Trifluoromethanesulfonic Acid Efficiently Catalyzed the Intramolecular Glycosidation of 1-*C*-Alkyl-D-hexopyranoses to Form the Anhydroketopyranoses Having 6,8-Dioxabicyclo[3.2.1]octane Structures

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Abstract: The intramolecular glycosidation of the 1-*C*-alkyl-D-hexopyranose derivatives to form the anhydroketopyranoses having 6,8-dioxabicyclo[3.2.1]octane structures was investigated. We synthesized several 1-*C*-alkyl-2,3,4-tri-*O*-benzyl-D-hexopyranoses and found that only 5 mol% trifluoromethanesulfonic acid efficiently promoted the intramolecular glycosidation to afford the desired anhydroketopyranoses in good yields.

Key words: anhydro form, anhydroketopyranose, 1-*C*-alkyl-hexopyranose, intramolecular glycosidation, trifluoromethanesulfonic acid

The anhydroketopyranoses having 6,8-dioxabicyclo[3.2.1]octane structures are widely found in biologically important natural products such as *Sedum spectabile*, *Coriaria japonica A*, and so on.[1] They are also useful chiral building blocks in synthetic organic chemistry.[2] Several of these anhydroketopyranoses have been prepared by the acid-catalyzed conversions of aldoses. These conversion reactions, however, are limited to the synthesis of the anhydroheptulopyranoses having 6,8-dioxabicyclo[3.2.1]octane structures.[3] Francisco et al. have recently developed a novel synthetic method for affording these anhydroketopyranoses from *C*-glycopyranosides by the intramolecular cyclization via the intramolecular hydrogen abstraction reaction using radical species.[4] Although their method increased the available varieties of the synthesizable anhydroketopyranoses, it required a complicated process of synthesizing the stereoselective *C*-glycosides.

The anhydroketopyranoses having 6,8-dioxabicyclo[3.2.1]octane structures can be regarded as intramolecular *O*-glycosides. We considered that they could be synthesized by the direct intramolecular glycosidation of the corresponding ketopyranoses, and that the 1-*C*-alkyl-hexopyranoses, ketopyranoses having alkyl groups at their anomeric carbon centers, would be useful precursors to afford various kinds of anhydroketopyranoses having 6,8-dioxabicyclo[3.2.1]octane structures.

The 1-*C*-alkyl-hexopyranoses can be readily prepared by the reaction of the glycono-1,5-lactones with organometallic reagents such as organolithium reagents or Grignard reagents.[5] We have studied O-glycosidation using 1-*C*-alkyl-hexopyranose derivatives as glycosyl donors to synthesize the 1-*C*-alkyl-hexopyranosides, which attract considerable attention as units of biologically important glycoconjugates and artificial substitutes for naturally occurring *O*-glycosides.[6] Prior to our study, only a few O-glycosidation methods using the 1-*C*-alkyl-hexopyranose derivatives as glycosyl donors had ever been reported.[7] Li et al. developed the O-glycosidations of 1-hydroxy-1-*C*-methyl (or vinyl)-hexopyranoses or methyl 1-*C*-methyl-hexopyranosides using TMSOTf or $SnCl_4$ as the activators. In their glycosidations, however, the glycosyl donors could not be activated by a catalytic amount of Lewis acids. In contrast, our recent study showed that only a catalytic amount of scandium(III) trifluoromethanesulfonate efficiently promoted the O-glycosidation between the 1-*C*-alkyl-D-glucopyranosyl acetates and alcohols to afford the 1-*C*-alkyl-*O*-D-glucopyranosides.[8]

In these reported O-glycosidation methods, the 1-*C*-alkyl-α-*O*-D-hexopyranosides were stereoselectively obtained and the production of their β-isomers was scarcely observed. This suggests that the glycosidations of the 1-*C*-alkyl-D-hexopyranose derivatives have some unknown characteristics to be elucidated. We expected that the investigation of the intramolecular glycosidation of 1-*C*-alkyl-D-hexopyranoses would lead to the elucidation of their reactivity and stereoselectivity, especially the appearance of the β-stereoselectivity.

The formation of the 1,6-anhydro rings from the D-aldopyranose derivatives involves conformational changes in the pyranosyl rings from $^4C_1$ into $^1C_4$. During the formation of the anhydroketopyranoses having 6,8-dioxabicyclo[3.2.1]octane structures from 1-*C*-alkyl-D-hexopyranose derivatives, the alkyl groups at the anomeric positions of the anhydroketopyranoses, which inevitably indicate the equatorial orientations, are expected to stabilize the $^1C_4$ conformations. We speculated that the steric factor of the alkyl groups of the 1-*C*-alkyl-D-hexopyranose derivatives would accelerate the intramolecular β-O-glycosidation to form the $^1C_4$ conformational anhydroketopyranoses having 6,8-dioxabicyclo[3.2.1]octane structures (Scheme 1).

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Scheme 1

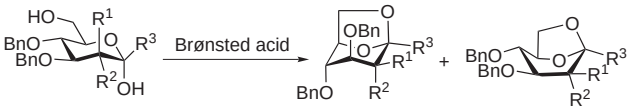
In this paper, we report the synthesis of 1-*C*-alkyl-2,3,4-tri-*O*-benzyl-D-hexopyranoses and their intramolecular β-O-glycosidation to afford various kinds of anhydroketopyranoses having 6,8-dioxabicyclo[3.2.1]octane structures. The reactivity and stereoselectivity of the 1-*C*-alkyl-hexopyranosyl donors are also described in detail.

We first synthesized several 1-*C*-alkyl-2,3,4-tri-*O*-benzyl-α-D-hexopyranoses (**1a**–**e**, **6a**; alkyl = methyl, allyl, *n*-butyl, phenyl, benzyl) as the compounds to investigate the intramolecular glycosidation to form the corresponding anhydroketopyranoses.[9]

We then investigated the intramolecular glycosidation of **1a** to afford the corresponding anhydroketopyranose (**2a**) having a 6,8-dioxabicyclo[3.2.1]octane structure (Scheme 2). Brønsted acids were used as the activating reagents in order to develop the convenient dehydration condensation type glycosidation. Each reaction using 20 mol% of camphorsulfonic acid, Tf_2NH, and TfOH as the Brønsted acids in MeCN at 0 °C gave the desired **2a** in 59%, 82%, and 84% yields, respectively. The Brønsted acids Tf_2NH and TfOH were very efficient for this intramolecular glycosidation. The amount of TfOH was then varied. The reactions using only 1 mol% or 0.5 mol% of TfOH proceeded to give **2a** in 86% and 68% yields, respectively. The maximum yield of 93% was attained in the reaction using 5 mol% of TfOH. These results showed that the intramolecular glycosidation of **1a** could successfully proceed without introducing any leaving groups into the anomeric center of **1a**.

In order to investigate the effect of the methyl group at C-1 of **1a** on this intramolecular glycosidation, we attempted the intramolecular glycosidation of 2,3,4-tri-*O*-benzyl-D-glucopyranose (**3**), which had no methyl group at C-1. The production of 1,6-anhydro-2,3,4-tri-*O*-benzyl-β-D-glucopyranose (**4**) was scarcely observed by TLC under the similar reaction conditions using 20 mol% TfOH for two hours, and unreacted **3** was quantitatively recovered from the reaction mixture. It was difficult to activate the hydroxyl group of **3** as the leaving group under the above reaction conditions. This result corresponds to the report that the conventional methods for forming 1,6-anhydro species from aldopyranoses generally required the glycosyl donors having adequate leaving groups.[10] In contrast, the presence of the methyl group at the anomeric position of **1a** drastically increased the reactivity of the intramolecular glycosidation. This high reactivity of **1a** would be explained as follows; after the stable glycosyl cation intermediate was produced by the effect of the tertiary anomeric carbon center of **1a**, the conformation flip of the pyranosyl ring smoothly occurred by the effect of the methyl group indicating the equatorial orientation in the anhydro form.

We next attempted the intramolecular glycosidation of **1b**–**e** in order to demonstrate the synthesis of various kinds of anhydroketopyranoses **2b**–**e**. The reactions using **1b**,**c** in MeCN at 0 °C for two hours in the presence of 5 mol% TfOH afforded the desired anhydroketopyranoses **2b**,**c** in the excellent yields of 95% and 91%, respectively. The $^1C_4$ conformational **2d**,**e** were similarly obtained from **1d**,**e** in 78% and 70% yields. Interestingly, in these two reactions, the twist-boat conformational isomers **5d**,**e** were also formed in 14% and 26% yields. Therefore, the total yields of these glycosidations were 92% and 96%, respectively. These results showed that the difference in the alkyl groups at the anomeric centers of **1a**–**e** had almost no influence on the glycosidation yields, though the electron-withdrawing benzyl and phenyl groups of **1d**,**e** influenced the conformations of the anhydro forms. The anhydro formation from **6a** under the same reaction conditions smoothly proceeded in the high yield of 93%. The structures of these anhydroketopyranoses were confirmed by the ^1H NMR spectra, which were consistent with the reported data of 1,6-anhydroaldopyranoses.[11]



1a–**e**, **6a** **2a**–**e**, **7a** **5d**,**e**

1a–**e**, **2a**–**e**, **5d**,**e**: R^1 = H, R^2 = –OBn

6a, **7a**; R^1 = –OBn, R^2 = H

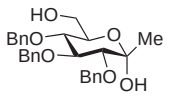
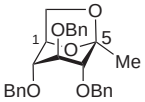
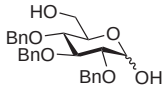
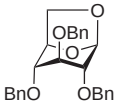
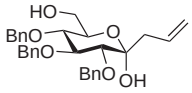
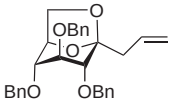
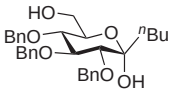
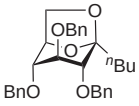
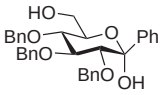
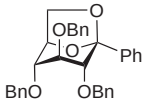
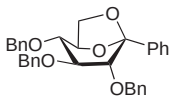
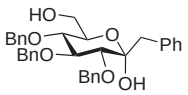
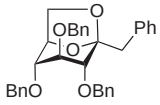
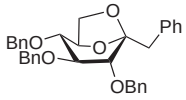
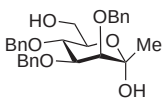
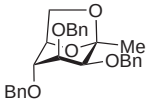
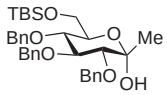
R^3 = **a**: Me; **b**: $–CH_2CH=CH_2$; **c**: *n*-Bu; **d**: Ph; **e**: Bn

Scheme 2

Furthermore, the reaction using 2,3,4-tri-*O*-benzyl-6-*O*-*tert*-butyldimethylsilyl-α-D-glucopyranose (**8**) also afforded **2a** in 80% yield. In this reaction, TfOH not only promoted the intramolecular glycosidation but also removed the TBS group of **8**. This result showed the possibility that the intramolecular glycosidation method could utilize the 1-*C*-alkyl-hexopyranose derivatives whose hydroxyl groups at C-6 were protected with adequate protective groups which were removable by TfOH. In all the above reactions, the production of the oligosaccharides by the intermolecular O-glycosidation was not observed at all. These results are summarized in Table 1.[12]

As mentioned above, we investigated in detail the specificities of the intramolecular glycosidation using the 1-*C*-alkyl-2,3,4-tri-*O*-benzyl-D-hexopyranoses and found that TfOH efficiently catalyzed the intramolecular glycosidation to afford various kinds of anhydroketopyranoses having 6,8-dioxabicyclo[3.2.1]octane structures. This method can be applicable to the synthesis of natural products and chiral building blocks having these structures.

Table 1 Synthesis of Anhydroketopyranose Derivatives (**2a**–**e**, **5d**–**e**, and **7a**) by the Intramolecular Glycosidation of **1a**–**e**, **6a**, and **8** in the Presence of Brønsted Acid[a]

Entry	1-*C*-Alkyl-hexopyranose	Brønsted acid (mol%)	Product, yield (%)	
1[b]	 **1a**	Camphorsulfonic acid (20)	 **2a** (59)	
2	**1a**	Tf_2NH (20)	**2a** (82)	
3	**1a**	TfOH (20)	**2a** (84)	
4	**1a**	TfOH (5)	**2a** (93)	
5	**1a**	TfOH (1)	**2a** (86)	
6	**1a**	TfOH (0.5)	**2a** (68)	
7	 **3**	TfOH (20)	 **4** (trace)	
8	 **1b**	TfOH (5)	 **2b** (95)	
9	 **1c**	TfOH (5)	 **2c** (91)	
10	 **1d**	TfOH (5)	 **2d** (78)	 **5d** (14)
11	 **1e**	TfOH (5)	 **2e** (70)	 **5e** (26)
12	 **6a**	TfOH (5)	 **7a** (93)	
13	 **8**	TfOH (5)	**2a** (80)	

[a] Reaction conditions: MeCN, 2 h, 0 °C.
[b] Reaction time: 30 h.

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(9) Compounds **1a**–**e** and **6a** were synthesized as follows (Scheme 3). The reaction of 6-*O*-acetyl-2,3,4-tri-*O*-benzyl-D-glucopyranose (**9**) using DMSO–Ac_2O gave the corresponding 6-*O*-acetyl-2,3,4-tri-*O*-benzyl-D-glucono-1,5-lactone (**10**) in the good yield of 92%. The alkyl groups were then introduced into C-1 of **10** by the reaction of the carbonyl group at C-1 with organometallic reagents such as RMgX or RLi. The reaction of **10** with MeLi (2.4 equiv) in dry THF at –78 °C gave 6-*O*-acetyl-2,3,4-tri-*O*-benzyl-1-*C*-methyl-α-D-glucopyranose (**11a**) and 2,3,4-tri-*O*-benzyl-1-*C*-methyl-α-D-glucopyranose (**1a**) in 14% and 64% yields, respectively. The treatment of **11a** using NaOMe in MeOH quantitatively afforded **1a**. The reaction using AllMgCl and *n*-BuLi similarly gave the mixtures of 6-*O*-acetyl-1-*C*-allyl-2,3,4-tri-*O*-benzyl-α-D-glucopyranose (**11b**) and 1-*C*-allyl-2,3,4-tri-*O*-benzyl-α-D-glucopyranose (**1b**) in 30% and 54% yields, and of 6-*O*-acetyl-2,3,4-tri-*O*-benzyl-1-*C*-*n*-butyl-D-glucopyranose (**11c**) and 2,3,4-tri-*O*-benzyl-1-*C*-*n*-butyl-α-D-glucopyranose (**1c**) in 64% and 12% yields, respectively. The reactions using PhMgCl and $PhCH_2MgCl$ afforded 6-*O*-acetyl-2,3,4-tri-*O*-benzyl-1-*C*-phenyl-α-D-glucopyranose (**11d**) and 6-*O*-acetyl-1-*C*-benzyl-2,3,4-tri-*O*-benzyl-α-D-glucopyranose (**11e**) in 89% and 82% yields, respectively, with almost no production of the deacetylated compounds. It seemed that these bulky organometallic reagents were apt to produce the nucleophilic attack on the conformationally fixed carbonyl group at C-1 of **10** rather than on the acetyl group at C-6. The treatment of **11b**–**e** using NaOMe in MeOH quantitatively afforded **1b**-**e**. 2,3,4-Tri-*O*-benzyl-1-*C*-methyl-α-D-mannopyranose (**6a**) was similarly prepared in 82% yield from 6-*O*-acetyl-2,3,4-tri-*O*-benzyl-D-manno-1,5-lactone(**13**). Preparation of **9** and **12** was reported in the following literature. See: (a) Koto, S.; Morishima, N.; Takenaka, K.; Kanemitsu, K.; Shimoura, N.; Kase, M.; Kojiro, S.; Nakamura, T.; Kawase, T.; Zen, S. *Bull. Chem. Soc. Jpn.* **1989**, *62*, 3549. (b) Murakata, C.; Ogawa, T. *Carbohydr. Res.* **1992**, *235*, 95. (c) The oxidation of **9** using pyridinium chlorochromate also gave **10** in a moderate yield. See: Horito, S.; Asano, K.; Umemura, K.; Hashimoto, H.; Yoshimura, J. *Carbohydr. Res.* **1983**, *121*, 175.
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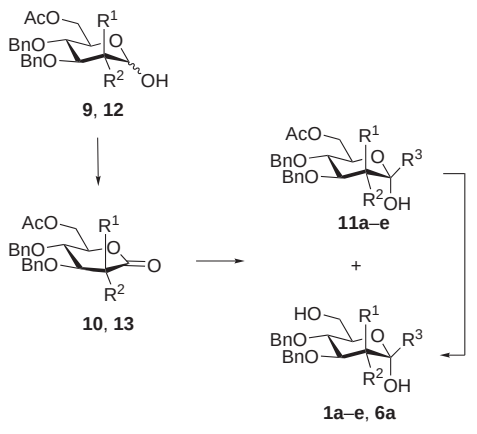

9, **10**, **11a**–**e**, **1a**–**e**: R^1 = H, R^2 = –OBn
12, **13**, **6a**: R^1 = –OBn, R^2 = H
R^3 = **a**: Me; **b**: $–CH_2CH=CH_2$; **c**: *n*-Bu; **d**: Ph; **e**: Bn

Scheme 3

(12) **Typical Intramolecular Glycosidation Procedure (Table 1, Entry 4).**
A typical glycosidation procedure is as follows. To a stirred solution of TfOH (0.48 μL, 0.0054 mmol) was added **1a** (50 mg, 0.11 mmol) in MeCN (2 mL) at 0 °C in the presence of dry $MgSO_4$ (ca. 100 mg) in an Ar atmosphere. The resulting mixture was stirred for 2 h. The reaction was then quenched by the addition of a sat. $NaHCO_3$ solution (5 mL). The reaction mixture was extracted with EtOAc, and the organic layer was washed with H_2O and a sat. NaCl solution. After the organic layer was dried over Na_2SO_4, the solvent was evaporated under reduced pressure. The crude product was purified by preparative silica gel TLC (EtOAc–hexane = 1:2) to give **2a** (45 mg, 93%).
Compound **2a**: $[\alpha]_D^{23}$ –47.7 (*c* 1.54, $CHCl_3$). ^1H NMR (600 MHz, $CDCl_3$): δ = 1.49 (3 H, s, H-2′), 3.23 (1 H, s, H-4), 3.31 (1 H, s, H-2), 3.59 (1 H, s, H-3), 3.75 (1 H, dd, *J* = 6.2 Hz, *J* = 6.9 Hz, H-7a), 3.96 (1 H, d, *J* = 6.9 Hz, H-7b), 4.34–4.39 (3 H, m, OC*H*$_2$Ph and OC*H*aHbPh), 4.53 (1 H, m, OCHa*H*bPh), 4.53 (1 H, d, *J* = 6.2 Hz, H-1), 4.58–4.61 (2 H, m, OC*H*$_2$Ph). ^{13}C NMR (150 MHz, $CDCl_3$): δ = 21.0 (C-2′), 65.5 (C-7), 71.0 (O*C*H$_2$Ph), 71.2 (O*C*H$_2$Ph), 72.3 (O*C*H$_2$Ph), 74.5 (C-2), 75.2 (C-3), 75.7 (C-1), 77.3 (C-4), 107.0 (C-5). HRMS (ESI): *m/z* calcd for $C_{28}H_{30}O_5Na^+$: 469.1991; found: 469.2032.
Compound **2b**: $[\alpha]_D^{23}$ +7.6 (*c* 4.57, $CHCl_3$). ^1H NMR (600 MHz, $CDCl_3$): δ = 2.56 (1 H, dd, *J* = 7.6 Hz, *J* = 14.4 Hz, H-2′a), 2.64 (1 H,dd, *J* = 7.6 Hz, *J* = 14.4 Hz, H-2′b), 3.24 (1 H, s, H-4), 3.26 (1 H, s, H-2), 3.54 (1 H, s, H-3), 3.66 (1 H, dd, *J* = 6.2 Hz, *J* = 6.9 Hz, H-7a), 3.94 (1 H, d, *J* = 6.9 Hz, H-7b), 4.29–4.34 (3 H, m, OC*H*$_2$Ph and OC*H*aHbPh), 4.41–4.52 (3 H, m, OC*H*$_2$Ph and OCHa*H*bPh), 4.56 (1 H, d, *J* = 5.5 Hz, H-1), 5.03–5.05 (2 H, m, H-4′), 5.77 (1 H, m, H-3′). ^{13}C NMR (150 MHz, $CDCl_3$): δ = 38.1 (C-2′), 65.7 (C-7), 70.9 (O*C*H$_2$Ph), 71.5 (O*C*H$_2$Ph), 72.2 (O*C*H$_2$Ph), 74.6 (C-2), 74.9 (C-3), 75.5 (C-1), 76.2 (C-4), 107.2 (C-5), 118.4 (C-4′), 132.0 (C-3′). HRMS (ESI): *m/z* calcd for $C_{30}H_{32}O_5Na^+$: 495.2147; found: 495.2195.
Compound **2c**: $[\alpha]_D^{23}$ –36.7 (*c* 1.08, $CHCl_3$). ^1H NMR (600 MHz, $CDCl_3$): δ = 0.84 (3 H, t, *J* = 6.9 Hz, H-5′), 1.16 (1 H, m, H-3′a), 1.25 (2 H, m, H-4′), 1.36 (1 H, m, H-3′b), 1.75 (1 H, m, H-2′a), 1.90 (1 H, ddd, *J* = 13.1 Hz, *J* = 3.4 Hz, *J* = 13.7 Hz, H-2′b), 3.25 (1 H, s, H-4), 3.31 (1 H, s, H-2),

3.60 (1 H, s, H-3), 3.70 (1 H, dd, *J* = 6.9 Hz, *J* = 6.2 Hz, H-7a), 3.98 (1 H, d, *J* = 6.9 Hz, H-7b), 4.32–4.40 (3 H, m, OC*H*$_2$Ph and OC*H*aHbPh), 4.49–4.57 (3 H, m, OC*H*$_2$Ph and OCHa*H*bPh), 4.59 (1 H, d, *J* = 6.2 Hz, H-1). ^{13}C NMR (150 MHz, $CDCl_3$): δ = 14.0 (C-5′), 22.9 (C-4′), 24.1 (C-3′), 32.9 (C-2′), 65.6 (C-7), 70.9 (O*C*H$_2$Ph), 71.4 (O*C*H$_2$Ph), 72.0 (O*C*H$_2$Ph), 74.7 (C-2), 75.0 (C-3), 75.4 (C-1), 76.2 (C-4), 107.9 (C-5). HRMS (ESI): *m/z* calcd for $C_{31}H_{36}O_5Na^+$: 511.2460; found: 511.2510.

Compound **2d**: $[\alpha]_D^{23}$ –3.5 (*c* 2.71, $CHCl_3$). ^{1}H NMR (600 MHz, $CDCl_3$): δ = 3.39 (1 H, s, H-4), 3.50 (1 H, s, H-2), 3.68 (1 H, s, H-3), 3.81 (1 H, dd, *J* = 5.5 Hz, *J* = 6.2 Hz, H-7a), 4.03 (2 H, dd, *J* = 12.4 Hz, *J* = 3.4 Hz, OC*H*$_2$Ph), 4.07 (1 H, d, *J* = 6.9 Hz, H-7b), 4.34 (2 H, dd, *J* = 12.4 Hz, *J* = 3.4 Hz, OC*H*$_2$Ph), 4.56 (1 H, d, *J* = 13.1 Hz, OC*H*aHbPh), 4.67 (1 H, d, *J* = 13.1 Hz, OCHa*H*bPh), 4.79 (1 H, d, *J* = 6.2 Hz, H-1). ^{13}C NMR (150 MHz, $CDCl_3$): δ = 65.6 (C-7), 71.0 (O*C*H$_2$Ph), 71.6 (O*C*H$_2$Ph), 72.2 (O*C*H$_2$Ph), 74.6 (C-2), 76.2 (C-3), 76.3 (C-1), 77.6 (C-4), 106.9 (C-5). HRMS (ESI): *m/z* calcd for $C_{33}H_{32}O_5Na^+$: 531.2147; found: 531.2196.

Compound **5d**: $[\alpha]_D^{23}$ –74.5 (*c* 0.47, $CHCl_3$). ^{1}H NMR (600 MHz, $CDCl_3$): δ = 3.55 (1 H, s, H-2), 3.77 (1 H, d, *J* = 5.5 Hz, H-4), 3.86 (1 H, d, *J* = 5.5 Hz, H-3), 3.94 (1 H, dd, *J* = 8.2 Hz, *J* = 5.5 Hz, H-7a), 3.95 (1 H, d, *J* = 11.7 Hz, OC*H*aHbPh), 4.04 (1 H, d, *J* = 11.7 Hz, OCHa*H*bPh), 4.42 (1 H, d, *J* = 8.2 Hz, H-7b), 4.44 (1 H, d, *J* = 12.4 Hz, OC*H*a′Hb′Ph), 4.45 (1 H, d, *J* = 12.4 Hz, OCHa′*H*b′Ph), 4.53 (1 H, d, *J* = 12.4 Hz, OC*H*a″Hb″Ph), 4.63 (1 H, d, *J* = 6.2 Hz, H-1), 4.66 (1 H, d, *J* = 12.4 Hz, OCHa″*H*b″Ph). ^{13}C NMR (150 MHz, $CDCl_3$): δ = 66.1 (C-7), 71.2 (O*C*H$_2$Ph), 72.4 (O*C*H$_2$Ph), 73.3 (O*C*H$_2$Ph), 75.0 (C-3), 75.4 (C-1), 76.9 (C-2), 77.7 (C-4), 107.6 (C-5). HRMS (ESI): *m/z* calcd for $C_{33}H_{32}O_5Na^+$: 531.2147; found: 531.2178.

Compound **2e**: $[\alpha]_D^{23}$ –35.1 (*c* 2.32, $CHCl_3$). ^{1}H NMR (600 MHz, $CDCl_3$): δ = 2.97 (1 H, d, *J* = 13.4 Hz, H-2′a), 3.23 (1 H, s, H-4), 3.29 (1 H, s, H-2), 3.34 (1 H, d, *J* = 13.7 Hz, H-2′b), 3.45 (1 H, dd, *J* = 6.9 Hz, *J* = 6.2 Hz, H-7a), 3.60 (1 H, s, H-3), 3.91 (1 H, d, *J* = 6.9 Hz, H-7b), 4.33 (3 H, m, OC*H*$_2$Ph and OC*H*aHbPh), 4.43 (1 H, d, *J* = 12.4 Hz, OC*H*a′Hb′Ph), 4.50 (1 H, d, *J* = 12.4 Hz, OCHa*H*bPh), 4.53 (1 H, d, *J* = 5.5 Hz, H-1), 4.56 (1 H, d, *J* = 13.0 Hz, OCHa′*H*b′Ph). ^{13}C NMR (150 MHz, $CDCl_3$): δ = 39.5 (C-2′), 65.7 (C-7), 70.9 (O*C*H$_2$Ph), 71.5 (O*C*H$_2$Ph), 72.0 (O*C*H$_2$Ph), 74.5 (C-2), 74.9 (C-3), 75.3 (C-1), 76.8 (C-4), 107.2 (C-5). HRMS (ESI): *m/z* calcd for $C_{34}H_{34}O_5Na^+$: 545.2304; found: 545.2354.

Compound **5e**: $[\alpha]_D^{23}$ –19.3 (*c* 1.97, $CHCl_3$). ^{1}H NMR (600 MHz, $CDCl_3$): δ = 2.95 (1 H, d, *J* = 14.4 Hz, H-2′a), 3.43 (1 H, d, *J* = 14.4 Hz, H-2′b), 3.48 (1 H, d, *J* = 1.4 Hz, H-2), 3.52 (1 H, dd, *J* = 6.9 Hz, *J* = 5.5 Hz, H-7a), 3.56 (1 H, d, *J* = 4.8 Hz, H-4), 3.81 (1 H, dd, *J* = 5.5 Hz, *J* = 1.4 Hz, H-3), 4.12 (1 H, d, *J* = 6.9 Hz, H-7b), 4.26 (1 H, d, *J* = 11.7 Hz, OC*H*aHbPh), 4.40 (1 H, d, *J* = 5.5 Hz, H-1), 4.43–4.51 (5 H, m, OC*H*$_2$Ph × 2 and OCHa*H*bPh). ^{13}C NMR (150 MHz, $CDCl_3$): δ = 39.1 (C-2′) 65.9 (C-7), 71.2 (O*C*H$_2$Ph), 71.3 (O*C*H$_2$Ph), 73.0 (O*C*H$_2$Ph), 74.2 (C-3), 75.1 (C-1), 76.2 (C-2), 76.5 (C-4), 107.8 (C-5). HRMS (ESI): *m/z* calcd for $C_{34}H_{34}O_5Na^+$: 545.2304; found: 545.2352.

Compound **7a**: $[\alpha]_D^{23}$ +12.1 (*c* 2.4, $CHCl_3$). ^{1}H NMR (600 MHz, $CDCl_3$): δ = 1.52 (3 H, s, H-2′), 3.48 (1 H, s, H-2), 3.53 (1 H, d, *J* = 5.5 Hz, H-4), 3.78–3.81 (2 H, m, H-3 and H-7a), 4.18 (1 H, d, *J* = 7.6 Hz, H-7b), 4.38 (1 H, d, *J* = 12.4 Hz, OC*H*aHbPh), 4.44–4.50 (4 H, m, H-1 and OC*H*$_2$Ph and OCHa*H*bPh), 4.53–4.56 (2 H, m, OC*H*$_2$Ph). ^{13}C NMR (150 MHz, $CDCl_3$): δ = 20.9 (C-2′), 65.7 (C-7), 71.2 (O*C*H$_2$Ph), 71.7 (O*C*H$_2$Ph), 73.1 (O*C*H$_2$Ph), 74.1 (C-3), 75.1 (C-1), 76.3 (C-2), 77.1 (C-4), 107.1 (C-5). HRMS (ESI): *m/z* calcd for $C_{28}H_{30}O_5Na^+$: 469.1991; found: 469.2030.