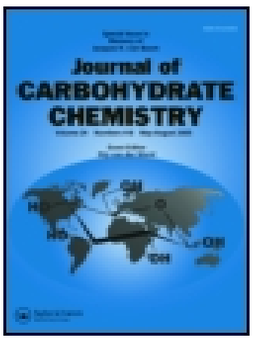

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Chemical synthesis of the *Pseudomonas aeruginosa* O11 O-antigen trisaccharide based on neighboring electron-donating effect

Chunjun Qin[a*], Zhonghua Liu[a*], Meiru Ding[a], Juntao Cai[a,b], Junjie Fu[a], Jing Hu[a,c], Peter H. Seeberger[b], and Jian Yin[a]

[a]Key Laboratory of Carbohydrate Chemistry and Biotechnology, Ministry of Education, School of Biotechnology, Jiangnan University, Wuxi, China; [b]Department of Biomolecular Systems, Max-Plank Institute of Colloids and Interfaces, Potsdam, Germany; [c]Wuxi School of Medicine, Jiangnan University, Wuxi, China

ABSTRACT

Pseudomonas aeruginosa O11 O-antigen is immunologically active but an exact protective epitope has not yet been identified. Synthesis of O11 O-antigen trisaccharide is of importance for identifying the epitopes. Here, neighboring electron-donating effects are keys to enhance the nucleophilicity of the C3 hydroxyl groups of D- and L-fucosamines, to facilitate the efficient synthesis of the trisaccharide. The disarmed peracetylated glycosyl donor with low glycosylation reactivity and glycosyl trifluoroacetimidate with good stability allowed for the glycosylation under mild conditions. The C6 nucleophilic tosylate substitution of D-galactose with iodine was found to be dependent on the steric effect of the axial C4.

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Chemical synthesis; *Pseudomonas aeruginosa*; O-antigen; protecting group; glycosylation

Introduction

Pseudomonas aeruginosa, a notorious opportunistic human nosocomial pathogen, causes acute infections such as bacteremia and pneumonia.[1] *Pseudomonas aeruginosa* infects about 51,000 patients in the US each year with a mortality rate of 5%.[2,3] In 2017, *P. aeruginosa* was ranked as a top priority pathogen in the WHO antibiotic-resistant bacteria priority list, highlighting the urgent need for vaccines.[4] Few experimental vaccines have reached clinical evaluation [e.g. lipopolysaccharide (LPS), flagella] but no vaccines have been licensed yet.[5]

Vaccine development has focused on the 20 serotypes of the LPS O-antigen of *P. aeruginosa*.[6] The O-antigen of *P. aeruginosa* serotype O11, the second most prevalent serotype in critically ill patients, has drawn the most attention.[2,6,7] The O11 O-antigen structure has been elucidated to consist of

CONTACT Jian Yin jianyin@jiangnan.edu.cn Key Laboratory of Carbohydrate Chemistry and Biotechnology, Ministry of Education, School of Biotechnology, Jiangnan University, Wuxi, China.
*These authors contributed equally to this work.

a trisaccharide repeating unit, [→2)-β-D-Glc*p*-(1→3)-α-L-Fuc*p*NAc-(1→3)-β-D-Fuc*p*NAc-(1→]. [8] Notably, the α-L-FucNAc-(1→3)-D-FucNAc unit is also a component of the capsular polysaccharides (CPS) of *Staphylococcus aureus* type 5 and 8, [9] *Acinetobacter baumannii* type K12, [10] K13, and K73. [11] A heptavalent *P. aeruginosa* O-antigen vaccine (serotypes O1, O2, O3, O5, O6, O10, and O11) induced a robust serotype-specific antibody response in mice and rabbits. [12] In addition, the attenuated *Salmonella* mutant strains expressing the *P. aeruginosa* O11 O-antigen protected mice from acute *P. aeruginosa* infection. [7,13] However, these experimental vaccines were limited by side effects associated with contaminants. [6] While the glucose residue proved to be essential for the epitopes of the O11 O-antigen, [14] it remains to be determined whether the α-L-FucNAc-D-FucNAc unit is immunogenic. Synthetic oligosaccharides offer an attractive means to procure vaccines free of contaminants. Well-defined oligosaccharides can facilitate epitope mapping as an essential step for vaccine design. [15] Intense efforts have been devoted to the synthesis of rare deoxy aminosugars as a basis for the construction of bacterial glycans. [16–27] The outcome of glycosylation reactions relies on the reactivities of the glycosyl donor and acceptor, that can be tuned by protecting group strategy based on conformational [28–31] and electronic effects, [32–35] and assembly sequence planning based on steric effect. [36–40] Recently, the Kulkarni group reported the first synthesis of the *P. aeruginosa* O11 trisaccharide O-antigen based on protecting group pattern tuning of the reactivities of glycosyl donors and acceptors (Fig. 1). [18]

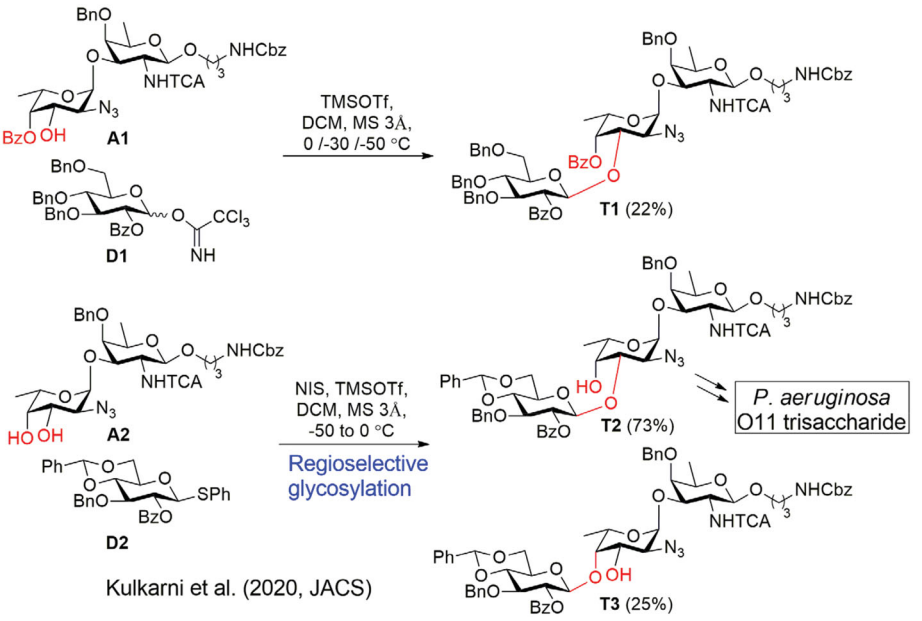


Figure 1. Previous synthesis of the *P. aeruginosa* O11 O-antigen trisaccharide via a regioselective glycosylation.

The inefficient glycosylation at *O*3 of acceptor **A1**, a regioselective glycosylation with the 3,4-diol **A2** smoothly afforded the 1→3 coupled trisaccharide **T2**, indicating that the protecting group pattern of 4-OH dramatically influences the reactivity of 3-OH in L-fucosamine. The syntheses of *S. aureus* type 5 and 8 CPS trisaccharides taught lessons on the successful glycosylation at *O*3 of D- and L-fucosamines. D-Fucosamine acceptors with three protecting group patterns 2-N_3-4-OBn-D-Fuc,[17,41–44] 2-NHTroc-4-OBn-D-Fuc[45] and 2-NHTCA-4-OBn-D-Fuc,[18] have been utilized to enhance the nucleophilicity of 3-OH group. Demchenko employed a 3-OH L-fucosamine acceptor bearing a 2-azido group and 4-*O*-benzyl group to smoothly install the (1→3) glycosidic bond.[43] Replacement of an electron-withdrawing acetyl group by an electron-donating 2-naphthylmethyl group at the 3-hydroxyl group significantly increased the reactivity of 4-OH in the L-fucosamine acceptor in the context of another synthesis.[46] Here, we report a synthesis of the conjugation-ready *P. aeruginosa* O11 O-antigen trisaccharide. The key to efficient glycosylation is the use of the neighboring electron-donating effect to enhance the nucleophilicity of the glycosyl acceptor. Facile synthetic routes to D-fucosamine and L-fucosamine building blocks from D-galactose and L-fucose are disclosed as well.

Results and discussion

An aminopropyl linker was placed at the reducing end of synthetic trisaccharide **1** for conjugation to carrier proteins or immobilization on glycan array surfaces (Fig. 2). Since the D-glucose residue in the O11 O-antigen is an essential part of the antigenic epitope,[14] trisaccharide **1** assembly started from the nonreducing end to facilitate the preparation of disaccharide containing β-D-glucose residue. Peracetylated glucose **5**, the most accessible building block, was chosen to enable the stereoselective formation of the β-glycosidic bond. D-Fucosamine **4** and L-fucosamine **6** were

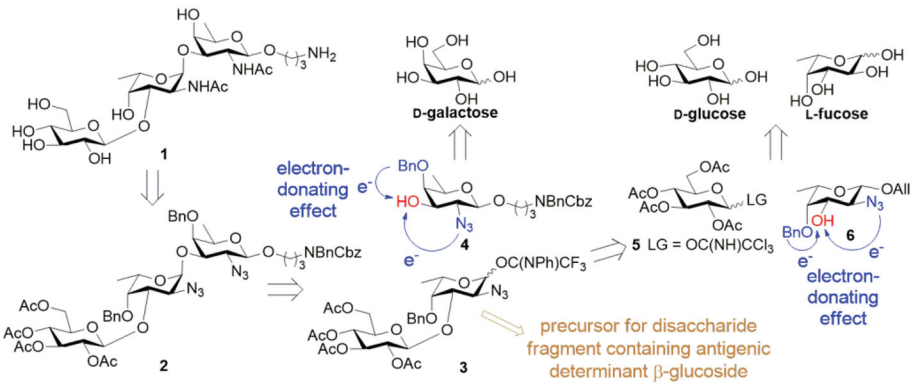
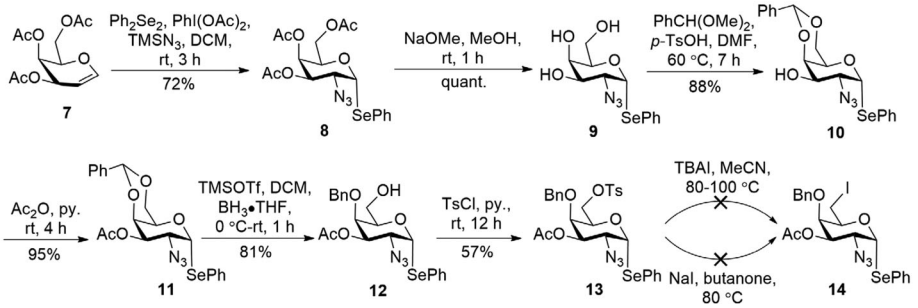


Figure 2. Retrosynthetic analysis of trisaccharide **1**.

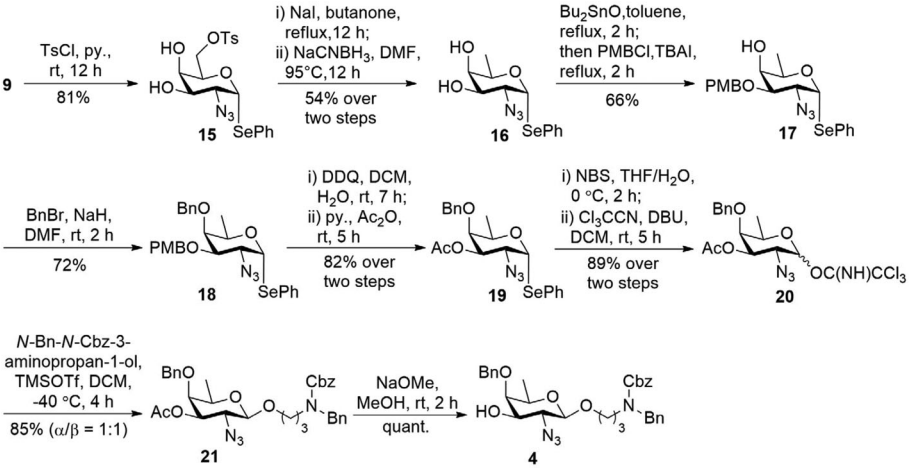
identified in retrosynthetic analysis, the electron-donating C2 azide and C4 benzyl ether were designed to increase the nucleophilicity of the adjacent C3 hydroxyl group. Particularly, the nonparticipating C2 azide of the L-fucosamine **6** would be beneficial for the stereoselective formation of the 1,2-*cis*-glycosidic bond. Various aminosugars have been prepared by chemical methods, including nucleophilic substitution suitable for amination at each position of the sugar ring,[19,21] and glycal addition specific to 2-aminosugars.[43,46] Glycal addition can simultaneously introduce a C1 protecting group and a C2 azide into peracetylated glycal, significantly improving the synthesis efficiency. Here, fucal addition was adapted to introduce a C2 azide into D-fucosamine **4** and L-fucosamine **6**. To shorten the reaction steps, an *O*1-allyl group in **6** was to be placed via fucal addition instead of conventional acid-catalyzed O-glycosylation. In addition to the synthesis procedure, the large-scale preparation of 6-deoxy aminosugars that are rare in nature,[46,47] has to take the cost of starting materials into account. Thus, L-fucose and D-galactose were chosen as starting materials.

D-Galactal **7**[48] derived from D-galactose served for the synthesis of D-fucosamine **4** (Scheme 1). Azidoselenation of **7** gave the C2 azide derivative **8**, which was converted to **11** by deacetylation, benzylidene acetal formation, and *O*3-acetylation. A regioselective reductive ring opening of the 4,6-*O*-benzylidene acetal of **11** using trimethylsilyl trifluoromethanesulfonate (TMSOTf)/borane tetrahydrofuran complex (BH_3•THF) afforded the 4-*O*-benzyl-6-hydroxy derivative **12** in 81% yield. Tosylation of **12** delivered 6-*O*-tosyl derivative **13** as a substrate for deoxygenation at C6. Since the presence of C2 azide precludes the use of strong reducing agents like lithium aluminum hydride, the iodination/reduction strategy that previously worked well for glucose stereoisomer[46] of **13** was employed. However, the treatment of **13** with tetrabutylammonium iodide (TBAI) or NaI at high temperatures (80–100 °C) failed to produce 6-iodide **14**.

In view of the steric hindrance effect of axial C4-OBn group of **13**, 6-*O*-tosyl derivative **15** derived from **9** by regioselective tosylation was employed



Scheme 1. Attempt to prepare 6-iodo-D-galactose **14**.

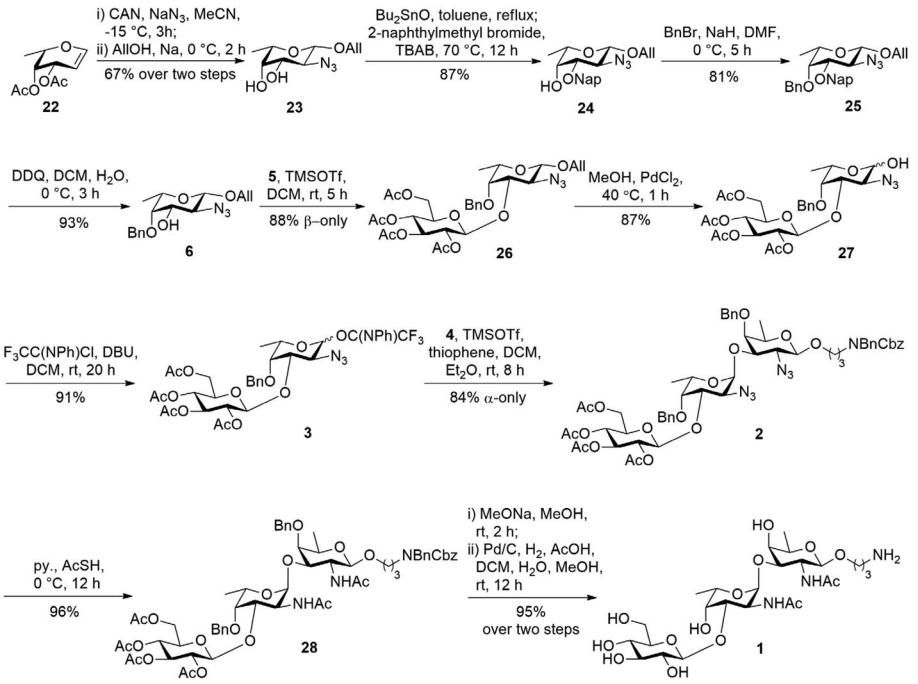


Scheme 2. Synthesis of D-fucosamine **4**.

(Scheme 2). Nucleophilic tosylate substitution with NaI in refluxing butanone and subsequent reduction with sodium cyanoborohydride furnished D-fucosamine **16** in 54% overall yield. The tin-mediated regioselective 4-methoxybenzylation at *O*3 of diol **16** was followed by *O*4 benzylation to deliver **18** in good yield. Considering the partial cleavage of 4-methoxybenzyl ether (PMB) during acid-mediated glycosylation reactions,[46] 3-*O*-acetyl derivative **19** was obtained by oxidative removal of the PMB group and subsequent acetylation in 82% overall yield. For the insertion of an aminopropyl linker, the hydrolyzed product of **19** was converted to donor **20** followed by TMSOTf-catalyzed glycosylation with *N*-Bn-*N*-Cbz-3-aminopropan-1-ol in DCM at −40 °C to give **21**. Deacetylation of **21** afforded D-fucosamine **4**.

The synthesis of the L-fucosamine **6** started from L-fucose via known L-fucal **22**[46] (Scheme 3). Azidonitration of **22** with sodium azide and ceric ammonium nitrate (CAN) at −15 °C and subsequent treatment with sodium and allyl alcohol gave **23** in 67% overall yield. The tin-mediated regioselective naphthylmethylation at *O*3 of the diol **23** was followed by *O*4 benzylation to afford **25** in good yield. Removal of 3-ONap with DDQ converted **25** to **6** in 93% yield.

Assembly of trisaccharide started from the nonreducing to the reducing end (Scheme 3). The union of glucosyl donor **5**[49] and L-fucosamine acceptor **6** in the presence of TMSOTf at room temperature furnished desired disaccharide **26** in 88% yield and complete β-selectivity (the anomeric proton of the donor residue: $^{3}J_{H1/H2} = 7.7$ Hz, $\delta_{H\text{-}1} = 4.77$ ppm). Notably, the relatively low glycosylation reactivity of disarmed peracetylated glycosyl donor **5** required higher reaction temperatures than that of



Scheme 3. Synthesis of trisaccharide **1**.

common trichloroacetimidate glycosylation conditions (−70 to −20 °C), facilitating the operation of the glycosylation reaction. The removal of the anomeric allyl group with $PdCl_2$ gave hemiacetal **27**, that was transformed to Yu donor **3** upon trifluoroacetimidation[50] in 79% overall yield. TMSOTf-catalyzed glycosylation of D-fucosamine acceptor **4** with Yu donor **3** in a blended solvents system including DCM, diethyl ether, and thiophene at room temperature lead to desired trisaccharide **2** in 84% yield and complete α-selectivity. The α-configuration of the newly formed glycosidic bond in **2** was confirmed by the anomeric proton $J_{C,H}$ coupling of 171 Hz. The exclusive α-glycosylation can be attributed to the nonparticipating C2 azide group in donor **3**, anomeric, and solvent effects. The utilization of glycosyl trifluoroacetimidate **3**, generally activated at 0 °C to room temperature,[37,51] helped to perform the glycosylation reaction under mild conditions. The protecting group patterns of L-fucosamine acceptor **6** and D-fucosamine acceptor **4** served well for enhancing their nucleophilicity. Subsequent azide reduction and *N*-acetylation of **2** using AcSH/pyridine afforded the corresponding acetamide derivative 28 in 96% yield. Finally, global deprotection of **28** with deacetylation and subsequent Pd/C hydrogenation afforded target trisaccharide **1** in 95% overall yield. The ^{1}H and ^{13}C NMR data of **1** is identical to the earlier reported data.[18]

Conclusion

Chemical synthesis of *P. aeruginosa* O11 O-antigen trisaccharide **1** was achieved. Rare D- and L-fucosamine acceptors **4** and **6**, designed based on the neighboring electron-donating effect, were prepared from D-galactose and L-fucose starting from glycal addition. The nucleophilic tosylate substitution at C6 of the D-galactose derivative containing an azido group for C6 deoxygenation was largely dependent upon the steric effect of the axial C4 position. The corresponding 6-iodine-D-galactose derivative was successfully obtained from 4-OH tosylate **15**, but not from 4-OBn tosylate **13**. The efficient assembly of trisaccharide **1** indicated that the electron-donating C2 azides and C4 benzyl ethers of L-fucosamine acceptor **6** and D-fucosamine acceptor **4** are important for enhancing the nucleophilicity of the adjacent C3 hydroxyl groups. Moreover, the disarmed peracetylated glycosyl donor **5** with relatively low glycosylation reactivity and glycosyl trifluoroacetimidate **3** (Yu donor) with good stability allowed for the glycosylation under mild conditions. An aminopropyl linker installed at the reducing end of **1** enables the further conjugation or immobilization, which may facilitate immunological evaluation of *P. aeruginosa* O11 O-antigen. The design of glycosyl acceptor based on neighboring electron-donating effect will be valuable for the syntheses of other complex glycans.

Experimental section

Materials and methods

Commercial reagents and solvents (analytical grade) were used without further purification, unless otherwise stated. The anhydrous solvents used in the reactions were obtained from an MBraun MB-SPS 800 Dry Solvent System. Analytical TLC was performed on silica gel 60-F254 precoated on glass plate. Spots were visualized with sugar stain (0.1% (*v*/*v*) 3-methoxyphenol, 2.5% (*v*/*v*) sulfuric acid in EtOH), CAM stain (5% (*w*/*v*) ammonium molybdate, 1% (*w*/*v*) cerium(II) sulfate, and 10% (*v*/*v*) sulfuric acid in water) dipping solutions. The normal phase column chromatography was performed on silica gel (200–300 mesh). Size exclusion chromatography (SEC) was performed using Sephadex® LH-20 (GE Healthcare). ^{1}H, ^{13}C, and two-dimensional NMR spectra were recorded on a Bruker Ultrashield Plus 400 MHz spectrometer at 25 °C. Optical rotations (OR) were measured with a Schmidt & Haensch UniPol L 1000 at 589 nm and a concentration (c) expressed in g/100 mL. High-resolution mass spectrometry was performed on an Agilent 6220 ESI-TOF mass spectrometer. IR spectra were recorded on Thermo Fisher Scientific Nicolet iS5 spectrometer.

Synthetic procedure for trisaccharide 1

Phenyl 2-azido-3,4,6-tri-*O*-acetyl-2-deoxy-1-seleno-α-D-galactopyranoside (8). D-Galactal **7**[48] (2.0 g, 7.35 mmol) was dissolved in anhydrous DCM (35 mL) and cooled to −30 °C under argon. Diphenyl diselenide (2.3 g, 7.37 mmol), (diacetoxyliodo) benzene (BAIB) (2.4 g, 7.45 mmol) and trimethylsilyl azide (1.8 mL, 13.69 mmol) were added. The solution was then allowed to warm to room temperature for 3 h. After the complete conversion of the starting material, the solution was extracted with satd. aq. $NaHCO_3$ (3 × 20 mL), combined the organic layer and dried over Na_2SO_4. The solvent was removed under vacuum and the residue was purified by silica gel column chromatography (petroleum ether: ethyl acetate 6: 1 *v/v*) to give compound **8** (2.5 g, 5.32 mmol, 72%). $[\alpha]_D^{20}$ = 931.7° (*c* = 1.00, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ = 7.78 − 7.11 (m, 5H, Ar-H), 6.01 (d, *J* = 5.4 Hz, 1H, 1-H), 5.47 (dd, *J* = 3.4, 1.4 Hz, 1H, 4-H), 5.12 (dd, *J* = 10.9, 3.3 Hz, 1H, 3-H), 4.67 (ddd, *J* = 7.1, 5.8, 1.3 Hz, 1H, 5-H), 4.26 (dd, *J* = 10.9, 5.4 Hz, 1H, 2-H), 4.08 (dd, *J* = 11.5, 5.9 Hz, 1H, 6-CH_2), 4.02 (dd, *J* = 11.4, 7.1 Hz, 1H, 6-CH_2), 2.15 (s, 3H, $COCH_3$), 2.07 (s, 3H, $COCH_3$), 1.98 (s, 3H, $COCH_3$); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 170.4, 170.0, 169.7, 134.9, 129.3, 128.3, 127.7, 84.2, 71.3, 69.1, 67.3, 61.6, 58.8, 29.8, 20.74, 20.71.

Phenyl 2-azido-4,6-*O*-benzylidene-2-deoxy-1-seleno-α-D-galactopyranoside (10). Compound **8** (0.5 g, 1.06 mmol) was dissolved in MeOH (2.2 mL). NaOMe (29 mg, 0.54 mmol) was added and the solution was stirred at room temperature for 1 h. The solution was neutralized with Amberlite IR 120 (H^+) ion exchange resin. The filtrate was evaporated to afford **9** (364 mg, 1.06 mmol, quant.). Compound **9** (364 mg, 1.06 mmol) was then dissolved in 2.2 mL anhydrous DMF under argon, followed by the addition of benzaldehyde dimethyl acetal (0.2 mL, 1.33 mmol) and *p*-TsOH (24 mg, 0.14 mmol) at room temperature. The reaction mixture was stirred at 60 °C for 7 h, DMF was removed under reduced pressure. The residue was diluted with ethyl acetate (3 mL) and washed with satd. aq. $NaHCO_3$ (3 × 5 mL). The aqueous phase was extracted with ethyl acetate (2 × 10 mL), and the combined organic phase was washed with brine (30 mL) and dried over Na_2SO_4. The crude residue was purified by silica gel column chromatography (petroleum ether: ethyl acetate 2: 1 *v/v*) to yield 10 (400 mg, 0.93 mmol, 88%). ^{1}H NMR (400 MHz, $CDCl_3$) δ = 7.70 − 6.95 (m, 10H, Ar-H), 6.04 (d, *J* = 5.0 Hz, 1H, 1-H), 5.61 (s, 1H, PhCH), 4.33 (dd, *J* = 3.7, 1.3 Hz, 1H, 3-H), 4.19 (dd, *J* = 7.0, 1.5 Hz, 1H, 6-CH_2), 4.17 (d, *J* = 1.3 Hz, 1H, 5-H), 4.16 − 4.12 (m, 1H, 2-H), 4.10 (dd, *J* = 12.9, 2.1 Hz, 1H, 6-CH_2), 3.94 (td, *J* = 10.2, 3.7 Hz, 1H, 3-H), 2.55 (d, *J* = 10.2 Hz, 1H, 3-OH); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 137.1, 133.8,

129.5, 129.2, 128.4, 127.8, 126.2, 101.4, 85.2, 77.2, 75.0, 70.7, 69.1, 65.1, 62.1.

Phenyl 2-azido-3-*O*-acetyl-4,6-*O*-benzylidene-2-deoxy-1-seleno-α-D-galactopyranoside (11). To a solution of compound **10** (400 mg, 0.93 mmol) in pyridine (1.9 mL) under argon, Ac_2O (0.34 mL, 3.60 mmol) was added dropwise at 0 °C. After stirring for 4 h at room temperature, the volatiles was evaporated under reduced pressure at 30 °C. The residue was co-evaporated with toluene to give product **11** (417 mg, 0.88 mmol, 95%). ^{1}H NMR (400 MHz, $CDCl_3$) $\delta = 7.88 - 7.21$ (m, 10H, Ar-H), 6.09 (d, $J = 5.2$ Hz, 1H, 1-H), 5.55 (s, 1H, PhCH), 5.07 (dd, $J = 10.8$, 3.4 Hz, 1H, 3-H), 4.52 (d, $J = 2.7$ Hz, 1H, 4-H), 4.50 (d, $J = 5.2$ Hz, 1H, 2-H), $4.17 - 4.16$ (m, 1H, 5-H), $4.15 - 4.11$ (m, 1H, 6-CH_2), 4.06 (dd, $J = 12.7$, 1.7 Hz, 1H, 6-CH_2), 2.17 (s, 3H, $COCH_3$).

Phenyl 2-azido-3-*O*-acetyl-4-*O*-benzyl-2-deoxy-1-seleno-α-D-galactopyranoside (12). Compound **11** (100 mg, 0.21 mmol) was co-evaporated with toluene and dissolved under argon in anhydrous DCM (2 mL). A 1 M solution of BH_3•THF (1.2 mL, 1.20 mmol) was added and the solution was cooled to 0 °C, TMSOTf (180 µL, 0.99 mmol) was added dropwise. The reaction mixture was stirred at room temperature for 1 h. The solution was diluted with DCM (3 mL) and extracted with satd. aq. $NaHCO_3$ (2×20 mL). The organic phase was dried over Na_2SO_4 and the solvent was removed under vacuum. The residue was purified by silica gel column chromatography (petroleum ether: ethyl acetate 8: 1 *v/v*) to give **12** (80 mg, 0.17 mmol, 81%). ^{1}H NMR (400 MHz, $CDCl_3$) $\delta = 7.89 - 7.07$ (m, 10H, Ar-H), 6.00 (d, $J = 5.4$ Hz, 1H, 1-H), 5.07 (dd, $J = 10.8$, 3.0 Hz, 1H, 3-H), 4.70 (d, $J = 11.5$ Hz, 1H, $PhCH_2$), 4.52 (d, $J = 11.5$ Hz, 1H, $PhCH_2$), 4.45 (dd, $J = 10.8$, 5.4 Hz, 1H, 2-H), 4.28 (dd, $J = 6.9$, 5.3 Hz, 1H, 5-H), 4.07 (dd, $J = 3.0$, 1.2 Hz, 1H, 4-H), 3.67 (dd, $J = 11.4$, 7.1 Hz, 1H, 6-CH_2), 3.49 (dd, $J = 11.4$, 5.0 Hz, 1H, 6-CH_2), 2.12 (s, 3H, $COCH_3$), 1.57 (s, 1H, 6-OH).

Phenyl 2-azido-3-*O*-acetyl-4-*O*-benzyl-2-deoxy-6-*O*-(*p*-toluenesulfonyl)-1-seleno-α-D-galactopyranoside (13). To a solution of **12** (68 mg, 0.14 mmol) in anhydrous pyridine (1 mL), *p*-toluene-sulfonyl chloride (68 mg, 0.36 mmol) was added under argon. The reaction mixture was stirred at room temperature for 12 h. The mixture was diluted with DCM (2 mL), washed with 1 M aq. HCl (2×3 mL), satd. aq. $NaHCO_3$ (3×5 mL) and water (2×5 mL). The combined organic phase was dried (Na_2SO_4) and concentrated. The residue was purified by silica gel column chromatography (petroleum ether: ethyl acetate 4: 1 *v/v*) to give product **13** (48 mg, 0.08 mmol, 57%). ^{1}H NMR (400 MHz, $CDCl_3$) $\delta = 7.88 - 7.14$ (m, 14H, Ar-H), 5.85 (d, $J = 5.3$ Hz, 1H, 1-H), 4.98 (dd, $J = 10.8$, 2.9 Hz, 1H, 3-H), 4.63 (d, $J = 11.3$ Hz, 1H, $PhCH_2$), 4.48 (td, $J = 6.4$, 1.3 Hz, 1H, 5-H), 4.44 (d, $J = 11.3$ Hz, 1H, $PhCH_2$), 4.35 (dd, $J = 10.8$, 5.4 Hz, 1H, 2-H), 4.03

(dd, $J = 3.0$, 1.2 Hz, 1H, 4-H), 3.98 (dd, $J = 10.1$, 6.3 Hz, 1H, 6-CH_2), 3.90 (dd, $J = 10.1$, 6.5 Hz, 1H, 6-CH_2), 2.42 (s, 3H, CH_3), 2.10 (s, 3H, CH_3); ^{13}C NMR (100 MHz, $CDCl_3$) $\delta = 169.9$, 145.1, 137.1, 135.1, 132.4, 129.9, 129.2, 128.6, 128.2, 128.04, 127.97, 127.4, 84.4, 75.3, 73.7, 73.4, 70.1, 67.1, 59.0, 21.7, 20.8.

Phenyl 2-azido-2-deoxy-6-*O*-(*p*-toluenesulfonyl)-1-seleno-α-D-galactopyranoside (15). The trihydroxygalatose **9** (327 mg, 0.95 mmol) was dissolved in anhydrous pyridine (8 mL), then *p*-toluene-sulfonyl chloride (253 mg, 1.33 mmol) was added under nitrogen. The reaction mixture was stirred at room temperature for 12 h. When the starting material was consumed completely, the solution was diluted by DCM (10 mL) and treated with 1 M aq. HCl (2 × 20 mL) and washed with satd. aq. $NaHCO_3$ (3 × 20 mL) and water (2 × 20 mL). Combined the organic layer and dried over Na_2SO_4. The residue was concentrated *in vacuo* and then purified by column chromatography on silica gel (DCM: MeOH 200: 1, *v/v*) to yield **15** (384 mg, 0.77 mmol, 81%). $[\alpha]_D^{20} = 133.6°$ (c = 1.00, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) $\delta = 7.72$ (d, $J = 8.3$ Hz, 2H, Ar-H), 7.58 (dt, $J = 6.7$, 1.6 Hz, 2H, Ar-H), 7.36 − 7.23 (m, 5H, Ar-H), 5.86 (d, $J = 5.3$ Hz, 1H, 1-H), 4.57 − 4.50 (m, 1H, 5-H), 4.29 (dd, $J = 10.6$, 6.0 Hz, 1H, 6-CH_2), 4.10 − 3.93 (m, 3H, 2-H, 4-H, 6-CH_2), 3.78 (ddd, $J = 9.8$, 6.0, 3.3 Hz, 1H, 3-H), 2.68 (dd, $J = 6.5$, 4.8 Hz, 2H, 3-OH, 4-OH), 2.44 (s, 3H, CH_3); ^{13}C NMR (100 MHz, $CDCl_3$) $\delta = 145.2$, 135.0, 132.4, 132.1, 132.0, 129.9, 129.2, 128.8, 128.7, 128.2, 128.0, 127.7, 84.6, 77.2, 70.6, 70.0, 67.9, 67.6, 61.6, 21.7.

Phenyl 2-azido-2-deoxy-1-seleno-α-D-fucopyranoside (16). Tosylate compound 15 (380 mg, 0.76 mmol) was refluxed for 12 h in butanone (10 mL) together with NaI (568 mg, 3.79 mmol) under nitrogen. When the TLC showed the starting material was complete, the reaction mixture was cooled to room temperature and diluted with ethyl acetate (10 mL) and then washed with 1 M aq. $Na_2S_2O_3$ (2 × 30 mL) and water (2 × 30 mL). Combine the organic layer, dried with Na_2SO_4, and concentrated *in vacuo*. The residue was purified by column chromatography on silica gel (petroleum ether: ethyl acetate 5: 1 *v/v*) to yield iodide compound **15a** (259 mg, 0.57 mmol, 75%). $[\alpha]_D^{20} = 317.6°$ (c = 1.00, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) $\delta = 7.65 - 7.63$ (m, 2H, Ar-H), 7.33 − 7.29 (m, 3H, Ar-H), 5.96 (d, $J = 5.3$ Hz, 1H, 1-H), 4.41 (m, 1H, 5-H), 4.28 (d, $J = 3.7$ Hz, 1H, 4-H), 4.09 (dd, $J = 10.2$, 5.3 Hz, 1H, 2-H), 3.79 (ddd, $J = 9.9$, 6.1, 3.3 Hz, 1H, 3-H), 3.37 (dd, $J = 12.7$, 8.2 Hz, 1H, 6-Ha), 3.20 (dd, $J = 12.7$, 6.0 Hz, 1H, 6-Hb), 2.55 (d, $J = 6.2$ Hz, 1H, 3-OH), 2.35 (d, $J = 3.9$ Hz, 1H, 4-OH).

Then to a solution of the iodide compound **15a** (259 mg, 0.57 mmol) in anhydrous DMF (15 mL), sodium cyanoborohydride (182 mg, 2.90 mmol) was added. The reaction mixture was heated to 95 °C and stirred for 12 h. When the TLC showed the starting material consumed completely, the

reaction mixture was cooled to room temperature and then quenched with water (2 mL), extracted with ethyl acetate (2 × 10 mL). Separated organic phase and washed with water (3 × 30 mL). The organic layer was dried over Na_2SO_4, filtered, and concentrated *in vacuo*. The residue was purified by silica gel column chromatography (petroleum ether: ethyl acetate 1: 1 *v/v*) to afford **16** (133 mg, 0.41 mmol, 72%). $[\alpha]_D^{20}$ =259.4° (c = 1.00, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ = 7.73 − 7.45 (m, 2H, Ar-H), 7.40 − 6.93 (m, 3H, Ar-H), 5.92 (d, J = 5.3 Hz, 1H, 1-H), 4.39 (dt, J = 7.4, 6.0 Hz, 1H, 5-H), 4.05 (dd, J = 10.0, 5.3 Hz, 1H, 2-H), 3.91 − 3.74 (m, 2H, 3-H, 4-H), 2.60 (d, J = 6.3 Hz, 1H, 3-OH), 2.26 (d, J = 4.0 Hz, 1H, 4-OH), 1.27 (d, J = 6.6 Hz, 3H, 6-CH_3); ^{13}C NMR (100 MHz, $CDCl_3$) δ = 134.5, 129.2, 127.9, 85.0, 77.2, 71.5, 71.3, 68.7, 61.9, 16.0; HR-ESI-MS m/z: $[M + Na]^+$ Calcd for $C_{12}H_{15}N_3O_3SeNa^+$ 346.0230; Found 346.0226.

Phenyl 2-azido-3-*O*-methoxybenzyl-2-deoxy-1-seleno-α-D-fucopyranoside (17). Compound **16** (3 g, 9.14 mmol) was dissolved in anhydrous toluene (54 mL) and dibutyltin oxide (3.5 g, 14.06 mmol) was added under argon. The reaction mixture was heated to 118 °C and refluxed for 2 h. Then the solution was cooled to 60 °C, 4-methoxybenzylchloride (1.9 mL, 14.01 mmol) and tetrabutylammonium iodide (5.1 g, 13.81 mmol) was added and refluxed for 2 h. The solution was cooled to room temperature, diluted with ethyl acetate (80 mL), and washed with water (2 × 100 mL). The organic phase was dried over Na_2SO_4 and concentrated under reduced pressure. The residue was purified by column chromatography on silica gel (petroleum ether: ethyl acetate 6: 1 *v/v*) to afford the compound **17** (2.7 g, 6.02 mmol, 66%). $[\alpha]_D^{20}$ = 137.9° (c = 1.00, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ = 7.60 − 7.52 (m, 2H, Ar-H), 7.33 (d, J = 8.6 Hz, 2H, Ar-H), 7.28 (dd, J = 5.0, 2.0 Hz, 3H, Ar-H), 6.92 (d, J = 8.6 Hz, 2H, Ar-H), 5.88 (d, J = 5.4 Hz, 1H, 1-H), 4.70 (d, J = 11.0 Hz, 1H, $PhCH_2$), 4.63 (d, J = 11.0 Hz, 1H, $PhCH_2$), 4.36 − 4.24 (m, 1H, 5-H), 4.15 (dd, J = 10.2, 5.3 Hz, 1H, 2-H), 3.86 (dt, J = 3.2, 1.5 Hz, 1H, 4-H), 3.82 (s, 3H, CH_3), 3.69 (dd, J = 10.2, 3.2 Hz, 1H, 3-H), 2.35 (t, J = 1.6 Hz, 1H, 4-OH), 1.26 (d, J = 6.6 Hz, 3H, 6-CH_3); ^{13}C NMR (100 MHz, $CDCl_3$) δ = 159.7, 134.4, 129.8, 129.10, 129.08, 127.8, 114.1, 85.3, 78.9, 71.8, 68.61, 68.55, 60.2, 55.3, 16.1; HR-ESI-MS m/z: $[M + Na]^+$ Calcd for $C_{20}H_{23}N_3O_4SeNa^+$ 472.0751; Found 472.0725.

Phenyl 2-azido-4-*O*-benzyl-3-*O*-methoxybenzyl-2-deoxy-1-seleno-α-D-fucopyranoside (18). Compound **17** (2.2 g, 4.91 mmol) was dissolved in anhydrous DMF (30 mL) and cooled to 0 °C for 30 min. Sodium hydride (235 mg, 9.79 mmol) was added and kept in ice bath for 30 min. Benzyl bromide (1.2 mL, 10.10 mmol) was added dropwise and the solution was allowed to warm to room temperature for 2 h. After the complete conversion of the starting material, the reaction mixture was diluted with DCM (80 mL) and then quenched with water (50 mL). Extracted with DCM

(3 × 100 mL) and brine (100 mL), the organic phase was separated, dried over Na_2SO_4 and concentrated *in vacuo*. The residue was purified with column chromatography on silica gel (petroleum ether: ethyl acetate 20: 1 *v/v*) to yield **18** (1.9 g, 3.53 mmol, 72%). $[\alpha]_D^{20} = 71.5^\circ$ (c = 1.00, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$) $\delta = 7.57 - 7.55$ (m, 2H, Ar-H), 7.36 − 7.25 (m, 10H, Ar-H), 6.94 − 6.91 (m, 2H, Ar-H), 5.92 (d, $J = 5.3$ Hz, 1H, 1-H), 4.94 (d, $J = 11.4$ Hz, 1H, $PhCH_2$), 4.77 − 4.66 (m, 2H, $PhCH_2$), 4.60 (d, $J = 11.5$ Hz, 1H, $PhCH_2$), 4.33 (dd, $J = 10.2$, 5.3 Hz, 1H, 2-H), 4.21 (q, $J = 6.5$ Hz, 1H, 5-H), 3.83 (s, 3H, OCH_3), 3.71 (dd, $J = 10.3$, 2.7 Hz, 1H, 3-H), 3.68 (dd, $J = 2.8$, 1.1 Hz, 1H, 4-H), 1.12 (d, $J = 6.4$ Hz, 3H, 6-CH_3); ^{13}C NMR (100 MHz, $CDCl_3$) $\delta = 159.6$, 138.3, 134.5, 129.7, 129.2, 128.9, 128.4, 128.3, 127.9, 127.8, 114.1, 85.8, 80.5, 77.2, 76.0, 75.1, 72.4, 69.6, 61.0, 55.5, 16.7; HR-ESI-MS m/z: $[M + Na]^+$ Calcd for $C_{27}H_{29}N_3O_4SeNa^+$ 562.1221; Found 562.1209.

Phenyl 2-azido-3-*O*-acetyl-4-*O*-benzyl-2-deoxy-1-seleno-α-D-fucopyranoside (19). To a solution of compound **18** (900 mg, 1.67 mmol) in DCM (84 mL) and water (5 mL), 2,3-dicyano-5,6-dichlorobenzoquinone (DDQ) (564 mg, 2.48 mmol) was added. The reaction mixture was stirred at room temperature for 7 h. After that, the solution was diluted with DCM (100 mL), washed with 10% (*w/v*) $Na_2S_2O_3$. Combined all organic layer, dried over Na_2SO_4 and concentrated under vacuum. The residue was purified by column chromatography on silica gel (petroleum ether: ethyl acetate 10: 1 *v/v*) to afford 3-OH compound **18a** (573 mg, 1.37 mmol, 82%). Then the 3-OH compound **18a** (535 mg, 1.28 mmol) was dissolved in pyridine (3 mL) at 0 °C followed by addition of acetic anhydride (0.5 mL, 5.29 mmol). After stirring at room temperature for 5 h, the solution was washed with 1 M aq. HCl, and then extracted with ethyl acetate, satd. aq. $NaHCO_3$. The organic layer was dried over Na_2SO_4, concentrated under vacuum. The residue was purified by column chromatography (petroleum ether: ethyl acetate 20: 1 *v/v*) to afford **19** (587 mg, 1.28 mmol, quant.). ^1H NMR (400 MHz, $CDCl_3$) $\delta = 7.68 - 7.21$ (m, 10H, Ar-H), 5.91 (d, $J = 5.3$ Hz, 1H, 1-H), 5.46 (dd, $J = 3.3$, 1.2 Hz, 1H, 4-H), 4.75 (d, $J = 10.7$ Hz, 1H, $PhCH_2$), 4.53 (d, $J = 10.7$ Hz, 1H, $PhCH_2$), 4.48 − 4.37 (m, 1H, 5-H), 4.12 (dd, $J = 10.3$, 5.4 Hz, 1H, 2-H), 3.78 (dd, $J = 10.4$, 3.3 Hz, 1H, 3-H), 2.15 (s, 3H, $COCH_3$), 1.12 (d, $J = 6.5$ Hz, 3H, 6-CH_3); ^{13}C NMR (100 MHz, $CDCl_3$) $\delta = 170.5$, 136.9, 134.5, 129.1, 128.5, 128.3, 128.1, 127.9, 85.1, 71.7, 68.9, 67.8, 60.4, 20.8, 16.1; HR-ESI-MS m/z: $[M + Na]^+$ Calcd for $C_{21}H_{23}N_3O_4SeNa^+$ 484.0751; Found 484.0749.

***N*-Benzyl-*N*-benzyloxycarbonyl-3-aminopropyl 2-azido-3-*O*-acetyl-4-*O*-benzyl-2-deoxy-β-D-fucopyranoside (21)**. To a mixture of compound **19** (580 mg, 1.26 mmol) in tetrahydrofuran (6 mL) and water (6 mL) at 0 °C, *N*-bromosuccinimide (538 mg, 3.02 mmol) was added. The stirring was

continued for 2 h at room temperature and TLC showed the starting material consumed. The mixture was diluted with DCM (15 mL), washed with 10% (*w/v*) $Na_2S_2O_3$, satd. aq. $NaHCO_3$. Organic layer was separated, dried over Na_2SO_4 and concentrated. The residue was purified by column chromatography (petroleum ether: ethyl acetate 4: 1 *v/v*) to give hemiacetal **19a** (404 mg, 1.26 mmol, quant.). $[\alpha]_D^{20}$ = 54.9° (c = 1.00, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ = 7.43 − 7.30 (m, 8H, Ar-H), 5.47 (dd, *J* = 3.3, 1.3 Hz, 1H, 1a-H), 5.34 (dd, *J* = 3.4, 1.1 Hz, 0.8H, 4 b-H), 5.32 (d, *J* = 3.6 Hz, 1H, 4a-H), 4.77 (d, *J* = 10.8 Hz, 1H, $PhCH_2$), 4.75 (d, *J* = 11.1 Hz, 0.8H, $PhCH_2$), 4.54 (d, *J* = 7.9 Hz, 1H, 1 b-H), 4.53 (d, *J* = 10.8 Hz, 1H, $PhCH_2$), 4.53 (d, *J* = 11.1 Hz, 0.8H, $PhCH_2$), 4.32 (qd, *J* = 6.6, 1.3 Hz, 1H, 5-H) , 4.03 (dd, *J* = 10.5, 3.2 Hz, 1H, 2a-H), 3.74 (dd, *J* = 10.5, 3.5 Hz, 1H, 3a-H), 3.69 (td, *J* = 6.4, 1.1 Hz, 0.8H, 5 b-H), 3.58 (dd, *J* = 10.2, 7.9 Hz, 0.8H, 2 b-H), 3.45 (dd, *J* = 10.3, 3.4 Hz, 0.8H, 3 b-H), 2.19 (s, 2.4H, $COCH_3$), 2.18 (s, 3H, $COCH_3$), 1.25 (d, *J* = 6.5 Hz, 2.4H, 6 b-CH_3), 1.19 (d, *J* = 6.5 Hz, 3H, 6a-CH_3); ^{13}C NMR (100 MHz, $CDCl_3$) δ = 170.90, 170.88, 137.2, 137.0, 128.6, 128.5, 128.4, 128.22, 128.17, 96.2, 92.5, 77.9, 77.5, 77.4, 77.2, 76.8, 74.4, 71.9, 71.7, 69.7, 69.5, 68.4, 65.2, 64.0, 59.8, 21.0, 20.9, 16.6, 16.4; HR-ESI-MS m/z: $[M + Na]^+$ Calcd for $C_{15}H_{19}N_3O_5Na^+$ 344.1217; Found 344.1208.

To a solution of the hemiacetal **19a** (404 mg, 1.26 mmol) in anhydrous DCM (14 mL) at 0 °C was added trichloroacetonitrile (0.4 mL, 3.99 mmol) and 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) (23 µL, 0.15 mmol). The stirring was continued for 5 h and concentrated under 30 °C. The residue was purified by column chromatography (petroleum ether: ethyl acetate 10: 1 *v/v*) to give imidate **20** (520 mg, 1.12 mmol, 89%).

Trichloroacedimidate donor **20** (520 mg, 1.12 mmol), *N*-Bn-*N*-Cbz-3-aminopropan-1-ol[46] (700 mg, 2.34 mmol) were dissolved in anhydrous DCM (130 mL). This solution was treated with freshly activated 4 Å MS and was stirred for 30 min at room temperature. This solution was then cooled to −40 °C and TMSOTf (0.3 mL, 1.66 mmol) was slowly added. The mixture stirring was continued for 4 h at −40 °C and TLC showed the reaction complete. The mixture was quenched with Et_3N (1 mL) and filtered. The filtrate was evaporated and the residue was purified by column chromatography (petroleum ether: ethyl acetate 6: 1 *v/v*) to give coupled product (572 mg, 0.95 mmol, 85%, α/β = 1: 1) including target β-product **21** (286 mg, 0.47 mmol). $[\alpha]_D^{20}$ = −10.8° (c = 1.00, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ = 7.45–7.10 (m, 15H, 3Ph), 5.17 (d, *J* = 9.3 Hz, 2H, $PhCH_2$), 4.74–4.59 (m, 3H, 3-H, $PhCH_2$), 4.57–4.44 (m, 2H, $NPhCH_2$), 4.21 (d, *J* = 8.0 Hz, 1H, 1-H), 4.02–3.83 (m, 1H, linker-OCH), 3.75 (t, *J* = 9.5 Hz, 1H, 2-H), 3.64 (d, *J* = 3.0 Hz, 1H, 4-H), 3.59–3.27 (m, 4H, 5-H, linker-OCH, linker-NCH_2), 2.04 (s, 3H, $COCH_3$), 1.98–1.76 (m, 2H, linker-CH_2), 1.21 (d, *J* = 6.4 Hz, 3H, 6-CH_3); ^{13}C NMR (100 MHz, $CDCl_3$)

$\delta = 170.4$, 138.0, 137.7, 128.52, 128.46, 128.4, 128.3, 128.0, 127.92, 127.87, 127.3, 102.0, 77.3, 76.2, 75.6, 74.2, 70.5, 67.4, 67.2, 61.1, 50.9, 44.7, 43.6, 28.5, 28.0, 20.9, 16.6; HR-ESI-MS m/z: $[M + Na]^+$ Calcd for $C_{33}H_{38}N_4O_7Na^+$ 625.2633; Found 625.2650.

***N*-Benzyl-*N*-benzyloxycarbonyl-3-aminopropyl 2-azido-4-*O*-benyzl-2-deoxy-β-D-fucopyranoside (4)**. To a solution of compound 21 (262 mg, 0.43 mmol) in MeOH (4 mL), NaOMe (40 mg, 0.74 mmol) was added. The solution was stirred at room temperature for 2 h. The reaction mixture was diluted with methanol and neutralized with Amberlite IR 120 H^+ resin. After filtration, the filtrate was concentrated in reduced pressure and purified by column chromatography (petroleum ether: ethyl acetate 3:1 *v/v*) to afford **4** (243 mg, 0.43 mmol, quant.). $[\alpha]_D^{20} = -24.1°$ ($c = 1.00$, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$) $\delta = 7.76 - 7.10$ (m, 15H, Ar-H), 5.22 (d, $J = 9.4$ Hz, 2H, $PhCH_2$), 4.83 (d, $J = 11.6$ Hz, 1H, $PhCH_2$), 4.78 (d, $J = 11.6$ Hz, 1H, $PhCH_2$), 4.58 (d, $J = 14.0$ Hz, 2H, $PhCH_2$), $4.25 - 4.08$ (m, 1H, 1-H), $4.05 - 3.86$ (m, 1H, linker-OCH_2), $3.62 - 3.34$ (m, 7H, 2-H, 3-H, 4-H, 5-H, linker-OCH, linker-NCH_2), 2.46 (s, 1H, 3-OH), $1.96 - 1.76$ (m, 2H, linker-CH_2), 1.30 (d, $J = 6.4$ Hz, 3H, 6-CH_3); ^{13}C NMR (100 MHz, $CDCl_3$) $\delta = 138.0$, 128.58, 128.56, 128.5, 128.3, 128.1, 128.0, 127.9, 102.1 (1-C), 78.5, 77.4, 75.9, 73.0, 70.8, 67.2, 64.7, 50.9, 44.8, 43.7, 28.6, 28.1, 16.9; HR-ESI-MS m/z: $[M + Na]^+$ Calcd for $C_{31}H_{36}N_4O_6Na^+$ 583.2527; Found 583.2531.

Allyl 2-azido-2-deoxy-β-L-fucopyranoside (23). Ceric ammonium nitrate (8.2 g, 14.96 mmol) and sodium azide (0.73 g, 11.23 mmol) were added to a solution of L-fucal **22**[46] (1.0 g, 4.67 mmol) in anhydrous acetonitrile (25 mL) at −15 °C under argon, and the resulting mixture was stirred for 3 h at −15 °C. After that, the volatiles were evaporated under reduced pressure at 28 °C. The residue was dissolved in a mixture of diethyl ether and ethyl acetate (1: 1 *v/v*, 50 mL) and washed with water (10 mL). The organic phase was separated and the aqueous layer was extracted with a mixture of diethyl ether and ethyl acetate (1: 1 *v/v*) (2 × 25 mL). The combined organic phase was dried with Na_2SO_4 and concentrated, and the residue was dried *in vacuo* for 4 h.

The crude residue was dissolved in allyl alcohol (5.0 mL, 73.17 mmol) under argon, cooled to 0 °C, sodium (100 mg, 4.35 mmol) was added portionwise, and the resulting mixture was stirred for 2 h at 0 °C. After that, the reaction mixture was diluted with MeOH (20 mL), neutralized with Amberlite IR 120 (H^+) ion exchange resin. The combined filtrate was dried with Na_2SO_4 and concentrated *in vacuo*. The residue was purified by column chromatography on silica gel (petroleum ether: ethyl acetate) to yield product **23** (713 mg, 3.11 mmol, 67%). $[\alpha]_D^{20} = -27.6°$ ($c = 1.00$, $CHCl_3$); IR ν_{max} (film) 3312, 2865, 2111, 1348, 1279, 1162, 1071, 999, 925, 755

cm^{-1}; ^1H NMR (400 MHz, $CDCl_3$) $\delta = 6.04–5.85$ (m, 1H, CH=C), 5.34 (dq, $J = 17.3$, 1.6 Hz, 1H, C=CHa), 5.23 (dd, $J = 10.5$, 1.6 Hz, 1H, C = CHb), 4.41 (ddt, $J = 12.9$, 5.3, 1.5 Hz, 1H, OCHa), 4.30 (d, $J = 7.9$ Hz, 1H, 1-H), 4.14 (ddt, $J = 12.8$, 6.1, 1.4 Hz, 1H, OCHb), 3.70 (d, $J = 3.2$ Hz, 1H, 4-H), 3.63–3.53 (m, 1H, 5-H), 3.53 (dd, $J = 10.1$, 7.8 Hz, 1H, 2-H), 3.45 (dd, $J = 10.1$, 3.3 Hz, 1H, 3-H), 3.04 (s, 1H, OH), 2.68 (s, 1H, OH), 1.35 (d, $J = 6.5$ Hz, 3H, 6-CH_3); ^{13}C NMR (100 MHz, $CDCl_3$) $\delta = 133.5$, 117.8, 101.1, 72.6, 70.9, 70.6, 70.3, 64.0, 16.3; HR-ESI-MS m/z: $[M + Na]^+$ Calcd for $C_9H_{15}N_3O_4Na^+$ 252.0960; Found 252.0954.

Allyl 2-azido-2-deoxy-3-*O*-(2-naphthyl)methyl-β-L-fucopyranoside (24). To a mixture of compound **23** (450 mg, 1.96 mmol) in toluene (22 mL), dibutyltin oxide (814 mg, 3.27 mmol) was added. The reaction mixture was heated to 110 °C and continued for 1 h. Then the solution was cooled to 40 °C, 2-(bromomethyl)naphthalene (723 mg, 3.27 mmol) and tetrabutylammonium bromide (1.05 g, 3.26 mmol) was added. The stirring at 70 °C was continued for 12 h. After that, the solution was diluted with ethyl acetate (30 mL), washed with brine and evaporated. The residue was purified by column chromatography (petroleum ether: ethyl acetate 5: 1 *v/v*) to afford **24** (628 mg, 1.70 mmol, 87%). $[\alpha]_D^{20} = 34.0°$ (c = 1.00, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$) $\delta = 7.85$ (dt, $J = 10.5$, 7.7 Hz, 4H, Ar-H), 7.59 − 7.45 (m, 3H, Ar-H), 5.94 (ddt, $J = 16.8$, 10.9, 5.6 Hz, 1H, Ally-CH), 5.33 (dd, $J = 17.2$, 1.7 Hz, 1H, Ally-CH_2), 5.21 (dd, $J = 10.5$, 1.5 Hz, 1H, Ally-CH_2), 4.88 (s, 2H, NapCH_2), 4.42 (dd, $J = 12.9$, 6.2 Hz, 1H, Ally-OCH_2), 4.23 (d, $J = 8.1$ Hz, 1H, 1-H), 4.12 (dd, $J = 12.9$, 6.2 Hz, 1H, Ally-OCH_2), 3.74 (d, $J = 3.3$ Hz, 1H, 4-H), 3.66 (dd, $J = 10.0$, 8.0 Hz, 1H, 2-H), 3.47 (q, $J = 6.5$ Hz, 1H, 5-H), 3.35 (dd, $J = 10.0$, 3.3 Hz, 1H, 3-H), 2.32 (s, 1H, 4-OH), 1.34 (d, $J = 6.4$ Hz, 3H, 6-CH_3); ^{13}C NMR (100 MHz, $CDCl_3$) $\delta = 134.7$, 133.7, 133.2, 128.6, 127.9, 127.8, 127.0, 126.3, 126.2, 125.8, 117.6, 100.8, 79.4, 77.2, 72.2, 70.2, 70.0, 68.3, 62.6, 16.3; HR-ESI-MS m/z: $[M + Na]^+$ Calcd for $C_{20}H_{23}N_3O_4Na^+$ 391.1581; Found 391.1564.

Allyl 2-azido-4-*O*-benzyl-3-*O*-(2-naphthyl)methyl-2-deoxy-β-L-fucopyranoside (25). Compound **24** (527 mg, 1.43 mmol) was dissolved in anhydrous DMF (17 mL) and cooled to 0 °C for 30 min. Sodium hydride (140 mg, 5.83 mmol) was added and was continued for 30 min at 0 °C. Then, benzyl bromide (0.5 mL, 4.21 mmol) was added. The reaction mixture was stirred for 5 h and diluted with DCM (20 mL), quenched with iced water, extracted with satd. aq. $NaHCO_3$. Separated organic phase, dried over Na_2SO_4, and concentrated *in vacuo*. The residue was purified by column chromatography (petroleum ether: ethyl acetate 25: 1 *v/v*) to afford **25** (531 mg, 1.16 mmol, 81%). $[\alpha]_D^{20} = 50.3°$ (*c* = 1.00, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$) $\delta = 7.90 − 7.77$ (m, 4H, Ar-H), 7.57 − 7.45 (m, 3H, Ar-H), 7.38 − 7.21 (m, 5H, Ar-H), 5.94 (dddd, $J = 16.9$, 10.8, 6.1, 5.0 Hz, 1H,

Ally-CH), 5.32 (dt, $J = 17.2$, 1.7 Hz, 1H, Ally-CH_2), 5.19 (dq, $J = 10.5$, 1.5 Hz, 1H, Ally-CH_2), 4.97 (d, $J = 11.7$ Hz, 1H, $PhCH_2$), 4.87 (s, 2H, $NapCH_2$) 4.71 (d, $J = 11.7$ Hz, 1H, $PhCH_2$), 4.39 (ddt, $J = 12.9$, 5.0, 1.6 Hz, 1H, Ally-OCH_2), 4.22 (d, $J = 8.0$ Hz, 1H, 1-H), 4.10 (ddt, $J = 12.9$, 6.1, 1.4 Hz, 1H, Ally-OCH_2), 3.87 (dd, $J = 10.4$, 8.0 Hz, 1H, 2-H), 3.55 (d, $J = 2.8$ Hz, 1H, 4-H), 3.42 − 3.38 (m, 1H, 5-H), 3.36 (dd, $J = 10.4$, 2.8 Hz, 1H, 3-H), 1.20 (d, $J = 6.4$ Hz, 3H, 6-CH_3). ^{13}C NMR (100 MHz, $CDCl_3$) $\delta = 138.4$, 135.3, 133.9, 133.4, 133.2, 128.6, 128.5, 128.4, 128.1, 127.9, 127.8, 126.8, 126.4, 126.2, 125.9, 117.6, 101.1, 81.1, 75.2, 74.9, 72.9, 70.7, 70.1, 63.3, 17.0; HR-ESI-MS m/z: $[M + Na]^+$ Calcd for $C_{27}H_{29}N_3O_4Na^+$ 482.2050; Found 482.2041.

Allyl 2-azido-4-*O*-benzyl-2-deoxy-β-L-fucopyranoside (6). To a stirring mixture of compound **25** (531 mg, 1.16 mmol) in DCM (50 mL) and water (5 mL) at 0 °C, DDQ (540 mg, 2.38 mmol) was added. After stirring at room temperature for 3 h, the mixture was washed by 10% (w/v) $Na_2S_2O_3$ and concentrated *in vacuo*. The residue was purified by column chromatography (petroleum ether: ethyl acetate 6: 1 *v/v*) to afford **6** (345 mg, 1.08 mmol, 93%). $[\alpha]_D^{20} = -3.6°$ (c = 1.00, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) $\delta = 7.42 - 7.28$ (m, 5H, Ar-H), 5.94 (dddd, $J = 16.7$, 10.4, 6.1, 5.1 Hz, 1H, Ally-CH), 5.33 (dq, $J = 17.2$, 1.6 Hz, 1H, Ally-CH_2), 5.21 (dq, $J = 10.5$, 1.4 Hz, 1H, Ally-CH_2), 4.81 (d, $J = 11.6$ Hz, 1H, $PhCH_2$), 4.72 (d, $J = 11.6$ Hz, 1H, $PhCH_2$), 4.41 (ddt, $J = 12.9$, 5.1, 1.6 Hz, 1H, Ally-CH_2), 4.26 (d, $J = 7.7$ Hz, 1H, 1-H), 4.11 (ddt, $J = 12.9$, 6.1, 1.4 Hz, 1H, Ally-CH_2), 3.58 − 3.49 (m, 3H, 2-H, 4-H, 5-H), 3.45 (dd, $J = 10.4$, 3.3 Hz, 1H, 3-H), 2.14 (s, 1H, 3-OH), 1.31 (d, $J = 6.5$ Hz, 3H, 6-CH_3); ^{13}C NMR (100 MHz, $CDCl_3$) $\delta = 138.0$, 133.8, 128.7, 128.3, 128.2, 117.6, 101.1, 78.6, 76.0, 73.1, 71.0, 70.2, 64.7, 17.0; HR-ESI-MS m/z: $[M + Na]^+$ Calcd for $C_{16}H_{21}N_3O_4Na^+$ 342.1424; Found 342.1430.

Ally 2-azido-4-*O*-benzyl-3-*O*-(2,3,4,6-tetra-*O*-acetyl-β-D-glucopyranosyl)-2-deoxy-β-L-fucopyranoside (26). To a stirring mixture of glucosyl donor **5**[49] (500 mg, 1.01 mmol), fucosyl acceptor **6** (165 mg, 0.52 mmol) and fresh activated 4 Å MS in anhydrous DCM (10 mL) under argon. This solution was stirred at room temperature for 30 min and cooled to 0 °C and TMSOTf (36 μL, 0.20 mmol) was added. The temperature was allowed to warm at room temperature and the stirring continued for 5 h. After that, the mixture was quenched with Et_3N and filtrated. The filtrate was concentrated *in vacuo* to give a residue that was purified by silica gel column chromatography (petroleum ether: ethyl acetate 2: 1 *v/v*) to give **26** (300 mg, 0.46 mmol, 88%, β-only). $[\alpha]_D^{20} = 2.3°$ (*c* = 1.00, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) $\delta = 7.29 - 7.20$ (m, 5H, Ar-H), 5.84 (ddt, $J = 16.4$, 10.8, 5.6 Hz, 1H, Ally-CH), 5.23 (d, $J = 17.3$ Hz, 1H, Ally-CH_2), 5.17 − 5.05 (m, 3H, Ally-CH_2, 3′-H, 4′-H), 5.03 (t, $J = 8.2$ Hz, 1H, 2′-H), 4.80 (d,

$J = 11.3$ Hz, 1H, Bn-H), 4.77 (d, $J = 7.7$ Hz, 1H, 1′-H), 4.46 (d, $J = 11.4$ Hz, 1H, Bn-H), 4.29 (dd, $J = 13.0$, 5.0 Hz, 1H, Ally-CH_2), 4.20 (dd, $J = 12.3$, 4.4 Hz, 1H, 6′-Ha), 4.17 − 4.08 (m, 2H, 6′-Hb, 1-H), 4.00 (dd, $J = 13.0$, 6.2 Hz, 1H, Ally-CH_2), 3.66 (qd, $J = 10.3$, 4.9 Hz, 3H, 5′-H, 2-H, 3-H), 3.43 (d, $J = 2.5$ Hz, 1H, 4-H), 3.35 (d, $J = 6.4$ Hz, 1H, 5-H), 1.99 (s, 3H, CH_3CO), 1.95 (s, 3H, CH_3CO), 1.92 (s, 3H, CH_3CO), 1.79 (s, 3H, CH_3CO), 1.10 (d, $J = 6.3$ Hz, 3H, 6-CH_3); ^{13}C NMR (100 MHz, $CDCl_3$) $\delta = 170.4$, 170.1, 169.0, 168.9, 137.8, 133.5, 128.0, 127.9, 127.5, 117.2, 100.5, 98.5, 79.4, 77.0, 75.4, 74.7, 73.0, 71.9, 71.3, 70.1, 69.8, 68.0, 61.9, 61.6, 20.5, 20.3, 16.5; HR-ESI-MS m/z: $[M + Na]^+$ Calcd for $C_{30}H_{39}N_3O_{13}Na^+$ 672.2375; Found 672.2377.

2-Azido-4-*O*-benzyl-3-*O*-(2,3,4,6-tetra-*O*-acetyl-β-D-glucopyranosyl)-2-deoxy-L-fucopyranose (27). Compound **26** (300 mg, 0.46 mmol) was dissolved in dry MeOH (23 mL) and heated to 40 °C. Palladium chloride (16 mg, 0.09 mmol) was added and continued for 1 h. The mixture was filtrated and the filtration was extracted with DCM and satd. aq. $NaHCO_3$. Separated organic layer and concentrated *in vacuo* to give a residue that was purified by column chromatography (petroleum ether: ethyl acetate 1: 1 *v/v*) to afford **27** (246 mg, 0.40 mmol, 87%). $[\alpha]_D^{20} = -7.1°$ (c = 1.00, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) α-anomer $\delta = 7.35 - 7.22$ (m, 5H, Ar-H), 5.23 (d, $J = 3.5$ Hz, 1H, 1-H), 5.22 − 5.00 (m, 3H, 2′-H, 3′-H, 4′-H), 4.86 − 4.72 (m, 2H, 1′-H, $PhCH_2$), 4.43 (d, $J = 11.0$ Hz, 1H, $PhCH_2$), 4.38 (d, $J = 7.8$ Hz, 1H, 1′-H), 4.28 (dd, $J = 10.6$, 2.7 Hz, 1H, 3-H), 4.25 − 4.11 (m, 2H, 6′–CH_2), 4.11 − 4.02 (m, 1H, 5-H), 3.75 − 3.65 (m, 2H, 2-H, 5′-H), 3.61 (d, $J = 2.8$ Hz, 1H, 4-H), 2.01 (s, 3H, $COCH_3$), 1.97 (s, 3H, $COCH_3$), 1.93 (s, 3H, $COCH_3$), 1.72 (s, 3H, $COCH_3$), 1.10 (d, $J = 6.4$ Hz, 3H, 6-CH_3); β-anomer $\delta = 7.35 - 7.22$ (m, 5H, Ar-H), 5.22 − 5.00 (m, 3H, 2′-H, 3′-H, 4′-H), 4.80 (d, $J = 11.5$ Hz, 1H, $PhCH_2$), 4.47 (d, $J = 11.3$ Hz, 1H, $PhCH_2$), 4.38 (d, $J = 7.8$ Hz, 1H, 1′-H), 4.22 − 4.03 (m, 4H, 6′-CH2, 1′-H, 3-H), 3.74 − 3.58 (m, 3H, 2-H, 4-H, 5′-H), 3.51 − 3.41 (m, 1H, 5-H), 2.01 (s, 3H, $COCH_3$), 1.97 (s, 3H, $COCH_3$), 1.94 (s, 3H, $COCH_3$), 1.72 (s, 3H, $COCH_3$), 1.10 (d, $J = 6.4$ Hz, 3H, 6-CH_3); ^{13}C NMR (100 MHz, $CDCl_3$) $\delta = 170.8$, 170.7, 170.43, 170.38, 169.33, 169.29, 169.2, 169.1, 137.9, 128.44, 128.39, 128.36, 128.3, 128.2, 128.14, 128.12, 128.0, 127.9, 102.2, 101.5, 98.74, 98.67, 98.65, 96.2, 92.7, 79.5, 79.42, 79.37, 77.4, 77.3, 77.14, 77.05, 76.9, 76.7, 76.5, 75.7, 75.5, 75.2, 75.03, 75.0, 74.96, 74.1, 73.3, 73.23, 73.20, 72.13, 72.10, 72.0, 71.8, 71.6, 70.7, 70.6, 70.4, 68.3, 68.2, 66.6, 63.7, 63.5, 62.1, 62.0, 61.8, 58.9, 43.8, 29.7, 20.71, 20.69, 20.66, 20.58, 20.56, 20.5, 16.8, 16.7, 16.61, 16.57; HR-ESI-MS m/z: $[M + Na]^+$ Calcd for $C_{27}H_{35}N_3O_{13}Na^+$ 632.2062; Found 632.2039.

***N*-Benzyl-*N*-benzyloxycarbonyl-3-aminopropyl 2-azido-3-*O*-(2-azido-4-*O*-benzyl-3-*O*-(2,3,4,6-tetra-*O*-acetyl-β-D-glucopyranosyl)-2-deoxy-α-L-**

fucopyranosyl)-4-*O*-benyzl-2-deoxy-β-D-fucopyranoside (2). To a stirring solution of hemiacetal **27** (70 mg, 0.115 mmol) and 2,2,2-trifluoro-*N*-phenylacetimidoyl chloride (0.1 mL, 0.617 mmol) at 0 °C, DBU (30 μL, 0.201 mmol) was added. The reaction was continued at room temperature for 20 h and then concentrated *in vacuo* under 30 °C. The residue was purified by column chromatography (petroleum ether: ethyl acetate 2.5: 1 *v/v*) to give disaccharide donor **3** (82 mg, 0.105 mmol, 91%).

Disaccharide donor **3** (40 mg, 0.051 mmol) and D-fucosyl acceptor **4** (50 mg, 0.089 mmol) was dissolved in anhydrous DCM (0.9 mL) and 4 Å MS, anhydrous diethyl ether (2.7 mL) and thiophene (0.9 mL) was added. This mixture was stirred at room temperature for 30 min and then cooled to 0 °C. TMSOTf (5 μL, 0.028 mmol) was added and the solution was continued for 5 h at room temperature. After that, the solution was quenched with Et_3N (0.5 mL) and filtered. The filtrate was concentrated and the resulting residue was purified by column chromatography (petroleum ether: ethyl acetate 3: 1 *v/v*) to give **2** (50 mg, 0.043 mmol, 84%, α-only). $[\alpha]_D^{20} = -44.5°$ ($c = 1.00$, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$) $\delta = 7.41 - 7.19$ (m, 20H, Ar-H), $5.30 - 5.04$ (m, 6H, $PhCH_2$, 1′-H, 2”-H, 3”-H, 4”-H) , 4.83 (d, $J = 11.1$ Hz, 1H, $PhCH_2$), 4.77–4.75 (m, 3H, $PhCH_2$, 1”-H), $4.55 - 4.50$ (m, 2H, $NPhCH_2$), 4.42 (d, $J = 11.0$ Hz, 1H, $PhCH_2$), $4.33 - 4.21$ (m, 1H, 6”-H), 4.18 (d, $J = 7.0$ Hz, 1H, 1-H), 4.07 (m, 2H, 3′-H, 6”-H), 4.00-3.88 (m, 1H, linker-OCH_2), 3.81 (t, $J = 9.0$ Hz, 1H, 2-H), $3.79 - 3.67$ (m, 2H, 5′-H, 5”-H), 3.62 (dd, $J = 10.7$, 3.7 Hz, 1H, 2′-H), $3.53 - 3.26$ (m, 6H, linker-OCH_2, linker-NCH_2, 3-H, 4H, 4′-H), 2.04 (s, 6H, $2COCH_3$), 2.00 (s, 3H, $COCH_3$), $1.96 - 1.81$ (m, 2H, linker-CH_2), 1.80 (s, 3H, $COCH_3$), 1.30 (d, $J = 6.7$, 3H, 6-CH_3), 1.10 (d, $J = 6.4$ Hz, 3H, 6′-CH_3); ^{13}C NMR (100 MHz, $CDCl_3$) $\delta = 170.7$, 170.4, 169.2, 169.0, 138.5, 137.9, 137.8, 128.5, 128.44, 128.38, 127.99, 127.96, 127.89, 127.86, 127.8, 127.6, 127.3, 102.4, 100.5, 99.6, 79.2, 79.1, 77.2, 75.31, 75.26, 73.3, 72.3, 72.0, 70.7, 68.0, 67.5, 67.2, 63.6, 61.8, 58.3, 50.9, 49.8, 44.8, 43.7, 29.7, 28.5, 28.1, 23.4, 20.7, 20.6, 17.0, 16.5; HR-ESI-MS m/z: $[M + Na]^+$ Calcd for $C_{58}H_{69}N_7O_{18}Na^+$ 1174.4591; Found 1174.4626.

***N*-Benzyl-*N*-benzyloxycarbonyl-3-aminopropyl 2-acetamido-3-*O*-(2-acetamido-4-*O*-benzyl-3-*O*-(2,3,4,6-tetra-*O*-acetyl-β-D-glucopyranosyl)-2-deoxy-α-L-fucopyranosyl)-4-*O*-benyzl-2-deoxy-β-D-fucopyranoside (28)**. Trisaccharide **2** (30 mg, 0.026 mmol) was dissolved in a mixture of dry pyridine (0.5 mL) and thioacetic acid (0.5 mL) at 0 °C. After stirring for 12 h, the mixture was co-evaporated with toluene three times and then purified by column chromatography (DCM: MeOH 50: 1 *v/v*) to give **28** (30 mg, 0.025 mmol, 96%). $[\alpha]_D^{20} = 49.5°$ ($c = 1.00$, $CHCl_3$); ^1H NMR (400 MHz, $CDCl_3$) $\delta = 7.80 - 6.90$ (m, 20H, Ar-H), 6.83 (d, $J = 8.1$ Hz, 1H, N-H), 6.18 (d, $J = 9.2$ Hz, 1H, N-H), $5.27 - 5.13$ (m, 3H, 3′’-H, $PhCH_2$),

5.10 − 4.99 (m, 2H, 1′-H, 4′′-H), 4.96 (t, $J = 8.7$ Hz, 1H, 2′′-H), 4.88 (d, $J = 11.1$ Hz, 1H, $PhCH_2$), 4.84 − 4.79 (m, 1H, $PhCH_2$), 4.74 (d, $J = 15.5$ Hz, 2H, $PhCH_2$), 4.63 (d, $J = 8.0$ Hz, 3H, 1′′-H, 3-H, 2′-H), 4.41 (d, $J = 10.9$ Hz, 1H, $PhCH_2$), 4.34 − 4.25 (m, 2H, 6′′-H, 1-H), 4.25 − 4.13 (m, 2H, 2-H, $PhCH_2$), 4.09 (t, $J = 9.0$ Hz, 1H, 6′′-H), 4.01-3.76 (m, 5H, 5′-H, 4-H, 3′-H, linker-OCH_2, linker-NCH_2), 3.66 (dd, $J = 9.7$, 6.0 Hz, 1H, 5′′-H), 3.60 − 3.52 (m, 1H, 3-H), 3.44 (d, $J = 7.3$ Hz, 2H, 5-H, 4′-H), 3.34 − 3.08 (m, 1H, linker-OCH_2), 2.87 (dt, $J = 14.3$, 5.0 Hz, 1H, linker-NCH_2), 2.14 (s, 3H, $COCH_3$), 2.09 (s, 3H, $COCH_3$), 2.06 (s, 3H, $COCH_3$), 2.00 (s, 3H, $COCH_3$), 1.89 (s, 3H, $COCH_3$), 1.80 (s, 3H, $COCH_3$), 1.68 (d, $J = 9.6$ Hz, 2H, linker-CH_2), 1.32 (d, $J = 6.3$ Hz, 3H, 6′-CH_3), 1.17 (d, $J = 6.5$ Hz, 3H, 6-CH_3); ^{13}C NMR (100 MHz, $CDCl_3$) $\delta = 171.6$, 171.1, 170.8, 170.4, 169.3, 168.8, 156.6, 138.8, 138.2, 138.0, 137.4, 136.9, 128.7, 128.6, 128.51, 128.47, 128.4, 128.2, 128.1, 128.0, 127.9, 127.80, 127.76, 127.71, 127.65, 127.5, 127.3, 127.2, 126.4, 101.2, 100.8, 99.7, 80.0, 79.7, 78.9, 77.8, 77.2, 75.1, 73.2, 72.2, 72.1, 70.7, 68.2, 67.5, 67.3, 65.8, 62.0, 52.2, 49.7, 47.6, 42.5, 31.9, 29.7, 26.9, 23.3, 20.8, 20.58, 20.56, 17.2, 16.7; HR-ESI-MS m/z: $[M + Na]^+$ Calcd for $C_{58}H_{69}N_7O_{18}Na^+$ 1206.4998; Found 1206.4976.

3-Aminopropyl 2-acetamido-3-*O*-(2-acetamido-3-*O*-(-β-D-glucopyranosyl)-2-deoxy-α-L-fucopyranosyl)-2-deoxy-β-D-fucopyranoside (1). Compound **28** (22 mg, 0.019 mmol) was dissolved in MeOH (5 mL) and NaOMe (10 mg, 0.185 mmol) was added. After stirring at room temperature for 2 h, the reaction was treated with Amberlite IR120 H^+ resin. After filtration, the filtrate was concentrated in reduced pressure and purified by column chromatography (DCM: MeOH 10: 1 *v/v*) to afford deacetylated compound **28a** (18 mg, 0.018 mmol, 95%). $[\alpha]_D^{20} = -16.3^\circ$ ($c = 1.00$, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) $\delta = 7.60 - 7.13$ (m, 20H, Ar-H), 7.12 (d, $J = 7.3$ Hz, 1H, N-H), 6.69 (d, $J = 9.8$ Hz, 1H, N-H), 5.23 (d, $J = 12.6$ Hz, 1H, $PhCH_2$), 5.15 (d, $J = 12.4$ Hz, 1H, $PhCH_2$), 5.05 (d, $J = 12.3$ Hz, 1H, $PhCH_2$), 4.96 − 4.83 (m, 2H, 1′-H, $PhCH_2$), 4.79 (d, $J = 15.7$ Hz, 1H, $PhCH_2$), 4.72 (d, $J = 12.2$ Hz, 1H, $PhCH_2$), 4.66 − 4.49 (m, 2H, $PhCH_2$, 2′-H), 4.36 (s, 1H, OH), 4.28 (d, $J = 9.5$ Hz, 1H, 2-H), 4.22 (d, $J = 16.0$ Hz, 1H, $PhCH_2$), 4.03 (d, $J = 7.3$ Hz, 2H,1′′-H, linker-NCH_2), 4.00 − 3.84 (m, 4H, 3′-H, 1-H, 6′-H, linker-OCH_2), 3.72 (dd, $J = 12.5$, 6.1 Hz, 1H, 6′-H), 3.64 (q, $J = 6.7$ Hz, 1H, 5-H), 3.42 (m, 4H, 5-H, 2′-H, 3′-H, 4′-H), 3.33 (d, $J = 4.6$ Hz, 1H, 3-H), 3.31 − 3.19 (m, 2H, 4′-H, 5′-H), 3.15 (td, $J = 9.7$, 4.0 Hz, 1H, linker-OCH_2), 2.88 − 2.74 (m, 1H, linker-NCH_2), 2.09 (s, 3H, $COCH_3$), 1.96 (s, 3H, $COCH_3$), 1.72 − 1.57 (m, 2H, linker-CH_2), 1.32 (s, $J = 6.4$, 3H, 6-CH_3), 1.03 (s, $J = 6.3$, 3H, 6-CH_3); ^{13}C NMR (100 MHz, $CDCl_3$) $\delta = 173.0$, 172.7, 156.8, 138.9, 138.6, 137.1, 136.8, 128.8, 128.6, 128.4, 128.14, 128.05, 127.6, 127.5, 127.34, 127.26, 127.1, 101.4, 99.9, 82.1, 79.5, 76.3, 75.3, 74.6, 74.3, 74.1, 72.8, 71.7, 70.9, 67.7, 67.6, 65.6, 62.6, 52.0,

49.5, 48.1, 42.0, 29.7, 26.7, 23.5, 17.5, 16.8; HR-ESI-MS m/z: $[M+Na]^+$ Calcd for $C_{62}H_{77}N_3O_{20}Na^+$ 1038.4570; Found 1038.4538.

The deacetylated trisaccharide **28a** (10 mg, 9.84 µmol) was dissolved in a mixture of H_2O/DCM/MeOH (1: 1: 5 *v/v/v*), two drops of acetic acid were added. The solution was purged with nitrogen, 10% Pd/C was added and the solution was purged with H_2 for 5 min, then stirred under an H_2 atmosphere overnight. The mixture was filtered (celite) and concentrated. The residue was purified with a Sep-Pak cartridge C18 (Macherey-Nagel, Düren, Germany) using water and methanol as eluents to give **1** as white solid (6 mg, 9.81 µmol, quant.). ^{1}H NMR (400 MHz, D_2O) $\delta = 5.03$ (s, 1H, 1′-H), 4.51 (d, $J = 7.9$ Hz, 1H, 1′-H), 4.37 (d, $J = 8.4$ Hz, 1H, 1-H), 4.17 (s, 2H, 4-H, 2′-H), 4.07 (q, $J = 6.6$ Hz, 1H, 5′-H), 4.02 (s, 1H, 3′-H), 3.99 – 3.86 (m, 4H, 2-H, 4′-H, 6″-H, linker-OCH_2), 3.80 – 3.75 (m, 1H, 5-H), 3.67 (ddt, $J = 16.6$, 10.9, 6.0 Hz, 3H, 3-H, 6”-H, linker-OCH_2), 3.46 (m, 2H, 3″-H, 5″-H), 3.34 (t, $J = 9.3$ Hz, 1H, 4″-H), 3.26 (t, $J = 8.6$ Hz, 1H, 2”-H), 3.05 (t, $J = 6.9$ Hz, 2H, linker-NCH_2), 2.00 (s, 3H, $COCH_3$), 1.98 (s, 3H, $COCH_3$), 1.91 (t, $J = 6.4$ Hz, 2H, linker-CH_2), 1.23 (d, $J = 6.9$ Hz, 3H, 6-CH_3), 1.21 (d, $J = 6.8$ Hz, 3H, 6′-CH_3); ^{13}C NMR (100 MHz, D_2O) $\delta = 174.4$, 174.2, 101.5, 100.2, 98.9, 76.5, 76.0, 75.5, 74.8, 72.8, 70.6, 70.3, 69.6, 68.4, 67.9, 66.9, 60.8, 51.3, 47.9, 37.6, 26.6, 24.4, 22.20, 15.4, 15.3; HR-ESI-MS m/z: $[M+Na]^+$ Calcd for $C_{25}H_{45}N_3O_{14}Na^+$ 634.2794; Found 634.2789.

Supplemental material

NMR spectra for all pure products. This material is available free of charge via the Internet https://www.tandfonline.com/toc/lcar20/current.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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References

[1] Grimwood, K.; Kyd, J. M.; Owen, S. J.; Massa, H. M.; Cripps, A. W. Vaccination against respiratory *Pseudomonas aeruginosa* infection. *Hum. Vacc. Immunother.* **2015**, *11*(1), 14–20. DOI: 10.4161/hv.34296.

[2] Lu, Q.; Eggimann, P.; Luyt, C. E.; Wolff, M.; Tamm, M.; Francois, B.; Mercier, E.; Garbino, J.; Laterre, P. F.; Koch, H.; et al. *Pseudomonas aeruginosa* serotypes in nosocomial pneumonia: prevalence and clinical outcomes. *Crit. Care.* **2014**, *18*(1), R17. DOI: 10.1186/cc13697.

[3] Chirgwin, M. E.; Dedloff, M. R.; Holban, A. M.; Gestal, M. C. Novel therapeutic strategies applied to *Pseudomonas aeruginosa* infections in cystic fibrosis. *Materials.* **2019**, *12*(24), 4093. DOI: 10.3390/ma12244093.

[4] Horcajada, J. P.; Montero, M.; Oliver, A.; Sorlí, L.; Luque, S.; Gómez-Zorrilla, S.; Benito, N.; Grau, S. Epidemiology and treatment of multidrug-resistant and extensively drug-resistant *Pseudomonas aeruginosa* infections. *Clin. Microbiol. Rev.* **2019**, *32*(4), e00031. DOI: 10.1128/CMR.00031-19.

[5] Hoggarth, A.; Weaver, A.; Pu, Q.; Huang, T.; Schettler, J.; Chen, F.; Yuan, X.; Wu, M. Mechanistic research holds promise for bacterial vaccines and phage therapies for *Pseudomonas aeruginosa*. *Drug Des. Dev. Ther.* **2019**, *13*, 909–924. DOI: 10.2147/DDDT.S189847.

[6] Priebe, G. P.; Goldberg, J. B. Vaccines for *Pseudomonas aeruginosa*: a long and winding road. *Expert. Rev. Vaccines* **2014**, *13*(4), 507–519. DOI: 10.1586/14760584.2014.890053.

[7] Bridge, D. R.; Whitmire, J. M.; Makobongo, M. O.; Merrell, D. S. Heterologous *Pseudomonas aeruginosa* O-antigen delivery using a *Salmonella enterica* serovar Typhimurium *wecA* mutant strain. *Int. J. Med. Microbiol.* **2016**, *306*(7), 529–540. DOI: 10.1016/j.ijmm.2016.06.005.

[8] Dean, C. R.; Franklund, C. V.; Retief, J. D.; Coyne, M. J. Jr. Hatano, K.; Evans, D. J.; Pier, G. B.; Goldberg, J. B. Characterization of the serogroup O11 O-antigen locus of *Pseudomonas aeruginosa* PA103. *J. Bacteriol.* **1999**, *181*(14), 4275–4284. DOI: 10.1128/JB.181.14.4275-4284.1999.

[9] Jones, C. Revised structures for the capsular polysaccharides from *Staphylococcus aureus* types 5 and 8, components of novel glycoconjugate vaccines. *Carbohydr. Res.* **2005**, *340*(6), 1097–1106. DOI: 10.1016/j.carres.2005.02.001.

[10] Kenyon, J. J.; Marzaioli, A. M.; Hall, R. M.; De Castro, C. Structure of the K12 capsule containing 5,7-di-*N*-acetylacinetaminic acid from *Acinetobacter baumannii* isolate D36. *Glycobiology* **2015**, *25*(8), 881–887. DOI: 10.1093/glycob/cwv028.

[11] Kenyon, J. J.; Kasimova, A. A.; Notaro, A.; Arbatsky, N. P.; Speciale, I.; Shashkov, A. S.; De Castro, C.; Hall, R. M.; Knirel, Y. A. *Acinetobacter baumannii* K13 and K73 capsular polysaccharides differ only in K-unit side branches of novel non-2-ulosonic acids: di-*N*-acetylated forms of either acinetaminic acid or 8-epiacinetaminic acid. *Carbohydr. Res.* **2017**, *452*, 149–155. DOI: 10.1016/j.carres.2017.10.005.

[12] Hatano, K.; Boisot, S.; DesJardins, D.; Wright, D. C.; Brisker, J.; Pier, G. B. Immunogenic and antigenic properties of a heptavalent high-molecular-weight O-polysaccharide vaccine derived from *Pseudomonas aeruginosa*. *Infect. Immun.* **1994**, *62*(9), 3608–3616. DOI: 10.1128/IAI.62.9.3608-3616.1994.

[13] DiGiandomenico, A.; Rao, J.; Goldberg, J. B. Oral vaccination of BALB/c mice with *Salmonella enterica* serovar Typhimurium expressing *Pseudomonas aeruginosa* O

antigen promotes increased survival in an acute fatal pneumonia model. *Infect. Immun.* **2004**, *72*(12), 7012–7021. DOI: 10.1128/IAI.72.12.7012-7021.2004.

[14] Yokota, S.; Noguchi, H. Epitopes for human monoclonal antibodies and serotyping antisera against the O-specific polysaccharide of *Pseudomonas aeruginosa* O11. *Carbohydr. Res.* **1994**, *261*(1), 57–66. DOI: 10.1016/0008-6215(94)80005-7.

[15] Anish, C.; Schumann, B.; Pereira, C. L.; Seeberger, P. H. Chemical biology approaches to designing defined carbohydrate vaccines. *Chem. Biol.* **2014**, *21*(1), 38–50. DOI: 10.1016/j.chembiol.2014.01.002.

[16] Visansirikul, S.; Kolodziej, S. A.; Demchenko, A. V. Synthesis of D-FucNAc-D-ManNAcA disaccharides based on the capsular polysaccharides *Staphylococcus aureus* type 5 and 8. *J. Org. Chem.* **2019**, *84*(1), 216–227. DOI: 10.1021/acs.joc.8b02612.

[17] Danieli, E.; Proietti, D.; Brogioni, G.; Romano, M. R.; Cappelletti, E.; Tontini, M.; Berti, F.; Lay, L.; Costantino, P.; Adamo, R. Synthesis of *Staphylococcus aureus* type 5 capsular polysaccharide repeating unit using novel L-FucNAc and D-FucNAc synthons and immunochemical evaluation. *Bioorg. Med. Chem.* **2012**, *20*(21), 6403–6415. DOI: 10.1016/j.bmc.2012.08.048.

[18] Behera, A.; Rai, D.; Kulkarni, S. S. Total syntheses of conjugation-ready trisaccharide repeating units of *Pseudomonas aeruginosa* O11 and *Staphylococcus aureus* type 5 capsular polysaccharide for vaccine development. *J. Am. Chem. Soc.* **2020**, *142*(1), 456–467. DOI: 10.1021/jacs.9b11309.

[19] Sanapala, S. R.; Kulkarni, S. S. Expedient route to access rare deoxy amino L-sugar building blocks for the assembly of bacterial glycoconjugates. *J. Am. Chem. Soc.* **2016**, *138*(14), 4938–4947. DOI: 10.1021/jacs.6b01823.

[20] Emmadi, M.; Kulkarni, S. S. Recent advances in synthesis of bacterial rare sugar building blocks and their applications. *Nat. Prod. Rep.* **2014**, *31*(7), 870–879. DOI: 10.1039/c4np00003j.

[21] Emmadi, M.; Kulkarni, S. S. Synthesis of orthogonally protected bacterial, rare-sugar and D-glycosamine building blocks. *Nat. Protoc.* **2013**, *8*(10), 1870–1889. DOI: 10.1038/nprot.2013.113.

[22] Emmadi, M.; Kulkarni, S. S. Synthesis of rare deoxy amino sugar building blocks enabled the total synthesis of a polysaccharide repeating unit analogue from the LPS of *Psychrobacter cryohalolentis* $K5^T$. *J. Org. Chem.* **2018**, *83*(23), 14323–14337. DOI: 10.1021/acs.joc.8b02037.

[23] Liu, H.; Zhang, Y.; Wei, R.; Andolina, G.; Li, X. Total synthesis of *Pseudomonas aeruginosa* 1244 pilin glycan via de novo synthesis of pseudaminic acid. *J. Am. Chem. Soc.* **2017**, *139*(38), 13420–13428. DOI: 10.1021/jacs.7b06055.

[24] Wang, L.; Dong, M.; Lowary, T. L. Synthesis of unusual *N*-acylated aminosugar fragments of *Mycobacterium marinum* lipooligosaccharide IV. *J. Org. Chem.* **2015**, *80*(5), 2767–2780. DOI: 10.1021/acs.joc.5b00064.

[25] Zhu, D.; Baryal, K. N.; Adhikari, S.; Zhu, J. Direct synthesis of 2-deoxy-β-glycosides via anomeric O-alkylation with secondary electrophiles. *J. Am. Chem. Soc.* **2014**, *136*(8), 3172–3175. DOI: 10.1021/ja4116956.

[26] Zeng, J.; Sun, G.; Yao, W.; Zhu, Y.; Wang, R.; Cai, L.; Liu, K.; Zhang, Q.; Liu, X. W.; Wan, Q. 3-Aminodeoxypyranoses in glycosylation: diversity-oriented synthesis and assembly in oligosaccharides. *Angew. Chem. Int. Ed. Engl.* **2017**, *56*(19), 5227–5231. DOI: 10.1002/anie.201700178.

[27] Zeng, J.; Wang, R.; Zhang, S.; Fang, J.; Liu, S.; Sun, G.; Xu, B.; Xiao, Y.; Fu, D.; Zhang, W.; et al. Hydrogen-bonding-assisted exogenous nucleophilic reagent effect

for β-selective glycosylation of rare 3-amino sugars. *J. Am. Chem. Soc.* **2019**, *141*(21), 8509–8515. DOI: 10.1021/jacs.9b01862.

[28] Crich, D.; Yao, Q. Benzylidene acetal fragmentation route to 6-deoxy sugars: Direct reductive cleavage in the presence of ether protecting groups, permitting the efficient, highly stereocontrolled synthesis of beta-D-rhamnosides from D-mannosyl glycosyl donors. Total synthesis of alpha-D-Gal-(1->3)-alpha-D-Rha-(1->3)- beta-D-Rha-(1->4)-beta-D-Glu-OMe, the repeating unit of the antigenic lipopolysaccharide from Escherichia hermannii ATCC 33650 and 33652. *J. Am. Chem. Soc.* **2004**, *126*(26), 8232–8236. DOI: 10.1021/ja048070j.

[29] Crich, D.; Bowers, A. A. 4,6-O-[1-Cyano-2-(2-iodophenyl)ethylidene] acetals. Improved second-generation acetals for the stereoselective formation of beta-D-mannopyranosides and regioselective reductive radical fragmentation to beta-D-rhamnopyranosides. scope and limitations. *J. Org. Chem.* **2006**, *71*(9), 3452–3463. DOI: 10.1021/jo0526688.

[30] Zhang, L.; Shen, K.; Taha, H. A.; Lowary, T. L. Stereocontrolled synthesis of α-xylofuranosides using a conformationally restricted donor. *J. Org. Chem.* **2018**, *83*(15), 7659–7671. DOI: 10.1021/acs.joc.8b00410.

[31] Cai, J.; Hu, J.; Qin, C.; Li, L.; Shen, D.; Tian, G.; Zou, X.; Seeberger, P. H.; Yin, J. Chemical synthesis elucidates the key antigenic epitope of the autism-related bacterium *Clostridium bolteae* capsular octadecasaccharide. *Angew. Chem. Int. Ed. Engl.* **2020**. DOI: 10.1002/anie.202007209.

[32] Hsu, C. H.; Hung, S. C.; Wu, C. Y.; Wong, C. H. Toward automated oligosaccharide synthesis. *Angew. Chem. Int. Ed. Engl.* **2011**, *50*(50), 11872–11923. DOI: 10.1002/anie.201100125.

[33] van der Vorm, S.; Hansen, T.; van Hengst, J. M. A.; Overkleeft, H. S.; van der Marel, G. A.; Codée, J. D. C. Acceptor reactivity in glycosylation reactions. *Chem. Soc. Rev.* **2019**, *48*(17), 4688–4706. DOI: 10.1039/c8cs00369f.

[34] Pedersen, C. M.; Marinescu, L. G.; Bols, M. Conformationally armed glycosyl donors: reactivity quantification, new donors and one pot reactions. *Chem. Commun.* **2008**, *21*(21), 2465–2467. DOI: 10.1039/b801305e.

[35] van der Vorm, S.; van Hengst, J. M. A.; Bakker, M.; Overkleeft, H. S.; van der Marel, G. A.; Codée, J. D. C. Mapping the relationship between glycosyl acceptor reactivity and glycosylation stereoselectivity. *Angew. Chem. Int. Ed. Engl.* **2018**, *57*(27), 8240–8244. DOI: 10.1002/anie.201802899.

[36] Wu, Y.; Xiong, D. C.; Chen, S. C.; Wang, Y. S.; Ye, X. S. Total synthesis of mycobacterial arabinogalactan containing 92 monosaccharide units. *Nat. Commun.* **2017**, *8*, 14851. DOI: 10.1038/ncomms14851.

[37] Zou, X.; Qin, C.; Pereira, C. L.; Tian, G.; Hu, J.; Seeberger, P. H.; Yin, J. Synergistic glycosylation as key to the chemical synthesis of an outer core octasaccharide of *Helicobacter pylori*. *Chemistry* **2018**, *24*(12), 2868–2872. DOI: 10.1002/chem.201800049.

[38] Tian, G.; Qin, C.; Liu, Z.; Shen, D.; Zou, X.; Fu, J.; Hu, J.; Seeberger, P. H.; Yin, J. Total synthesis of the *Helicobacter pylori* serotype O2 O-antigen α-(1 → 2)- and α-(1 → 3)-linked oligoglucosides. *Chem. Commun. (Camb)* **2020**, *56*(3), 344–347. DOI: 10.1039/c9cc07915g.

[39] Geng, X.; Dudkin, V. Y.; Mandal, M.; Danishefsky, S. J. In pursuit of carbohydrate-based HIV vaccines, part 2: the total synthesis of high-mannose-type gp120 fragments-evaluation of strategies directed to maximal convergence. *Angew. Chem. Int. Ed. Engl.* **2004**, *43*(19), 2562–2565. DOI: 10.1002/anie.200353626.

[40] Tian, G.; Hu, J.; Qin, C.; Li, L.; Zou, X.; Cai, J.; Seeberger, P. H.; Yin, J. Chemical synthesis and immunological evaluation of *Helicobacter pylori* serotype O6 tridecasaccharide O-antigen containing a dd-Heptoglycan. *Angew. Chem. Int. Ed. Engl.* **2020**, *59*(32), 13362–13370. DOI: 10.1002/anie.202004267.

[41] Yasomanee, J. P.; Visansirikul, S.; Pornsuriyasak, P.; Thompson, M.; Kolodziej, S. A.; Demchenko, A. V. Synthesis of the repeating unit of capsular polysaccharide *Staphylococcus aureus* type 5 to study chemical activation and conjugation of native CP5. *J. Org. Chem.* **2016**, *81*(14), 5981–5987. DOI: 10.1021/acs.joc.6b00910.

[42] Hagen, B.; Ali, S.; Overkleeft, H. S.; van der Marel, G. A.; Codée, J. D. C. Mapping the reactivity and selectivity of 2-azidofucosyl donors for the assembly of *N*-acetylfucosamine-containing bacterial oligosaccharides. *J. Org. Chem.* **2017**, *82*(2), 848–868. DOI: 10.1021/acs.joc.6b02593.

[43] Visansirikul, S.; Yasomanee, J. P.; Pornsuriyasak, P.; Kamat, M. N.; Podvalnyy, N. M.; Gobble, C. P.; Thompson, M.; Kolodziej, S. A.; Demchenko, A. V. A concise synthesis of the repeating unit of capsular polysaccharide *Staphylococcus aureus* type 8. *Org. Lett.* **2015**, *17*(10), 2382–2384. DOI: 10.1021/acs.orglett.5b00899.

[44] Zhao, M.; Qin, C.; Li, L.; Xie, H.; Ma, B.; Zhou, Z.; Yin, J.; Hu, J. Conjugation of synthetic trisaccharide of *Staphylococcus aureus* type 8 capsular polysaccharide elicits antibodies recognizing intact bacterium. *Front. Chem.* **2020**, *8*, 258. DOI: 10.3389/fchem.2020.00258.

[45] Gagarinov, I. A.; Fang, T.; Liu, L.; Srivastava, A. D.; Boons, G. J. Synthesis of *Staphylococcus aureus* type 5 trisaccharide repeating unit: solving the problem of lactamization. *Org. Lett.* **2015**, *17*(4), 928–931. DOI: 10.1021/acs.orglett.5b00031.

[46] Qin, C.; Schumann, B.; Zou, X.; Pereira, C. L.; Tian, G.; Hu, J.; Seeberger, P. H.; Yin, J. Total synthesis of a densely functionalized *Plesiomonas shigelloides* serotype 51 aminoglycoside trisaccharide antigen. *J. Am. Chem. Soc.* **2018**, *140*(8), 3120–3127. DOI: 10.1021/jacs.8b00148.

[47] Adibekian, A.; Stallforth, P.; Hecht, M. L.; Werz, D. B.; Gagneux, P.; Seeberger, P. H. Comparative bioinformatics analysis of the mammalian and bacterial glycomes. *Chem. Sci.* **2011**, *2*(2), 337–344. DOI: 10.1039/c0sc00322k.

[48] Zhao, J.; Wei, S.; Ma, X.; Shao, H. A simple and convenient method for the synthesis of pyranoid glycals. *Carbohydr. Res.* **2010**, *345*(1), 168–171. DOI: 10.1016/j.carres.2009.10.003.

[49] Yang, Y.; Yang, L.; Han, Y.; Wu, Z.; Chen, P.; Zhang, H.; Zhou, J. Protective effects of hepatocyte-specific glycyrrhetic derivatives against carbon tetrachloride-induced liver damage in mice. *Bioorg. Chem.* **2017**, *72*, 42–50. DOI: 10.1016/j.bioorg.2017.03.009.

[50] Yu, B.; Tao, H. Part 1: Preparation and application as new glycosyl donors. *Tetrahedron Lett.* **2001**, *42*(12), 2405–2407. DOI: 10.1016/S0040-4039(01)00157-5.

[51] Yu, B.; Sun, J.; Yang, X. Assembly of naturally occurring glycosides, evolved tactics, and glycosylation methods. *Acc. Chem. Res.* **2012**, *45*(8), 1227–1236. DOI: 10.1021/ar200296m.