Available online at www.sciencedirect.com
SCIENCE DIRECT®
Carbohydrate Research 340 (2005) 235–244
Carbohydrate RESEARCH

Synthesis of *C*-5-thioglycopyranosides and their sulfonium derivatives from 1-*C*-(2′-oxoalkyl)-5-*S*-acetylglycofuranosides

Tian Yi,[a] Shih-Hsiung Wu[b] and Wei Zou[a,*]

[a]*Institute for Biological Sciences, National Research Council of Canada, Ottawa, Ontario, Canada K1A 0R6*
[b]*Institute of Biological Chemistry, Academia Sinica, Taipei 115, Taiwan*

Received 13 September 2004; accepted 18 November 2004
Available online 18 December 2004

Abstract—1-*C*-(2′-oxoalkyl)-5-*S*-acetylglycofuranosides of L-arabinose, D-ribose, and D-xylose were converted to 1-*C*-(2′-oxoalkyl)-5-thioglycopyranosides by base treatment. The transformation was achieved through β-elimination to an acyclic α,β-conjugated aldehyde (ketone or ester), followed by an intramolecular hetero-Michael addition by the 5-thiol group. The cycloaddition was highly stereoselective in favor of an equatorial 1-*C*-substitution. The resultant *C*-5-thioglycopyranosides were further converted to the sulfonium salts by treatment with cyclic sulfate and methyl iodide. Two sulfonium isomers were obtained due to the presence of both S-axial and S-equatorial substitutions. We observed that the chemical shifts of both C-1 and C-5 in the S-axial substituted sulfonium sugars are always shifted up-field (5–10 ppm) in comparison to those in the S-equatorial substitutions (δ_C 49–53 ppm vs 42–45 ppm at C-1 and 37–42 ppm vs 32–35 ppm at C-5), which provides an easy way for determination of the stereochemistry.

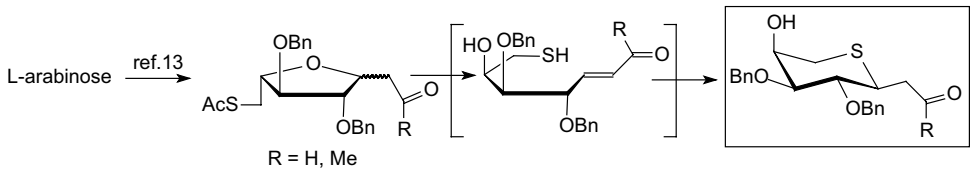
Keywords: Synthesis; Thiosugar; *C*-Glycoside; Sulfonium; Inhibitor; NMR spectroscopy

1. Introduction

Thiosugars are important intermediates to some nucleotide-based antiviral and anticancer agents, and numerous methods for their synthesis have been developed in the last two decades.[1] Although thiosugars are less potent glycosidase inhibitors than iminosugars,[2] the sulfonium salts of thiosugars such as salacinol[3] and kotalanol[4] are potent glucosidase inhibitors that have traditionally been used for the treatment of diabetes in India and Sri Lanka.[5] The synthesis of those sulfonium salts and their analogs has attracted considerable attention in the last few years.[6] Thiosugars have also been used as competitive glycosyl receptors instead of the enzyme inhibitors, for example, 1,5-dithio-β-D-xylopyranoside is used for the treatment of thrombosis as a competitive substrate in glycosaminoglycan biosynthesis.[7] One of the drawbacks of this compound is its metabolic instability.[8] On the other hand, metabolically stable *C*-glycosides can mimic the *O*-glycosides in terms of their binding to natural ligands and the solution conformation.[9] Hence, the *C*-glycosyl compounds were designed as possible enzyme inhibitors.[10] It is therefore reasonable to propose that the *C*-5-thioglycosides may be potentially better gylcosyl receptors and/or glycosidase inhibitors. Thus far, synthetic methods to *C*-5-thioglycosides are very limited. Praly and co-workers reported an electrophilic *C*-glycosylation using trichloroacetamide of thioxylopyranoside,[11] and Hashimoto and co-workers prepared *C*-5-thioglycosides by a thioglycosyl radical addition.[12] More recently, Grignard and Wittig reactions to thiosugars were used for the *C*-5-thioglycoside synthesis.[8] In a preliminary report,[13] we have described the synthesis of *C*-5-thioglycosides from 1-*C*-(2′-oxoalkyl)-4/5-*S*-acetylglycosides as illustrated in Scheme 1. Here, we report the synthesis of *C*-5-thioglycosides from D-ribose and D-xylose and the further transformation of these thiosugars into their sulfonium derivatives.

* Corresponding author. Tel.: +1 613 991 0855; fax: +1 613 952 9092; e-mail: wei.zou@nrc-cnrc.gc.ca

0008-6215/$ - see front matter
doi:10.1016/j.carres.2004.11.014

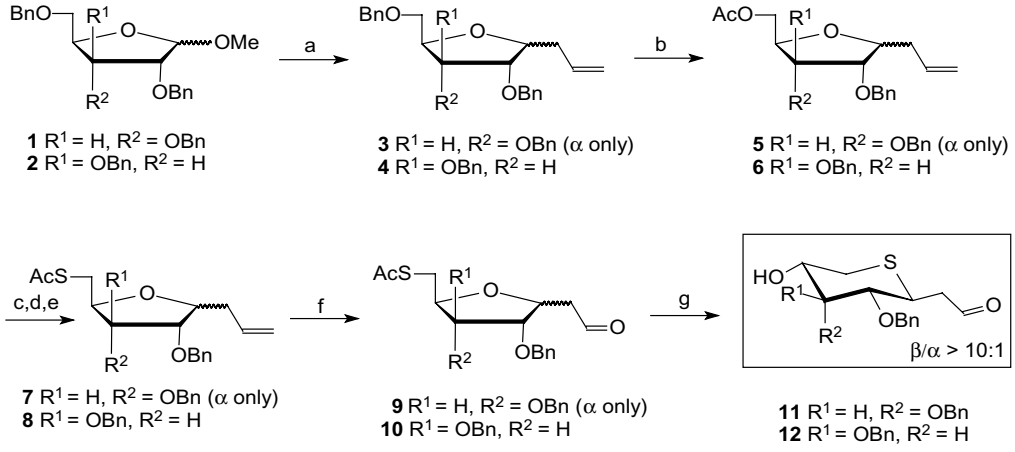


Scheme 1.

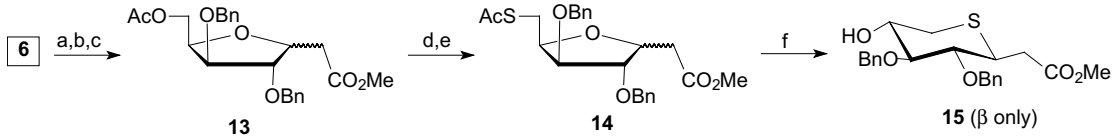
2. Results and discussion

Methyl tri-*O*-benzyl-α/β-glycofuranosides **1** and **2**[14] obtained from D-ribose and D-xylose were converted to respective *C*-allyl glycosides **3** and **4** by treatment with allyltrimethylsilane–TMSOTf,[15] which were further subjected to selective 5-*O*-acetolysis using 0.2% H_2SO_4–Ac_2O to afford **5** and **6** in 60–80% yield. Removal of the acetyl group from the 5-position of **5** and **6** was followed by 5-*O*-mesylation (MsCl–Et_3N) and 5-AcS substitution (KSAc–DMF) to give 1-*C*-allyl-5-*S*-acetylfuranosides **7** and **8** in 40–60% overall yield. 2′-Aldehydes **9** and **10** were then derived from **7** and **8** by ozonolysis (O_3 and Zn–HOAc) in 70–80% yield. Upon treatment of compounds **9** and **10** with 2% NaOMe in MeOH at 0 °C to room temperature for 4 h, 1-*C*-(2′-carbonylmethyl)-5-thio-β-D-glycopyranosides **11** and **12** were obtained, respectively, in ca. 70% yield. As expected, the reactions provided thermodynamically stable β anomers as the major products and the α-*C*-glycosides as the minor products,[16] which were inseparable by silica gel chromatography. According to ^1H NMR analysis, the ratio of two isomers was estimated to be β:α > 10:1 (Scheme 2).

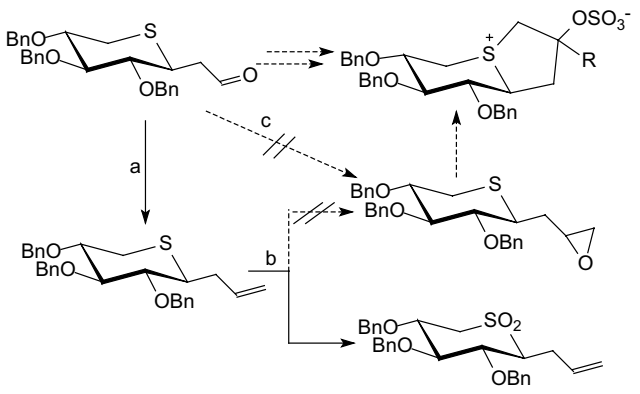
We expect the same chemistry also applicable to 1-*C*-(methoxycarbonylmethyl)-5-*S*-acetylglycosides. Thus, we prepared ester **13** from *C*-allyl glycoside **6** (38%) in three steps: (1) oxidation of the allyl group to the aldehyde by ozonolysis; (2) further oxidation of the aldehyde with $KMnO_4$ in acetone–water to a carboxylic acid;[17] and (3) esterification with MeI in $NaHCO_3$–DMF. The 5-*O*-Ac group of **13** was then transformed to 5-*S*-Ac to give **14** following the same procedures as described for the preparation of **7** and **8**. Finally, treatment of **14** with 4% NaOMe in MeOH at room temperature overnight provided the desired **15** stereospecifically in 54% yield (see Scheme 3). Although both the Wittig reaction to the lactol and the β-elimination of **14** pro-



Scheme 2. Reagents and conditions: (a) allyl-$SiMe_3$–TMSOTf in MeCN, −40 °C to room temperature, 80%; (b) 0.2% H_2SO_4–Ac_2O, room temperature, overnight, 60–80%; (c) 0.4% MeONa–MeOH, room temperature, 2 h; (d) MsCl–Et_3N in CH_2Cl_2, 0 °C to room temperature, overnight, 86%; (e) KSAc in DMF, 80 °C, overnight, 74%; (f) O_3 in CH_2Cl_2, −78 °C, 30 min, then, Zn–HOAc, 2 h, room temperature, 70%; (g) 2% MeONa–MeOH, 0 °C to room temperature, 4 h, 71%.



Scheme 3. Reagents and conditions: (a) O_3 in CH_2Cl_2, then, Zn–HOAc, 67%; (b) $KMnO_4$ in 1:1 acetone–H_2O, 92%; (c) MeI–$NaHCO_3$ in DMF, 61%; (d) 2% NaOMe–MeOH, then, MsCl–Et_3N in CH_2Cl_2, 77%; (e) KSAc in DMF, 80 °C, 74%; (f) 4% MeONa–MeOH, overnight, 54%.



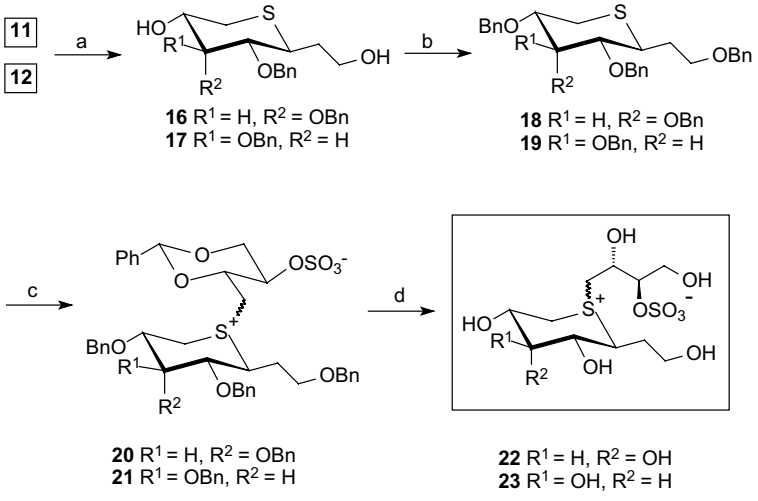
Scheme 4. Reagents and conditions: (a) $Ph_3P^+CH_3Br^-$–*t*-BuOK in ether, −78 to 0 °C, 62%; (b) *m*-CPBA in CH_2Cl_2, 0 °C; (c) $Me_3S^+I^-$–*n*-BuLi in THF, −78 to 0 °C.

duce the similar α,β-conjugated ester as an intermediate prior to a hetero-Michael addition to form *C*-glycosides, the transition state under two conditions must be very different because poor stereoselectivity is often observed in the Wittig reaction (β:α ca. 1:1).[8,18]

The sulfonium salts of the thiosugars are better glycosidase inhibitors because they are able to mimic the transition state.[19] With the thiosugars in hand we turned our attention to the synthesis of the sulfonium salts of the 5-thiosugars. Initially, we attempted to synthesize the bicyclic sulfonium inner salts as illustrated in Scheme 4. However, the reaction of the 2′-aldehyde to a sulfur ylide did not provide the desired epoxide intermediate, nor did the oxidation of the double bond because the oxidation of the thioether to sulfone occurred more rapidly.

Consequently, **11** and **12** were reduced using $NaBH_4$ to 1-*C*-(2′-hydroxyethyl)-5-thioglycosides **16** and **17**, and the resultant diols were in turn protected by benzylation to give **18** and **19** in ca. 60% yield. The respective sulfonium inner salts were then prepared by coupling **18** and **19** with 2,4-*O*-benzylidene-D-erythritol-1,3-cyclic sulfate (see Scheme 5) in 1,1,1,3,3,3-hexafluoro-2-propanol (HFIP) using the method of Pinto and co-workers[6d] to afford **20** and **21** in 75–85% yield. The polar solvent HFIP was critical to the coupling reaction. Pinto and co-workers have proposed that the increased reactivity was due to better solvation by HFIP of the polar transition states.[6] Unlike the trans-selectivity obtained in the coupling reaction between the cyclic sulfate and 4-thioglycofuranosides,[6] sulfonium salts **20** and **21** from 5-thioglycopyranosides were obtained as a mixture of two isomers in a ratio of about 1:1 based on NMR analysis.[20] One was axially substituted at the S-atom, and the other was equatorially substituted. We were able to obtain one pure compound, **20**-ax, by chromatography and determine its stereochemistry by NOE analysis as illustrated in Figure 1. Catalytic hydrogenation of **20** and **21** produced **22** and **23** in 61% and 45% yield, respectively.

In addition to the sulfonium inner salts, the methyl sulfonium salts of thiosugars also inhibit some glycosidases.[19a] Thus, we prepared methyl sulfonium salts (**24** and **25**) by treatment of thiosugars (**18** and **19**) with MeI–$AgClO_4$ (see Scheme 6) in excellent yield. Surprisingly, both reactions were stereoselective, and only one isomer (**24** and **25**) was formed, respectively, in each case. However, NOE analysis (see Fig. 1) indicated the methyl group in **24** is equatorial, while methyl group in **25** was axially oriented. After removal of benzyl groups by catalytic hydrogenation, the sulfonium salts **26** and **27** were obtained as a mixture of two diastereomers with both axial and equatorial substitutions of methyl group presented. The low-recovery yields (ca. 20%) for **26** and **27** in the catalytic hydrogenation were



Scheme 5. Reagents and conditions: (a) $NaBH_4$–MeOH, 30 min, 87% for **16**, 85% for **17**; (b) BnBr–NaH in DMF, 0 °C to room temperature, 2.5 h, 57% for **18**, 65% for **19**; (c) 2,4-*O*-benzylidene-D-erythritol-1,3-cyclic sulfate and K_2CO_3–HFIP, 70 °C, overnight, 75% for **20**, 85% for **21**; (d) 10% Pd–C/H_2, 61% for **22**, 45% for **23**.

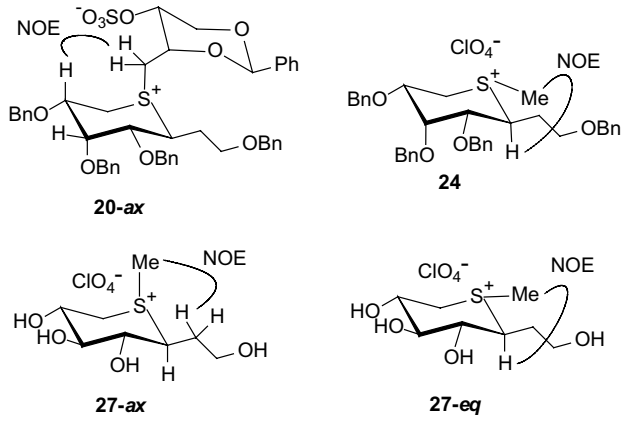


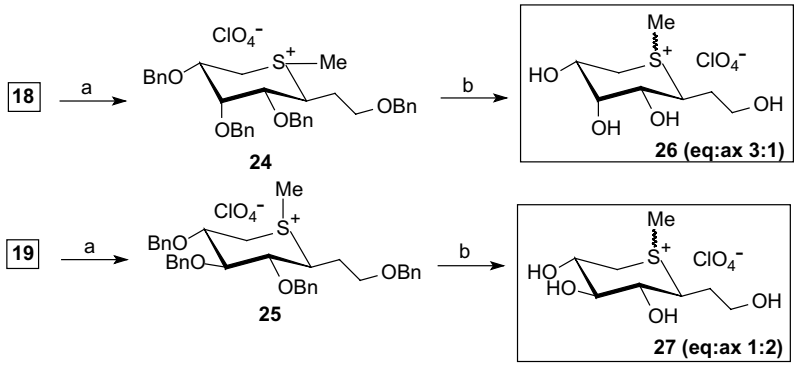
Figure 1. NOE analysis of compounds **20**, **24**, **24**-ax, and **27**-eq.

likely due to the absorption of those compounds by activated charcoal.

The sulfonium salts **20**–**27** were characterized by spectroscopic analysis. Although **20**–**23**, **26**, and **27** were mixtures, we were able to assign the chemical shifts for the protons and carbons using various NMR techniques (COSY, TOCSY, HMQC, and ROESY). The data are summarized in Tables 1 and 2.

The configurations of the sulfonium salts of *C*-5-thioglycopyranosides were established primarily by NOE analysis. However, the ^{13}C NMR analysis indicates that the stereochemistry of *S*-substitution can also be assigned directly based on the chemical shifts of adjacent *S*-connected carbons (C-1 and C-5). The chemical shifts of C-1 and C-5 with an equatorial *S*-alkyl substitution are always downfield (5–10 ppm) in comparison to those with an axial substitution (see Table 2 and Fig. 2). This conclusion is supported by the data available in the literature.[21]

In summary, we have developed a new method for the synthesis of *C*-5-thioglycopyranosides by a tandem β-elimination and intramolecular hetero-Michael addition from 1-*C*-(2′-oxoalkyl)-5-*S*-Ac-glycofuranosides. These *C*-5-thiopyranosides were further transformed to their sulfonium derivatives as potential glycosidase inhibitors.



Scheme 6. Reagents and conditions: (a) CH_3I–$AgClO_4$ in MeCN, room temperature, overnight, 95% for **24**, 87% for **25**; (b) 10% Pd–C/H_2, 18% for **26**, 22% for **27**.

Table 1. NMR data for *C*-5-thioglycopyranosides (**11**, **12**, and **15**–**19**)[a]

Compd	Atom	Chemical shifts (ppm)[b,c]							
		1	2	3	4	5	1′	2′	OMe
11	^1H	3.70	3.44	4.07	3.76	2.43, 2.92	2.34, 2.76	9.66	
	^{13}C	34.1	83.6	77.1	71.2	29.6	44.5	198.5	
12	^1H	3.56	3.71	3.52	3.85	2.58, 3.05	2.62, 2.79	9.63	
	^{13}C	35.1	78.2	76.8	68.5	30.4	43.9	199.6	
15	^1H	3.60	3.51	3.80	3.84	2.61, 2.98	2.55, 2.80		3.65
	^{13}C	37.4	77.3	78.7	69.4	30.0	34.4	171.9	52.0
16	^1H	3.29	3.47	4.02	3.76	2.44, 2.85	1.51, 2.26	3.76	
	^{13}C	37.5	84.2	77.7	71.3	29.7	33.2	61.1	
17	^1H	3.25	3.68	3.57	3.85	2.58, 2.94	1.75, 1.94	3.74	
	^{13}C	38.7	79.8	69.1	72.9	32.1	29.9	60.6	
18	^1H	3.38	3.29	4.09	3.60	2.68, 3.13	1.55, 2.38	3.60	
	^{13}C	37.4	83.9	75.4	80.5	26.3	30.5	68.2	
19	^1H	3.14	3.85	3.47	3.67	2.59–2.63	1.68, 2.41	3.67	
	^{13}C	38.5	82.5	83.6	82.3	26.4	26.0	67.7	

[a] Recorded in $CDCl_3$ at 25 °C.
[b] Obtained from HMQC experiments.
[c] Chemical shifts of benzyl groups not included.

Table 2. NMR data for sulfonium salts of *C*-5-thioglycopyranosides (**20**–**27**)[a]

Compd	Atom	Chemical shifts (ppm)[b,c]												
		1	2	3	4	5	1′	2′	1″	2″	3″	4″	C*H*Ph	Me
20-ax	^{1}H	3.78	3.59	3.87	3.94	3.27, 4.55	1.60, 1.94	2.55, 3.04	4.47, 4.67	4.01	4.50	4.64, 3.71	5.45	
	^{13}C	44.4	75.0	68.7	69.4	33.8	29.4	64.4	40.5	75.2	65.6	69.3	101.0	
20-eq	^{1}H	3.97	3.66	3.90	3.75	3.57, 4.59	2.20, 2.33	3.30, 3.45	3.94, 4.66	4.11	4.55	4.66	5.50	
	^{13}C	52.4	73.9	68.7	71.5	39.3	27.0	66.6	42.2	75.8	67.1	69.4	101.6	
21-ax	^{1}H	3.87	3.58	3.86	4.06	4.44, 4.52	1.67, 1.97	2.64, 3.09	4.40, 4.66	4.06	4.50	4.61, 4.63	5.00	
	^{13}C	44.7	74.7	68.5	69.4	33.9	29.3	64.5	40.3	75.2	66.0	69.1	101.1	
21-eq	^{1}H	4.04	3.86	4.02	4.48	3.55, 3.68	2.15, 2.28	3.26, 3.45	3.75, 4.03	4.40	4.50	3.76, 4.06	5.45	
	^{13}C	52.5	70.8	71.3	67.5	39.9	27.0	66.3	42.1	75.3	59.2	60.1	101.5	
22-ax	^{1}H	4.10	4.35	4.02	4.35	3.75, 3.90	2.27, 2.35	3.93, 4.08	4.20, 4.20	4.22	4.35	3.85		
	^{13}C	44.4	67.1	69.0	65.9	35.7	29.9	59.6	40.5	69.3	80.7	58.1		
22-eq	^{1}H	4.10	4.35	4.35	4.46	3.75, 3.90	2.12, 2.31	3.93, 4.08	3.80, 3.90	4.20	4.40	3.82		
	^{13}C	50.7	66.6	68.6	64.8	39.1	28.4	59.6	42.7	67.9	80.3	57.6		
23-ax	^{1}H	3.99	4.44	4.17	4.59	3.58, 3.68	2.15–2.28	3.81, 4.05	4.09, 4.16	4.30	4.42	3.75, 3.92		
	^{13}C	43.9	64.6	69.3	59.6	32.1	29.4	59.6	43.9	67.1	80.3	57.6		
23-eq	^{1}H	4.07	4.49	4.09	4.48	3.52, 3.70	2.15–2.28	3.81, 4.05	3.84, 3.92	4.39	4.36	3.75, 3.92		
	^{13}C	49.7	68.6	69.0	63.5	36.2	28.4	59.6	44.7	72.6	80.6	58.2		
24-eq	^{1}H	3.66	3.76	4.11	4.06	3.26, 4.05	2.05, 2.33	3.35, 3.42						2.90
	^{13}C	50.9	75.8	73.9	73.7	37.4	26.4	65.3						25.4
25-ax	^{1}H	3.95	3.79	4.00	4.07	3.66, 3.91	2.00, 2.22	3.63, 3.64						3.16
	^{13}C	44.2	74.7	68.7	69.9	32.3	28.7	66.6						20.4
26-eq	^{1}H	3.72	3.89	4.19	4.21	3.41, 3.56	2.20–2.32	3.80–3.84						3.12
	^{13}C	49.4	68.3	71.4	65.3	37.5	27.9	57.5						23.9
27-ax	^{1}H	3.99	4.25	4.23	4.36	3.51, 3.79	2.20–2.30	3.85, 3.87						3.28
	^{13}C	42.3	69.3	67.9	65.5	34.8	29.4	57.3						19.8
27-eq	^{1}H	3.97	4.35	4.10	4.39	3.72, 3.72	2.15, 2.27	3.94–3.98						3.06
	^{13}C	52.0	68.6	68.4	66.4	41.7	28.6	57.8						21.8

[a] Recorded in $CDCl_3$ (**20**, **21**, **24**, and **25**) and in D_2O (**22**, **23**, **26**, and **27**) at 25 °C.
[b] Obtained from HMQC experiments.
[c] Chemical shifts of benzyl groups not included.

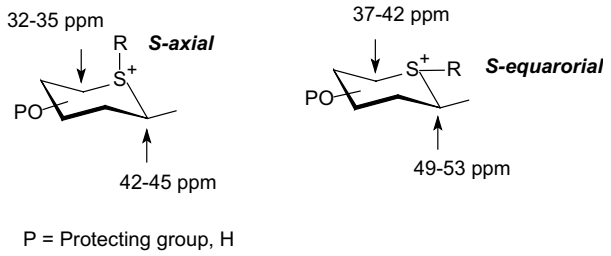


Figure 2. ^{13}C chemical shifts correlate to sulfonium conformations.

In addition, a simple ^{13}C NMR-based method was proposed to determine the stereochemistry of the sulfonium salts.

3. Experimental

3.1. General method

^{1}H and ^{13}C NMR spectra were recorded at 400 and 100 MHz, respectively, with a Varian instrument at 293 K. Chemical shifts are given in ppm downfield from the signal of internal TMS and are assigned on the basis of 2D ^{1}H COSY, TOCSY and ^{1}H–^{13}C chemical-shift correlated experiments. High-resolution fast-atom bombardment mass spectrometry (HRFABMS) was carried out on a JEOL JMS-AX505H mass spectrometer using a 6 kV xenon beam at an accelerating voltage of 3 kV. *m*-Nitrobenzyl alcohol (*m*-NBA) was used as the matrix, and polyethylene glycol (PEG) was the internal calibrant. All chemicals were purchased from Aldrich Chemical Co. and used without further purification.

3.2. 3-*C*-(5-*O*-Acetyl-2,3-di-*O*-benzyl-α-D-ribofuranosyl)propene (5)

To a solution of **1** (8.69 g, 20 mmol) and allyl-$SiMe_3$ (3.42 g, 30 mmol) in 150 mL of MeCN was added TMSOTf (2.7 g, 12 mmol) at −40 °C. The mixture was stirred overnight while the temperature was allowed to rise from −40 °C to room temperature. The reaction was quenched by the addition of water, and the aqueous solution was extracted with EtOAc (2 × 150 mL). The combined organic extract was washed with water and brine, dried, and concentrated. Purification by silica gel column chromatography (8:1 hexanes–EtOAc) gave **3** (7.1 g) as a syrup. A solution of **3** (7.1 g) in 40 mL of 0.2% (v/v) H_2SO_4–Ac_2O solution was stirred overnight at room temperature, and then diluted with EtOAc (200 mL). The resulting solution was washed with water and satd $NaHCO_3$, dried, and concentrated to a residue. Purification by chromatography (8:1 hexanes–EtOAc) gave **5** as a syrup (4.5 g, 58% in two steps): $[\alpha]_D$ +44.5 (*c* 4.2, $CHCl_3$); ^{1}H NMR ($CDCl_3$): δ 7.39–7.24 (m, 10H, Ph), 5.82 (m, 1H, =*CH*), 5.12 (m, 2H, =CH_2), 4.85 (d, 1H, *J* 11.6 Hz, PhCH_2), 4.68 (d, 1H, *J* 12.0 Hz, PhCH_2), 4.62 (d, 1H, *J* 11.6 Hz, PhCH_2), 4.51 (d, 1H, *J* 12.0 Hz, PhCH_2), 4.27 (m, 1H, H-5), 4.24 (m, 1H, H-2), 4.22 (m, 1H, H-5), 4.04 (m, 1H, H-4), 3.98 (m, 1H, H-1), 3.93 (m, 1H, H-3), 2.52 (dd, 2H, *J* 6.8 Hz, CH_2CH=CH_2), 1.99 (s, 3H, CH_3CO); ^{13}C NMR ($CDCl_3$): δ 170.8 (C=O), 138.2 (Ph), 137.5 (Ph), 134.5 (=*CH*), 128.5–127.7 (Ph), 117.1 (=CH_2), 80.3 (C-4), 80.1 (C-3), 77.4 (C-2), 77.0 (C-1), 73.5 (PhCH_2), 73.8 (PhCH_2), 64.5 (C-5), 34.2 (CH_2CH=CH_2), 20.9 (CH_3CO); HRFABMS: Calcd for $C_{24}H_{29}O_5$ (M+H), *m*/*z* 397.2015; found, *m*/*z* 397.2450.

3.3. 3-*C*-(5-*O*-Acetyl-2,3-di-*O*-benzyl-α,β-D-xylofuranosyl)propene (6)

The same procedures as described above were used for the preparation of **6** (79% in two steps) as a mixture of α/β (ca. 1:1) anomers; ^{1}H NMR ($CDCl_3$): δ 7.39–7.24 (m, 10H, Ph), 5.78 (m, 1H, =*CH*), 5.06 (m, 2H, =CH_2), 4.57–4.41 (m, 4H, PhCH_2), 4.32 (m, 1H, H-5), 4.26 (m, 0.5H, H-3b), 4.21–4.16 (m, 2H, H-1b, H-2b, H-5), 4.01 (d, 0.5H, *J* 4.0 Hz, H-4b), 3.96 (m, 1H, H-1a, H-2a), 3.93 (d, 0.5H, *J* 3.2 Hz, H-4a), 3.79 (d, 0.5H, *J* 2.8 Hz, H-3a), 2.48 (m, 2H, CH_2CH=CH_2), 2.07 and 2.03 (s and s, 3H, CH_3CO); ^{13}C NMR ($CDCl_3$): δ 170.9 (C=O), 137.7 (Ph), 137.5 (Ph), 134.7–134.2 (=*CH*), 128.5–127.7 (Ph), 117.5–117.1 (=CH_2), 85.0 (C-3a), 83.6 (C-1a), 82.9 (C-2a), 81.4 (C-4a), 81.3 (C-4b), 80.2 (C-1b), 78.8 (C-2b), 77.7 (C-3b), 72.3–71.6 (PhCH_2), 63.7 (C-5a), 63.5 (C-5b), 38.4 (CH_2-CH=CH_2-a), 33.5 (CH_2CH=CH_2-b), 21.2 (CH_3CO); HRFABMS: Calcd for $C_{24}H_{29}O_5$ (M+H), *m*/*z* 397.2015; found, *m*/*z* 397.2019.

3.4. 3-*C*-(5-*S*-Acetyl-2,3-di-*O*-benzyl-α-D-ribofuranosyl)propene (7)

To the solution of **5** (5 g, 12.6 mmol) in MeOH (100 mL) was added 4% NaOMe–MeOH (10 mL). The mixture was stirred for 2 h, neutralized by the addition of solid NH_4Cl (5 g), and evaporated to a residue. The residue was partitioned between EtOAc and water. The water layer was extracted with EtOAc twice, and the combined organic extract was washed with water, brine, dried, and concentrated to a residue (4.5 g). To a solution of above residue in 1:10 Et_3N–CH_2Cl_2 (100 mL) was slowly added at 0 °C a solution MsCl (1.95 g, 17.05 mmol) in CH_2Cl_2 (5 mL). The mixture was stirred overnight at room temperature, then diluted with EtOAc, washed with water, and brine, dried, and concentrated. Purification by chromatography (2:1 hexanes–EtOAc) gave the 5-*O*-Ms product (4.2 g). A mixture of above product (4.2 g, 9.72 mmol) and KSAc (2.2 g, 19 mmol) in DMF (30 mL) was stirred at 80 °C overnight, then diluted with EtOAc. The solution was washed with water and brine,

dried, and concentrated to a residue. Purification by chromatography (2:1 hexanes–EtOAc) gave **7** (2.93 g, 63% in three steps): $[\alpha]_D$ +18.4 (*c* 0.8, $CHCl_3$); ^1H NMR ($CDCl_3$): δ 7.35–7.25 (m, 10H, Ph), 5.80 (m, 1H, =*CH*), 5.11 (m, 2H, =CH_2), 4.81 (d, 1H, *J* 11.6 Hz, PhCH_2), 4.65 (d, 1H, *J* 11.6 Hz, PhCH_2), 4.58 (d, 1H, *J* 11.2 Hz, PhCH_2), 4.57 (d, 1H, *J* 12.0 Hz, PhCH_2), 4.28 (m, 1H, H-4), 4.04 (m, 1H, H-1), 3.81 (dd, 1H, *J* 7.2, 4.4 Hz, H-3), 3.2 (m, 2H, H-5a, 5b), 2.48 (dd, 2H, *J* 6.8 Hz, CH_2CH=CH_2), 2.31 (s, 3H, CH_3CO); ^{13}C NMR ($CDCl_3$): δ 194.4 (C=O), 137.8, 137.2 (Ph), 134.3 (=*CH*), 128.1–127.3 (Ph), 116.7 (=CH_2), 82.5 (C-3), 80.3 (C-1), 78.1 (C-4), 77.5 (C-2), 73.5 (PhCH_2), 73.0 (PhCH_2), 34.6 (CH_2CH=CH_2), 32.7 (C-5), 31.0 (CH_3CO); HRFABMS: Calcd for $C_{24}H_{29}O_4S$ (M+H), *m*/*z* 413.1787; found, *m*/*z* 413.1760.

3.5. 3-*C*-(5-*S*-Acetyl-2,3-di-*O*-benzyl-α,β-D-xylofuranosyl)propene (8)

The same procedures as described above were used for the preparation of **8** (41% in three steps) as a mixture of α/β (ca. 1:1) anomers; ^1H NMR ($CDCl_3$): δ 7.35–7.25 (m, 10H, Ph), 5.79 (m, 1H, =*CH*), 5.09 (m, 2H, =CH_2), 4.57–4.42 (m, 4H, PhCH_2), 4.26 (m, 0.5H, H-4a), 4.14 (m, 0.5H, H-4b), 4.05 (m, 0.5H, H-1a), 3.95 (d, 0.5H, *J* 4.4 Hz, H-2a), 3.90 (m, 1H, H-1b, H-3a), 3.84 (d, 0.5H, *J* 4.0 Hz, H-2b), 3.77 (d, 0.5H, *J* 4.0 Hz, H-3b), 3.23 (m, 1H, H-1′), 3.12 (dd, 1H, *J* 13.2, 6.8 Hz, H-5), 2.46 (m, 1H, H-5), 2.36 (m, 1H, CH_2CH=CH_2), 2.37 and 2.31 (s and s, 3H, CH_3CO); ^{13}C NMR ($CDCl_3$): δ 195.5 (C=O), 137.8–137.7 (Ph), 134.9, 134.3 (=*C*H-a, -b), 128.5–127.7 (Ph), 117.4, 117.0 (=CH_2-a, -b), 85.3 (C-3b), 83.5 (C-4a), 83.2 (C-3a), 81.7 (C-2b), 81.5 (C-2a), 80.1 (C-1a), 79.8 (C-1b), 78.8 (C-4b), 72.4, 72.1, 71.77, 71.70 (2 × Ph*C*H_2-a, b), 38.4 (*C*H_2CH=CH_2-a), 33.5 (*C*H_2CH=CH_2-b), 30.6 (*C*H_3CO), 28.4, 28.1 (C-5a, b); HRFABMS: Calcd for $C_{24}H_{29}O_4S$ (M+H), *m*/*z* 413.1787; found, *m*/*z* 413.1997.

3.6. 2-*C*-(5-*S*-Acetyl-2,3-di-*O*-benzyl-α-D-ribofuranosyl)acetaldehyde (9)

A solution of **7** (2.51 g, 5.44 mmol) in CH_2Cl_2 (80 mL) was bubbled with ozone at −78 °C for 1 h and then concentrated to a residue. To a solution of above residue in AcOH (20 mL) was added zinc dust (1 g), and the mixture was stirred at room temperature for 2 h and filtered. The filtrate was diluted with EtOAc, and the solution was washed with water, satd $NaHCO_3$ solution and brine, dried, and concentrated. Purification by chromatography (2:1 hexane–EtOAc) gave **9** (1.6 g, 70%): $[\alpha]_D$ +9.1 (*c* 2.0, $CHCl_3$); ^1H NMR ($CDCl_3$): δ 9.72 (s, 1H, C*H*O), 7.38–7.21 (m, 10H, Ph), 4.75 (d, 1H, *J* 11.6 Hz, PhCH_2), 4.64 (d, 1H, *J* 12.0 Hz, PhCH_2), 4.59 (d, 1H, *J* 11.6 Hz, PhCH_2), 4.53 (m, 1H, H-1), 4.47 (d, 1H, *J* 11.6 Hz, PhCH_2), 4.24 (dd, 1H, *J* 6.5, 5.6 Hz, H-4), 4.12 (dd, 1H, *J* 4.4 Hz, H-2), 3.81 (dd, 1H, *J* 2.0, 4.4 Hz, H-3), 3.18 (dd, 1H, *J* 13.6, 4.8 Hz, H-5), 3.12 (dd, 1H, *J* 14.0, 5.2 Hz, H-5), 2.90 (dd, 1H, *J* 17.6, 6.4 Hz, CH_2CH=CH_2), 2.81 (dd, 1H, *J* 17.6, 6.4 Hz, CH_2CH=CH_2), 2.31 (s, 3H, CH_3CO); ^{13}C NMR ($CDCl_3$): δ 200.4 (CH_3C=*O*), 194.8 (CHO), 137.6 (Ph), 137.3 (Ph), 127.7–127.8 (Ph), 81.8 (C-3), 78.6 (C-4), 77.5 (C-2), 75.4 (C-1), 73.5 (PhCH_2), 73.0 (PhCH_2), 44.6 (CH_2CH=CH_2), 32.1 (C-5), 30.8 (CH_3CO); HRFABMS: Calcd for $C_{23}H_{27}O_5S$ (M+H), *m*/*z* 415.1578; found, *m*/*z* 415.1078.

3.7. 2-*C*-(5-*S*-Acetyl-2,3-di-*O*-benzyl-α,β-D-xylofuranosyl)acetaldehyde (10)

Compound **10** was prepared from **8** by the same procedure as those used for **9** (80%) as a mixture of α/β (ca. 1:1) anomers: ^1H NMR ($CDCl_3$): δ 9.77 (ds, 1H, C*H*O), 7.38–7.21 (m, 10H, Ph), 4.59 (m, 0.5H, H-1a), 4.53–4.33 (m, 3H, PhCH_2), 4.45 (d, 1H, *J* 12.0 Hz, PhCH_2), 40.38 (m, 0.5H, H-1b), 4.22 (dt, 0.5H, *J* 3.6 Hz, 7.2 Hz, H-4b), 4.13 (dt, 0.5H, *J* 3.2, 6.8 Hz, H-4a), 4.02 (d, 0.5H, *J* 4.0 Hz, H-3b), 3.94 (d, 0.5H, *J* 4.0 Hz, H-2b), 3.91 (d, 0.5H, *J* 4.0 Hz, H-3a), 3.80 (d, 0.5H, *J* 2.8 Hz, H-2a), 3.23 (dd, 1H, *J* 6.8, 14.0 Hz, H-5a), 3.15 (dd, 1H, *J* 6.8, 13.6 Hz, H-5b), 2.81 (m, 1H, CH_2CH=CH_2-a), 2.70 (dd, 1H, *J* 6.4, 16.8 Hz, CH_2CH=CH_2-b), 2.33 (s, 3H, CH_3CO); ^{13}C NMR ($CDCl_3$): δ 200.4 (CH_3C=*O*), 195.1 (CHO-a), 195.0 (CHO-b), 137.3 (Ph), 137.2 (Ph), 128.4–127.6 (Ph), 85.5 (C-2a), 82.7 (C-3a), 81.7 (C-2b), 81.6 (C-2b), 80.3 (C-4), 79.0 (C-1b), 75.8 (C-1a), 72.5, 72.3, 72.171.8 (2 × Ph*C*H_2-a, -b), 48.0 (*C*H_2CH=CH_2-a), 43.8 (*C*H_2CH=CH_2-b), 30.7 (*C*H_3CO), 28.3 (C-5b), 28.1 (C-5a); HRFABMS: Calcd for $C_{23}H_{27}O_5S$ (M+H), *m*/*z* 415.1578; found, *m*/*z* 415.1410.

3.8. 2-*C*-(2,3-Di-*O*-benzyl-5-thio-β-D-ribopyranosyl)acetaldehyde (11)

To a solution of **9** (1.1 g, 2.65 mmol) in MeOH (20 mL) was added 4% NaOMe–MeOH (40 mL). After stirring at 0 °C to room temperature for 5 h, solid NH_4Cl (5 g) was added, and the solvent was evaporated. The residue was extracted with EtOAc, and the organic extract was washed with water. Purification by chromatography (2:1 hexanes–EtOAc) gave **11** as colorless syrup (0.7 g, 71%): $[\alpha]_D$ −0.08 (*c* 1.27, $CHCl_3$); HRFABMS: Calcd for $C_{21}H_{25}O_4S$ (M+H), *m*/*z* 373.1473; found, *m*/*z* 373.1444. For NMR data see Table 1.

3.9. 2-*C*-(2,3-Di-*O*-benzyl-5-thio-β-D-xylopyranosyl)acetaldehyde (12)

Compound **12** was prepared from **10** by the same procedure as that used for **11** (67%): $[\alpha]_D$ −0.02 (*c* 0.5,

$CHCl_3$); HRFABMS: Calcd for $C_{21}H_{25}O_4S$ (M+H), *m*/*z* 373.1473; found, *m*/*z* 373.1656. For NMR data see Table 1.

3.10. Methyl 2-*C*-(5-*O*-acetyl-2,3-di-*O*-benzyl-α,β-D-xylofuranosyl)acetate (13)

Compound **6** (1.5 g, 3.79 mmol) was subjected to ozonolysis to give the 2′-aldehyde (1.0 g) after chromatography (2:1 hexane–EtOAc). The aldehyde was then dissolved in 1:1 H_2O–acetone (100 mL), and $KMnO_4$ (0.6 g) and H_2SO_4 (concd 0.2 mL) were added. After stirring for 4 h at room temperature, the suspension was filtered. The filtrate was evaporated to remove acetone, and the aqueous solution was extracted with EtOAc. The organic solution was dried and concentrated to give 0.96 g of crude carboxylic acid. To a solution of the carboxylic acid in DMF (30 mL) was added MeI (0.49 g, 3.45 mmol) and $NaHCO_3$ (0.19 g, 2.3 mmol). The mixture was stirred overnight and diluted with Et_2O, washed with water and brine, dried, and concentrated. Purification by chromatography (2:1 hexanes–EtOAc) gave **13** (0.6 g, 38% in three steps) as a mixture of α/β (1:4) anomers: ^{1}H NMR ($CDCl_3$): δ 7.40–7.20 (m, 10H, Ph), 4.85 (m, 1H, PhCH_2), 4.55 (m, 3H, PhCH_2), 4.38 (m, 3H, H-1, 2 × H-5), 4.27 (m, 1H, H-4), 4.18–4.05 (m, 1H, H-2), 3.94 (m, 1H, H-3), 3.67 and 3.62 (s and s, 3H, OCH_3), 2.85–2.59 (m, 2H, CH_2CO$_2$CH$_3$), 2.03 (s, 3H, CH_3CO); ^{13}C NMR ($CDCl_3$): δ 171.2 (C═O), 170.9 (C═O), 128.5–127.6 (Ph), 84.8 (C-3), 84.6 (C-3), 82.5 (C-1), 81.3 (C-1), 80.1 (C-2), 79.0 (C-4), 77.7 (C-2), 76.7 (C-4), 72.3–71.5 (Ph*C*H$_2$), 63.4 (C-5), 63.3 (C-5), 51.6 (O*C*H$_3$), 38.8 (*C*H$_2$CO$_2$CH$_3$-a), 34.0 (*C*H$_2$CO$_2$CH$_3$-b), 20.9 (*C*H$_3$CO); HRFABMS: Calcd for $C_{24}H_{29}O_7$ (M+H), *m*/*z* 429.1913; found, *m*/*z* 429.2068.

3.11. Methyl 2-*C*-(5-*S*-acetyl-2,3-di-*O*-benzyl-α/β-D-xylofuranosyl)acetate (14)

To a solution of **13** (0.6 g, 1.4 mmol) in MeOH (10 mL) was added 4% NaOMe–MeOH (5 mL). After stirring for 15 min, the solution was neutralized by the addition of solid NH_4Cl (2 g), and the solvent was evaporated. The residue was partitioned between EtOAc and water. The organic solution was washed with water and brine, dried and concentrated to a residue. To a solution of above residue and Et_3N (0.7 mL) in CH_2Cl_2 (20 mL) was added at 0 °C a solution of MsCl (0.25 g, 2.1 mmol) in CH_2Cl_2 (1 mL). The mixture was stirred overnight at room temperature and then diluted with EtOAc, washed with water and brine, dried and concentrated. Purification by chromatography (2:1 hexanes–EtOAc) gave the 5-*O*-Ms product (0.5 g) as a syrup. To a solution of the 5-*O*-Ms product (0.5 g) in DMF (10 mL) was added KSAc (0.4 g, 3.5 mmol), and the mixture was stirred at 60 °C overnight. Usual workup and chromatography (2:1 hexanes–EtOAc) gave **14** (0.4 g, 57% in two steps) as a mixture of α/β (1:4) anomers: ^{1}H NMR ($CDCl_3$): δ 7.41–7.22 (m, 10H, Ph), 4.57–4.47 (m, 4H, PhCH_2), 4.33 (m, 1H, H-1), 4.19–4.12 (m, 1H, H-4), 3.92–3.65 (m, 2H, H-2, 3), 3.67 and 3.62 (s and s, 3H, OCH_3), 3.23–3.13 (m, 2H, H-5a, 5b), 2.73–2.57 (m, 2H, CH_2CO$_2$CH$_3$), 2.32 (s, 3H, CH_3CO); ^{13}C NMR ($CDCl_3$): δ 195.4 (CH_3*C*═O), 171.4 (O═*C*OCH$_3$), 128.6-127.7 (Ph), 85.0 (C-3), 82.9 (C-2), 81.6 (C-1), 80.2 (C-4), 72.1 (Ph*C*H$_2$), 71.6 (Ph*C*H$_2$), 51.8 (OCH_3), 38.9 (*C*H$_2$CO$_2$CH$_3$), 30.6 (*C*H$_3$CO), 28.1 (C-5); HRFABMS: Calcd for $C_{24}H_{29}O_6S$ (M+H), *m*/*z* 445.1684; found, *m*/*z* 445.1731.

3.12. Methyl 2-*C*-(2,3-di-*O*-benzyl-5-thio-β-D-xylopyranosyl)acetate (15)

A solution of **14** (0.4 g, 0.9 mmol) in 4% NaOMe–MeOH (20 mL) was stirred overnight. Solid NH_4Cl (2 g) was then added, and the solvent was evaporated. Usual workup and chromatography (2:1 hexanes–EtOAc) gave **15** (0.2 g, 54%) as a syrup: $[\alpha]_D$ −0.03 (*c* 0.6, $CHCl_3$); HRFABMS: Calcd for $C_{22}H_{27}O_5S$ (M+H), *m*/*z* 403.1579; found, *m*/*z* 403.1624. For NMR data see Table 1.

3.13. 2-*C*-(2,3-Di-*O*-benzyl-5-thio-β-D-ribopyranosyl)ethanol (16)

To a solution of **11** (0.65 g, 1.75 mmol) in MeOH (20 mL) was added $NaBH_4$ (0.13 g, 3.5 mmol) at 0 °C. The mixture was stirred for 0.5 h, and solid NH_4Cl (2.0 g) was added. Usual workup and chromatography gave **16** (0.57 g, 87%) as a syrup: $[\alpha]_D$ −69.0 (*c* 0.2, $CHCl_3$); HRFABMS: Calcd for $C_{21}H_{27}O_4S$ (M+H), *m*/*z* 375.1630; found, *m*/*z* 375.1531. For NMR data see Table 1.

3.14. 2-*C*-(2,3-Di-*O*-benzyl-5-thio-β-D-xylopyranosyl)ethanol (17)

Compound **17** was obtained from **12** by the same procedure (85%); $[\alpha]_D$ +25.2 (*c* 1.5, $CHCl_3$); HRFABMS: Calcd for $C_{21}H_{27}O_4S$ (M+H), *m*/*z* 375.1630; found, *m*/*z* 375.1630. For NMR data see Table 1.

3.15. 1-Benzyloxy-2-*C*-(2,3,4-tri-*O*-benzyl-5-thio-β-D-ribopyranosyl)ethane (18)

To a solution of **16** (0.57 g, 1.52 mmol) in dry DMF (60 mL) was added NaH (209 mg, 5.19 mmol). After 0.5 h, BnBr (0.64 g, 3.8 mmol) was added to the mixture. The reaction was quenched after 2 h by the addition of water, and the mixture was extracted with ether. Usual workup and chromatography (5:1 hexanes–EtOAc) gave

18 (0.57 g, 57%) as a syrup: $[\alpha]_D$ −18.8 (*c* 1.8, $CHCl_3$); HRFABMS: Calcd for $C_{35}H_{39}O_4S$ (M+H), *m/z* 555.2569; found, *m/z* 555.2527. For NMR data see Table 1.

3.16. 1-Benzyloxy-2-*C*-(2,3,4-tri-*O*-benzyl-5-thio-β-D-xylopyranosyl)ethane (19)

Compound **19** was obtained from **17** by the same procedure (65%); $[\alpha]_D$ +55.5 (*c* 2.0, $CHCl_3$); HRFABMS: Calcd for $C_{35}H_{39}O_4S$ (M+H), *m/z* 555.2569; found, *m/z* 555.2238. For NMR data see Table 1.

3.17. 1-Benzyloxy-2-*C*-{2,3,4-tri-*O*-benzyl-5-[(2*r*,3*r*)-2,4-*O*-benzylidene-3-(sulfooxy)butyl]sulfoniumylidene-β-D-ribopyranosyl}ethane inner salt (20)

To a solution of **18** (120 mg, 0.22 mmol) in HFIP (1 mL) was added 2,4-*O*-benzylidene-D-erythritol-1,3-cyclic sulfate (100 mg, 0.36 mmol) and K_2CO_3 (10 mg). The mixture was stirred at 70 °C overnight. The crude product was purified by chromatography (20:1 CH_2Cl_2–MeOH) to get **20** (0.19 g, 75%) as a mixture of two isomers (1:1): $[\alpha]_D$ −30.6 (*c* 0.7, $CHCl_3$); HRFABMS: Calcd for $C_{46}H_{51}O_{10}S_2$ (M+H), *m/z* 827.2924; found, *m/z* 827.4528. For NMR data see Table 2.

3.18. 1-Benzyloxy-2-*C*-{2,3,4-tri-*O*-benzyl-5-[(2*r*,3*r*)-2,4-*O*-benzylidene-3-(sulfooxy)butyl]sulfoniumylidene-β-D-xylopyranosyl}ethane inner salt (21)

The same procedure as those for **20** was used to afford **21** (85%) as a mixture of two isomers (1:1): $[\alpha]_D$ −30.6 (*c* 3.5, $CHCl_3$); HRFABMS: Calcd for $C_{46}H_{51}O_{10}S_2$ (M+H), *m/z* 827.2924; found, *m/z* 827.2896. For NMR data see Table 2.

3.19. 2-*C*-{5-[(2*r*,3*r*)-2,4-dihydroxy-3-(sulfooxy)butyl]sulfoniumylidene-β-D-ribopyranosyl}ethanol inner salt (22)

Compound **20** (83 mg, 0.1 mmol) was subjected to catalytic hydrogenation (50 psi) with 10% Pd–C (50 mg) first in 1:1 MeOH–HOAc (10 mL) and then in 1:1 HOAc–H_2O (10 mL) overnight. The filtrate was concentrated to a residue, which was purified by silica gel column chromatography (10:2:1 EtOAc–MeOH–H_2O) to yield **22** (16 mg, 61%) as a white foam: $[\alpha]_D$ −3.1 (*c* 0.3, H_2O); HRFABMS: Calcd for $C_{11}H_{23}O_{10}S_2$ (M+H), *m/z* 379.0733; found, *m/z* 379.0799. For NMR data see Table 2.

3.20. 2-*C*-{5-[(2*r*,3*r*)-2,4-dihydroxy-3-(sulfooxy)butyl]sulfoniumylidene]-β-D-xylopyranosyl}ethanol inner salt (23)

Compound **23** was obtained from **21** (45%) as a 1:1 mixture of two isomers: $[\alpha]_D$ −2.3 (*c* 0.2, H_2O); HRFABMS: Calcd for $C_{11}H_{23}O_{10}S_2$ (M+H), *m/z* 379.0733; found, *m/z* 379.0710. For NMR data see Table 2.

3.21. 1-Benzyloxy-2-*C*-(2,3,4-tri-*O*-benzyl-5-methylsulfoniumylidene-β-D-ribopyranosyl)ethane perchlorate salt (24)

To a solution of **18** (200 mg, 0.36 mmol) in MeCN (5 mL) was added MeI (200 mg, 1.4 mmol) and $AgClO_4$ (110 mg, 0.54 mmol). The mixture was stirred overnight at room temperature. The solvent was removed, and the residue was partitioned between EtOAc (100 mL) and water (30 mL). The organic phase was dried and concentrated to a residue. Purification by silica gel column chromatography (10:1 EtOAc–MeOH) yielded **24** (230 mg, 95%) as a colorless foam: $[\alpha]_D$ −27.7 (*c* 1.45, $CHCl_3$); HRFABMS: Calcd for $C_{36}H_{41}O_4S$ (M), *m/z* 569.2725; found, *m/z* 569.2838. For NMR data see Table 2.

3.22. 1-Benzyloxy-2-*C*-(2,3,4-tri-*O*-benzyl-5-methylsulfoniumylidene-β-D-xylopyranosyl)ethane perchlorate salt (25)

Compound **25** was obtained from **19** (87%) by the same procedure: $[\alpha]_D$ −2.5 (*c* 0.5, $CHCl_3$); HRFABMS: Calcd for $C_{36}H_{41}O_4S$ (M), *m/z* 569.2725; found, 569.2875. For NMR data see Table 2.

3.23. 2-*C*-(5-methylsulfoniumylidene-β-D-ribopyranosyl)ethanol perchlorate salt (26)

Compound **24** (239 mg, 0.34 mmol) was subjected to catalytic hydrogenation (50 psi) with 10% Pd–C (50 mg) three times, respectively, in 5:1 EtOAc–EtOH (20 mL), 10:1 MeOH–HOAc (20 mL), and 5:1 HOAc–H_2O (20 mL). The filtrate was concentrated and purified through an LH-20 column, eluted with 2:1 H_2O–MeOH to yield **26** (19 mg, 18%) as a mixture of two isomers (1:3 ax:eq): $[\alpha]_D$ +2.2 (*c* 1.0, H_2O); HRFABMS: Calcd for $C_8H_{17}O_4S$ (M), *m/z* 209.0847; found, (M) *m/z* 209.0862. For NMR data see Table 2.

3.24. 2-*C*-(5-methylsulfoniumylidene-β-D-xylopyranosyl)ethanol perchlorate salt (27)

Compound **27** was obtained from **25** by catalytic hydrogenation (22%) as a mixture of two isomers (2:1 ax:eq): $[\alpha]_D$ +0.02 (*c* 0.4, H_2O); HRFABMS: Calcd for $C_8H_{17}O_4S$ (M), *m/z* 209.0847; found (M), *m/z* 209.0797. For NMR data see Table 2.

Acknowledgements

This is NRCC publication no. 42495. We are grateful to Lisa Morrison for the mass spectroscopic analysis.

Supplementary data

NMR spectra for compounds **11**, **12**, **15**, and **18**–**27**, associated with this article can be found, in the online version, at doi:10.1016/j.carres.2004.11.014.

References

1. (a) Fernandez-Bolanos, J. G.; Al-Masoudi, N. A.; Maya, I. *Adv. Carbohydr. Chem. Biochem.* **2001**, *57*, 21–98; (b) Ganem, B. *Acc. Chem. Res.* **1996**, *29*, 340–347; (c) Garg, R.; Gupta, S. P.; Gao, H.; Babu, M. S.; Debnath, A. K.; Hansch, C. *Chem. Rev.* **1999**, *99*, 3535–3601; (d) Scott, L. J.; Spencer, C. M. *Drugs* **2000**, *59*, 521–549; (e) Alper, J. *Science* **2001**, *291*, 2338–2343; (f) Witczak, Z. J. *Curr. Med. Chem.* **1999**, *6*, 165–178; (g) Robina, I.; Vogel, P.; Witczak, Z. J. *Curr. Org. Chem.* **2001**, *5*, 1137–1214; (h) Robina, I.; Vogel, P. *Curr. Org. Chem.* **2002**, *6*, 471–491; (i) Witczak, Z. J.; Chhabra, R.; Chen, H.; Xie, X.-Q. *Carbohydr. Res.* **1997**, *301*, 167–175.
2. (a) Merrer, Y. L.; Fuzier, M.; Dosbaa, I.; Foglietti, M.-J.; Depezay, J.-C. *Tetrahedron* **1997**, *53*, 16731–16746; (b) Stutz, A. E. Iminosugars as Glycosidase Inhibitors Nojirimycin and Beyond; Wiley-VCH: New York, 1999; (c) Lillelund, V. H.; Jensen, H. H.; Liang, X.; Bols, M. *Chem. Rev.* **2002**, *102*, 515–553.
3. Yoshikawa, M.; Murakami, T.; Shimada, H.; Matsuda, H.; Yamahara, J.; Tanabe, G.; Muraoka, O. *Tetrahedron Lett.* **1997**, *38*, 8367–8370.
4. Yoshikawa, M.; Murakami, T.; Yashiro, K.; Matsuda, H. *Chem. Pharm. Bull.* **1998**, *46*, 1339–1340.
5. (a) Jayaweera, D. M. A. *Medicinal Plants used in Ceylon. Part 1*; National Science Council of Sri Lanka: Colombo, 1981, p 77; (b) Serasinghe, S.; Seresinghe, P.; Yamazaki, H.; Nishiguchi, K.; Hombhanje, F.; Nakanishi, S.; Sawa, K.; Hattori, M.; Namba, T. *Phytother. Res.* **1990**, *4*, 205–206.
6. (a) Johnston, B. D.; Ghavami, A.; Jensen, M. T.; Svansson, L.; Pinto, B. M. *J. Am. Chem. Soc.* **2002**, *124*, 8245–8250; (b) Ghavami, A.; Sadalapure, K. S.; Johnston, B. D.; Lobera, M.; Snider, B. B.; Pinto, B. M. *Synlett* **2003**, 1259–1262; (c) Ghavami, A.; Chen, J. J.-w.; Pinto, B. M. *Carbohydr. Res.* **2004**, *339*, 401–407; (d) Ghavami, A.; Johnston, B. D.; Pinto, B. M. *J. Org. Chem.* **2001**, *66*, 2312–2317; (e) Cere, V.; Pollicino, S.; Ricci, A. *J. Org. Chem.* **2003**, *68*, 3311–3314.
7. Bellamy, F.; Barberousse, V.; Martin, N.; Passon, P.; Millet, J.; Samreth, S.; Sepulchre, C.; Theveniaux, J.; Horton, D. *Eur. J. Med. Chem.* **1995**, *30*, 101–115.
8. Mignon, L.; Goichot, C.; Ratel, P.; Cagnin, G.; Baudry, M.; Praly, J.-P.; Boubia, B.; Barberousse, V. *Carbohydr. Res.* **2003**, *338*, 1271–1282.
9. (a) Ravishankar, R.; Surolia, A.; Vijayan, M.; Lim, S.; Kishi, Y. *J. Am. Chem. Soc.* **1998**, *120*, 11297–11303; (b) Wei, A.; Boy, K. M.; Kishi, Y. *J. Am. Chem. Soc.* **1995**, *117*, 9432–9436; Different conformations between *C*- and *O*-glycosides, see: Jimenez-Barbero, J.; Espinosa, J.; Asensio, J.; Canada, F.; Poveda, A. *Adv. Carbohydr. Chem. Biochem.* **2000**, *56*, 235–284.
10. (a) Watson, K. A.; Mitchell, E. P.; Johnson, L. N.; Son, J. C.; Bichard, C. J. F.; Orchard, M. G.; Fleet, G. W. J.; Oikonomakos, N. G.; Leonidas, D. D.; Kontou, M.; Papageorgioui *Biochemistry* **1994**, *33*, 5745–5758; (b) Schmidt, R. R.; Dietrich, H. *Angew. Chem., Int. Ed. Engl.* **1991**, *30*, 1328–1329; (c) Lai, W.; Martin, O. R. *Carbohydr. Res.* **1993**, *250*, 185–193; (d) Johns, B. A.; Pan, Y. T.; Elbein, A. D.; Johnson, C. R. *J. Am. Chem. Soc.* **1997**, *119*, 4856–4865; (e) Leeuwenburgh, M. A.; Picasso, S.; Overkleeft, H. S.; van der Marel, G. A.; Vogel, P.; van Boom, J. H. *Eur. J. Org. Chem.* **1999**, *5*, 1185–1189.
11. Baudry, M.; Barberousse, V.; Descotes, G.; Faure, R.; Pires, J.; Praly, J.-P. *Tetrahedron* **1998**, *54*, 7431–7446.
12. (a) Tsuruta, O.; Yuasa, H.; Kurono, S.; Hashimoto, H. *Bioorg. Med. Chem. Lett.* **1999**, *9*, 807–810; (b) Yuasa, H.; Kurono, S.; Hashimoto, H. *Tetrahedron* **1993**, *49*, 8977–8998.
13. Zou, W.; Lacroix, E.; Wang, Z.; Wu, S.-H. *Tetrahedron Lett.* **2003**, *44*, 4431–4433.
14. (a) Thome, M. A.; Giudicelli, M. B.; Picq, D.; Anker, D. *J. Carbohydr. Chem.* **1991**, *10*, 923–926; (b) Capon, B. *Chem. Rev.* **1969**, *69*, 407–498.
15. (a) Zou, W.; Wang, Z.; Lacroix, E.; Wu, S.-H.; Jennings, H. *Carbohydr. Res.* **2001**, *334*, 223–231; (b) Uchiyama, T.; Vassilev, V. P.; Kajimoto, T.; Wong, W.; Huang, H.; Lin, C.-C.; Wong, C.-H. *J. Am. Chem. Soc.* **1995**, *117*, 5395–5396; (c) Minehan, T. G.; Kishi, Y. *Tetrahedron Lett.* **1997**, *38*, 6815–6818; (d) Praly, J.-P.; Chen, G.-R.; Gola, J.; Hetzer, G.; Raphoz, C. *Tetrahedron Lett.* **1997**, *38*, 8185–8188; (e) Roe, B. A.; Boojamra, C. G.; Griggs, J. L.; Bertozzi, C. R. *J. Org. Chem.* **1996**, *61*, 6442–6445; (f) Araki, Y.; Kobayashi, N.; Watanabe, K.; Ishido, Y. *J. Carbohydr. Chem.* **1985**, *4*, 565–585.
16. (a) Shao, H.; Wang, Z.; Laroix, E.; Wu, S.-H.; Jennings, H.; Zou, W. *J. Am. Chem. Soc.* **2002**, *124*, 2130–2131; (b) Wang, Z.; Shao, H.; Laroix, E.; Wu, S.-H.; Jennings, H.; Zou, W. *J. Org. Chem.* **2003**, *68*, 8097–8105.
17. McDevitt, J. P.; Lansbury, P. T. *J. Am. Chem. Soc.* **1996**, *118*, 3818–3828.
18. (a) Dawe, R. D.; Fraser-Reid, B. *J. Org. Chem.* **1984**, *49*, 522–528; (b) Dheilly, L.; Frechou, C.; Beaupere, D.; Uzan, R.; Demailly, G. *Carbohydr. Res.* **1992**, *224*, 301–306; (c) Pougny, J. R.; Nassr, M. A. M.; Sinaÿ, P. *J. Chem. Soc., Chem. Commun.* **1981**, 375–376; (d) Orhui, H.; Jones, G. H.; Moffat, J. G.; Maddox, M. L.; Christensen, A. T.; Byram, S. K. *J. Am. Chem. Soc.* **1975**, *97*, 4602–4613; (e) Hanessian, S.; Ogawa, T.; Guindon, Y. *Carbohydr. Res.* **1974**, *38*, C12–14.
19. (a) Yuasa, H.; Takada, J.; Hashimoto, H. *Bioorg. Med. Chem. Lett.* **2001**, *11*, 1137–1139; (b) Yuasa, H.; Kajimoto, T.; Wong, C.-H. *Tetrahedron Lett.* **1994**, *35*, 8243–8246.
20. Similar results were also obtained by Szezepina, M. G.; Pinto, B. M. 87th Canadian Chemical Conference and Exhibition, London, Ontario, Canada, May 29–June 1, 2004; Abstr. 471.
21. Svansson, L.; Johnston, B. D.; Gu, J.-H.; Patrick, B.; Pinto, B. M. *J. Am. Chem. Soc.* **2000**, *122*, 10769–10775.