Aryl and Allyl *C*-Glycosidation Methods Using Unprotected Sugars

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Practical and highly stereoselective aryl and allyl *C*-glycosidation methods using unprotected sugars as glycosyl donors have been developed. Aryl *C*-glycosidations of several unprotected 2-deoxy sugars with phenol and naphthol derivatives by the combined use of trimethylsilyl trifluoromethanesulfonate (TMSOTf)−$AgClO_4$ or TMSOTf exclusively gave the corresponding unprotected *o*-hydroxyaryl *β*-*C*-glycosides which appear in many biologically attractive aryl *C*-glycoside antibiotics as the key subunit. On the other hand, allyl *C*-glycosidations of several unprotected glycals with allyltrimethylsilane by TMSOTf afforded the corresponding unprotected and 2,3-unsaturated allyl α-*C*-glycosides in high yields which are versatile synthetic intermediates for the syntheses of optically active natural products.

Introduction

An efficient *C*-glycosidation[2] with high regio- and stereoselectivity is of particular interest as well as *O*-glycosidation[3] in the syntheses of biologically important natural products. Many biologically attractive *C*-glycosides such as aryl *C*-glycoside antibiotics have already been found in nature, and several types of *C*-glycosides such as alkyl and allyl *C*-glycosides are well recognized to be useful chiral building blocks for the synthesis of optically active natural products.[2] Furthermore, carbon-linked glycosides, stable analogues of naturally occurring *O*- and *N*-glycosides, have become the subject of considerable interest in bioorganic and medicinal chemistry. Although remarkable progress has been made in the *C*-glycoside synthesis,[2] the development of simple and practical *C*-glycosidation methods is still one of the central problems in synthetic organic chemistry. In this context, the use of an unprotected sugar as a glycosyl donor in the glycosidation reaction undoubtedly has considerable advantages. However, practical *C*-glycosidations using totally unprotected sugars have never been reported. The main reasons why the glycosidation of an unprotected sugar is difficult are the undesirable generation of self-coupling products of the glycosyl donor and the deactivation of a glycosidation reagent by the free hydroxy groups of the glycosyl donor. Therefore, we undertook development of novel *C*-glycosidation methods employing unprotected sugars which overcame such difficulties. For this purpose, we carried out two approaches which were based on the differences in the stability between the *C*-glycoside bond and *O*-glycoside bond, and on their formation rate. Thus, if we could find a reaction that cleaves any *O*-glycoside bond and then forms a *C*-glycoside bond, or a reaction in which the formation of the *C*-glycoside bond is much faster than that of the *O*-glycoside bond, *C*-glycosidation using an unprotected sugar as the glycosyl donor could be achieved. In this paper, we report the aryl and allyl *C*-glycosidations utilizing unprotected sugars based on these concepts.[4,5]

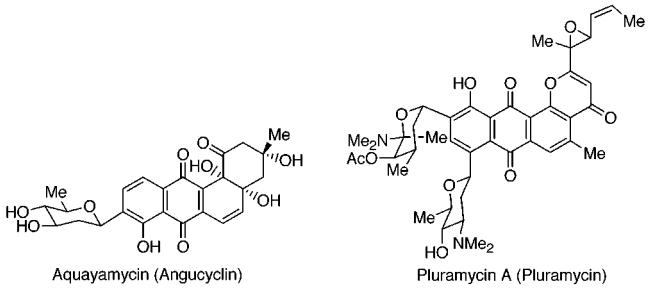

Figure 1. Molecular structures of the representative aryl *C*-glycoside antibiotics.

Results and Discussion

Aryl *C*-Glycosidations of Unprotected 2-Deoxy Sugars. Over the past several years, aryl *C*-glycoside antibiotics such as the angucyclin[6] and pluramycin[7] families have attracted considerable attention due to their significant biological properties and architecturally attractive structures (Figure 1). 2-Deoxy sugars are the most common and important of the sugar residues. Therefore, the effective and practical coupling of the sugar part into the aglycon, the aromatic moiety, has become an important task in contemporary organic

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(1) Taken in part from the Ph.D. Thesis of Goh Matsuo, Keio University, 1997.

(2) For recent reviews of *C*-glycosidation method, see: (a) Postema, M. H. D. *Tetrahedron* **1992**, *40*, 8545. (b) Levy, D. E.; Tang, C. *The Chemistry of C-Glycosides*; Pergamon Press: Oxford, 1995.

(3) For a recent review of *O*-glycosidation method, see: Toshima, K.; Tatsuta, K. *Chem. Rev.* **1993**, *93*, 1503.

(4) For our preliminary communications on aryl *C*-glycosidation, see: (a) Toshima, K.; Matsuo, G.; Tatsuta, K. *Tetrahedron Lett.* **1992**, *33*, 2175. (b) Toshima, K.; Matsuo, G.; Ishizuka, T.; Nakata, M.; Kinoshita, M. *J. Chem. Soc., Chem. Commun.* **1992**, 1641. (c) Toshima, K.; Matsuo, G.; Nakata, M. *J. Chem. Soc., Chem. Commun.* **1994**, 997.

(5) For our preliminary communication on allyl *C*-glycosidation, see: Toshima, K.; Ishizuka, T.; Matsuo, G.; Nakata, M. *Tetrahedron Lett.* **1994**, *35*, 5673.

(6) For a recent review of angucycline antibiotics, see: Rohr, J.; Thiericke, R. *Nat. Prod. Rep.* **1992**, 103.

(7) For a recent review of pluramycin antibiotics, see: Hansen, M. R.; Hurley, L. H. *Acc. Chem. Res.* **1996**, *29*, 249.

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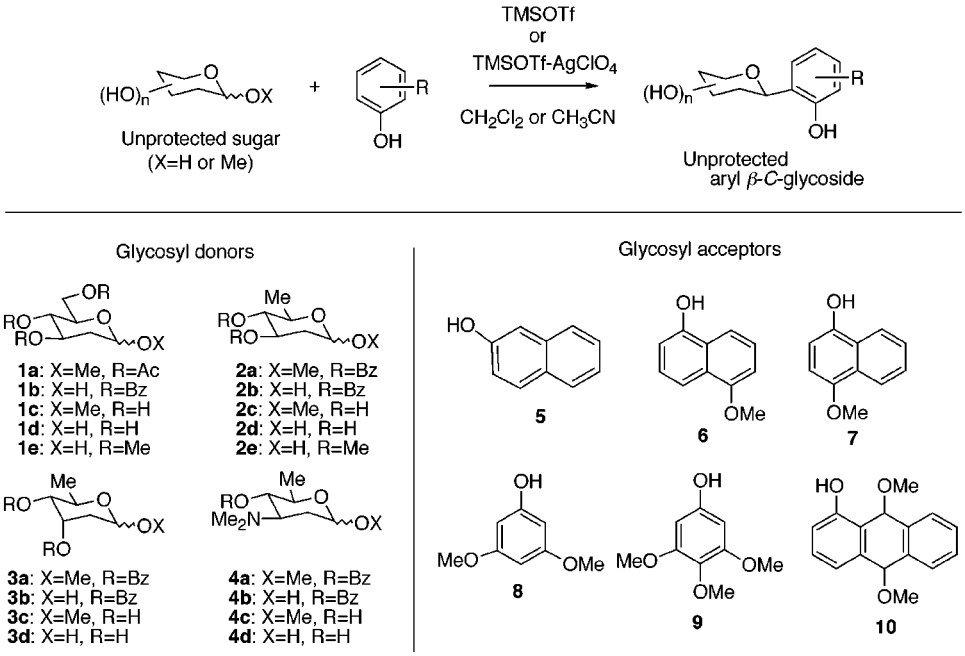
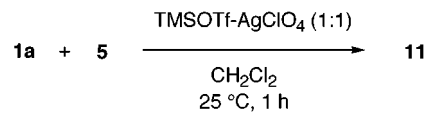


Figure 2. Aryl *C*-glycosidations.

synthesis. Efficient aryl *C*-glycoside syntheses via *O*→*C*-glycoside rearrangement were independently announced by Kometani[8] and Suzuki.[9] In this context, we investigated the aryl *C*-glycosidation of an unprotected sugar based on the higher stability of the *C*-glycoside bond compared to that of the *O*-glycoside bond (Figure 2).

In our initial attempts at searching for such a reaction, we examined the aryl *C*-glycosidation of a glycosyl donor possessing a methyl glycoside because the methyl glycoside bond is one of the most stable *O*-glycoside bonds. If the methyl glycoside is converted into the *C*-glycoside, any *O*-glycoside bond could be cleaved and then converted into the *C*-glycoside bond. Therefore, we first tested the *C*-glycosidations of the methyl glycoside **1a** with 2-naphthol (**5**) using several Lewis acids such as trimethylsilyl trifluoromethanesulfonate (TMSOTf), trifluoromethanesulfonic anhydride (Tf_2O), TMSOTf−$AgClO_4$, Tf_2O−$AgClO_4$, TMSOTf−silver trifluoromethanesulfonate (AgOTf), or Tf_2O−AgOTf. Among them, it was found that only the combined use of TMSOTf−$AgClO_4$ (1:1) showed a sharp contrast to the other activators and worked efficiently in this case. As seen in the results shown in Table 1, the methyl glycoside **1a** was smoothly glycosidated to the *ortho*-position of **5** by using TMSOTf−$AgClO_4$ (1:1) in CH_2Cl_2 at 25 °C for 1 h to give the aryl *β*-*C*-glycoside of **11** (Figure 3) in 91% yield together with 1% of its α-anomer (entry 1 in Table 1).[10] Furthermore, even the use of 20 mol % of the present activator was found to be good enough to perform the reaction with a quite satisfactory chemical yield and stereoselectivity (entry 3 in Table 1), while the use of 10 mol % of the activator gave a significant amount of an *O*-glycosidated product (entry 4 in Table 1). We further confirmed that

Table 1. Aryl *C*-Glycosidations of 1a and 5 by TMSOTf−$AgClO_4$[a]



entry	mol % of activator	yield (%)[b]	α/β[c]
1	100	92	1:94
2	50	98	1:>99
3	20	99	1:>99
4	10	72	1:>99

[a] All reactions were carried out by use of 2.0 equiv of **5** to **1a**. [b] Isolated yields after purification by column chromatography. [c] α:*β* Ratios were determined by ^{1}H-NMR (270 MHz) spectroscopy and/or isolation of pure isomers.

the *O*-glycosidated product was smoothly converted into the corresponding *C*-glycoside under the conditions for the entry 3 in Table 1. This reaction process involved the *O*→*C*-glycoside rearrangement which was similar to the Lewis acid-catalyzed *C*-glycosidation mechanism.[8,9,11] To enhance the synthetic utility of this reaction, the *C*-glycosidations of several other methyl glycosides **2a**−**4a**, which occurred as subunits in a variety of *C*-glycoside antibiotics,[6,7] with **5** were next examined and showed an additional feature. Not only the neutral sugars **1a**−**3a** but also the amino sugar **4a** were smoothly glycosidated in a similar manner to give the corresponding aryl *C*-glycoside **15a** with high *β*-stereoselectivity in high yield as shown in Table 2.

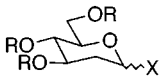
From these observations, it was made clear that the novel TMSOTf−$AgClO_4$ catalyst system cleanly cleaved the alkyl *O*-glycosidic bond and then smoothly formed the aryl *C*-glycosidic bond. Therefore, we next expected that if the TMSOTf−$AgClO_4$ combined activator was not

(8) Kometani, T.; Kondo, H.; Fujimori, Y. *Synthesis* **1988**, 1005.

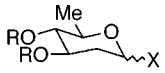
(9) (a) Matsumoto, T.; Katsuki, M.; Suzuki, K. *Tetrahedron Lett.* **1988**, *29*, 6935. (b) Matsumoto, T.; Katsuki, T.; Jona, H.; Suzuki, K. *J. Am. Chem. Soc.* **1991**, *113*, 6982.

(10) The structures of all *o*-hydroxyaryl *β*-*C*-glycosides were assigned from their ^{1}H NMR data which exhibited typical chemical shifts and coupling constants for both α- and *β*-anomers; see ref 9. The regioselectivity of the glycosidic bond could be derived from the ^{1}H NOE experiments of the aromatic moiety.

(11) For other representative aryl *C*-glycosidations via *O*→*C*-glycoside migration, see: (a) Ramesh, N. G.; Balasubramanian, K. K. *Tetrahedron Lett.* **1992**, *33*, 3061. (b) Gasiraghi, G.; Cornia, M.; Rassu, G.; Zetta, L.; Fava, G. G.; Belicchi, M. F. *Tetrahedron Lett.* **1988**, *29*, 3323. (c) Mahling, J.-A.; Schmidt, R. R. *Synthesis* **1993**, 325.

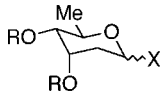


11: X=A, R=Ac
12a: X=A, R=Bz
12b: X=A, R=H
12c: X=A, R=Me

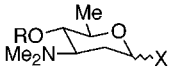


13a: X=A, R=Bz
13b: X=A, R=H
13c: X=A, R=Me

16: X=B, R=H
17: X=C, R=H
18: X=D, R=H
19: X=E, R=H
20: X=F, R=H



14a: X=A, R=Bz
14b: X=A, R=H



15a: X=A, R=Bz
15b: X=A, R=H

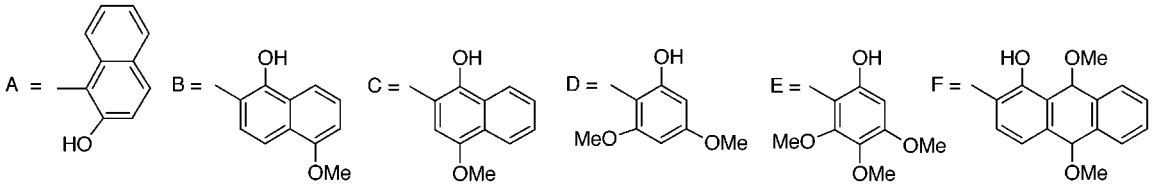


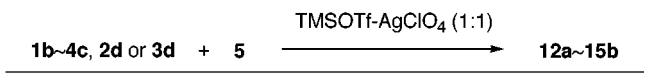
Figure 3. Aryl *C*-glycosides.

Table 2. Aryl *C*-Glycosidations of 2a, 3a, and 4a with 5 by TMSOTf−$AgClO_4$[a]

entry	sugar	temp (°C)	time (h)	product	yield (%)[b]	α/β[c]
1	**2a**	25	1	**13a**	99	1:>99
2	**3a**	25	1	**14a**	98	1:87
3	**4a**	40	2	**15a**	99	1:>99

[a] All reactions were carried out by use of 2.0 equiv of **5** to the glycosyl donor. [b] Isolated yields after purification by column chromatography. [c] α:β Ratios were determined by ^{1}H-NMR (270 MHz) spectroscopy and/or isolation of pure isomers.

Table 3. Aryl *C*-Glycosidations by TMSOTf−$AgClO_4$[a]



entry	sugar	mol % of activator	solvent	temp (°C)	time (h)	product	yield (%)[b]	α/β[c]
1	**1b**	20	CH_2Cl_2	25	1	**12a**	85	1:>99
2	**2b**	20	CH_2Cl_2	25	0.5	**13a**	99	1:70
3	**3b**	20	CH_2Cl_2	25	0.5	**14a**	90	1:15
4	**4a**	50	CH_2Cl_2	40	2	**15a**	83	1:>99
5	**1c**	50	CH_3CN	25	1	**12b**	86	1:>99
6	**2c**	20	CH_3CN	25	1	**13b**	91	1:>99
7	**3c**	20	CH_3CN	25	1	**14b**	92	1:32
8	**4c**	50	CH_2Cl_2	40	2	**15b**	72	1:>99
9	**2d**	20	CH_3CN	25	1	**13b**	92	1:>99
10	**3d**	20	CH_3CN	25	1	**14b**	84	1:97

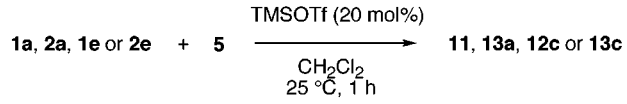
[a] All reactions were carried out by use of 2.0 equiv of **5** to the glycosyl donor. [b] Isolated yields after purification by column chromatography. [c] α:β Ratios were determined by ^{1}H-NMR (270 MHz) spectroscopy and/or isolation of pure isomers.

deactivated by any hydroxyl group and could effectively activate the 1-OH group of the glycosyl donor, aryl *C*-glycosidation of a totally unprotected sugar would be achieved. We examined the aryl *C*-glycosidations of the benzoylated glycoses **1b**−**4b** with 2-naphthol (**5**) to assess the ability of the TMSOTf−$AgClO_4$ catalyst to activate the 1-OH group of the sugars. The results summarized as entries 1−4 in Table 3 showed these glycosidations proceeded smoothly under mild conditions to afford the corresponding benzoylated aryl β-*C*-glycosides of **12a**−**15a**[9b] with high stereoselectivity in very good to excellent yields. These results clearly indicated that the TMSOTf−$AgClO_4$ catalyst was effective in activating not only the 1-OMe group but also the 1-OH group of the sugars. Our next attempts were the aryl *C*-glycosidations of the unprotected methyl glycosides **1c**−**4c** with **5** to examine the activating capacity of the TMSOTf−$AgClO_4$ system in the presence of other hydroxyl groups of the glycosyl donor. In the case of the glycosyl donors **1c**−**3c**, CH_3CN was used as an appropriate solvent instead of CH_2Cl_2, considering their solubility. However, the use of CH_2Cl_2 as a solvent was crucial for the effective glycosidation of the amino sugar **4c**. The results summarized as entries 5−8 in Table 3 showed an additional feature of the present method. Even the trihydroxy sugar **1c** and monohydroxy amino sugar **4c** were smoothly glycosidated with **5** by use of 50 mol % of the present activator to give the corresponding unprotected aryl β-*C*-glycosides of **12b** and **15b**, respectively, in high yields (entries 5 and 8 in Table 3). These results suggested that the ability of the TMSOTf−$AgClO_4$ system as a catalytic activator was not significantly influenced by any hydroxyl group of the glycosyl donor.

Having these favorable results, we tried the aryl *C*-glycosidations of totally unprotected sugars by using the present catalyst system. Although the totally unprotected sugars **1d** and **4d** were not able to be applied to the glycosidation reaction due to their low solubility in both CH_3CN and CH_2Cl_2, both aryl *C*-glycosidations of **2d** and **3d** with **5** in CH_3CN were effectively achieved under similar conditions to afford the unprotected aryl β-*C*-glycosides of **13b** and **14b**, respectively, with high chemical yield and stereoselectivity (entries 9 and 10 in Table 3). At this stage, it was unfortunately found that other polar solvents, MeOH, *i*-PrOH, *t*-BuOH, DMF, and THF, were found to be not suitable for the present glycosidation reaction.

In our extended studies of this project, we further investigated a more practical method without $AgClO_4$, which would not be employed for large scale experiments and industrial processes due to its hazardous and explosive properties. Since sugars having acyl protecting groups such as acetyl and benzoyl groups could become useful glycosyl donors in a wide variety of glycosidation reactions, we tried the aryl *C*-glycosidations of the acylated methyl glycosides **1a** and **2a** with 2-naphthol (**5**) using only TMSOTf as the catalyst. The results summarized in Table 4 as entries 1 and 2 showed that the chemical yields of these reactions were much lower

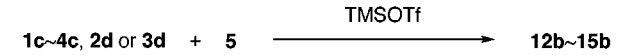
Table 4. Protecting Group Effect in Aryl *C*-Glycosidations by TMSOTf [a]



entry	sugar	product	yield (%)[b]	α/β[c]
1	**1a**	**11**	19	1:>99
2	**2a**	**13a**	57	1:>99
3	**1e**	**12c**	99	1:>99
4	**2e**	**13c**	89	1:>99

[a] All reactions were carried out by use of 2.0 equiv of **5** to the glycosyl donor. [b] Isolated yields after purification by column chromatography. [c] α:β Ratios were determined by ^{1}H-NMR (270 MHz) spectroscopy and/or isolation of pure isomers.

Table 5. Aryl *C*-Glycosidations by TMSOTf [a]



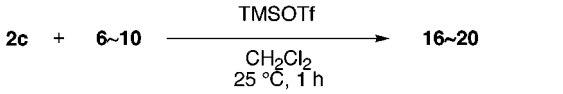
entry	sugar	mol % of activator	solvent	temp (°C)	time (h)	product	yield (%)[b]	α/β[c]
1	**1c**	50	CH_3CN	40	1	**12b**	89	1:>99
2	**2c**	20	CH_2Cl_2	25	1	**13b**	98	1:>99
3	**3c**	20	CH_2Cl_2	25	1	**14b**	91	1:>99
4	**4c**	120	CH_2Cl_2	40	8	**15b**	93	1:>99
5	**2d**	20	CH_2Cl_2	25	1	**13b**	97	1:>99
6	**3d**	20	CH_2Cl_2	25	1	**14b**	72	1:>99

[a] All reactions were carried out by use of 2.0 equiv of **5** to the glycosyl donor. [b] Isolated yields after purification by column chromatography. [c] α:β Ratios were determined by ^{1}H-NMR (270 MHz) spectroscopy and/or isolation of pure isomers.

than those with TMSOTf−$AgClO_4$ as expected from our earlier observations. After many attempts to optimize the new activator which has no hazardous or explosive properties, our attention turned to the effect of the protecting groups of the glycosyl donors. Therefore, we next examined the glycosidations of the methylated methyl glycosides **1e** and **2e** with **5** by TMSOTf. It was found that the results including both chemical yields and stereoselectivity of these glycosidations were quite satisfactory as shown in Table 4 as entries 3 and 4. Furthermore, unexpected favorable results were obtained for the glycosidations of the corresponding unprotected methyl glycosides **1c**−**4c** with **5** by TMSOTf. The results illustrated in Table 5 as entries 1 and 2 showed that these glycosidations proceeded much more effectively than those of the corresponding acylated methyl glycosides **1a** and **2a** to afford only the unprotected *o*-hydroxyaryl *β*-*C*-glycosides of **12b** and **13b** in high yields, respectively. These results clearly indicated that unprotected sugars could become very versatile glycosyl donors in the aryl *C*-glycosidation reaction using TMSOTf. Our attention next turned to the scope and limitations of the present method. The results summarized in Table 5 as entries 3 and 4 showed that other unprotected methyl glycosides **3c** and **4c** also reacted with **5** to give high yields of the unprotected aryl *β*-C-glycosides of **14b** and **15b**, respectively. Furthermore, it was found that both glycosidations of totally unprotected sugars **2d** and **3d** with **5** using a catalytic amount of TMSOTf were effectively achieved under similar conditions to afford the aryl *β*-*C*-glycosides of **13b** and **14b** with quite satisfactory chemical yield and stereoselectivity (entries 5 and 6 in Table 5).

Finally, we tried the aryl *C*-glycosidations of the unprotected methyl glycoside, methyl olivoside **2c**, and

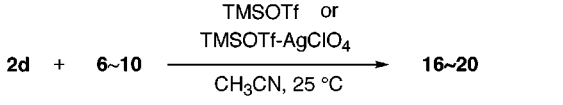
Table 6. Aryl *C*-Glycosidations of 2c and 6−10 by TMSOTf [a]



entry	glycosyl acceptor	mol % of activator	product	yield (%)[b]	α/β[c]
1	**6**	20	**16**	76	1:>99
2	**7**	20	**17**	79	1:>99
3	**8**	20	**18**	98	1:>99
4	**9**	20	**19**	91	1:>99
5	**10**	50	**20**	64	1:>99

[a] All reactions were carried out by use of 2.0 equiv of the glycosyl acceptor to **2c**. [b] Isolated yields after purification by column chromatography. [c] α:β Ratios were determined by ^{1}H-NMR (270 MHz) spectroscopy and/or isolation of pure isomers.

Table 7. Aryl *C*-Glycosidations of 2d and 6−10 by TMSOTf or TMSOTf−$AgClO_4$[a]



entry	glycosyl acceptor	activator (mol %)	time (h)	product	yield (%)[b]	α/β[c]
1	**6**	TMSOTf (20)	1	**16**	77	1:>99
2	**6**	TMSOTf−$AgClO_4$ (20)	0.5	**16**	87	1:>99
3	**7**	TMSOTf (20)	1	**17**	63	1:>99
4	**7**	TMSOTf−$AgClO_4$ (20)	0.5	**17**	91	1:>99
5	**8**	TMSOTf (20)	1	**18**	89	1:>99
6	**8**	TMSOTf−$AgClO_4$ (20)	0.5	**18**	98	1:>99
7	**9**	TMSOTf (20)	1	**19**	71	1:>99
8	**9**	TMSOTf−$AgClO_4$ (20)	0.5	**19**	90	1:>99
9	**10**	TMSOTf (20)	1	**20**	42	1:>99
10	**10**	TMSOTf−$AgClO_4$ (20)	0.5	**20**	75	1:>99

[a] All reactions were carried out by use of 2.0 equiv of the glycosyl acceptor to **2d**. [b] Isolated yields after purification by column chromatography. [c] α:β Ratios were determined by ^{1}H-NMR (270 MHz) spectroscopy and/or isolation of pure isomers.

the unprotected glycose, olivose **2d**, with some other phenol and naphthol derivatives **6**−**10** by TMSOTf−$AgClO_4$ or TMSOTf because olivose is a very representative sugar which exists as a glycosidic component in many aryl *C*-glycoside antibiotics.[6,7] These results are summarized in Tables 6 and 7. It was found that all glycosidations of **2c** proceeded only using a catalytic amount of TMSOTf under mild conditions to give the corresponding unprotected aryl *β*-C-glycosides of **16**−**20** in very good to excellent yields (Table 6). On the other hand, in the case of **2d**, the combined use of TMSOTf−$AgClO_4$ gave significantly better results than the use of TMSOTf especially when **7** and **10** were employed as the glycosyl acceptors (Table 7). In the case of the combined use of TMSOTf−$AgClO_4$, the true activating species for the glycosyl donor is presumably $TMSClO_4$[12] and/or $HClO_4$ which is generated due to the presence of the free hydroxy groups of the glycosyl acceptor and donor, while TMSOTf and/or TfOH is the activating spices when TMSOTf is used.[13] Indeed, it was confirmed that when TfOH was used instead of TMSOTf as the activating reagent for the glycosyl donors, a 20−30% decrease in chemical yields was observed.

Allyl *C*-Glycosidations of Unprotected Glycals. The *C*-glycosidations of unprotected sugars based on the

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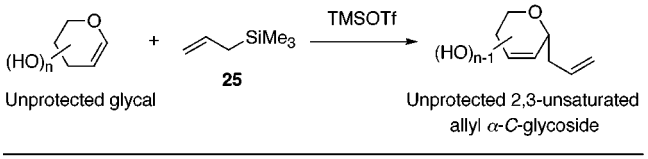


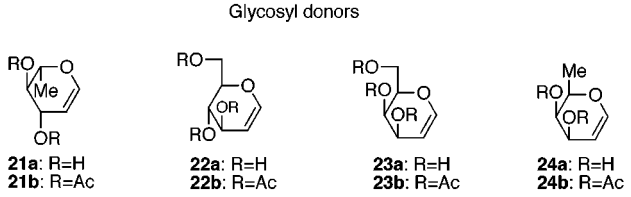
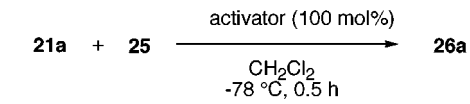


Figure 4. Allyl *C*-glycosidations.

Table 8. Allyl *C*-Glycosidations of 21a and 25[a]



entry	activator	yield (%)[b]	α/β[c]
1	TMSOTf	94	>99:1
2	TBSOTf	46	>99:1
3	BF_3·Et_2O	trace	–
4	Tf_2O	0	–
5	TfOH	73	35:1
6	CSA	0	–

[a] All reactions were carried out by use of 2.0 equiv of **25** to **21a**. [b] Isolated yields after purification by column chromatography. [c] α:β Ratios were determined by ^{1}H-NMR (270 MHz) spectroscopy and/or isolation of pure isomers.

faster formation of the *C*-glycoside bond compared to that of the *O*-glycoside bond were investigated and realized as the allyl *C*-glycosidations of unprotected glycals and allyltrimethysilane at low temperature. These glycosidations exclusively gave the corresponding unprotected and 2,3-unsaturated allyl α-*C*-glycosides, which are very versatile synthetic intermediates for natural products syntheses,[14] in a fashion similar to the carbon-Ferrier rearrangement[15,16] (Figure 4).

In our initial attempts to find a suitable activator, we examined several acid activators such as TMSOTf, *tert*-butyldimethylsilyl trifluoromethanesulfonate (TBSOTf), BF_3·Et_2O, Tf_2O, TfOH, and *dl*-10-camphorsulfonic acid (CSA) for the allyl *C*-glycosidation of the unprotected L-rhamnal (**21a**) and allyltrimethylsilane (**25**). To avoid the self *O*-glycosidation of the unprotected glycal **21a**, these reactions were carried out at low temperature (−78 °C). From the results shown in Table 8, it was found that TMSOTf, in sharp contrast to the other activators, worked effectively. Thus, the unprotected glycal **21a** was smoothly coupled with **25** by using 100 mol % of TMSOTf in CH_2Cl_2 (0.1 M for **21a**) at −78 °C for 0.5 h to afford

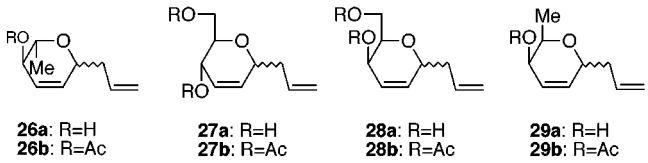
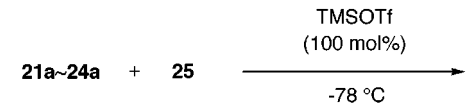


Figure 5. 2,3-Unsaturated allyl *C*-glycosides.

Table 9. Allyl *C*-Glycosidations of 21a−24a and 25 by TMSOTf[a]



entry	sugar	solvent (M for sugar)	time (h)	product	yield (%)[b]	α/β[c]
1	**21a**	CH_2Cl_2 (0.2)	0.5	**26a**	91	>99:1
2	**21a**	CH_2Cl_2 (0.1)	0.5	**26a**	94	>99:1
3	**22a**	CH_2Cl_2 (0.2)	0.5	**27a**	14	>99:1
4	**22a**	CH_2Cl_2[2]−CH_3CN[1] (0.2)	0.5	**27a**	85	>99:1
5	**22a**	CH_2Cl_2[2]−CH_3CN[1] (0.05)	0.5	**27a**	91	>99:1
6	**23a**	CH_2Cl_2 (0.2)	0.5	**28a**	2	>99:1
7	**23a**	CH_2Cl_2[2]−CH_3CN[1] (0.05)	1	**28a**	59	>99:1
8	**23a**	CH_2Cl_2[2]−CH_3CN[1] (0.02)	1	**28a**	90	>99:1
9	**24a**	CH_2Cl_2 (0.2)	0.5	**29a**	9	>99:1
10	**24a**	CH_2Cl_2[2]−CH_3CN[1] (0.02)	2	**29a**	66	>99:1

[a] All reactions were carried out by use of 2.0 equiv of **25** to the glycosyl donor. [b] Isolated yields after purification by column chromatography. [c] α:β Ratios were determined by ^{1}H-NMR (270 MHz) spectroscopy and/or isolation of pure isomers.

only the unprotected and 2,3-unsaturated allyl α-*C*-glycoside of **26a** (Figure 5) in 94% yield. Since self-coupling products came from the *O*-glycosidation of **21a** were not detected during the reaction at any stage, the present method depended on the faster trapping of **25** than any hydroxyl group of the glycosyl donor **21a**. Furthermore, it was confirmed that use of low temperature (−78 °C) was important for the selective formation of the *C*-glycoside bond.

To enhance the synthetic utility of this reaction, the allyl *C*-glycosidations of several other unprotected glycals, D-glucal (**22a**), D-galactal (**23a**), and D-fucal (**24a**), with **25** were next examined. The results summarized in Table 9 as entries 5, 8, and 10 showed that although the yield of the glycosidation of **24a** was not very high, the glycosidations of **22a** and **23a** proceeded under similar conditions to give the allyl α-*C*-glycosides of **27a** and **28a**, respectively, in high yields. Remarkably, the stereoselectivity of these glycosidations was quite α-selective in all cases.[17] In the glycosidations of **22a**−**24a**, the use of MeCN as a cosolvent and the low concentration of the glycals in the solvent were necessary to get high yields of the desired allyl *C*-glycosides owing to the low solubility of **22a**−**24a** in CH_2Cl_2 at low temperature (−78 °C) (entries 3−10 in Table 9).

We then compared the unprotected glycals **21a**−**24a** and the corresponding acetylated glycals **21b**−**24b** from the viewpoint of chemical yield and stereoselectivity in their allyl *C*-glycosidations with **25** by TMSOTf. Although acetylated glycals have been frequently used as suitable glycosyl donors in the carbon-Ferrier rearrangement,[14,16] the allyl *C*-glycosidations of the acetylated glycals **21b**−**24b** using TMSOTf have never been re-

(14) For representative application to natural products syntheses, see: (a) Nicolaou, K. C.; Duggan, M. E.; Hwang, C.-K.; Somers, P. K. *J. Chem. Soc., Chem. Commun.* **1985**, 1359. (b) Wincott, F. E.; Danishefsky, S. J.; Schulte, G. *Tetrahedron Lett.* **1987**, *28*, 4951. (c) Danishefsky, S. J.; DeNinno, S.; Lartey, P. *J. Am. Chem. Soc.* **1987**, *109*, 2082. (d) Ichikawa, Y.; Isobe, M.; Goto, T. *Tetrahedron* **1987**, *43*, 4749.

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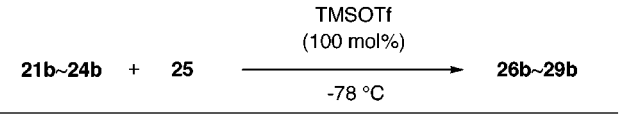
(17) The α-configurations of the anomeric positions were confirmed by the comparison between the corresponding acetylated glycosides, which were obtained by standard acetylation, and the authentic samples reported in ref 16.

Table 10. Allyl *C*-Glycosidations of 21b−24b and 25 by TMSOTf [a]



entry	sugar	solvent (M for sugar)	time (h)	product	yield (%)[b]	α/β[c]
1	**21b**	CH_2Cl_2 (0.1)	0.5	**26b**	95	9.9:1
2	**22b**	CH_2Cl_2[2]−CH_3CN[1] (0.05)	0.5	**27b**	63	37:1
3	**23b**	CH_2Cl_2[2]−CH_3CN[1] (0.02)	1	**28b**	19	>99:1
4	**24b**	CH_2Cl_2[2]−CH_3CN[1] (0.02)	2	**29b**	20	>99:1

[a] All reactions were carried out by use of 2.0 equiv of **25** to the glycosyl donor. [b] Isolated yields after purification by column chromatography. [c] α:β Ratios were determined by ^{1}H-NMR (270 MHz) spectroscopy and/or isolation of pure isomers.

ported. The results of the *C*-glycosidations of **21b**−**24b** under similar conditions as those for **21a**−**24a**, respectively, are summarized in Table 10. Notably, it was found that the allyl *C*-glycosidations of the totally unprotected glycals **22a**−**24a** with **25** proceeded much more effectively than those of the acetylated glycals **22b**−**24b** to give high yields of the allyl α-*C*-glycosides of **27a**−**29a**, respectively. Furthermore, the stereoselectivity of the glycosidations of **21a** and **22a** was higher than that of the corresponding acetylated glycals **21b** and **22b**.

From these results, the allyl *C*-glycosidations of the unprotected glycals with allyltrimethylsilane using TMSOTf exhibits two significant advantages. The first one is the higher reactivity of such glycosyl donors compared to the acylated derivatives. The second advantage is the extremely high α-stereoselectivity obtained in the glycosidation reactions. Since the epimerization at the anomeric position of the resulting *C*-glycoside was not observed during the *C*-glycosidation, the high α-stereoselectivity must arise from a kinetic anomeric effect.[18]

Conclusions

The present novel aryl and allyl *C*-glycosidations using unprotected sugars as simple glycosyl donors offered promising entries to the practical and effective syntheses of totally unprotected aryl and allyl *C*-glycosides. Application of these methods to natural product synthesis will be reported elsewhere in detail.[19]

Experimental Section

General Methods. Melting points are uncorrected. ^{1}H NMR spectra were measured in $CDCl_3$ using TMS as internal standard unless otherwise noted. High-resolution mass spectra (HRMS) were recorded under electron impact (EI) conditions. Silica gel TLC and column chromatography were performed on Merck TLC 60F-254 (0.25 mm) and Fuji-Davison BW-820MH or BW-300, respectively. Air- and/or moisture-sensitive reactions were carried out under an atmosphere of argon with oven-dried glassware. In general, organic solvents were purified and dried by the appropriate procedure, and evaporation and concentration were carried out under reduced pressure below 30 °C, unless otherwise noted.

Aryl *C*-Glycosidations of Unprotected 2-Deoxy Sugars by TMSOTf−$AgClO_4$. General Procedure. To a mixture of glycosyl donor (0.1 mmol), glycosyl acceptor (0.2 mmol), and silver perchlorate (0.02 or 0.05 mmol) in dry CH_2Cl_2 or CH_3CN (1 mL) was added trimethylsilyl trifluoromethanesulfonate (0.02 or 0.05 mmol) dropwise at 0 °C under argon. The reaction mixture was stirred at 25 or 40 °C for 0.5, 1, or 2 h as described in Tables 3 and 7. In the case of neutral sugars, the reaction mixture was quenched with triethylamine under ice-cooling and then concentrated in vacuo. On the other hand, in the case of amino sugar, the reaction mixture was quenched with ice-cold and saturated aqueous $NaHCO_3$, the resultant mixture was extracted with ethyl acetate several times, and the extracts were washed with saturated aqueous NaCl, dried over anhydrous Na_2SO_4, and concentrated in vacuo. Purification of the residue by flash column chromatography gave the corresponding unprotected aryl *C*-glycoside.

Aryl *C*-Glycosidations of Unprotected 2-Deoxy Sugars by TMSOTf. General Procedure. To a mixture of glycosyl donor (0.1 mmol) and glycosyl acceptor (0.2 mmol) in dry CH_2Cl_2 or CH_3CN (1 mL) was added trimethylsilyl trifluoromethanesulfonate (0.02, 0.05, or 0.12 mmol) dropwise at 0 °C under argon. The reaction mixture was stirred at 25 or 40 °C for 1, 2, or 8 h as described in Tables 5, 6, and 7. The reaction mixture was worked up and purified as described above to give the corresponding unprotected aryl *C*-glycoside.

1-(2′-Deoxy-β-D-*arabino*-hexopyranosyl)-2-naphthol (12b-β). R_f 0.38 (5:1 chloroform−methanol); $[\alpha]^{26}_D$ +92.6° (*c* 0.81, MeOH); ^{1}H NMR (CD_3OD) δ 2.02 (1H, ddd, *J* = 13.6, 11.9, and 11.9 Hz), 2.17 (1H, ddd, *J* = 13.6, 4.6, and 2.4 Hz), 3.45−3.55 (2H, m), 3.8−4.0 (3H, m), 5.60 (1H, dd, *J* = 11.9 and 2.4 Hz), 7.0−8.15 (6H). Anal. Calcd for $C_{16}H_{18}O_5$: C, 66,20; H, 6.25. Found: C, 66.14; H, 6.43.

1-(2′,6′-Dideoxy-β-D-*arabino*-hexopyranosyl)-2-naphthol (13b-β). R_f 0.63 (4:1 chloroform−methanol); $[\alpha]^{28}_D$ +155.5° (*c* 1.24, $CHCl_3$); mp 152.0−153.0 °C (ethyl acetate−hexane); ^{1}H NMR δ 1.46 (3H, d, *J* = 6.0 Hz), 1.98 (1H, ddd, *J* = 13.6, 11.9, and 11.9 Hz), 2.37 (1H, ddd, *J* = 13.6, 4.4, and 2.1 Hz), 2.75 (1H, br s), 3.03 (1H, br s), 3.30 (1H, br dd, *J* = 9.2 and 9.2 Hz), 3.60 (1H, dq, *J* = 9.2 and 6.0 Hz), 3.8−3.95 (1H, m), 5.50 (1H, dd, *J* = 11.9 and 2.1 Hz), 7.05−7.8 (6H), 8.89 (1H, s). Anal. Calcd for $C_{16}H_{18}O_4$: C, 70.06; H, 6.61. Found: C, 69.99; H, 6.69.

1-(2′,6′-Dideoxy-α-D-*ribo*-hexopyranosyl)-2-naphthol (14b-α). R_f 0.37 (1:1 hexane−acetone); $[\alpha]^{24}_D$ −85.1° (*c* 0.83, $CHCl_3$); ^{1}H NMR δ 1.45 (3H, d, *J* = 6.4 Hz), 2.04 (1H, ddd, *J* = 13.2, 5.2, and 3.0 Hz), 2.19 (1H, br s), 2.26 (1H, ddd, *J* = 13.2, 11.8, and 11.8 Hz), 2.66 (1H, br s), 3.86 (1H, br s), 4.15−4.35 (1H, m), 4.53 (1H, dq, *J* = 6.4 and 1.0 Hz), 5.71 (1H, dd, *J* = 11.8 and 3.0 Hz), 7.1−7.8 (6H), 9.10 (1H, s). HRMS (EI) *m*/*z* 274.1212 (274.1205 calcd for $C_{16}H_{18}O_4$, M^+).

1-(2′,6′-Dideoxy-β-D-*ribo*-hexopyranosyl)-2-naphthol (14b-β). R_f 0.65 (5:1 chloroform−methanol); $[\alpha]^{31}_D$ +159.1° (*c* 0.90, $CHCl_3$); mp 207.5−208.5 °C (ethyl acetate−hexane); ^{1}H NMR δ 1.45 (3H, d, *J* = 6.0 Hz), 2.12 (1H, ddd, *J* = 14.2, 11.8, and 1.9 Hz), 2.19 (1H, d, *J* = 6.4 Hz), 2.29 (1H, ddd, *J* = 14.2, 3.6, and 2.4 Hz), 2.43 (1H, br s), 3.51 (1H, ddd, *J* = 9.6, 6.4, and 4.4 Hz), 4.03 (1H, dq, *J* = 9.6 and 6.0 Hz), 4.2−4.3 (1H, m), 5.88 (1H, dd, *J* = 11.8 and 2.4 Hz), 7.05−7.8 (6H), 9.00 (1H, s). Anal. Calcd for $C_{16}H_{18}O_4$: C, 70.06; H, 6.61. Found: C, 69.81; H, 6.66.

1-(3′-(Dimethylamino)-2′,3′,6′-trideoxy-β-D-*ribo*-hexopyranosyl)-2-naphthol (15b-β). R_f 0.62 (2:1 chloroform−methanol); $[\alpha]^{31}_D$ +159.7° (*c* 1.15, $CHCl_3$); ^{1}H NMR δ 1.50 (3H, d, *J* = 6.0 Hz), 1.87 (1H, ddd, *J* = 13.6, 11.8, and 11.8 Hz), 2.13 (1H, ddd, *J* = 13.6, 3.7, and 2.0 Hz), 2.3−2.8 (1H, br), 2.39 (6H, s), 2.92 (1H, ddd, *J* = 11.8, 9.2, and 3.7 Hz), 3.33 (1H, dd, *J* = 9.2 and 9.2 Hz), 3.67 (1H, dq, *J* = 9.2 and 6.0 Hz), 5.88 (1H, dd, *J* = 11.8 and 2.0 Hz), 7.05−7.8 (6H), 8.9−9.1 (1H, br s). Anal. Calcd for $C_{18}H_{23}NO_3$: C, 71.73; H, 7.69; N, 4.65. Found: C, 71.59; H, 7.86; N, 4.64.

2-(2′,6′-Dideoxy-β-D-*ribo*-hexopyranosyl)-5-methoxy-1-naphthol (16-β). R_f 0.48 (6:1 chloroform−methanol); $[\alpha]^{28}_D$ +32.8° (*c* 0.58, CH_3OH); mp 138.5−139.5 °C (ethyl ether−hexane); ^{1}H NMR δ 1.48 (3H, d, *J* = 6.2 Hz), 2.01 (1H, ddd, *J* = 13.9, 11.8, and 11.8 Hz), 2.14 (1H, br d, *J* = 2.8 Hz), 2.34 (1H, ddd, *J* = 13.9, 4.8, and 2.2 Hz), 2.37 (1H, br), 3.28 (1H,

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ddd, J = 9.2, 9.2, and 2.8 Hz), 3.59 (1H, dq, J = 9.2 and 6.2 Hz), 3.81 (1H, m), 3.98 (3H, s), 4.88 (1H, dd, J = 11.8 and 2.2 Hz), 6.82 (1H, d, J = 8.2 Hz), 7.02 (1H, d, J = 8.4 Hz), 7.37 (1H, dd, J = 8.4 and 8.4 Hz), 7.73 (1H, d, J = 8.4 Hz), 7.82 (1H, d, J = 8.2 Hz), 8.67 (1H, s). Anal. Calcd for $C_{17}H_{20}O_5$: C, 67.09; H, 6.62. Found: C, 66.90; H, 6.61.

2-(2′,6′-Dideoxy-*β*-D-*ribo*-hexopyranosyl)-4-methoxy-1-naphthol (17-*β*). R_f 0.48 (6:1 chloroform−methanol); $[\alpha]^{23}_D$ +38.2° (*c* 1.20, CH_3OH); ^{1}H NMR δ 1.47 (3H, d, J = 6.0 Hz), 2.02 (1H, ddd, J = 13.2, 11.5, and 11.5 Hz), 2.23 (1H, br d, J = 2.6 Hz), 2.37 (1H, ddd, J = 13.2, 5.0, and 2.2 Hz), 2.42 (1H, br d, J = 2.6 Hz), 3.29 (1H, ddd, J = 9.2, 9.2, and 2.6 Hz), 3.57 (1H, dq, J = 9.2 and 6.0 Hz), 3.80 (1H, m), 3.92 (3H, s), 4.81 (1H, dd, J = 11.5 and 2.2 Hz), 6.35 (1H, s), 7.41−7.57 (2H), 8.1−8.24 (2H), 8.24 (1H, s). Anal. Calcd for $C_{17}H_{20}O_5$: C, 67.09; H, 6.62. Found: C, 66.98; H, 6.85.

2-(2′,6′-Dideoxy-*β*-D-*ribo*-hexopyranosyl)-3,5-dimethoxyphenol (18-*β*). R_f 0.54 (5:1 chloroform−methanol); $[\alpha]^{28}_D$ +82.8° (*c* 2.07, CH_3OH); mp 185.0−186.0 °C (acetone−hexane); ^{1}H NMR δ 1.41 (3H, d, J = 6.0 Hz), 1.81 (1H, ddd, J = 13.4, 11.6, and 11.6 Hz), 2.16 (1H, d, J = 4.4 Hz), 2.21 (1H, ddd, J = 13.4, 4.8, and 2.2 Hz), 2.47 (1H, d, J = 3.5 Hz), 3.22 (1H, ddd, J = 9.2, 9.2, and 4.4 Hz), 3.49 (1H, dq, J = 9.2 and 6.0 Hz), 3.7−3.82 (1H, m), 3.75 (3H, s), 3.76 (3H, s), 5.06 (1H, dd, J = 11.6 and 2.2 Hz), 6.00 (1H, d, J = 2.0 Hz), 6.07 (1H, d, J = 2.0 Hz), 8.45 (1H, s). Anal. Calcd for $C_{14}H_{20}O_6$: C, 59.14; H, 7.09. Found: C, 59.05; H, 7.31.

2-(2′,6′-Dideoxy-*β*-D-*ribo*-hexopyranosyl)-3,4,5-trimethoxyphenol (19-*β*). R_f = 0.39 (6:1 chloroform−methanol); $[\alpha]^{27}_D$ +56.7° (*c* 0.67, CH_3OH); mp 106.5−107.5 °C (ethyl acetate−hexane); ^{1}H NMR δ 1.47 (3H, d, J = 6.0 Hz), 1.88 (1H, ddd, J = 13.4, 11.6, and 11.6 Hz), 2.17 (1H, ddd, J = 13.4, 4.8, and 2.3 Hz), 2.40 (1H, br s), 2.66 (1H, br s), 3.21 (1H, br dd, J = 9.2 and 9.2 Hz), 3.50 (1H, dq, J = 9.2 and 6.0 Hz), 3.7−3.85 (1H, m), 3.76 (3H, s), 3.80 (3H, s), 3.89 (3H, s), 4.95 (1H, dd, J = 11.6 and 2.3 Hz), 6.77 (1H, s), 8.11 (1H, s). Anal. Calcd for $C_{15}H_{22}O_7$: C, 57.32; H, 7.05. Found: C, 57.29; H, 7.35.

2-(2′,6′-Dideoxy-*β*-D-*ribo*-hexopyranosyl)-9,10-dimethoxy-1-hydroxyanthracene (20-*β*). R_f 0.42 (8:1 chloroform−methanol); $[\alpha]^{23}_D$ +72.1° (*c* 1.17, CH_3OH); ^{1}H NMR δ 1.47 (3H, d, J = 6.0 Hz), 1.6−2.5 (2H, br), 1.75 (1H, ddd, J = 13.8, 11.6, and 11.6 Hz), 2.38 (1H, ddd, J = 13.8, 5.0, and 2.1 Hz), 3.28 (1H, dd, J = 9.2 and 9.2 Hz), 3.58 (1H, dq, J = 9.2 and 6.0 Hz), 3.89 (1H, ddd, J = 11.6, 9.2, and 5.0 Hz), 4.07 (3H, s), 4.12 (3H, s), 5.19 (1H, dd, J = 11.6 and 2.1 Hz), 7.45−7.55 (2H), 7.60 (1H, d, J = 8.6 Hz), 7.82 (1H, d, J = 8.6 Hz), 8.13−8.21 (1H), 8.26−8.30 (1H), 11.5 (1H, s). Anal. Calcd for $C_{22}H_{24}O_6$: C, 68.74; H, 6.29. Found: C, 68.50; H, 6.49.

Allyl *C*-Glycosidations of Unprotected Glycals by TMSOTf. General Procedure. To a mixture of glycosyl donor (0.1 mmol) and allyltrimethysilane (0.2 mmol) in dry solvent described in Table 9 was added trimethylsilyl trifluoromethanesulfonate (0.1 mmol) dropwise at −78 °C under argon. The reaction mixture was stirred at the same temperature for 0.5, 1, or 2 h and quenched with ice-cold and saturated aqueous $NaHCO_3$. The resultant mixture was then extracted with ethyl acetate several times, and the extracts were washed with saturated aqueous NaCl, dried over anhydrous Na_2SO_4, and concentrated in vacuo. Purification of the residue by flash column chromatography gave the corresponding unprotected and 2,3-unsaturated allyl α-*C*-glycoside.

3-(2′,3′,6′-Trideoxy-α-L-*erythro*-hex-2′-enopyranosyl)-1-propene (21a-α): R_f 0.60 (3:2 hexane−acetone); $[\alpha]^{27}_D$ −2.3° (*c* 0.77, $CHCl_3$); ^{1}H NMR δ 1.27 (3H, d, J = 6.2 Hz), 1.73 (1H, d, J = 8.4 Hz), 2.31 (1H, br ddd, J = 13.8, 6.8, and 6.8 Hz), 2.42 (1H, br ddd, J = 13.8, 6.8, and 6.8 Hz), 3.65−3.75 (1H, m), 3.77 (1H, dq, J = 6.2 and 4.6 Hz), 4.20 (1H, m), 5.05−5.2 (2H, m), 5.75−5.95 (3H, m); HRMS (EI) *m*/*z* 155.1085 (155.1072 calcd for $C_9H_{15}O_2$, M + H^+). Anal. Calcd for $C_9H_{14}O_2$: C, 70.10; H, 9.15. Found: C, 69.98; H, 9.33.

3-(2′,3′-Dideoxy-α-D-*erythro*-hex-2′-enopyranosyl)-1-propene (22a-α): R_f 0.50 (1:1 benzene−acetone); $[\alpha]^{27}_D$ −33.4° (*c* 0.94, $CHCl_3$); mp 27.5−28.5 °C (hexane, needle); ^{1}H NMR δ 2.06 (2H, br s), 2.31 (1H, br ddd, J = 13.8, 6.8, and 6.8 Hz), 2.47 (1H, br ddd, J = 13.8, 6.8, and 6.8 Hz), 3.55 (1H, ddd, J = 7.9, 5.9, and 4.3 Hz), 3.77 (1H, dd, J = 11.7 and 5.9 Hz), 3.83 (1H, dd, J = 11.7 and 4.3 Hz), 4.10 (1H, br d, J = 7.9 Hz), 4.24 (1H, m), 5.05−5.2 (2H, m), 5.75−5.95 (3H, m); HRMS (EI) *m*/*z* 171.1003 (171.1021 calcd for $C_9H_{15}O_3$, M + H^+). Anal. Calcd for $C_9H_{14}O_3$: C, 63.51; H, 8.29. Found: C, 63.44; H, 8.46.

3-(2′,3′-Dideoxy-α-D-*threo*-hex-2′-enopyranosyl)-1-propene (23a-α): R_f 0.44 (1:1 benzene−acetone); $[\alpha]^{27}_D$ −285.5° (*c* 0.77, $CHCl_3$); mp 50.0−51.0 °C (hexane, needle); ^{1}H NMR δ 2.06 (2H, br s), 2.28 (1H, br ddd, J = 13.8, 6.8, and 6.8 Hz), 2.46 (1H, br ddd, J = 13.8, 6.8, and 6.8 Hz), 3.75−3.95 (4H, m), 4.32 (1H, m), 5.12 (1H, br d, J = 10.2 Hz), 5.19 (1H, br d, J = 17.2 Hz), 5.84 (1H, ddt, J = 17.2, 10.2, and 6.8 Hz), 5.94 (1H, dd, J = 10.2 and 3.2 Hz), 6.05 (1H, ddd, J = 10.2, 5.4, and 2.0 Hz); HRMS (EI) *m*/*z* 170.0957 (170.0942 calcd for $C_9H_{14}O_3$, M^+). Anal. Calcd for $C_9H_{14}O_3$: C, 63.51; H, 8.29. Found: C, 63.37; H, 8.48.

3-(2′,3′,6′-Trideoxy-α-D-*threo*-hex-2′-enopyranosyl)-1-propene (24a-α): R_f 0.62 (3:2 hexanes−ethyl acetate); $[\alpha]^{28}_D$ −292.2° (*c* 0.98, $CHCl_3$); ^{1}H NMR δ 1.26 (3H, d, J = 6.2 Hz), 1.55 (1H, br s), 2.27 (1H, br ddd, J = 13.8, 6.8, and 6.8 Hz), 2.44 (1H, br ddd, J = 13.8, 6.8, and 6.8 Hz), 3.68 (1H, br dd, J = 5.4 and 2.1 Hz), 3.92 (1H, dq, J = 6.2 and 2.1 Hz), 4.23 (1H, m), 5.10 (1H, br d, J = 10.1 Hz), 5.12 (1H, br d, J = 17.3 Hz), 5.86 (1H, ddt, J = 17.3, 10.1, and 6.8 Hz), 5.89 (1H, dd, J = 10.2 and 3.2 Hz), 6.04 (1H, ddd, J = 10.2, 5.4, and 2.0 Hz). HRMS (EI) *m*/*z* 154.1008 (154.0994 calcd for $C_9H_{14}O_2$, M^+). Anal. Calcd for $C_9H_{14}O_2$: C, 70.10; H, 9.15. Found: C, 69.91; H, 9.42.

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