



HAL
open science

Sugar γ -Amino Acids as Building Blocks for the Synthesis of Cyclic Neoglycopeptides.

Mylène Richard, Julen Ariztia, Sandrine Lamandé-Langle, Nadia Pellegrini moïse

► **To cite this version:**

Mylène Richard, Julen Ariztia, Sandrine Lamandé-Langle, Nadia Pellegrini moïse. Sugar γ -Amino Acids as Building Blocks for the Synthesis of Cyclic Neoglycopeptides.. ChemistrySelect, Wiley, 2018, 3 (31), pp.9121-9126. 10.1002/slct.201802146 . hal-02953389

HAL Id: hal-02953389

<https://hal.univ-lorraine.fr/hal-02953389>

Submitted on 29 Sep 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Sugar γ -amino acids as building blocks for the synthesis of cyclic neoglycopeptides

Mylène Richard,^a Julen Ariztia,^a Sandrine Lamandé-Langle,^a Nadia Pellegrini Moïse^{a*}

a: Université de Lorraine, CNRS, L2CM, F-5400 Nancy, France

*Corresponding author, E-mail address: nadia.pellegrini@univ-lorraine.fr (N. Pellegrini Moïse)

Keywords: sugar amino acids, cyclopeptides, C-glycosyl lactone, multivalent scaffold

Abstract: Cyclopeptides have interesting biological properties or find potential applications as templates for anchoring of a wide range of biomolecules or detection dyes. Anomeric sugar γ -amino acids efficiently obtained by nucleophilic addition of nitronate anion on sugar olefins are usefull building blocks for the preparation of new cyclic glycopeptides. We report here the synthesis of two types of cyclic systems containing γ -glyco amino acid and α -amino acid units. A first example was prepared to demonstrate the feasibility of the cyclization of these original structures. To explore these systems as template for multivalency, α -amino acid and sugar amino-acid moieties bearing additional functions were choosen as building blocks for the second macrocyle. Furthermore, we describe and explain some unexpected results obtained during deprotection of these new cyclic glycopeptides.

Cyclic peptides are naturally occurring substances exhibiting improved properties compared to the linear ones. Indeed, linear peptides usually show low metabolic stability limiting their use as drugs and display conformational flexibility reducing the strength of the ligand-target binding.¹⁻⁶ Therefore, the development of original cyclopeptide-based therapeutics is currently a growing interest. Some of them like the well-known vancomycin and its derivatives,^{6,7} gramicidin,^{8,9} colistin,¹⁰ octreotide,¹¹ and RGD derivatives^{12,13} exhibit useful biological properties as antibiotics, anticancer and integrin inhibitors. Cyclic peptides also proved to be useful for the design of functional nanotubes from self-assembly.^{14,15} Cyclic peptides or peptidomimetics can be useful in drug design¹⁶⁻²¹ and serve as templates for attaching and assembling a wide variety of ligands.^{5,22,23} Such templates allow the facile and versatile attachment of multiple ligands (multivalency) by suitable functions.^{5,23-25} One noteworthy example are the Regioselectively Addressable Functionalized Templates (RAFT) developed by Dumy *et al.*²⁶⁻²⁸ which have found powerful applications in biology and imaging.^{27,29,30} A wide range of multivalent (glyco)cyclopeptides and synthetic glycoclusters based on cyclic peptides have been described for their related applications in glycobiology.^{5,25,31-34}

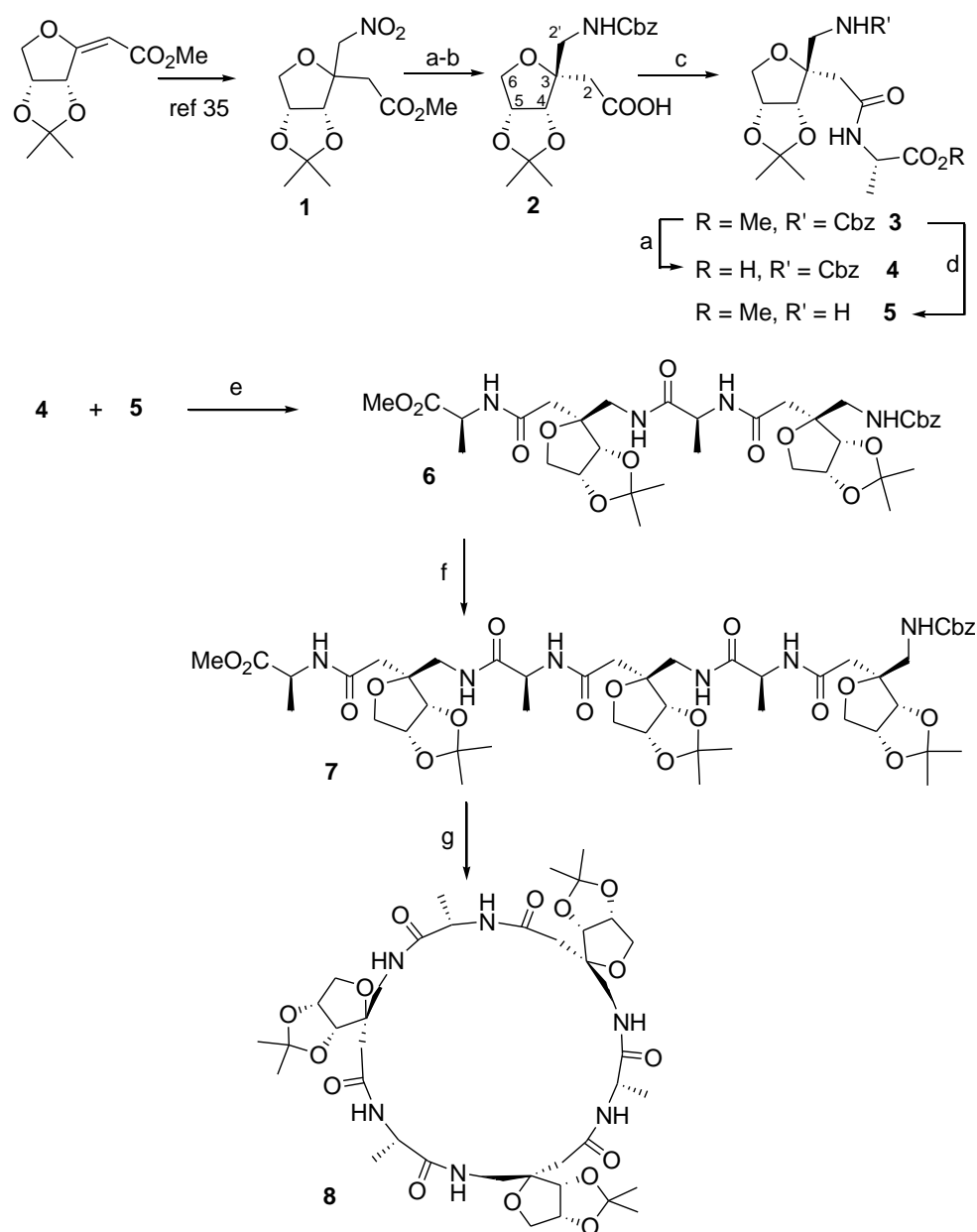
Designing and synthesizing new types of biocompatible and functionalizable molecular scaffolds for multivalent presentation are great challenges for synthetic chemists. As unusual amino acids with multiple functionalization points, sugar amino acids are good candidates and can be incorporated into peptidic structures. A few years ago, we developed anomeric sugar β - and γ -amino acids³⁵⁻³⁷ and we integrated them into small mixed peptides,^{38,39} and cyclic glycopeptides.^{38,40}

In connection with our research on new carbohydrates-containing peptides, we proposed the construction of original hybrid macrocyclic structures built with sugar γ -amino acids and α -amino acids. Furthermore, to explore the scope of these structures as templates for multivalency, both amino-acid moieties were carefully chosen to provide additional anchoring points. We give in this paper a full account of the synthesis of these original cyclic hybrid glycopeptides.

Results and discussion

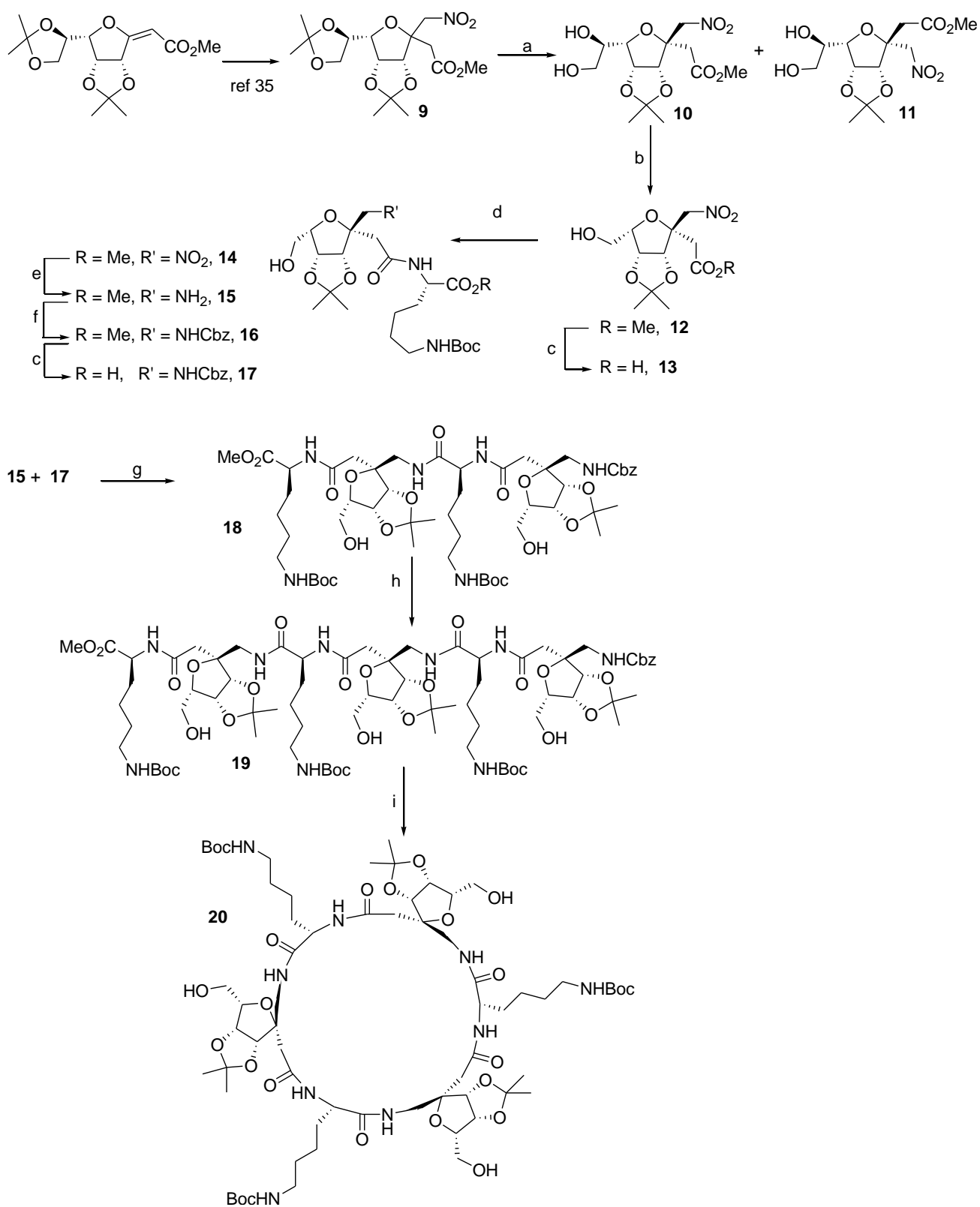
The nucleophilic addition of a nitronate anion on push-pull anomeric sugar olefins has been previously studied in our group (Scheme 1).³⁵ Michael adducts **1** were obtained in excellent yield as a mixture of inseparable nitro esters starting from the corresponding *erythro*-glycosylidene (14/86: α/β ratio), the major anomer bearing the nitro group on the less hindered face of the sugar. We have previously demonstrated that both anomers are in equilibrium, likely as a result of opening and closure of the sugar ring. The configuration of the major anomer (methyl carboxylate and isopropylidene on the same face) was established on the basis of ¹H NMR spectroscopic data by NOESY experiments on α/β mixture and X-ray crystallographic analysis.³⁵ Anomeric mixture of nitro esters **1** was treated with lithium hydroxide in THF/H₂O to give the corresponding carboxylic acid in very good yield. At this stage, the separation of both anomers could be performed by chromatography and the subsequent steps were carried out on the major isomer. Reduction of the nitro group required medium hydrogen pressure (40 psi) to give the expected amine subsequently protected with a benzyloxycarbonyl group under standard conditions. The NH-Cbz protected compound **2** thusly prepared was coupled with H-L-ala-OMe giving **3** in 85% yield. At this point, either amine or acid terminal functions of **3** were deprotected by hydrogenolysis (H₂, Pd/C, MeOH) or by saponification (LiOH, THF/H₂O) respectively. Building blocks **5** and **4** were then coupled using HATU (1-[bis(dimethylamino)methylene]-1H-1,2,3-triazolo[4,5-b]pyridinium 3-oxid hexafluorophosphate) as activating agent and led to the tetrapeptide **6** in 78% yield. Compound **7** was obtained in 79% yield by hydrogenolysis of *N*-benzyloxycarbonyl protecting group and subsequent coupling with **4**. Having achieved the synthesis of the linear hexapeptide **7**, we next envisioned the cyclization step using classical peptide chemistry. First, saponification of the ester function of **7** with LiOH in THF/MeOH mixture led to the crude carboxylic acid. The *N*-benzyloxycarbonyl group was then removed by catalytic hydrogenolysis using Pd/C in MeOH. Without purification, the fully deprotected glycopeptide was treated with HATU as coupling agent in CH₂Cl₂/DMF mixture for 3 days under high dilution conditions ($c = 0.1$ mmol/L) to promote macrocyclization over poly(oligo)merization.⁴¹ After purification, the cyclic glycopeptide **8** was obtained in 42% yield. The use of other coupling agent (benzotriazol-1-yl-oxytripyrrolidinophosphonium hexafluorophosphate, PyBop) did not significantly improve the yield of **8**. As expected by the symmetric structure of **8**, ¹H and ¹³C NMR spectra revealed only one set of signals corresponding to a sugar/alanine unit. Nevertheless, mass spectrometry unambiguously

confirmed the formation of expected cyclic structure (see SI, Figure S1, see scheme 1 for atom numbering).



Scheme 1. a: LiOH, THF/H₂O (3/1), **4**: quantitative yield; b: 1) H₂, Pd/C (10%), MeOH, 3 bars, 80%; 2) TMSCl (2 eq.), DCM, 3) DIEA, CbzCl, 65% three steps; c: H-L-Ala-OMe, DIEA, HATU, DMF, 85%; d) H₂, Pd/C, MeOH, 99%; e) DIEA, HATU, DMF, 78%; f) i. H₂, Pd/C, MeOH, ii. **4**, DIEA, HATU, DMF, 79%; g) i. LiOH, THF/H₂O, ii. H₂, Pd/C, MeOH, iii. DIEA, HATU, DMF/CH₂Cl₂, 42%.

After the validation of this proof of concept, *i.e.* the successful synthesis of **8** and the confirmation of the cyclization of these structures, we continued our work with the synthesis of a more functionalized cyclic peptide. This second example is built with γ -glycoamino acid and α -amino acid bearing additional reactive groups (Scheme 2). For this purpose, L-lysine with a *tert*-butyloxycarbonyl as side chain protecting group was selected as α -amino acid partner. Derivative **9** was chosen as γ -glycoamino acid partner and modified in order to display a hydroxymethyl arm. As explained above, the nitro ester **9** was obtained as a mixture of anomers (15/85 α/β ratio) by addition of the nitromethane carbanion on the corresponding *exo*-glycal. The selective removal of the 7,8-*O*-isopropylidene protecting group was achieved by treatment with 1N HCl in MeOH. The corresponding diol was obtained as a mixture of anomers and separated by column chromatography.³⁵ We decided to go ahead with the major isomer **10** and oxidative cleavage of the diol followed by reduction of the aldehyde intermediate led to compound **12** bearing a hydroxymethyl arm. The nitro function acting as an amino protecting group was maintained for the first coupling with H-L-Lysine(Boc)-OMe and the compound **14** was obtained in 90% yield. We first planned to protect the hydroxyl group as a silyl ether derivative but this protection step appeared unnecessary since the unprotected hydroxyl was not affecting the peptidic coupling. The nitro group was next hydrogenated and the resulting amine **15** was protected with a benzyloxycarbonyl group. Methyl ester of **16** could be selectively removed by saponification leading to acid **17** in quantitative yield. Coupling of compounds **15** and **17** using HATU in DMF led to glycopeptides **18** and then **19** in 69% and 47% yields respectively. Cyclic derivative **20** was obtained after amine and acid deprotection followed by activation with HATU and intramolecular coupling in CH₂Cl₂/DMF mixture under high dilution conditions (*c* = 0.1 mmol/L). Retrieval of compound **20** in the crude was tedious and purification inefficient although the expected molecular pic was detected by mass spectrometry ($[M+Na]^+ = 1436.7626$, calculated for C₆₆H₁₁₁N₉O₂₄Na: 1436.7634). We next turned to PyBop as activating agent in the same high dilution conditions. In this case, the recovery of **20** was easier but also required two purifications by column chromatography on silica gel explaining the low yield of **20** (22%). Even though the cyclization step was tedious, we were pleased to obtain a macrocycle bearing two different reactive groups.



Scheme 2. a) 1N HCl, MeOH, 0°C, 68%; b) i. NaIO₄, MeOH; ii. NaBH₄, MeOH, 0°C, 98%; c) LiOH, THF/H₂O, **13** 98%, **17** 99%; d) HCl.H-L-Lys(Boc)-OMe, DIEA, HATU, DMF, 0°C, 90%; e) H₂, Pd/C, MeOH, 99%; f) DIEA, CbzCl, DCM, 0°C, 70%; g) HATU, DIEA, DMF,

0°C, 69%; h) i. H₂, Pd/C, MeOH, ii. **17**, HATU, DIEA, DMF, 0°C, 47%; i) i. LiOH, THF/H₂O, ii. H₂, Pd/C, MeOH, , iii. HATU, DIEA, DMF/CH₂Cl₂, 0°C, 22%.

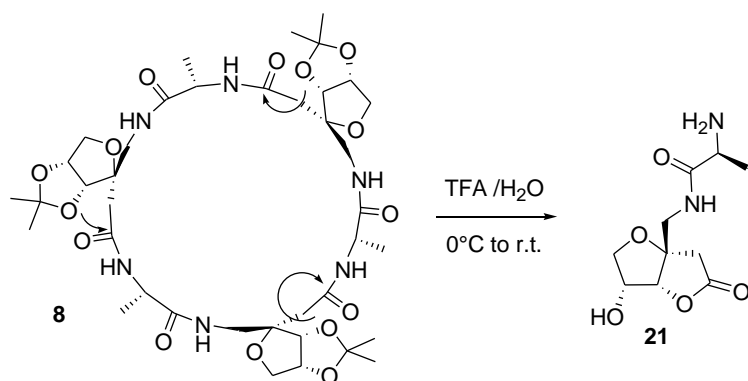
To go further with these macrocyclic structures, we envisaged to modulate their hydrosolubility by removing the sugar hydroxyl protecting groups, namely 4,5-isopropylidene. Moreover, these hydroxyls could also be considered as additional functionalization points. The cycloglycopeptide **8** was treated by a mixture of TFA/H₂O (1/1) at 0°C, commonly used for isopropylidene removal (Scheme 3). Unexpectedly, we only observed the formation of *C*-glycosyl lactone **21** in quantitative yield, as a result of several concomitant intramolecular amide-to-ester conversions of **8**. We postulated that compound **21** results from TFA promoted acetal removal followed by nucleophilic attack of O4 on carboxamide function. Few intramolecular lactonizations of *C*-glycosyl ester derivatives have already been described in the literature and led to the formation of *C*-glycosyl bicyclic lactones where the lactone ring is annulated to a furanoid⁴² or a pyranoid⁴³ system. However, to the best of our knowledge, no lactonization of amide derivatives in such saccharidic systems has been described. This prompted us to study this reaction on less elaborate precursors in order to find experimental conditions enabling deprotection while preventing lactonization (Scheme 4). We first envisioned the 4,5-isopropylidene removal on β-nitro ester **10** (major isomer with methyl carboxylate and isopropylidene on the same face). As expected, the lactone **22** was obtained by treating **10** with a TFA/H₂O mixture at 0°C, and no traces of nitro ester **23** were detected. The same reaction performed on α-nitro ester **11** (minor anomer) gave the nitro ester **24** in quantitative yield without lactonization reaction since the methyl carboxylate and O4 are not on the same face. Taking into account the formation of lactone **21** resulting from intramolecular esterification of amide functions of **8**, we planned to investigate the 4,5-isopropylidene removal on a simple amide like **25**, obtained from **10** after saponification of methyl ester and coupling with H-L-ala-OMe (Scheme 4). To find efficient experimental conditions for 4,5-isopropylidene removal leading to compound **26** without concomitant lactonization, the nature of the acid, the solvent, the temperature and the reaction time were studied (Table 1). Treatment of **25** by a 1/1 TFA/H₂O mixture led to *C*-glycosyl lactone **22** in quantitative yield (entry 1) although no reaction was observed while maintaining the temperature at 0°C (entry 2). Similarly, compound **26** was not formed when AcOH (entry 3), acidic resin (Amberlite IR 120, entry 4)⁴⁴ or FeCl₃⁴⁵ (entry 5) were used. In these conditions, 30 to 50% of starting amide **25** were recovered and lactonization occurred up to 10 %. Moreover, prolonged reaction time led to the degradation of the starting compound **25**.

We eventually investigated the use of HCl in MeOH. When performed at 50°C, the reaction only gave the lactone **22** in 82% yield in 2 hours (entry 6). TLC monitoring showed that maintaining the temperature at -5° C could lead to the expected 4,5-diol **26** without lactonization (compound **26** is more polar than lactone **22** on TLC) but this nitro ester was immediately converted into lactone **22** during evaporation of the solvent, even though the reaction mixture was neutralized with NaHCO₃. Despite investigating various experimental conditions, it clearly appeared that lactonization of amide **25** during removal of the 4,5-isopropylidene moiety could not be prevented. Consequently, removal of the isopropylidene group for hydrosolubility modulation or for additional functionalization was not an option in this context.

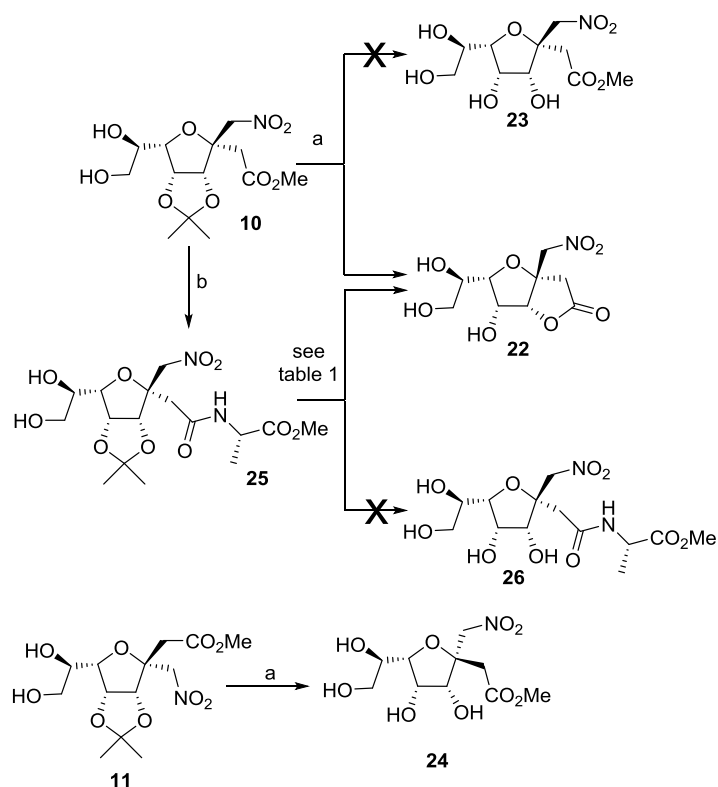
Table 1. 4,5-isopropylidene removal of **25**

entry	solvent	acid	temperature	reaction time (h)	yield of 22 (%)	recovery of 25 (%)
1	H ₂ O	TFA	0°C then rt	7	99	0
2	H ₂ O	TFA	0°C	7	0	99
3	H ₂ O	AcOH	50°C	48	<10	50
4	CHCl ₃ /MeOH	acidic resin	40°C	48	<10	30
5	CH ₂ Cl ₂	FeCl ₃ .H ₂ O	40°C	48	<10	30
6	MeOH	HCl	50°C	2	82	0
7	MeOH	HCl	0°C then rt	7	80	20
8	MeOH	HCl	-5°C	12	80*	20

* The reaction mixture was maintained at -5°C during 12h and then neutralized with NaHCO₃. The formation of the lactone was observed during evaporation of the solvent.



Scheme 3. Deprotection of cyclopeptide **8**



Scheme 4. a: TFA/H₂O, (1/1), 0°C; quantitative yield; b) i. LiOH, THF/H₂O, 74%, ii. H-L-alan-
 OMe, DIEA, HATU, DMF, 40%; c) HCl/MeOH, 0°C, 82%.

These results unambiguously suggested that the minor α -anomer **11** displaying the methyl carboxylate on one side of the sugar ring and the isopropylidene on the other side could be a valuable unit for cyclic hybrid glycopeptides synthesis and efficient isopropylidene deprotection. A similar pathway was thus investigated starting from **11** (see SI, scheme S1). However, it is important to note that compound **11** was obtained in 15% yield after addition of nitromethane anion (minor anomer). Furthermore, after preliminary intramolecular coupling experiments, the cyclic product could not be isolated. The nature and structure of the linear precursor clearly affected the macrocyclization process. In particular, the anomeric configuration did not seem to induce a favorable folding of this linear precursor or provide the required spatial arrangement between amino and carboxylic acid moieties. Moreover, the steric hindrance around the anomeric aminomethyl moiety (on the same face of isopropylidene and hydroxymethyl chain) could prevent the cyclization reaction.

Conclusion

To sum up this work, we have synthesized new and original cyclic glycopeptides containing two types of amino acids, a γ -glycoamino acid and an α -amino acid. The construction of the linear precursors based on two building blocks was achieved by a multistep sequence. A first macrocycle was obtained as a proof of concept to validate the cyclization capabilities of these glycopeptides. The second structure is more elaborate and has proved challenging to synthesize and purify. Nevertheless, this later presents an extended number of chemical functionalities, with the idea of exploring their scope as template for multivalency. During acid catalyzed removal of isopropylidene of these new cyclic glycopeptides, a C-glycosyl lactone in which the lactone ring is annulated to a furanoid system was unexpectedly and spontaneously formed. Intense investigations are now devoted to functionalization of these cyclopeptides via coupling of the amino or hydroxymethyl moieties to relevant biomolecules and/or dyes for biological applications.

Experimental part

Reagents and general methods

DMF was dried by distillation from calcium hydride. Other solvents and reagents were purchased from commercial sources and used without further purification. TLC analyses were performed using standard procedures on Kieselgel 60 F254 plates (Merck). Compounds were visualized using UV light (254 nm) and 30% methanolic H₂SO₄/heat as developing agent. Column chromatography was performed on silica gel SI 60 (63-200 μ m) or Lichroprep RP-18 (40-63 μ m) (Merck). FTIR spectra were recorded on a Perkin-Elmer spectrum 1000 on NaCl windows (film) or KBr pellets (cm⁻¹). Melting points were determined with a Tottoli apparatus and are uncorrected. Optical rotations were measured on an Anton Paar MC300 polarimeter. ¹H and ¹³C NMR spectra were recorded on a Bruker spectrometer DPX250 (250 MHz and 62.9 MHz, respectively) and DRX400 (400 MHz and 100.6 MHz, respectively). For complete assignment of ¹H and ¹³C signals, two-dimensional ¹H,¹H COSY and ¹H,¹³C correlation spectra were recorded. Mass spectra (MS) were recorded on an ESI/QqTOF Bruker spectrometer. Ethyl acetate = EA, Cyclohexane = cyH. Compounds **1**, **2**, **9**, **10**, **11** were prepared in accordance with literature procedures.³⁵

Procedure A: General procedure for peptidic coupling with HATU

To a solution of amine (1.1 mmol, 1.1 eq.) and carboxylic acid (1 mmol, 1 eq.) in DMF (10 mL) were added HATU (570 mg, 1.5 mmol, 1.5 eq.) and DIEA (363 μ L, 2.1 mmol, 2.1 eq.) at 0°C under argon atmosphere. After stirring at room temperature for 24h, the solvent was evaporated. The residue was dissolved in ethyl acetate (20 mL), washed with HCl 1N (5 mL), a saturated aqueous solution of NaHCO₃ (5 mL) and brine (5 mL). The organic layer was dried over MgSO₄, filtered and concentrated. The product was purified by column chromatography (silica gel, cyH/EA).

Procedure B: General procedure for saponification with LiOH

To a solution of methyl ester (2 mmol) in THF (15 mL) and water (5 mL) was added LiOH (144 mg, 6 mmol, 3 eq.) and the mixture was stirred until completion of the reaction. THF was removed under reduced pressure, ethyl acetate (20 mL) was added and the pH was adjusted to 2-3 with aqueous 1N HCl. The organic layer was washed with brine and dried over MgSO₄, filtered and concentrated. When necessary, the crude residue was purified by column chromatography (silica gel, cyH/EA).

Procedure C: General procedure for nitro reduction or Cbz hydrogenolysis

To a solution of protected compound (10 mmol) in MeOH (20 mL) was added Pd/C(10%) (40%w/w). The mixture was hydrogenated under H₂ atmosphere (40 psi) for 24 h. The reaction mixture was then filtered through a pad of celite and concentrated to give the desired product. The crude product was used without further purification.

Compound 3

The above described procedure A was applied to **2** (580 mg, 1.59 mmol) and alanine methyl ester hydrochloride to provide **3** (608 mg, 85% yield). Colorless gum. R_f = 0.58 (EA), $[\alpha]_D = -30.9$ (c 0.5 in CHCl₃). ¹H NMR (CDCl₃, 250 MHz): δ = 1.33 (s, 3H, CH₃), 1.38 (d, 3H, J = 7.0 Hz, CH₃ alanine), 1.52 (s, 3H, CH₃), 2.61 (d, 1H, J_{gem} = 14.0 Hz, $H-2$), 2.67 (d, 1H, $H-2$), 3.20 (dd, 1H, J_{gem} = 14.5, $J_{2',NH}$ = 5.5 Hz, $H-2'$), 3.37 (dd, 1H, $J_{2',NH}$ = 7.5 Hz, $H-2'$), 3.72 (s, 3H, OMe), 3.92 (dd, 1H, J_{gem} = 11.0, $J_{5,6}$ = 3.5 Hz, $H-6$), 4.01 (d, 1H, $H-6$), 4.46-4.57 (m, 2H, $H-\alpha$, $H-4$), 4.90 (dd, 1H, $J_{4,5}$ = 6.0 Hz, $H-5$), 5.06 (d, 1H, J_{gem} = 12.0 Hz, CH₂-Ph), 5.12 (d, 1H, CH₂-Ph), 5.66 (t, 1H, N-H), 6.80 (d, 1H, $J_{\alpha,NH}$ = 6.5 Hz, N-H), 7.29-7.40 (m, 5H, $H-Ar$). ¹³C NMR (CDCl₃, 62.9 MHz): δ = 17.9 (CH₃ alanine), 24.6, 26.1 (2 C(CH₃)₂), 40.3 (C-2), 42.1 (C-2'), 48.1 (C- α), 52.4 (OCH₃), 66.8 (CH₂-Ph), 71.4 (C-6), 81.4, 83.0 (C-4, C-5), 85.6 (C-3), 112.6 (C(CH₃)₂), 128.0 (2 C-Ar), 128.5 (3 C-Ar), 136.4 (C-Ar), 156.8 (C=O Cbz),

170.4 (C=O), 173.2 (C=O). ESI-HRMS $[M+Na]^+$ m/z = found 473.1902 (calculated for $C_{22}H_{30}N_2O_8Na$: 473.1894). IR (NaCl) ν_{max}/cm^{-1} 3341, 1725, 1662

Compound 6

The above described procedure B was applied to **3** and acid **4** was obtained in quantitative yield. The amine **5** was obtained from **3** in 99 % yield *via* procedure C. Acid **4** (392 mg, 0.9 mmol, 1 eq.) and amine **5** (313 mg, 0.99 mmol, 1.1 eq.) were coupled according to procedure A to provide **6** (411 mg, 78% yield). Colorless gum. R_f = 0.29 (EA). $[\alpha]_D = -33.3^\circ$ (c 1 in $CHCl_3$). 1H NMR ($CDCl_3$, 400 MHz): δ = 1.32, 1.34 (s, 6H, $C(CH_3)_2$), 1.37 (d, 6H, J = 7.0 Hz, CH_3 alanine), 1.49, 1.52 (s, 6H, $C(CH_3)_2$), 2.64 (s, 2H, H_{A-2}), 2.65 (d, 1H, J_{gem} = 14.5 Hz, H_{B-2}), 2.70 (d, 1H, H_{B-2}), 3.19 (dd, 1H, J_{gem} = 14.5, J = 6.0 Hz, $H_{B-2'}$), 3.26 (dd, 1H, J_{gem} = 14.5, J = 6.0 Hz, $H_{A-2'}$), 3.38 (dd, 1H, J = 7.0 Hz, $H_{B-2'}$), 3.42 (dd, 1H, J = 7.0 Hz, $H_{A-2'}$), 3.74 (s, 3H, OCH_3), 3.90-4.01 (m, 4H, $H-6$), 4.41-4.54 (m, 3H, 2 $H-\alpha$, $H-4$), 4.57 (d, 1H, $J_{4,5}$ = 6.0 Hz, $H-4$), 4.88-4.91 (m, 2H, $H-5$), 5.10 (s, 2H, CH_2-Ph), 6.03 (t, 1H, J = 6.5 Hz, $NHCbz$), 6.71 (d, 1H, J = 7.0 Hz, N_3H), 6.86 (d, 1H, J = 7.0 Hz, N_1H), 7.19 (t, 1H, N_2H), 7.27-7.37 (m, 5H, $H-Ar$). ^{13}C NMR ($CDCl_3$, 100 MHz): δ = 17.6, 17.7 (2 CH_3 alanine), 24.6, 26.1 (4 CH_3), 39.5 (C_{B-2}), 39.9 (C_{A-2}), 40.2 ($C_{A-2'}$), 42.2 ($C_{B-2'}$), 48.2 (C- α), 49.2 (C- α), 52.5 (OCH_3), 66.8 (CH_2-Ph), 71.4, 71.5 (C_{A-6} , C_{B-6}), 81.3, 81.4 (C_{B-5} , C_{A-5}), 83.1, 83.4 (C_{B-4} , C_{A-4}), 85.5, 85.8 (C_{B-3} , C_{A-3}), 112.5 (2 $C(CH_3)_2$), 128.0 (3 C-Ar), 128.5 (2 C-Ar), 136.5 (C-Ar), 157.1 (C=O Cbz), 170.6 ($C_4=O$), 170.8 ($C_2=O$), 172.6 ($C_3=O$), 173.5 ($C_1=O$). ESI-HRMS $[M+Na]^+$ m/z = found 757.3257 (calculated for $C_{35}H_{50}N_4O_{13}Na$: 757.3267). IR (NaCl) ν_{max}/cm^{-1} 3322, 2985, 2938, 1721, 1659, 1532

Compound 7

Compound **6** was deprotected using general procedure C and the corresponding amine (396 mg, 0.66 mmol, 1.1 eq.) was coupled with acid **4** (262 mg, 0.6 mmol, 1 eq.) following procedure A to provide **7** (482 mg, 79% yield). Colorless gum R_f = 0.17 (EA). $[\alpha]_D = -35.2^\circ$ (c 0.6 in $CHCl_3$). 1H NMR ($CDCl_3$, 400 MHz): δ = 1.30-1.35 (m, 12H, 4 CH_3), 1.37 (d, 3H, J = 7.5 Hz, CH_3 alanine), 1.42 (d, 3H, J = 7.5 Hz, CH_3 alanine), 1.48 (s, 3H, CH_3), 1.51 (s, 6H, 2 CH_3), 2.59-2.75 (m, 6H, 6 $H-2$), 3.12 (dd, 1H, J_{gem} = 14.5, J = 5.0 Hz, $H-2'$), 3.23 (dd, 1H, J_{gem} = 14.5, J = 6.0 Hz, $H-2'$), 3.30 (dd, 1H, J_{gem} = 14.5, J = 5.5 Hz, $H-2'$), 3.39 (dd, 1H, J = 6.5 Hz, $H-2'$), 3.43 (dd, 1H, J = 6.5 Hz, $H-2'$), 3.51 (dd, 1H, J = 7.0 Hz, $H-2'$), 3.75 (s, 3H, OCH_3), 3.90 (dd, 1H, J_{gem} = 11.0, J = 4.0 Hz, $H-6$), 3.93-3.99 (m, 5H, 5 $H-6$), 4.39 (m, 1H, $H-\alpha$), 4.44-4.55 (m, 4H, 2 $H-\alpha$, 2 $H-4$), 4.57 (d, 1H, $J_{4,5}$ = 6.0 Hz, $H-4$), 4.87-4.92 (m, 3H, 3 $H-$

5), 5.08 (d, 1H, $J_{\text{gem}} = 12.5$ Hz, $\text{CH}_2\text{-Ph}$), 5.12 (d, 1H, $\text{CH}_2\text{-Ph}$), 6.06 (t, 1H, $J = 6.0$ Hz, NHCbz), 6.74 (d, 1H, $J = 7.0$ Hz, NH), 6.88 (d, 1H, $J = 7.0$ Hz, NH), 7.07 (d, 1H, $J = 7.0$ Hz, NH), 7.25 (m, 1H, NH), 7.30-7.39 (m, 5H, 5 H-Ar), 7.46 (t, 1H, $J = 6.0$ Hz, NH). ^{13}C NMR (CDCl_3 , 100 MHz): $\delta = 17.5, 17.7, 18.0$ (3 CH_3 alanine), 24.6 (3 CH_3), 26.1 (3 CH_3), 39.2, 39.7, 39.8, 40.1, 40.7, 41.9 (3 C-2 , 3 C-2'), 48.2, 49.2, 49.4 (3 $\text{C-}\alpha$), 52.5 (OCH_3), 66.8 ($\text{CH}_2\text{-Ph}$), 71.2, 71.4, 71.6 (3 C-6), 81.2, 81.3, 81.4 (3 C-5), 83.1, 83.3, 83.4 (3 C-4), 85.5, 85.7, 85.8 (3 C-3), 112.4, 112.5 (3 $\text{C}(\text{CH}_3)_2$), 128.0 (3 C-Ar), 128.5 (2 C-Ar), 136.6 (C-Ar), 157.1 (C=O Cbz), 170.5, 170.7, 171.2, 172.9, 173.5 (6 C=O). ESI-HRMS $[\text{M}+\text{Na}]^+$ $m/z =$ found 1041.4649 (calculated for $\text{C}_{48}\text{H}_{70}\text{N}_6\text{O}_{18}\text{Na}$: 1041.4639). IR (NaCl) $\nu_{\text{max}}/\text{cm}^{-1}$ 3327, 2985, 2938, 1718, 1657, 1529

Cyclopeptide 8

Compound **7** was deprotected using general procedures B and C. To a solution of the deprotected glyco-amino acid (348 mg, 0.4 mmol, 1 eq.) in $\text{CH}_2\text{Cl}_2/\text{DMF}$ (4/1) at 0°C under argon, were added DIEA (346 μL , 2.0 mmol, 5.0 eq.) and HATU (182 mg, 0.48 mmol, 1.2 eq.). After stirring at room temperature for 3 days, the solvents were evaporated and the residue was taken up in ethyl acetate (30 mL). The solution was washed with brine (10 mL), dried over MgSO_4 , filtered and concentrated. The product was purified by column chromatography (silica gel, AcOEt/MeOH) to provide **8** (143 mg, 42% yield). White solid. $\text{Mp} = 180^\circ\text{C}$. $\text{Rf} = 0.33$ ($\text{CH}_2\text{Cl}_2/\text{MeOH}$: 9/1). $[\alpha]_{\text{D}} = -50.5^\circ$ (c 0.5 in CHCl_3). ^1H NMR (CDCl_3 , 250 MHz): $\delta = 1.36$ (s, 3H, CH_3), 1.42 (d, 3H, $J = 7.0$ Hz, CH_3 alanine), 1.53 (s, 3H, CH_3), 2.64 (d, 1H, $J_{\text{gem}} = 14.5$ Hz, H-2), 2.79 (d, 1H, H-2), 3.32 (dd, 1H, $J_{\text{gem}} = 14.5$, $J_{2',\text{NH}} = 6.0$ Hz, H-2'), 3.47 (dd, 1H, $J_{2',\text{NH}} = 6.0$ Hz, H-2'), 3.98 (d, 1H, $J_{\text{gem}} = 11.5$ Hz, H-6), 4.05 (dd, 1H, $J_{5,6} = 3.5$ Hz, H-6'), 4.48 (m, 1H, $\text{H-}\alpha$), 4.51 (d, 1H, $J_{4,5} = 6.0$ Hz, H-4), 4.94 (dd, 1H, H-5), 6.72 (d, 1H, $J = 6.0$ Hz, NH ala), 7.40 (t, 1H, NH erythro). ^{13}C NMR (CDCl_3 , 62.9 MHz): $\delta = 17.8$ (CH_3 alanine), 24.8 (CH_3), 26.3 (CH_3), 40.7, 41.0 (C-2 , C-2'), 49.6 ($\text{C-}\alpha$), 71.7 (C-6), 81.6 (C-5), 83.4 (C-4), 85.9 (C-3), 112.8 ($\text{C}(\text{CH}_3)_2$), 171.5, 173.2 (2 C=O). ESI-HRMS $[\text{M}+\text{Na}]^+$ $m/z =$ found 875.4012 (calculated for $\text{C}_{39}\text{H}_{60}\text{N}_6\text{O}_{15}\text{Na}$: 875.4009). IR (NaCl) $\nu_{\text{max}}/\text{cm}^{-1}$ 3312, 3056, 2981, 2933, 2857, 1737, 1657, 1529

Compound 12

To a stirred solution of **10** (5.42 g, 16.2 mmol, 1 eq.) in methanol (340 mL) was added NaIO_4 (6.93 g, 32.4 mmol, 2 eq.) under argon. After stirring at room temperature until completion of the reaction, the solvent was removed by half *in vacuo*. The mixture was diluted with CH_2Cl_2

(300 mL). The organic layer was washed with water (3 x 100 mL), dried over MgSO₄, filtered and the solvent was removed under reduced pressure. The crude product was solubilized in MeOH (130 mL) and NaBH₄ (622 mg, 1.51 mmol, 1 eq.) was added at 0°C. After 1 h at room temperature, the solvent was removed under reduced pressure. The residue was diluted in CH₂Cl₂ (200 mL) and the organic layer was washed with a solution of 1N HCl (70 mL) and with water until pH = 7. The organic layer was dried over MgSO₄, filtered and evaporated under reduced pressure. The crude product **12** (5.10 g, 98% yield) was used without further purification. Colorless oil. *R_f* = 0.50 (cH/EA: 1/2). [α]_D = -10.4° (c 0.4 in CHCl₃). ¹H NMR (CDCl₃, 250 MHz): δ = 1.31 (s, 3H, CH₃), 1.48 (s, 3H, CH₃), 2.09 (br s, 1H, OH), 2.90 (d, 1H, *J*_{gem} = 18.0 Hz, *H*-2), 3.09 (d, 1H, *H*-2), 3.73 (s, 3H, OCH₃), 3.83-3.90 (m, 2H, *H*-7, *H*-7'), 4.11 (m, H, *H*-6), 4.59 (d, 1H, *J*_{gem} = 11.5 Hz, *H*-2'), 4.67 (d, 1H, *J*_{4,5} = 6.0 Hz, *H*-4), 4.90 (dd, 1H, *J*_{5,6} = 4.0 Hz, *H*-5), 5.06 (d, 1H, *H*-2'). ¹³C NMR (CDCl₃, 62.9 MHz): δ = 24.5 (CH₃), 25.8 (CH₃), 36.3 (*C*-2), 52.0 (OCH₃), 61.0 (*C*-7), 76.0 (*C*-2'), 79.7, 81.4, 83.7 (*C*-4, *C*-5, *C*-6), 83.3 (*C*-3), 113.6 (C(CH₃)₂), 171.1 (C=O). ESI-HRMS [M+Na]⁺ *m/z* = found 328.1014 (calculated for C₁₂H₁₉NO₈Na: 328.1003). IR (NaCl) $\nu_{\max}/\text{cm}^{-1}$ 3507, 2985, 2943, 1735, 1553

Compound 14

Compound **12** (5.10 g, 15.9 mmol) was saponified by LiOH (general procedure B) to provide **13** (4.78 g, 98% yield). Compound **13** (4.78 g, 15.6 mmol) was coupled with H-L-Lys(Boc)-OMe following procedure A to provide **14** (7.72 g, 90 %). Colorless oil. *R_f* = 0.21 (cH/EA: 3/7). [α]_D = -22.0° (c 0.4 in CHCl₃). ¹H NMR (CDCl₃, 250 MHz): δ = 1.25-1.54 (m, 4H, 2 CH₂ lys), 1.32 (s, 3H, CH₃), 1.43 (s, 9H, C(CH₃)₃ boc), 1.51 (s, 3H, CH₃), 1.66-1.90 (m, 2H, CH₂ lys), 2.77 (d, 1H, *J*_{gem} = 16.0 Hz, *H*-2), 2.99-3.12 (m, 3H, *H*-2, CH₂ lys), 3.75 (s, 3H, OCH₃), 3.80-3.92 (m, 2H, 2 *H*-7), 4.13 (m, 1H, *H*-6), 4.51-4.64 (m, 3H, *H*-2', *H*- α , NHBoc), 4.79 (d, 1H, *J*_{4,5} = 6.0 Hz, *H*-4), 4.92 (dd, 1H, *J*_{5,6} = 4.0 Hz, *H*-5), 5.09 (d, 1H, *J*_{gem} = 12.0 Hz, *H*-2'), 6.49 (d, 1H, *J* = 8.0 Hz, NH). ¹³C NMR (CDCl₃, 62.9 MHz): δ = 22.4 (CH₂ lys), 24.3 (CH₃), 25.8 (CH₃), 28.4 (C(CH₃)₃ boc), 29.5 (CH₂ lys), 31.9 (CH₂ lys), 38.5 (*C*-2), 40.4 (CH₂ lys), 52.0, 52.5 (*C*- α , OCH₃), 61.2 (*C*-7), 76.7 (*C*-2'), 79.9, 81.5 (C(CH₃)₃ boc, *C*-5, *C*-6), 83.4 (*C*-3), 83.9 (*C*-4), 113.3 (C(CH₃)₂), 156.2 (C=O boc), 169.4 (C=O), 172.7 (C=O lys). ESI-HRMS [M+Na]⁺ *m/z* = found 556.2485 (calculated for C₂₃H₃₉N₃O₁₁Na: 556.2477). IR (NaCl) $\nu_{\max}/\text{cm}^{-1}$ 3364, 2981, 2933, 2867, 1742, 1690, 1666, 1551, 1529

Compound 16

Compound **14** (3.85 g, 7 mmol) was deprotected according to general procedure C to provide amine **15** (3.52 g, 7 mmol, 99%) which was then protected with a benzyloxycarbonyl group. The crude was suspended in CH₂Cl₂ (30 mL) and DIEA (2.18 mL, 12.6 mmol, 1.8 eq.) followed by Cbz-Cl (1.5 mL, 10.5 mmol, 1.5 eq.) were added at 0°C. The reaction mixture was allowed to warm to room temperature and stirred overnight. Solvent was removed under vacuum and the residue was dissolved in ethyl acetate (40 mL), washed with 0.5M HCl (20 mL) and brine (20 mL). The organic layer was dried over MgSO₄, filtered and concentrated. The residue was purified by column chromatography (silica gel, cyH/EA) to provide **16** (3.12 g, 70%). Colorless oil. *R*_f = 0.08 (cH/EA: 1/1). [α]_D = -1.8° (c 0.5 in CHCl₃). ¹H NMR (CDCl₃, 250 MHz): δ = 1.28-1.58 (m, 4H, 2 CH₂ lys), 1.34 (s, 3H, CH₃), 1.47 (s, 9H, C(CH₃)₃ boc), 1.54 (s, 3H, CH₃), 1.66-1.92 (m, 2H, CH₂ lys), 2.38 (br s, 1H, OH), 2.63 (d, 1H, *J*_{gem} = 14.0 Hz, *H*-2), 2.72 (d, 1H, *H*-2), 3.08-3.15 (m, 2H, CH₂ lys), 3.22 (dd, 1H, *J*_{gem} = 15.0, *J*_{2',NH} = 6.5 Hz, *H*-2'), 3.46 (dd, 1H, *J*_{2',NH} = 7.5 Hz, *H*-2'), 3.74 (s, 3H, OCH₃), 3.84-3.96 (m, 2H, 2 *H*-7), 4.15 (m, 1H, *H*-6), 4.54 (m, 1H, *H*-α), 4.63 (d, 1H, *J*_{4,5} = 5.5 Hz, *H*-4), 4.70 (t, 1H, *J* = 5.0 Hz, *NH* Boc), 4.89 (dd, 1H, *J*_{5,6} = 4.5 Hz, *H*-5), 5.08 (d, 1H, *J*_{gem} = 13.0 Hz, *CH*-Ph), 5.15 (d, 1H, *CH*-Ph), 5.78 (m, 1H, *NH* Cbz), 6.98 (d, 1H, *J* = 7.5 Hz, *NH*), 7.33-7.41 (m, 5H, 5 *H*-Ar). ¹³C NMR (CDCl₃, 62.9 MHz): δ = 22.5 (CH₂ lys), 24.3 (CH₃), 25.8 (CH₃), 28.4 (C(CH₃)₃ boc), 29.5 (CH₂ lys), 31.8 (CH₂ lys), 40.1, 40.4 (*C*-2, CH₂ lys), 42.9 (*C*-2'), 52.2, 52.5 (*C*-α, OCH₃), 61.5 (*C*-7), 66.9 (CH₂-Ph), 79.4, 81.7 (C(CH₃)₃ boc, *C*-5, *C*-6), 83.7, 84.9 (*C*-3, *C*-4), 113.0 (C(CH₃)₂), 128.0 (2 *C*-Ar), 128.1 (*C*-Ar), 128.5 (2 *C*-Ar), 136.4 (*C*-Ar), 156.3, 156.9 (C=O Boc, C=O Cbz), 170.9 (C=O), 172.9 (C=O lys). ESI-HRMS [M+Na]⁺ *m/z* = found 660.3112 (calculated for C₃₁H₄₇N₃O₁₁Na: 660.3103). IR (NaCl) ν_{max}/cm⁻¹ 3345, 2976, 2933, 2867, 1709, 1662, 1525

Compound 18

Compound **14** was converted to amine **15** by catalytic hydrogenolysis (procedure C) and acid **17** was obtained by saponification of compound **16** (procedure B). Amine **15** (1.14 g, 2.2 mmol, 1.1 eq.) and acid **17** (1.28 g, 2 mmol, 1 eq.) were coupled according to procedure A to provide **18** (1.53 g, 69%). White foam. *R*_f = 0.6 (EA/MeOH: 9/1). [α]_D = +1.6° (c 0.2 in CHCl₃); ¹H NMR (CDCl₃, 400 MHz): δ = 1.30-1.54 (m, 8H, 4 CH₂ lys), 1.31 (s, 6H, 2 CH₃), 1.45 (s, 18H, 2 C(CH₃)₃ boc), 1.48 (s, 3H, CH₃), 1.51 (s, 3H, CH₃), 1.63-1.86 (m, 4H, 2 CH₂ lys), 2.50-2.77 (m, 6H, 2 OH, 4 *H*-2), 3.03-3.18 (m, 5H, 2 CH₂ lys, *H*-2'), 3.25 (dd, 1H, *J*_{gem} = 15.0, *J*_{2',NH} = 5.5 Hz, *H*-2'), 3.51 (dd, 1H, *J*_{gem} = 15.0, *J*_{2',NH} = 8.0 Hz, *H*-2'), 3.58 (dd, 1H, *J*_{gem} = 14.5, *J*_{2',NH} = 7.0 Hz, *H*-2'), 3.75 (s, 3H, OCH₃), 3.82-3.88 (m, 4H, 4 *H*-7), 4.13-4.18

(m, 2H, 2 *H*-6), 4.31 (m, 1H, *H*- α), 4.41-4.48 (m, 2H, *H*- α , *H*-4), 4.69 (d, 1H, $J_{4,5} = 5.5$ Hz, *H*-4), 4.79-4.88 (m, 4H, 2 *H*-5, 2 *NH* Boc), 5.07 (d, 1H, $J_{\text{gem}} = 13.0$ Hz, *CH*-Ph), 5.16 (d, 1H, *CH*-Ph), 6.43 (m, 1H, *NH* sucre), 7.15 (m, 1H, *NH* lys), 7.24 (m, 1H, *NH* lys), 7.31-7.41 (m, 6H, 5 *H*-Ar, *NH* sucre). ^{13}C NMR (CDCl_3 , 100 MHz): $\delta = 22.7, 22.9$ (2 CH_2 lys), 24.2, 24.3 (2 CH_3), 25.8 (2 CH_3), 28.4 (2 $\text{C}(\text{CH}_3)_3$), 29.5, 29.6 (2 CH_2 lys), 30.8, 31.5 (2 CH_2 lys), 39.6, 40.1, 40.7 (2 *C*-2, *C*-2', 2 CH_2 lys), 42.9 (*C*-2'), 52.7 (*C*- α , OCH_3), 53.8 (*C*- α), 61.4, 61.7 (2 *C*-7), 66.8 (CH_2 -Ph), 79.2, 79.3 (2 $\text{C}(\text{CH}_3)_3$), 79.9 (2 *C*-6), 81.2, 81.5 (2 *C*-5), 83.6, 84.0 (2 *C*-4), 85.0 (2 *C*-3), 112.9 (2 $\text{C}(\text{CH}_3)_2$), 128.0 (2 *C*-Ar), 128.1 (*C*-Ar), 128.5 (2 *C*-Ar), 136.5 (*C*-Ar), 156.2 (2 *C*=O Boc), 157.3 (*C*=O Cbz), 171.0, 171.6, 172.9, 173.9 (4 *C*=O). ESI-HRMS $[\text{M}+\text{Na}]^+$ $m/z =$ found 1131.5654 (calculated for $\text{C}_{53}\text{H}_{84}\text{N}_6\text{O}_{19}\text{Na}$: 1131.5683). IR (NaCl) $\nu_{\text{max}}/\text{cm}^{-1}$ 3336, 2976, 2933, 2862, 1692, 1655, 1525

Compound 19

Compound **18** was deprotected by catalytic hydrogenation (procedure C) and the corresponding amine (1.32 mg, 1.35 mmol, 1.1 eq.) was coupled with acid **17** (787 mg, 1.23 mmol, 1 eq.) according to procedure A to provide **19** (914 mg, 47% yield). White solid. Mp = 117 °C. $R_f = 0.39$ (EA/MeOH: 9/1). $[\alpha]_D = +1.2^\circ$ (c 0.4 in CHCl_3). ^1H NMR (CDCl_3 , 400 MHz): $\delta = 1.23$ -1.53 (m, 12H, 6 CH_2 lys), 1.28 (s, 3H, CH_3), 1.31 (s, 6H, 2 CH_3), 1.45 (s, 27H, 3 $\text{C}(\text{CH}_3)_3$ boc), 1.50 (s, 9H, 3 CH_3), 1.60-1.89 (m, 6H, 3 CH_2 lys), 2.42-2.60 (m, 3H, 3 *H*-2), 2.75-2.87 (m, 3H, 3 *H*-2), 3.03-3.19 (m, 7H, 3 CH_2 lys, *H*-2'), 3.26 (dd, 1H, $J_{\text{gem}} = 14.0$, $J_{2',\text{NH}} = 4.0$ Hz, *H*-2'), 3.35 (dd, 1H, $J_{\text{gem}} = 14.0$, $J_{2',\text{NH}} = 4.0$ Hz, *H*-2'), 3.46-3.56 (m, 2H, 2 *H*-2'), 3.65 (m, 1H, *H*-2'), 3.76 (s, 3H, OCH_3), 3.80-3.90 (m, 6H, 6 *H*-7), 4.13-4.21 (m, 4H, 3 *H*-6, *H*- α), 4.39-4.55 (m, 5H, 2 *H*- α , 2 *H*-4, *NH* Boc), 4.67 (d, 1H, $J_{4,5} = 6.0$ Hz, *H*-4), 4.81-4.96 (m, 5H, 3 *H*-5, 2 *NH* Boc), 5.07 (d, 1H, $J_{\text{gem}} = 12.0$ Hz, *CH*-Ph), 5.15 (d, 1H, *CH*-Ph), 6.47 (m, 1H, *NH*), 7.12 (m, 1H, *NH*), 7.31-7.43 (m, 8H, 5 *H*-Ar, 3 *NH*), 7.93 (m, 1H, *NH*). ^{13}C NMR (CDCl_3 , 100 MHz): $\delta = 22.7, 22.8$ (3 CH_2 lys), 24.3, 24.4 (3 CH_3), 25.8, 25.9 (3 CH_3), 28.5 (3 $\text{C}(\text{CH}_3)_3$), 29.4, 29.6, 29.7 (3 CH_2 lys), 30.9, 31.2, 31.7 (3 CH_2 lys), 39.6, 40.2, 40.3, 41.0, 42.7 (3 *C*-2, 3 *C*-2', 3 CH_2 lys), 52.5, 52.7 (*C*- α , OCH_3), 53.3 (*C*- α), 54.3 (*C*- α), 61.4, 61.7 (3 *C*-7), 66.8 (CH_2 -Ph), 79.1 (3 $\text{C}(\text{CH}_3)_3$), 79.7, 80.0, 80.3 (3 *C*-6), 81.3, 81.4, 81.6 (3 *C*-5), 83.7, 84.0, 84.2, 84.3, 84.9 (3 *C*-3, 3 *C*-4), 112.8 (2 $\text{C}(\text{CH}_3)_2$), 112.9 ($\text{C}(\text{CH}_3)_2$), 128.1 (2 *C*-Ar), 128.5 (3 *C*-Ar), 136.6 (*C*-Ar), 156.2 (3 *C*=O Boc), 157.2 (*C*=O Cbz), 170.8, 171.4, 171.6, 172.9, 173.2, 173.9 (6 *C*=O). ESI-HRMS $[\text{M}+\text{H}]^+$ $m/z =$ found 1580.8481 (calculated for $\text{C}_{75}\text{H}_{122}\text{N}_9\text{O}_{27}$: 1580.8445). IR (NaCl) $\nu_{\text{max}}/\text{cm}^{-1}$ 3331, 2981, 2933, 2867, 1692, 1655, 1525

Compound 20

Compound **19** was saponified (procedure B) and deprotected by catalytic hydrolysis (procedure C). To a solution of deprotected glyco-amino acid (573 mg, 0.4 mmol, 1 eq.) in CH₂Cl₂/DMF (4/1) at 0°C under argon, were added DIEA (346 μL, 2.0 mmol, 5.0 eq.) and HATU (182 mg, 0.48 mmol, 1.2 eq.). After stirring at room temperature for 3 days, the solvents were evaporated and the residue was taken up in ethyl acetate (30 mL). The solution was washed with brine (10 mL), dried over MgSO₄, filtered and concentrated. The product was purified by column chromatography (silica gel, AcOEt/MeOH) to provide **20** (123 mg, 22% yield). White foam. *R*_f = 0.24 (EtOAc/MeOH : 95/5). [α]_D = -20.7° (c 0.2 in CHCl₃). ¹H (MeOH-d₄, 250 MHz): 1.27-1.50 (m, 4H, 2 CH₂ lys), 1.30 (s, 3H, CH₃), 1.44 (s, 9H, C(CH₃)₃ boc), 1.46 (s, 3H, CH₃), 1.66 (m, 1H, CH₂ lys), 1.81 (m, 1H, CH₂ lys), 2.63 (d, 1H, *J*_{gem} = 14.0 Hz, *H*-2), 2.69 (d, 1H, *H*-2), 3.00-3.07 (m, 2H, CH₂ lys), 3.29 (m, 1H, *H*-2'), 3.66-3.76 (m, 2H, *H*-2', *H*-7), 3.82 (m, 1H, *J*_{gem} = 11.0, *J*_{6,7'} = 4.5 Hz, *H*-7'), 4.08 (m, 1H, *H*-6), 4.26 (m, 1H, *H*-α), 4.60 (d, 1H, *J*_{4,5} = 6.0 Hz, *H*-4), 4.87 (m, 1H, *H*-5). ¹³C (MeOH-d₄, 62.9 MHz): 24.3, 24.7 (CH₂ lys, CH₃), 26.3 (CH₃), 28.9 (C(CH₃)₃), 30.6 (CH₂ lys), 32.6 (CH₂ lys), 39.6 (*C*-2), 41.1, 41.2 (CH₂ lys, *C*-2'), 55.2 (*C*-α), 61.6 (*C*-7), 79.9 (*C*-6), 80.6 (C(CH₃)₃), 82.3 (*C*-5), 85.2 (*C*-4), 85.9 (*C*-3), 113.4 (C(CH₃)₂), 158.5 (C=O boc), 173.0, 175.1 (2 C=O). ESI-HRMS [M+Na]⁺ *m/z* = found 1436.7626 (calculated for C₆₆H₁₁₁N₉O₂₄Na: 1436.7634). IR (NaCl) ν_{max}/cm⁻¹ 3345, 2976, 2928, 2862, 1685, 1657, 1522, 1454

Compound 21

To a stirred solution of **8** (42 mg, 0.049 mmol) in H₂O (0.50 ml) at 0°C was added trifluoroacetic acid (0.50 ml). After completion of the reaction (TLC monitoring), the solvents were removed under reduced pressure and coevaporated with Et₂O (3x5 mL). The residue was purified by column chromatography (RP-18 silica gel, H₂O/MeOH) and lyophilized to provide **21** (35.6 mg, 99% yield).

White foam. *R*_f = 0.80 (H₂O/MeOH: 1/1). [α]_D = +14.5° (c 0.4 in H₂O). ¹H (D₂O, 250 MHz): δ = 1.57 (d, 3H, *J* = 7.0 Hz, CH₃ alanine), 2.88 (d, 1H, *J*_{gem} = 19.0 Hz, *H*-2), 3.04 (d, 1H, *H*-2), 3.67 (s, 2H, 2 *H*-2'), 3.79 (dd, 1H, *J*_{gem} = 9.5, *J*_{5,6} = 5.0 Hz, *H*-6), 4.13 (q, 1H, *H*-α), 4.17 (dd, 1H, *J*_{5,6'} = 6.0 Hz, *H*-6'), 4.54 (m, 1H, *H*-5), 4.96 (d, 1H, *J*_{4,5} = 5.0 Hz, *H*-4). ¹³C (D₂O, 62.9 MHz): δ = 16.6 (CH₃ alanine), 39.0, 43.2 (*C*-2, *C*-2'), 49.1 (*C*-α), 70.3, 70.4 (*C*-6, *C*-5), 84.6 (*C*-4), 87.2 (*C*-3), 114.0, 118.7 (TFA), 162.6, 163.2 (TFA), 171.4, 178.0 (2 C=O). ESI-HRMS [M+H]⁺ *m/z* = found 245.1165 (calculated for C₁₀H₁₇N₂O₅: 245.1132). IR (pellets) ν_{max}/cm⁻¹ 3383, 3255, 3094, 2995, 2938, 1782, 1678

Compound 22

To a stirred solution of **25** (488 mg, 1.2 mmol) in methanol (8 mL) was added HCl (0.8 mL) dropwise. After stirring at 50°C until completion of the reaction (2 h), the solvent was removed under reduced pressure. The residue was purified by column chromatography (silica gel, EA/MeOH) to provide **22** (259 mg, 82% yield). White solide. $R_f = 0.45$ (EA). mp 140°C (from diethyl ether). $[\alpha]_D = -25.1^\circ$ (c 0.1 in CH₃OH). ¹H NMR (CD₃OD, 400 MHz): $\delta = 2.93$ (d, 1H, $J_{gem} = 19.0$ Hz, *H*-2), 3.00 (d, 1H, *H*-2), 3.59 (dd, 1H, $J_{gem} = 11.5$ Hz, $J_{8a-7} = 6.0$ Hz, *H*-8), 3.65 (dd, 1H, $J_{8b-7} = 5.0$ Hz, *H*-8), 3.96 (app td, 1H, $J_{7-6} = J_{7-8b} = 5.0$ Hz, $J_{7-8a} = 6.0$ Hz, *H*-7), 4.07 (dd, 1H, $J_{6-5} = 4.0$ Hz, *H*-6), 4.49 (dd, 1H, $J_{5-4} = 5.0$ Hz, *H*-5), 4.88 (d, 1H, $J_{gem} = 14.0$ Hz, *H*-2'), 4.92 (d, 1H, *H*-2'), 5.14 (d, 1H, *H*-4). ¹³C NMR (CD₃OD, 100.6 MHz): $\delta = 41.30$ (*C*-2), 64.0 (*C*-8), 72.0 (*C*-7), 72.4 (*C*-5), 78.9 (*C*-2'), 83.9 (*C*-6), 84.7 (*C*-3), 85.8 (*C*-4), 176.7 (*C*=O). ESI-HRMS $[M+Na]^+$ $m/z =$ found 286.0463 (calculated for C₉H₁₃NNaO₈: 286.0539). IR (NaCl) ν_{max}/cm^{-1} 3343, 2949, 1730, 1647, 11548, 1436, 1375, 1207

Compound 24

To a stirred solution of **11** (503 mg, 1.5 mmol) in H₂O (3 mL) was added TFA (3 mL) dropwise at 0°C. After stirring at rt until completion of the reaction (6h), the solvent was removed under reduced pressure. The residue was co-evaporated with diethyl ether to provide **24** (438.4 mg, 99% yield). Colourless gum. $R_f = 0.40$ (MeOH/EA: 1/9). $[\alpha]_D = +14.9^\circ$ (c 0.1 in CH₃OH). ¹H NMR (CD₃OD, 400 MHz): $\delta = 2.93$ (d, 1H, $J_{gem} = 16.0$ Hz, *H*-2), 2.98 (d, 1H, *H*-2), 3.60 (dd, 1H, $J = 11.0$ Hz, $J = 5.5$ Hz, *H*-8), 3.66 (dd, 1H, $J = 11.0$ Hz, $J = 5.0$ Hz, *H*-8), 3.69 (s, 3H, *OCH*₃), 3.91 (app td, 1H, $J_{7-8a} = J_{7-6} = 5.5$ Hz, $J_{7-8b} = 5.0$ Hz, *H*-7), 4.04 (dd, 1H, $J_{6-7} = 5.5$ Hz; $J_{6-5} = 4.5$ Hz, *H*-6), 4.34 (app t, 1H, $J_{5-4} = J_{5-6} = 4.5$ Hz, *H*-5), 4.49 (d, 1H, *H*-4), 4.75 (d, 1H, $J_{gem} = 12.0$ Hz, *H*-2'), 5.10 (d, 1H, *H*-2'). ¹³C NMR (CD₃OD, 100.6 MHz) $\delta = 40.6$ (*C*-2), 52.2 (CH₃), 64.0 (*C*-8), 72.3 (*C*-7), 73.2 (*C*-5), 78.1 (*C*-4), 79.4 (*C*-2'), 81.8 (*C*-3), 82.1 (*C*-6), 172.3 (*C*=O). IR (NaCl) ν_{max}/cm^{-1} 3304, 2928, 1722, 1674, 1549, 1437, 1381, 1202.

Compound 25

Compound **10** was deprotected using general procedure B and the corresponding acide (1.30 g, 4.05 mmol, 1 eq.) was coupled with alanine methyl ester hydrochloride (905 mg, 1.6 eq, 6.48 mmol) following procedure A to provide **25** (658 mg, 40% yield). Yellow solide. $R_f = 0.55$ (EA). mp 70°C (from diethyl ether). $[\alpha]_D = -58.5^\circ$ (c 0.1 in CH₃OH). ¹H NMR (CD₃OD, 400 MHz): $\delta = 1.31$ (s, 3H, *CH*₃), 1.38 (d, 3H, $J_{CH_3ala-CHala} = 7.5$ Hz, *CH*₃ *ala*), 1.47 (s, 3H,

CH_3), 2.82 (d, 1H, $J_{gem} = 16.0$ Hz, $H-2$), 3.02 (d, 1H, $H-2$), 3.64 (dd, 1H, $J_{gem} = 11.5$ Hz, $J_{8a-7} = 5.5$ Hz, $H-8$), 3.72 (s, 3H, OCH_3), 3.73 (dd, 1H, $J_{8b-7} = 3.0$ Hz, $H-8$), 3.91 (ddd, 1H, $J_{7-6} = 7.5$ Hz, $H-7$), 4.01 (dd, 1H, $J_{6-5} = 3.5$ Hz, $H-6$), 4.43 (q, 1H, $J_{Hala-CH3ala} = 7.5$ Hz, $H-ala$), 4.68 (d, 1H, $J_{4-5} = 6.0$ Hz, $H-4$), 4.77 (d, 1H, $J_{gem} = 12.0$ Hz, $H-2'$), 4.89 (dd, 1H, $H-5$), 5.08 (d, 1H, $H-2'$). ^{13}C NMR (62.9 MHz, DMSO- D_6): $\delta = 17.1$ (CH_3 ala), 24.6 (CH_3), 25.9 (CH_3), 36.6 (C-2), 47.5 (C- α), 50.1 (OCH_3), 63.1 (C-8), 70.8 (C-7), 75.8 (C-2'), 80.1 (C-6), 80.7 (C-5), 82.8 (C-3), 83.5 (C-4), 111.5 (C(CH_3) $_2$), 169.3, 173.4 (2 C=O). ESI-HRMS $[M+Na]^+$ $m/z =$ found 429.1502 (calculated for $C_{16}H_{26}N_2NaO_{10}$: 429.1485). IR (NaCl) ν_{max}/cm^{-1} 3395, 2916, 1798, 1556, 1360, 1161.

Acknowledgments

This work was supported by The Région Lorraine and Institut Jean Barriol. The Ministère de l'Enseignement Supérieur et de la Recherche is acknowledged for PhD funding to M. Richard. We thank P. Lemièrre and F. Lachaud for technical assistance.

Electronic supplementary information

Copies of 1H and ^{13}C NMR spectra, experimental procedures and characterizations of intermediates obtained from minor anomer **11**.

References

- 1 D. J. Craik, D. P. Fairlie, S. Liras and D. Price, *Chemi. Biol. Drug Des.* **2013**, *81*, 136–147.
- 2 T. Szekely, O. Roy, S. Faure and C. Taillefumier, *Eur. J. Org. Chem.*, **2014**, *2014*, 5641–5657.
- 3 F. Giordanetto and J. Kihlberg, *J. Med. Chem.* **2014**, *57*, 278–295.
- 4 A. M. White and D. J. Craik, *Expert Opin. Drug Discov.*, **2016**, *11*, 1151–1163.
- 5 C. Pifferi, N. Berthet and O. Renaudet, *Biomater Sci.*, **2017**, *5*, 953–965.
- 6 M. A. T. Blaskovich, K. A. Hansford, M. S. Butler, Z. Jia, A. E. Mark and M. A. Cooper, *ACS Infect. Dis.*, DOI:10.1021/acsinfecdis.7b00258.
- 7 D. A. Evans, C. J. Dinsmore, P. S. Watson, M. R. Wood, T. I. Richardson, B. W. Trotter and J. L. Katz, *Angew. Chem. Int. Ed.*, **1998**, *37*, 2704–2708.
- 8 T. Mogi and K. Kita, *Cell. Mol. Life Sci.*, **2009**, *66*, 3821–3826.
- 9 M. A. Abdalla, *J. Nat. Med.*, **2016**, *70*, 708–720.
- 10 T. Velkov, K. D. Roberts and J. Li, *Nat. Prod. Rep.*, **2017**, *34*, 295–309.
- 11 W. Bauer, U. Briner, W. Doepfner, R. Haller, R. Huguenin, P. Marbach, T. J. Petcher and null Pless, *Life Sci.*, **1982**, *31*, 1133–1140.
- 12 R. Haubner, W. Schmitt, G. Hölzemann, S. L. Goodman, A. Jonczyk and H. Kessler, *J. Am. Chem. Soc.*, **1996**, *118*, 7881–7891.
- 13 T. G. Kapp, F. Rechenmacher, S. Neubauer, O. V. Maltsev, E. A. Cavalcanti-Adam, R. Zarka, U. Reuning, J. Notni, H.-J. Wester, C. Mas-Moruno, J. Spatz, B. Geiger and H. Kessler, *Sci. Rep.*, **2017**, *7*, 39805.

- 14 R. Chapman, M. Danial, M. L. Koh, K. A. Jolliffe and S. Perrier, *Chem. Soc. Rev.*, **2012**, *41*, 6023-6041.
- 15 N. Rodríguez-Vázquez, M. Amorín and J. R. Granja, *Org. Biomol. Chem.*, **2017**, *15*, 4490-4505.
- 16 A. Tapeinou, M.-T. Matsoukas, C. Simal and T. Tselios, *Biopolymers*, **2015**, *104*, 453-461.
- 17 D. J. Craik, J. E. Swedberg, J. S. Mylne and M. Cemazar, *Expert Opin. Drug Discov.*, **2012**, *7*, 179-194.
- 18 A. M. Webster and S. L. Cobb, *Chem. Eur J.*, DOI:10.1002/chem.201705340.
- 19 D. Arosio, L. Manzoni, C. Corno and P. Perego, *Recent Pat. Anticancer Drug Discov.*, **2017**, *12*, 148-168.
- 20 E. Valeur, S. M. Guéret, H. Adihou, R. Gopalakrishnan, M. Lemurell, H. Waldmann, T. N. Grossmann and A. T. Plowright, *Angew. Chem. Int. Ed.*, **2017**, *56*, 10294-10323.
- 21 R. Fransson, C. Sköld and A. Sandström, *Strategies for conversion of peptides to peptidomimetic drugs*, Ed by Vale, Nuno, in *Biomedical Chemistry*, **2015**, 245-274.
- 22 S. H. Joo, *Biomol. Ther.*, **2012**, *20*, 19-26.
- 23 E. Richard, C. Pifferi, M. Fiore, E. Samain, A. Le Gouëllec, S. Fort, O. Renaudet and B. Priem, *ChemBioChem*, **2017**, *18*, 1730-1734.
- 24 J. L. Jiménez Blanco, C. Ortiz Mellet and J. M. García Fernández, *Chem. Soc. Rev.*, **2013**, *42*, 4518-4531.
- 25 G. C. Daskhan, N. Berthet, B. Thomas, M. Fiore and O. Renaudet, *Carbohydr. Res.*, **2015**, *405*, 13-22.
- 26 P. Dumy, I. M. Eggleston, S. Cervigni, U. Sila, X. Sun and M. Mutter, *Tetrahedron Lett.*, **1995**, *36*, 1255-1258.
- 27 M. Galibert, O. Renaudet, P. Dumy and D. Boturyn, *Angew. Chem. Int. Ed.*, **2011**, *50*, 1901-1904.
- 28 I. Bossu, M. Šulc, K. Křenek, E. Dufour, J. Garcia, N. Berthet, P. Dumy, V. Křen and O. Renaudet, *Org. Biomol. Chem.*, **2011**, *9*, 1948-1959.
- 29 M. Fiore, N. Berthet, A. Marra, E. Gillon, P. Dumy, A. Dondoni, A. Imberty and O. Renaudet, *Org. Biomol. Chem.*, **2013**, *11*, 7113-7122.
- 30 J. W. Engle, H. Hong, Y. Zhang, H. F. Valdovinos, D. V. Myklejord, T. E. Barnhart, C. P. Theuer, R. J. Nickles and W. Cai, *Mol. Pharm.*, **2012**, *9*, 1441-1448.
- 31 M. C. Galan, P. Dumy and O. Renaudet, *Chem. Soc. Rev.*, **2013**, *42*, 4599-4612.
- 32 I. J. Krauss, J. G. Joyce, A. C. Finnefrock, H. C. Song, V. Y. Dudkin, X. Geng, J. D. Warren, M. Chastain, J. W. Shiver and S. J. Danishefsky, *J. Am. Chem. Soc.*, **2007**, *129*, 11042-11044.
- 33 T. Ohta, N. Miura, N. Fujitani, F. Nakajima, K. Niikura, R. Sadamoto, C.-T. Guo, T. Suzuki, Y. Suzuki, K. Monde and S.-I. Nishimura, *Angew. Chem. Int. Ed.*, **2003**, *42*, 5186-5189.
- 34 O. Renaudet, D. Boturyn and P. Dumy, *Synthesis and Biological Applications of Glycoconjugates*, **2011**, 129-144.
- 35 M. Richard, A.-S. Felten, C. Didierjean, M. Ruiz-Lopez, Y. Chapleur and N. Pellegrini-Moïse, *Eur. J. Org. Chem.*, **2014**, *33*, 7364-7376.
- 36 N. Pellegrini-Moïse, M. Richard and Y. Chapleur, in *Carbohydrate Chemistry*, Ed A. Pilar Rauter, T. Lindhorst and Y. Queneau, Royal Society of Chemistry, Cambridge, **2014**, vol. 40, pp. 99-117.
- 37 G. Enderlin, C. Taillefumier, C. Didierjean and Y. Chapleur, *J. Org. Chem.*, **2009**, *74*, 8388-8391.
- 38 M. Andreini, C. Taillefumier, F. Chrétien, V. Thery and Y. Chapleur, *J. Org. Chem.*, **2009**, *74*, 7651-7659.

- 39 M. Richard, A.-S. Felten, F. Chrétien, M.-C. Averlant-Petit and N. Pellegrini-Moïse, *Tetrahedron*, **2017**, *73*, 6795–6804.
- 40 A.-S. Felten, N. Pellegrini-Moïse, K. Selmeczi, B. Henry and Y. Chapleur, *Eur. J. Org. Chem.*, **2013**, *25*, 5645–5654.
- 41 V. Martí-Centelles, M. D. Pandey, M. I. Burguete and S. V. Luis, *Chem. Rev.*, **2015**, *115*, 8736–8834.
- 42 V. Popsavin, S. Grabež, M. Popsavin, I. Krstić, V. Kojić, G. Bogdanović and V. Divjaković, *Tetrahedron Lett.*, **2004**, *45*, 9409–9413.
- 43 A. Listkowski, O. Otman, S. Chambert and Y. Queneau, *Tetrahedron Lett.*, **2015**, *56*, 5051–5053.
- 44 K. . Ravikumar and D. Farquhar, *Tetrahedron Lett.*, **2002**, *43*, 1367–1368.
- 45 L. Schiavo, L. Jeanmart, S. Lanners, S. Choppin and G. Hanquet, *New J. Chem.*, **2017**, *41*, 1421–1424.