (m, 3H, OCH₂-Ph), 4.11 (t, J_{H-7a/H-7} = 8.4 Hz, 1H, H-7a), 4.09-4.05 (m, 1H, H-2), 3.95 (d, J = 13.9 Hz, 1H, NCHH-Ph), 3.88 (t, J_{H-7/H-7a} = 8.4 Hz, 1H, H-7), 3.69-3.58 (m, 5H, NCHH-Ph, CH₂-OBn, H-6, H-3a), 3.42 (dd, J = 12.9 Hz, J = 3.8 Hz, 1H, CHH-N₃), 3.33 (dd, J = 12.9 Hz, J = 5.5 Hz, 1H, CHH-N₃), 3.03 (q, J = 4.6 Hz, 1H, H-5), 2.06 (ddd, J = 10.5 Hz, J = 6.7 Hz, J = 5.2 Hz, 1H, H-3), 1.75 (q, J = 10.9 Hz, 1H, H-3); ¹³C NMR (100 MHz, CDCl₃) δ 139.3, 139.2, 138.5, 138.1 (C^{IV}-Ar), 128.5-127.2 (CH-Ar), 84.5 (C-7), 80.5 (C-7a), 80.0 (C-6), 77.3 (C-2), 74.3, 73.5, 73.0 (OCH₂-Ph), 67.1 (CH₂-OBn), 60.8 (C-3a), 59.4 (C-5), 54.9 (NCH₂-Ph), 54.7 (CH₂-N₃), 33.1 (C-3); HRMS (ESI⁺) m/z calcd for C₃₇H₄₁N₄O₄ [M+H]⁺: 605.3122, found: 605.3149.

N-(((2R,3aR,5R,6R,7S,7aS)-4-benzyl-6,7-bis(benzyloxy)-5-((benzyloxy)methyl)octahydrofuro[3,2-b]pyridin-2-yl)methyl)acetamide **15**

To a solution of **14** (60 mg, 0.099 mmol) in a mixture THF/NH₄OH (3 mL / 0.3 mL), at rt, was added triphenylphosphine polymer bound (153 mg, 3.2 mmol/g, 0.49 mmol). The mixture was stirred at 50 °C for 5 h, filtrated through a pad of Celite® and concentrated. The crude was taken up in Ac₂O/Pyridine (0.7 mL/0.7 mL) and stirred at rt overnight, then concentrated and co-evaporated twice with toluene. The crude was purified by flash chromatography (PE / EtOAc 85 : 15) to give **15** (32 mg, 52%) as a yellow oil. R_f = 0.35 (PE/EtOAc 85 : 15); [α]_D = - 70.2 (c 1.0, CHCl₃); ¹H NMR (400 MHz, CDCl₃) δ 7.37-7.30 (m, 20H, CH-Ar), δ 5.68 (t, 1H, N-H), 4.86 (s, 2H, OCH₂-Ph), 4.58 (d, J = 11.2 Hz, 1H, OCHH-Ph), 4.48-4.45 (m, 3H, OCHH-Ph, OCH₂-Ph), 4.06 (t, J = 8.1 Hz, 1H, H-7a), 3.99-3.92 (m, 2H, NCHH-Ph, H-2), 3.78 (t, J_{H-7/H-7a} = 7.5 Hz, 1H, H-7), 3.68-3.54 (m, 6H, NCHH-Ph, CH₂-OBn, H-6, H-3a, CHH-NHAc), 3.17 (m, 1H, CHH-NHAc), 3.05 (q, J = 4.7 Hz, 1H, H-5), 2.10 (m, 1H, H-3), 1.87 (s, 3H, CH₃), 1.58 (q, J = 10.4 Hz, H-3); ¹³C NMR (100 MHz, CDCl₃) δ 170.3 (C=O), δ 139.4, 139.2, 139.0, 138.9 (C^{IV}-Ar), 129.1-127.0 (CH-Ar), 82.9 (C-7), 80.1 (C-6), 79.3 (C-7a), 77.1 (C-2), 73.4, 73.4, 72.5 (OCH₂-Ph), 66.6 (CH₂-OBn), 60.4 (C-3a), 59.1 (C-5), 54.7 (NCH₂-Ph), 43.2 (CH₂NHAc), 33.1 (C-3), 23.2 (CH₃); HRMS (ESI⁺) m/z calcd for C₃₉H₄₄N₂O₅ [M+H]⁺: 621.3346, found: 621.3322.

(2R,3aR,5R,6R,7S,7aS)-4-benzyl-6,7-bis(benzyloxy)-5-((benzyloxy)methyl)-2-((4-heptyl-1H-1,2,3-triazol-1-yl)methyl)octahydrofuro[3,2-b]pyridine **16**

To a solution of **14** (35 mg, 57.8 μmol) in anhydrous CH₂Cl₂ (1 mL), at rt under Ar, were added lutidine (7.0 μL, 1 eq.), nonyne (11.4 μL, 69.4 μmol) and tetrakis(acetonitrile) copper(I) hexafluorophosphate complex (10.8 mg, 28.9 μmol). The mixture was stirred for 2h at rt, then diluted with CH₂Cl₂ and washed with a solution of Na₂EDTA (2M). The organic layer was dried over MgSO₄, filtrated and concentrated. The crude was purified by flash chromatography (PE/EtOAc 70/30) to give **16** (21 mg, 50 %) as a colorless oil. R_f (EP/AcOEt 60:40) = 0.41; [α]_D = - 12.5 (c 1.0, CHCl₃); ¹H NMR (500 MHz, CDCl₃): δ 7.32-7.10 (m, 21H, 20CH-Ar, CH-triazol), 4.75 (d, J = 6.4 Hz, 2H, OCH₂-Ph), 4.46 (m, 2H, OCHH-Ph, CHH-N-triazol), 4.34 (m, 3H, OCHH-Ph), 4.26 (dd, J = 6.7 Hz, J = 14.1 Hz, 1H, CHH-N-triazol), 4.11 (m, 1H, H-2), 4.02 (t, J = 8.2 Hz, 1H, H-7a), 3.80 (d, J = 13.8 Hz, 1H, NCHH-Ph), 3.68 (t, J = 7.8 Hz, 1H, H-7), 3.53 (m, 5H, NCHH-Ph, CH₂-OBn, H-6, H-3a), 2.92 (m, 1H, H-5), 2.57 (t, J = 7.8 Hz, 2H, CH₂-triazol), 2.10 (m, 1H, H-3), 1.52 (m, 3H, CH₂-chain, H-3), 1.22 (m, 8H, CH₂-chain), 0.79 (t, J = 7.0 Hz, 3H, CH₃); ¹³C NMR (125 MHz, CDCl₃): δ 148.4 (C-triazol), 138.9, 138.7, 138.2, 137.9 (C^{IV}-Ar), 128.4-127.1 (CH-Ar), 121.8 (CH-triazol), 83.5 (C-7), 80.1 (C-7a), 79.9 (C-6), 76.7 (C-2), 73.9, 73.2, 72.3 (OCH₂-Ph), 66.5 (CH₂-OBn), 60.2 (C-3a), 59.1 (C-5), 54.6 (NCH₂-Ph), 53.8 (CH₂-Ntriazol), 33.4 (C-3), 31.7, 29.5, 29.3, 29.0, 25.7, 22.6 (CH₂-chain), 14.1 (CH₃); HRMS (ESI⁺) m/z calcd for C₄₆H₅₆N₄NaO₄ [M+Na]⁺: 751.4194, found: 751.4200.

(2*R*,3*aR*,5*R*,6*R*,7*S*,7*aS*)-4-benzyl-6,7-bis(benzyloxy)-5-((benzyloxy)methyl)-2-((4-(4-phenylbutyl)-1*H*-1,2,3-triazol-1-yl)methyl)octahydrofuro[3,2-*b*]pyridine **17**

To a solution of **14** (60 mg, 0.099 mmol) in anhydrous CH₂Cl₂ (2 mL), at rt under Ar, were added lutidine (6 μ L, 0.049 mmol), 5-phenylpentyne (18 μ L, 0.12 mmol) and tetrakis(acetonitrile) copper(I) hexafluorophosphate complex (18.5 mg, 0.049 mmol). The mixture was stirred for 4h at rt, then diluted with CH₂Cl₂ and washed with a solution of Na₂EDTA (2M). The organic layer was dried over MgSO₄, filtrated and concentrated. The crude was purified by flash chromatography (PE/EtOAc 60/40) to give **17** (40 mg, 54 %) as a colorless oil. *R*_f (EP/AcOEt 60:40) = 0.25; [α]_D = -19.0 (c 1.0, CHCl₃); ¹H NMR (500 MHz, CDCl₃): δ 7.27-7.07 (m, 21H, 20*CH*-Ar, *CH*-triazol), 4.72 (s, 2H, OCH₂-Ph), 4.48 (m, 1H, *CHH*-N-triazol), 4.42 (d, 1H, *J* = 11.2 Hz, O*CHH*-Ph), 4.34 (m, 4H, *CHH*-N-triazol, 3xO*CHH*-Ph), 4.11 (m, 1H, H-2), 4.01 (t, 1H, *J* = 8.0 Hz, H-7a), 3.79 (d, 1H, *J* = 13.9 Hz, N*CHH*-Ph), 3.68 (t, 1H, *J* = 7.6 Hz, H-7), 3.59-3.47 (m, 5H, N*CHH*-Ph, CH₂-OBn, H-6, H-3a), 2.94 (m, 1H, H-5), 2.58 (m, 4H, CH₂-chain), 2.12 (m, 1H, H-3), 1.89 (brs, 2H, CH₂-chain), 1.50 (m, 1H, H-3); ¹³C NMR (125 MHz, CDCl₃): δ 141.7 (C-triazol), 138.8, 138.6, 138.2, 137.9 (C^{IV}-Ar), 128.5-127.1 (*CH*-Ar), 125.8 (*CH*-triazol), 83.1 (C-7), 80.1 (C-7a), 79.8 (C-6), 76.5 (C-2), 73.3, 73.3, 72.3 (OCH₂-Ph), 66.5 (CH₂-OBn), 60.1 (C-3a), 59.0 (C-5), 54.6 (NCH₂-Ph), 54.2 (CH₂-N-triazol), 35.4 (2xCH₂-chain), 34.5 (C-3), 31.0 (CH₂-chain); HRMS (ESI⁺) *m/z* calcd for C₄₈H₅₂N₄NaO₄ [M+Na]⁺: 771.3881, found: 771.3884.

N-(((2*R*,3*aR*,5*R*,6*R*,7*S*,7*aS*)-4-benzyl-6,7-bis(benzyloxy)-5-((benzyloxy)methyl)octahydrofuro[3,2-*b*]pyridin-2-yl)methyl)nonanamide **18**

To a solution of **14** (78 mg, 0.13 mmol) in a mixture THF/NH₄OH (3 mL / 0.3 mL), at rt, was added triphenylphosphine polymer bound (122 mg, 3.2 mmol/g, 0.39 mmol). The mixture was stirred at 50 °C for 15 h, filtrated through a pad of Celite® and concentrated to give the expected amino derivative. To a solution of the crude in dry CH₂Cl₂ (2.4 mL), at 0°C under argon, were added triethylamine (54 μ L, 0.39 mmol) and nonanoyl chloride (46 μ L, 0.26 mmol). The mixture was stirred at 0°C for 1h30, diluted with CH₂Cl₂ and washed with 1N HCl and brine. The organic layer was dried over MgSO₄, filtrated and concentrated. The crude was purified by flash chromatography (PE/EtOAc 70/30 then 60/40) to give **18** (45 mg, 48 %, 2 steps) as a colorless oil. *R*_f (EP/AcOEt 60:40) = 0.33; [α]_D = +21.2 (c 1.0, CHCl₃); ¹H NMR (500 MHz, CDCl₃): δ 7.33-7.10 (m, 20H, *CH*-Ar), 4.72 (s, 2H, OCH₂-Ph), 5.45 (t, 1H, *J* = 5.7 Hz, NH), 4.77 (s, 2H, OCH₂-Ph), 4.48 (d, 1H, *J* = 11.2 Hz, O*CHH*-Ph), 4.36 (m, 3H, 3xO*CHH*-Ph), 3.95 (t, 1H, *J* = 8.3 Hz, H-7a), 3.83 (m, 2H, H-2, N*CHH*-Ph), 3.65 (t, 1H, *J* = 8.4 Hz, H-7), 3.57-3.47 (m, 5H, N*CHH*-Ph, CH₂-OBn, H-6, H-3a), 3.45 (m, 1H, *CHH*-NHCO), 3.08 (m, 1H, *CHH*-NHCO), 2.90 (dd, 1H, *J* = 4.6 Hz, *J* = 9.1 Hz, H-5), 1.96 (m, 3H, H-3, CH₂-chain), 1.45 (m, 3H, H-3, CH₂-chain), 1.19 (m, 10H, 5xCH₂-chain), 0.80 (t, 3H, *J* = 6.9 Hz, CH₃); ¹³C NMR (125 MHz, CDCl₃): δ 173.2 (C=O), 139.2, 138.8, 138.3, 137.9 (C^{IV}-Ar), 128.4-127.0 (*CH*-Ar), 83.3 (C-7), 80.2 (C-6), 79.2 (C-7a), 77.2 (C-2), 73.3, 73.3, 72.5 (OCH₂-Ph), 66.5 (CH₂-OBn), 60.5 (C-3a), 59.1 (C-5), 54.6 (NCH₂-Ph), 42.8 (CH₂-NHCO), 36.7 (CH₂-chain), 32.8 (C-3), 31.8, 29.3, 29.2, 29.1, 25.8, 22.6 (6 x CH₂-chain), 14.1 (CH₃); HRMS (ESI⁺) *m/z* calcd for C₄₆H₅₉N₂O₅ [M+H]⁺: 719.4418, found: 719.4422.

(2*S*,3*aR*,5*R*,6*R*,7*S*,7*aS*)-5-(hydroxymethyl)-2-methyloctahydrofuro[3,2-*b*]pyridine-6,7-diol hydrochloride **5**

The general procedure A was applied to compound **12** (20 mg, 27.4 μ mol) to give compound **5** (24 mg, 99%) as a colorless oil. [α]_D = +45.0 (c 0.5, MeOH); ¹H NMR (400 MHz, methanol-*d*₄): δ 4.15 (m, 1H, H-3a), 4.06 (m, 1H, H-2), 3.97-3.89 (m, 3H, CH₂-OBn, H-7a), 3.79 (like t, *J* = 7.8, 6.1 Hz, 1H, H-7), 3.66 (t, *J* = 8.0 Hz, 1H, H-6), 3.28 (m, 1H, H-5), 2.57 (m, 1H, H-3), 1.71 (m, 1H, H-3), 1.42 (d, *J* = 5.4 Hz, 3H, CH₃); ¹³C NMR (100 MHz, methanol-*d*₄): δ 80.8 (C-7a), 76.1 (C-2), 73.5 (C-7), 67.7 (C-6), 59.5 (C-5), 59.2 (CH₂OBn), 55.5 (C-3a), 37.6 (C-3), 20.8 (CH₃); HRMS (ESI⁺) *m/z* calcd for C₉H₁₈NO₄ [M+H]⁺: 204.1236, found: 204.1233.

(2R,3aR,5R,6R,7S,7aS)-2,5-bis(hydroxymethyl)octahydrofuro[3,2-b]pyridine-6,7-diol hydrochloride
6

MeONa (0.4 mg, 4.5.10⁻⁶ mol) was added to a solution of **13** (28 mg, 4.5.10⁻⁵ mol) in dry methanol (1 mL) at 0 ° C under Ar. The mixture was stirred at rt overnight, then neutralized with acidic Amberlyst, filtrated and concentrated to give the expected deacetylated compound. The crude (18 mg, 3.1.10⁻⁵ mol) was directly submitted to the general procedure A to give **6** (9 mg, 72%, 2 steps) as a colorless oil. $[\alpha]_D^{20} = +70.7$ (c 1.0, H₂O); ¹H NMR (500 MHz, d₂O): δ 4.22 (m, 1H, H-2), 4.17 (dd, *J* = 4.3 Hz, *J* = 12.4 Hz, 1H, H-3a), 4.01 (t, *J* = 8.4 Hz, 1H, H-7a), 3.94 (dd, *J* = 4.3 Hz, *J* = 12.4 Hz, 1H, C5-CH₂-OH), 3.84 (dd, *J* = 4.3 Hz, *J* = 12.4 Hz, 1H, C5-CH₂-OH), 3.78 (m, 2H, H-7, C2-CH₂-OH), 3.66 (t, *J* = 8.4 Hz, 1H, H-6), 3.58 (dd, *J* = 4.3 Hz, *J* = 12.4 Hz, 1H, C2-CH₂-OH), 3.39 (m, 1H, H-5), 2.42 (m, 1H, H-3), 2.02 (m, 1H, H-3); ¹³C NMR (125 MHz, d₂O): δ 78.8 (C-2), 78.5 (C-7a), 71.5 (C-7), 65.8 (C-6), 62.2 (C2-CH₂-OH), 57.0 (C5-CH₂-OH), 56.9 (C-5), 52.6 (C-3a), 28.9 (C-3); HRMS (ESI⁺) *m/z* calcd for C₉H₁₈NO₅ [M+H]⁺: 220.1179, found: 220.1180.

(2R,3aR,5R,6R,7S,7aS)-2-(aminomethyl)-5-(hydroxymethyl)octahydrofuro[3,2-b]pyridine-6,7-diol dihydrochloride **7**

The general Procedure A was applied to compound **14** (35 mg, 0.06 mmol) to give compound **7** (17 mg, 99%) as a brown oil. $[\alpha]_D^{20} = -8.4$ (c 2.5, MeOH); ¹H NMR (400 MHz, methanol-d₄): δ 4.26-4.19 (m, 2H, H-3a, H-2), 4.04 (t, *J* = 6.2 Hz, 1H, H-7a), 3.96-3.90 (m, 2H, CH₂-OH), 3.86-3.82 (m, 1H, H-7), 3.68 (t, *J* = 7.9 Hz, 1H, H-6), 3.37-3.32 (m, 2H, H-5, CHH-NH₂), 3.19 (dd, *J* = 12.9 Hz, *J* = 9.8 Hz, 1H, CHH-NH₂), 2.68-2.61 (m, 1H, H-3), 2.01-1.93 (m, 1H, H-3); ¹³C NMR (100 MHz, methanol-d₄): δ 81.1 (C-7a), 76.1 (C-2), 73.0 (C-7), 67.8 (C-6), 59.1 (CH₂-OH, C-5), 54.9 (C-3a), 44.3 (CH₂-NH₂), 33.2 (C-3); HRMS (ESI⁺) *m/z* calcd for C₉H₁₉N₂O₄ [M+H]⁺: 219.1339, found: 219.1341.

N-(((2R,3aR,5R,6R,7S,7aS)-6,7-dihydroxy-5-(hydroxymethyl)octahydrofuro[3,2-b]pyridin-2-yl)methyl)acetamide hydrochloride **8**

The general procedure A was applied to compound **15** (32 mg, 5.2.10⁻⁵ mol) to give **8** (14 mg, 94 %) as a yellow foam. $[\alpha]_D^{20} = +24.0$ (c 1.0, MeOH); ¹H NMR (500 MHz, methanol-d₄): δ 4.18 (m, 1H, H-3a), 4.07 (m, 1H, H-2), 3.95 (t, *J* = 6.3 Hz, 1H, H-7a), 3.90 (m, 2H, CH₂-OH), 3.78 (dd, *J* = 6.4 Hz, *J* = 8.1 Hz, 1H, H-7), 3.61 (m, 2H, H-6, CHH-NHAc), 3.48 (dd, *J* = 6.8 Hz, *J* = 14.1 Hz, 1H, CHH-NHAc), 3.31 (m, 1H, H-5), 2.50 (m, 1H, H-3), 2.11 (s, 1H, CH₃), 1.85 (m, 1H, H-3); ¹³C NMR (125 MHz, methanol-d₄): δ 174.8 (C=O), 80.9 (C-7a), 78.2 (C-2), 73.4 (C-7), 67.8 (C-6), 59.23 (C-5), 59.19 (CH₂-OH), 55.1 (C-3a), 44.4 (CH₂-NHAc), 33.0 (C-3), 21.8 (CH₃); HRMS (ESI⁺) *m/z* calcd for C₁₁H₂₁N₂O₅ [M+H]⁺: 261.1445, found: 261.1444.

(2R,3aR,5R,6R,7S,7aS)-2-((4-heptyl-1H-1,2,3-triazol-1-yl)methyl)-5-(hydroxymethyl)octa-hydrofuro [3,2-b]pyridine-6,7-diol hydrochloride **9**

The general procedure A was applied to compound **16** (20 mg, 27.4 μmol) to give **9** (12 mg, quant.) as a colorless oil. *R_f* (AcOEt/MeOH 70:30) = 0.26; $[\alpha]_D^{20} = -19.0$ (c 1.0, MeOH); ¹H NMR (500 MHz, methanol-d₄): δ 8.43 (s, 1H, CH-triazol), 4.97 (m, 1H, CHH-N-triazol), 4.81 (dd, *J* = 8.2 Hz, *J* = 14.2 Hz, 1H, CHH-N-triazol), 4.43 (m, 1H, H-2), 4.23 (m, 1H, H-3a), 3.99 (t, *J* = 6.4 Hz, 1H, H-7a), 3.93 (dd, *J* = 5.9 Hz, *J* = 12.0 Hz, 1H, CHH-OH), 3.87 (dd, *J* = 3.4 Hz, *J* = 11.9 Hz, 1H, CHH-OH), 3.74 (dd, *J* = 6.3 Hz, *J* = 8.0 Hz, 1H, H-7), 3.63 (t, *J* = 8.2 Hz, 1H, H-6), 3.26 (m, 1H, H-5), 2.85 (t, *J* = 7.7 Hz, 2H, CH₂-C-triazol), 2.67 (m, 1H, H-3), 2.03 (m, 1H, H-3), 1.75 (m, 2H, CH₂-chain), 1.36 (m, 8H, CH₂-chain), 0.91 (t, *J* = 6.8 Hz, 3H, CH₃); ¹³C NMR (125 MHz, methanol-d₄): δ 146.6 (C-triazol), 128.0 (CH-triazol), 81.3 (C-7a), 77.4 (C-2), 73.3 (C-7), 67.7 (C-6), 59.05 (C-5), 59.02 (CH₂-OH), 56.5 (CH₂-N-triazol), 54.6 (C-3a), 32.8 (CH₂-chain), 32.7 (C-3), 30.1, 30.0, 29.5, 29.0, 24.7, 23.7 (CH₂-chain), 14.4 (CH₃); HRMS (ESI⁺) *m/z* calcd for C₁₈H₃₃N₄O₄ [M+H]⁺: 369.2496, found: 369.2503.

(2*R*,3*aR*,5*R*,6*R*,7*S*,7*aS*)-5-(hydroxymethyl)-2-((4-(4-phenylbutyl)-1*H*-1,2,3-triazol-1-yl)methyl)octahydrofuro[3,2-*b*]pyridine-6,7-diol hydrochloride **10**

The general procedure A was applied to compound **17** (30 mg, 40 μ mol) to give **10** (14 mg, 82%) as a colorless oil. *R*_f (AcOEt/MeOH 70:30) = 0.30; [α]_D = - 7.7 (c 1.0, MeOH); ¹H NMR (500 MHz, methanol-*d*₄): δ 7.87 (s, 1H, *CH*-triazol), 7.25-7.14 (m, 5H, 5*CH*-Ar), 4.72 (m, 1H, *CHH*-N-triazol), 4.60 (m, 1H, *CHH*-N-triazol), 4.33 (brs, 1H, H-2), 4.16 (brs, 1H, H-3a), 3.95 (s, 1H, H-7a), 3.86 (m, 2H, *CH*₂-OH), 3.61 (m, 2H, H-6, H-7), 3.26 (brs, 1H, H-5), 2.68 (m, 4H, *CH*₂-chain), 2.55 (brs, 1H, H-3), 1.98 (brs, 3H, *CH*₂-chain, H-3); ¹³C NMR (125 MHz, methanol-*d*₄): δ 149.0 (C^v-Ar), 143.1 (C-triazol), 129.5, 129.4, 126.9 (*CH*-Ar), 124.8 (CH-triazol), 81.1 (C-7a), 78.2 (C-2), 73.5 (C-7 or C-6), 67.9 (C-6 or C-7), 59.0 (*CH*₂-OH), 58.7 (C-5), 54.7 (C-3a), 54.2 (*CH*₂-N-triazol), 36.3 (*CH*₂-chain), 32.7 (C-3), 32.3, 25.8 (*CH*₂-chain); HRMS (ESI⁺) *m/z* calcd for C₂₀H₂₉N₄O₄ [M+H]⁺: 389.2183, found: 389.2182.

N-(((2*R*,3*aR*,5*R*,6*R*,7*S*,7*aS*)-6,7-dihydroxy-5-(hydroxymethyl)octahydrofuro[3,2-*b*]pyridin-2-yl)methyl)nonanamide hydrochloride **11**

The general procedure A was applied to compound **18** (43 mg, 60.0 μ mol) to give **11** (23 mg, 97%) as a colorless oil. *R*_f (AcOEt/MeOH 70:30) = 0.22; [α]_D = + 13.9 (c 1.0, MeOH); ¹H NMR (500 MHz, methanol-*d*₄): δ 4.15 (m, 1H, H-3a), 4.04 (m, 1H, H-2), 3.92 (m, 1H, H-7a), 3.86 (m, 2H, *CH*₂OH), 3.76 (dd, *J* = 6.6 Hz, *J* = 7.7 Hz, 1H, H-7), 3.62 (t, *J* = 8.3 Hz, 1H, H-6), 3.53 (dd, *J* = 4.0 Hz, *J* = 14.0 Hz, 1H, *CHNHCO*), 3.44 (dd, *J* = 6.6 Hz, *J* = 14.0 Hz, 1H, *CHNHCO*), 3.27 (m, 1H, H-5), 2.48 (m, 1H, H-3), 2.25 (t, *J* = 7.5 Hz, 2H, *COCH*₂-chain), 1.83 (m, 1H, H-3), 1.61 (t, *J* = 6.9 Hz, 2H, *CH*₂-chain), 1.31 (m, 10H, *CH*₂-chain), 0.89 (t, *J* = 6.7 Hz, 3H, *CH*₃); ¹³C NMR (125 MHz, methanol-*d*₄): δ 177.0 (C=O), 80.8 (C-7a), 78.6 (C-2), 73.5 (C-7), 67.9 (C-6), 59.2 (*CH*₂-OH), 59.0 (C-5), 55.1 (C-3a), 43.9 (*CONHCH*₂-chain), 36.9 (*COCH*₂-chain), 33.0 (C-3), 30.4, 30.3, 30.3, 27.0, 23.2 (*CH*₂-chain), 14.5 (*CH*₃); HRMS (ESI⁺) *m/z* calcd for C₁₈H₃₅N₂O₅ [M+H]⁺: 359.2540, found: 359.2540.

Supplementary Materials: Copies of ¹H and ¹³C NMR spectra of compounds **5-18**; Conformational analysis of compounds **9** and **11**.

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