Epoxidation and Bis-hydroxylation of C-Phenyl-Δ^{2,3}-glycopyranosides.

Ghada Fakha and Denis Sinou*

Laboratoire de Synthèse Asymétrique, UMR 5181, CPE Lyon, Université Claude Bernard Lyon 1, 43, Boulevard du 11 novembre 1918, 69622 Villeurbanne, France. Tel. +33 (0)472448183, Fax +33 (0)478898914

* Author to whom correspondence should be addressed; e-mail sinou@univ-lyon1.fr

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Abstract: Epoxidation and cis-hydroxylation of C-phenyl-Δ^{2,3}-glycopyranosides have been carried out with a view to developing C-aryl glycoside synthesis. Epoxidation of (2,3-dideoxy-D-erythro-hex-2-enopyranosyl)benzene and (6-O-tert-butyldimethylsilyl-2,3-dideoxy-D-erythro-hex-2-enopyranosyl)benzene gave predominantly the allo-adducts whatever the configuration at the anomeric center. Epoxidation of (4,6-di-O-tert-butyldimethylsilyl-2,3-dideoxy-D-erythro-hex-2-enopyranosyl)benzene gave the manno-adduct only, whatever the substituents at positions 4 and 6, whereas hydroxylation of (2,3-dideoxy-β-D-erythro-hex-2-enopyranosyl)benzene and (4,6-di-O-tert-butyldimethylsilyl-2,3-dideoxy-β-D-erythro-hex-2-enopyranosyl)benzene gave the manno- and allo-adducts in 25:75 and 80:20 ratios, respectively.

Keywords: (2,3-Unsaturated-glycopyranosyl)benzene, epoxidation, cis-hydroxylation.

Introduction

There is a great interest in C-aryl glycosides. This is due to their occurrence in many natural products possessing important medicinal and therapeutic properties [1-3], as well as to their use as valuable chiral building blocks [4-6]. However, it is important to obtain the two anomers of these C-
aryl glycopyranosides with the highest stereoselectivity. Several synthetic methods are now available for the stereoselective and even stereospecific preparation of C-aryl glycopyranosides possessing a double bond in the 2,3-position [7-14]. It is to be noted that these unsaturated glycosides are useful precursors of the corresponding saturated C-aryl glycosides by simple functionalization of this unsaturation. Whereas epoxidation or hydroxylation of 2,3-dideoxy-hex-2-pyranosides has been well studied [15], there have not been any such systematic studies in the case of C-glycopyranosides, although some examples of cis-hydroxylation of C-aryl glycopyranosides appeared in the literature [14, 16]. We report in this paper some stereochemical aspects concerning the epoxidation and cis-hydroxylation of both anomers of some C-phenyl-Δ2,3-glycopyranosides (Scheme 1).

Scheme 1

Results and Discussion

The different C-phenyl-Δ2,3-glycopyranosides having the α- and the β-configuration used in this study are shown in Scheme 1. The synthesis of bis-silylated 2,3-unsaturated-C-phenyl glycopyranosides 1a and 2a has already been described [12]. The deprotected unsaturated C-phenyl glycopyranosides 1b and 2b were obtained by a simple desilylation of compounds 1a and 2a, whereas monosilylation of 1b and 2b with tert-butyldimethylsilyl chloride afforded compounds 3a and 3b, respectively.

We studied first the epoxidation of these substrates using as the epoxidation reagent m-chloroperbenzoic acid in CHCl₃ at 50 °C for 24 h. Epoxidation of bis-silylated pseudo-glucal 1a possessing the α-configuration gave in 79% yield a 11:89 mixture of the α−allo- and α−manno-epoxides 4a and 5a, which were separated by column chromatography, whereas the non-protectected pseudo-glucal 1b gave only the α−allo isomer 4b, albeit in a quite low yield (20%) (Scheme 2); even prolonged reaction times did not improve this yield, degradation products being observed in these cases. Epoxidation of the monosilylated pseudo-glucal 3a (Scheme 2) gave the reverse selectivity to that observed for the bis-silylated compound 1a: a 86:14 mixture of the α−allo- and α−manno-epoxides 6 and 7 was now obtained in 70% yield, the α−allo-epoxide being now predominant. These results are quite different from those observed in the epoxidation of alkyl 2,3-dideoxy-hex-2-pyranosides [15].

The allo or manno configuration of those epoxides was established through comparison of the coupling constants J₁,₂ and J₃,₄ [15, 17, 18], these two values being always higher for the α-allo than for the α-manno derivative. Effectively no H-1/H-2 or H-3/H-4 couplings were observed for compounds 5a and 7, whilst compounds 4a and 6 showed J₁,₂ = 3.6 and 3.4 Hz, and J₃,₄ = 1.7 and 2.3
Hz, respectively. The observed stereoselectivities could be rationalized by assuming that the epoxidation of compound 1a is under steric control, the peracid attacking on the β face because of the increased steric requirements on α face imparted by the two substituents at C-1 and C-4, whereas the epoxidation of compounds 1b and 3a was reversed, due to the cis-directing influence of the allylic hydroxyl group at position 4.

**Scheme 2**

![Scheme 2 Diagram]

**Scheme 3**

![Scheme 3 Diagram]
The epoxidation was then extended to the unsaturated β-phenyl glycopyranosides (Scheme 3). The non-protected unsaturated glycoside 2b and the monosilylated compound 3b gave the unique β-allo-epoxides 8b and 10 in 86 and 50% yield, respectively. This stereospecific epoxidation could again be attributed to the cis-directing effect of the hydroxyl function at position 4. Conversely, epoxidation of the bis-silylated β-anomer 2a gave a 60:40 mixture of the β-allo and β-manno-epoxides 8a and 9a in 69% yield; this lack of stereoselectivity was probably due to similar crowding of the two faces of the double bond of this compound.

The allo and manno-configurations were assigned from the NMR spectra; whereas H-1 appears as a singlet for all the compounds, the value of \( J_{3,4} \) is characteristic, this value being 0 for the β-manno configuration and varying from 1.5 to 2.2 Hz for the β-allo configuration. Moreover the β-allo configuration was confirmed for compound 9a by NoE experiments. Irradiation of the signal of H-1 at \( \delta = 4.83 \) ppm resulted in an increase of the signal of H-2 of 10%, when the irradiation of the signal of H-4 at \( \delta = 3.90 \) ppm showed a small enhancement (2%) of the signal of H-3. This implied that H-1 and H-2 and H-3 and H-4 have cis relationships.

The cis-hydroxylation was then examined using osmium tetroxide and N-methylmorpholine oxide as the re-oxidant. The bis-silylated and bis-hydroxy pseudo-glucals 1a and 1b afforded exclusively α-D-phenyl-mannopyranosides 11 and 12 in 70 and 43% chemical yield, respectively, after acetylation in the last case (Scheme 4). This very high stereoselectivity could be explained, as for alkyl 2,3-dideoxy-α-D-hex-enopyranosides, by the approach of the reactant on the less sterically crowded face of the C-glycoside [14-16, 19].

**Scheme 4**

\[
\begin{align*}
\text{Me}_2\text{Bu'SiO} & \quad \text{Me}_2\text{Bu'SiO} \\
\begin{array}{c}
\text{O} \\
\text{Me}_2\text{Bu'SiO} \\
\end{array} & \quad \begin{array}{c}
\text{Ph} \\
\text{Ph} \\
\end{array}
\end{align*}
\]

Reactants: i) OsO\(_4\), NMO, H\(_2\)O/acetone, 70% yield; ii) OsO\(_4\), NMO, H\(_2\)O/acetone, then Ac\(_2\)O, pyridine, 43% yield

Application of the cis-hydroxylation process to the β-anomers 2a and 2b gave a mixture of C-phenyl β-manno- and allo-pyranosides (Scheme 5). The bis-O-silylated compound 2a gave in 70% yield a 80:20 ratio of β-manno-pyranoside 13 and β-allo-pyranoside 14, which could not be separated, while unprotected 2b gave in 75% yield after acetylation a 25:75 ratio of β-manno-pyranoside 15 and β-allo-pyranoside 16, which were not separated. This difference in stereoselectivity could be explained by the presence of the crowded Me\(_2\)Bu'SiO group for 2a versus the OH group for 2b.

Configuration assignments for the compounds obtained by bis-hydroxylation were made on the basis of simple \(^{1}\text{H-NMR}\) analyses and by comparison with previously described compounds.
Conclusions

We have shown that epoxidation and cis-hydroxylation of both anomers of C-phenyl-Δ²,³-glycopyranosides are highly selective, the selectivity depending mostly on the substituent at position 4. Epoxidation of C-phenyl-Δ²,³-glycopyranosides having a free hydroxyl group at position 4 afforded predominantly, if not only, the allo-epoxide, whatever the anomer used. When the hydroxyl function at position 4 was protected as a tert-butyldimethylsilyl ether, the α-anomer gave predominantly the manno-epoxide, when the β-anomer afforded a 60:40 mixture of the two-adducts. Cis-dihydroxylation of C-phenyl-Δ²,³-α-glycopyranosides afforded the manno-adduct as the unique compound. For the cis-dihydroxylation of C-phenyl-Δ²,³-β-glycopyranosides, the presence of the free hydroxyl group at C-4 caused formation of the allo-adduct as the major isomer, when the allo-adduct was obtained predominantly when the hydroxyl function was protected with a tert-butyldimethylsilyl group.

Experimental

General

Solvents were purified by standard methods and dried if necessary. Melting points (uncorrected) were determined with a capillary melting point apparatus Büchi SMP-20. Optical rotations were recorded using a Perkin-Elmer 241 polarimeter. Thin-layer chromatography was performed using Merck silica gel 60 F₂₅₄ precoated aluminium plates, 0.2 mm thickness. Column chromatography was performed on silica gel (Merck 60, 70–230 mesh). NMR spectra were recorded on a Bruker 300 MHz spectrometer (operating at 300.13 MHz for ¹H, and 75.01 MHz for ¹³C).
Preparation of compounds 1a,b.

A solution of the unsaturated bis-silylated C-phenyl glycopyranoside 1a (or 2a) (3 g, 7.7 mmol) [12], and NBu₄F·3H₂O (2.43 g, 7.7 mmol) in THF (50 mL) was stirred at rt for 2 h. After evaporation of the solvent, CH₂Cl₂ was added (50 mL), and the solution was washed with brine. Evaporation of the solvent under reduced pressure gave a residue that was purified by column chromatography on silica using petroleum ether/ethyl acetate as the eluent to gave compound 1b (or 2b).

(2,3-Dideoxy-α-D-erythro-hex-2-enopyranosyl)benzene (1b). Yield 80%, oil, Rf 0.40 (petroleum ether/ethyl acetate 1:4), [α]D²⁰⁻72 (c 1, CHCl₃); H-NMR (CDCl₃) δ 2.10 (bs, 2H, OH), 3.45 (ddd, 1H, J = 8.5, 4.4, 4.0 Hz, H-5), 3.78 (m, 2H, H-6), 4.28 (d, 1H, J = 8.5 Hz, H-4), 5.29 (s, 1H, H-1), 6.08 (m, 2H, H-2, H-3), 7.34 (m, 5H, H arom); C-NMR (CDCl₃) δ 63.0 (C-6), 64.6 (C-4), 73.1 (C-5), 74.5 (C-1), 128.8, 128.9, 129.3, 129.8, 130.8 and 140.1 (C-2, C-3, C arom); Anal. calcd for C₁₂H₁₄O₃: C, 69.89; H, 6.84. Found: C, 70.05; H, 6.61.

Preparation of compounds 3.

To a solution of the unsaturated C-phenyl glycopyranoside 1b (or 2b) (1 g, 4.8 mmol), imidazole (32 mg, 05 mmol) and triethylamine (1 mL, 6.7 mmol) in CH₂Cl₂ (8 mL) maintained at rt was added a solution of tert-BuMe₂SiCl (990 mg, 6.6 mmol) in CH₂Cl₂ (10 mL). After being stirred at rt for 24 h, the solution was poured into cold water (10 mL), and the mixture was extracted with CH₂Cl₂. (3x10 mL). After evaporation of the solvent under reduced pressure, the residue was purified by column chromatography on silica using petroleum ether/diethyl ether as the eluent to give compound 3b (or 3b).

(2,3-Dideoxy-β-D-erythro-hex-2-enopyranosyl)benzene (2b). Yield 75%, oil, Rf 0.40 (petroleum ether/ethyl acetate 1:4), [α]D²⁰+192 (c 0.8, CHCl₃); H-NMR (CDCl₃) δ 1.94 (bs, 2H, OH), 3.59 (ddd, 1H, J = 8.7, 5.2, 4.1 Hz, H-5), 3.86 (dd, 1H, J = 11.6, 5.2 Hz, H-6), 3.96 (dd, 1H, J = 11.6, 4.1 Hz, H-6), 4.35 (ddd, 1H, J = 8.7, 1.6, 1.2 Hz, H-4), 5.18 (bs, 1H, H-1), 5.84 (d, 1H, J = 10.4 Hz, H-2 or H-3), 5.92 (d, 1H, J = 10.4 Hz, H-3 or H-2), 7.34 (m, 5H, H arom); C-NMR (CDCl₃) δ 63.3 (C-6), 64.3 (C-4), 77.5 (C-5), 79.5 (C-1), 127.4, 128.4, 128.7, 129.0 and 131.1 (C-2, C-3, C arom); Anal. calcd for C₁₂H₁₄O₃: C, 69.89; H, 6.84. Found: C, 69.81; H, 6.77.
(6-O-tert-Butyldimethylsilyl-2,3-dideoxy-β-D-erythro-hex-2-enopyranosyl)benzene (3b). Yield 82%, oil, R<sub>f</sub> 0.36 (petroleum ether-diethyl ether 2:1), [α]<sup>D</sup> <sub>20</sub> +120 (c 0.9, CHCl<sub>3</sub>); 1H-NMR (CDCl<sub>3</sub>) δ 0.10 (s, 6H, SiMe), 0.90 (s, 9H, CMe<sub>3</sub>), 3.40 (bs, 1H, OH), 3.65 (ddd, 1H, J = 8.1, 5.1, 4.4 Hz, H-5), 3.77 (dd, 1H, J = 9.5, 8.1 Hz, H-6), 4.03 (dd, 1H, J = 9.5, 5.1 Hz, H-6), 4.40 (dd, 1H, J = 4.4, 1.5 Hz, H-4), 5.15 (s, 1H, H-1), 5.83 (dd, 1H, J = 10.3, 1.5 Hz, H-3), 5.90 (d, 1H, J = 10.3 Hz, H-3), 7.21 (m, 5H, Harom); 13C-NMR (CDCl<sub>3</sub>) δ -5.5 (SiMe), -5.6 (SiMe), 18.2 (CMe<sub>3</sub>), 25.9 (CMe<sub>3</sub>), 66.5 (C-6), 67.9 (C-4), 77.2, and 77.3 (C-1, C-5), 127.3, 128.2, 128.3, 130.4 and 140.5 (C-2, C-3, C<sub>arom</sub>); Anal. calcd for C<sub>18</sub>H<sub>28</sub>O<sub>3</sub>Si: C, 67.46; H, 8.81. Found: C, 67.40; H, 8.75.

**General procedure for the epoxidation.**

A solution of the unsaturated carbohydrate (0.23 mmol) and m-CPBA (1.17 g, 0.69 mmol) in CHCl<sub>3</sub> (10 mL) was stirred at 50 °C for 24 h. The solution was neutralized with a saturated aqueous solution of NaHCO<sub>3</sub>, the organic phase was separated, and the aqueous phase was extracted with CHCl<sub>3</sub> (2x10 mL). The organic phases were dried over Na<sub>2</sub>SO<sub>4</sub>. After evaporation of the solvent under reduced pressure, the residue was purified by column chromatography on silica using the appropriate eluent.

(4,6-Di-O-tert-butyldimethylsilyl-2,3-anhydro-α-D-allopyranosyl)benzene (4a). Yield 9%, oil, R<sub>f</sub> 0.18 (petroleum ether-ethyl acetate-triethylamine 40:1:1), [α]<sup>D</sup> <sub>20</sub> +18 (c 0.9, CH<sub>2</sub>Cl<sub>2</sub>); 1H-NMR (CDCl<sub>3</sub>) δ 0.13 (s, 6H, SiMe), 0.17 (s, 3H, SiMe), 0.20 (s, 3H, SiMe), 0.94 (s, 9H, CMe<sub>3</sub>), 0.98 (s, 9H, CMe<sub>3</sub>), 3.54 (dd, 1H, J = 4.2, 1.7 Hz, H-3), 3.48-3.57 (m, 1H, H-5), 3.75 (dd, 1H, J = 11.2, 6.1 Hz, H-6), 3.95 (dd, 1H, J = 11.2, 1.9 Hz, H-6), 3.98 (dd, 1H, J = 4.2, 3.6 Hz, H-2), 4.02 (dd, 1H, J = 9.1, 1.7 Hz, H-4), 5.26 (bd, 1H, J = 3.6 Hz, H-1), 7.31-7.61 (m, 5H, Harom); 13C-NMR (CDCl<sub>3</sub>) δ -5.2 (SiMe), -5.0 (SiMe), -4.7 (SiMe), -4.0 (SiMe), 18.1 (CMe<sub>3</sub>), 18.6 (CMe<sub>3</sub>), 25.8 (CMe<sub>3</sub>), 26.1 (CMe<sub>3</sub>), 55.8 and 57.5 (C-2, C-3), 63.4 (C-6), 66.9 (C-4), 71.1 (C-5), 72.4 (C-1), 126.5, 127.4, 128.5 and 139.1 (C<sub>arom</sub>); Anal. calcd for C<sub>24</sub>H<sub>42</sub>O<sub>4</sub>Si<sub>2</sub>: C, 63.95; H, 9.39. Found: C, 63.61; H, 9.38.

(4,6-Di-O-tert-butyldimethylsilyl-2,3-anhydro-α-D-mannopyranosyl)benzene (5a). Yield 70%, oil, R<sub>f</sub> 0.20 (petroleum ether-ethyl acetate-triethylamine 40:1:1), [α]<sup>D</sup> <sub>20</sub> +21 (c 0.9, CH<sub>2</sub>Cl<sub>2</sub>); 1H-NMR (CDCl<sub>3</sub>) δ 0.06 (s, 3H, SiMe), 0.08 (s, 3H, SiMe), 0.15 (s, 3H, SiMe), 0.22 (s, 3H, SiMe), 0.92 (s, 9H, CMe<sub>3</sub>), 0.95 (s, 9H, CMe<sub>3</sub>), 3.27 (ddd, 1H, J = 9.0, 6.7, 2.2 Hz, H-5), 3.36 (d, 1H, J = 3.7 Hz, H-2 or H-3), 3.60 (d, 1H, J = 3.7 Hz, H-2 or H-3), 3.65 (dd, 1H, J = 11.1, 6.7 Hz, H-6), 3.77 (d, 1H, J = 9.0 Hz, H-4), 3.83 (dd, 1H, J = 11.1, 2.2 Hz, H-6), 5.27 (s, 1H, H-1), 7.31-7.61 (m, 5H, H<sub>arom</sub>); 13C-NMR (CDCl<sub>3</sub>) δ -5.2 (SiMe), -5.1 (SiMe), -4.8 (SiMe), -4.3 (SiMe), 18.0 (CMe<sub>3</sub>), 18.5 (CMe<sub>3</sub>), 25.8 (CMe<sub>3</sub>), 26.1 (CMe<sub>3</sub>), 55.8 and 57.5 (C-2, C-3), 63.4 (C-6), 66.9 (C-4), 71.1 (C-5), 72.4 (C-1), 126.5, 127.4, 128.5 and 139.1 (C<sub>arom</sub>); Anal. calcd for C<sub>24</sub>H<sub>42</sub>O<sub>4</sub>Si<sub>2</sub>: C, 63.95; H, 9.39. Found: C, 63.61; H, 9.38.

(2,3-Anhydro-α-D-allopyranosyl)benzene (4b). Yield 20%, oil, R<sub>f</sub> 0.24 (diethylether), [α]<sup>D</sup> <sub>20</sub> -6.0 (c 0.7, CHCl<sub>3</sub>); 1H-NMR (CDCl<sub>3</sub>) δ 2.84 (bs, 2H, OH), 3.31 (ddd, 1H, J = 8.8, 4.5, 3.4 Hz, H-5), 3.50 (dd, 1H, J = 4.3, 1.7 Hz, H-3), 3.63 (dd, 1H, J = 11.8, 4.5 Hz, H-6), 3.69 (dd, 1H, J = 11.8, 3.4 Hz, H-6), 3.79 (dd, 1H, J = 4.3, 3.6 Hz, H-2), 3.93 (dd, 1H, J = 8.8, 1.7 Hz, H-4), 5.06 (d, 1H, J = 3.6 Hz, H-1),
7.16-7.34 (m, 5H, H arom); 13C-NMR (CDCl3) δ 55.6 and 58.2 (C-2, C-3), 62.8 (C-6), 66.2 (C-4), 71.4 (C-5), 72.4 (C-1), 126.9, 128.2, 129.9 and 138.8 (C arom); Anal. calcd for C12H14O4: C, 64.85; H, 6.35. Found: C, 64.65; H, 6.46.

(6-O-tert-Butyldimethylsilyl-2,3-anhydro-α-D-allopyranosyl)benzene (6). Yield 60%, oil, Rf 0.40 (petroleum ether-ethyl acetate 2:1), [α]D20 -22 (c 1.2, CHCl3); 1H-NMR (CDCl3) δ 0.00 (s, 6H, SiMe), 0.81 (s, 9H, CMe3), 2.48 (bs, 1H, OH), 3.51 (dt, 1H, J = 7.1, 5.3 Hz, H-5), 3.66 (dd, 1H, J = 4.1, 2.3 Hz, H-3), 3.86 (d, 1H, J = 5.3 Hz, H-6), 3.93 (dd, 1H, J = 4.1, 3.4 Hz, H-2), 4.10 (dd, 1H, J = 7.1, 2.3 Hz, H-4), 5.21 (d, 1H, J = 3.4 Hz, H-1), 7.30-7.54 (m, 5H, H arom); 13C-NMR (CDCl3) δ 55.6 and 58.2 (C-2, C-3), 62.8 (C-6), 66.2 (C-4), 71.4 (C-5), 72.4 (C-1), 126.9, 128.2, 129.9 and 138.8 (C arom); Anal. calcd for C12H14O4Si: C, 64.25; H, 8.39. Found: C, 64.26; H, 8.59.

(6-O-tert-Butyldimethylsilyl-2,3-anhydro-α-D-mannopyranosyl)benzene (7). Yield 10%, oil, Rf 0.54 (petroleum ether-ethyl acetate 2:1), [α]D20 -21 (c 1.2, CHCl3); 1H-NMR (CDCl3) δ 0.00 (s, 3H, SiMe), 0.03 (s, 3H, SiMe), 0.83 (s, 9H, CMe3), 2.50 (bs, 1H, OH), 3.17 (ddd, 1H, J = 8.7, 5.3, 4.3 Hz, H-5), 3.44 (d, 1H, J = 3.6 Hz, H-2 or H-3), 3.55 (d, 1H, J = 3.6 Hz, H-2 or H-3), 3.58 (dd, 1H, J = 9.4, 4.3 Hz, H-6), 3.70 (dd, 1H, J = 9.4, 3.4 Hz, H-6), 3.87 (d, 1H, J = 8.7 Hz, H-4), 5.11 (s, 1H, H-1), 7.32-7.46 (m, 5H, H arom); 13C-NMR (CDCl3) δ -5.3 (SiMe), -5.2 (SiMe), 18.5 (CMe3), 26.2 (CMe3), 51.9 and 55.3 (C-2, C-3), 66.3 (C-6), 66.9, 69.4, and 72.9 (C-1, C-4, C-5), 128.6, 128.9, 129.1 and 136.8 (C arom).

(4,6-Di-O-tert-butyldimethylsilyl-2,3-anhydro-β-D-allopyranosyl)benzene (8a). Yield 32%, oil, Rf 0.22 (petroleum ether-ethyl acetate-triethylamine 50:1:1), [α]D20 +116 (c 1.2, CH2Cl2); 1H-NMR (CDCl3) δ 0.02 (s, 3H, SiMe), 0.03 (s, 3H, SiMe), 0.17 (s, 3H, SiMe), 0.19 (s, 3H, SiMe), 0.90 (s, 9H, CMe3), 0.95 (s, 9H, CMe3), 3.33-3.40 (m, 2H, H-2, H-3), 3.49 (ddd, 1H, J = 9.0, 2.9, 2.7 Hz, H-5), 3.77-3.88 (m, 2H, H arom); 13C-NMR (CDCl3) δ -5.2 (SiMe), -5.1 (SiMe), -4.7 (SiMe), -4.2 (SiMe), 18.1 (CMe3), 18.4 (CMe3), 25.8 (CMe3), 26.0 (CMe3), 55.4 and 60.5 (C-2, C-3), 62.3 (C-6), 65.9 (C-4), 74.7 (C-5), 76.0 (C-1), 126.6, 127.9, 128.4 and 139.7 (C arom); Anal. calcd for C24H42O4Si2: C, 63.95; H, 9.39. Found: C, 63.93; H, 9.34.

(4,6-Di-O-tert-butyldimethylsilyl-2,3-anhydro-β-D-mannopyranosyl)benzene (9a). Yield 20%, oil, Rf 0.18 (petroleum ether-ethyl acetate-triethylamine 50:1:1), [α]D20 +89 (c 1.1, CH2Cl2); 1H-NMR (CDCl3) δ 0.01 (s, 3H, SiMe), 0.04 (s, 3H, SiMe), 0.15 (s, 3H, SiMe), 0.19 (s, 3H, SiMe), 0.88 (s, 9H, CMe3), 0.94 (s, 9H, CMe3), 3.22 (ddd, 1H, J = 9.1, 5.1, 2.0 Hz, H-5), 3.33-3.40 (s, 2H, H-2, H-3), 3.72 (dd, 1H, J = 11.5, 5.1 Hz, H-6), 3.83 (dd, 1H, J = 11.5, 2.0 Hz, H-6), 3.90 (d, 1H, J = 9.1 Hz, H-4), 4.83 (s, 1H, H-1), 7.30-7.48 (m, 5H, H arom); 13C-NMR (CDCl3) δ -5.1 (2xSiMe), -4.9 (SiMe), -4.4 (SiMe), 18.0 (CMe3), 18.5 (CMe3), 25.8 (CMe3), 26.0 (CMe3), 53.4 and 57.4 (C-2, C-3), 62.6 (C-4), 63.1 (C-6), 75.7 (C-5), 80.5 (C-1), 128.0, 128.3, 128.4 and 138.7 (C arom); Anal. calcd for C24H42O4Si2: C, 63.95; H, 9.39. Found: C, 63.95; H, 9.38.
(2,3-Anhydro-β-D-allopyranosyl)benzene (8b). Yield 80%, oil, \( R_f \) 0.26 (diethyl ether); \(^1\)H-NMR (CDCl\(_3\)) \( \delta \) 2.80 (bs, 2H, OH), 3.46 (d, 1H, \( J = 4.4 \) Hz, H-2), 3.50-3.58 (m, 2H, H-3, H-5), 3.78 (dd, 1H, \( J = 11.7, 5.5 \) Hz, H-6), 3.90 (dd, 1H, \( J = 11.7, 3.7 \) Hz, H-6), 4.10 (dd, 1H, \( J = 9.2, 1.8 \) Hz, H-4), 4.89 (s, 1H, H-1), 7.25-7.50 (m, 5H, Harm); \(^13\)C-NMR (CDCl\(_3\)) \( \delta \) 54.9 and 60.3 (C-2, C-3), 62.4 (C-6), 65.9 (C-4), 74.0 (C-5), 76.3 (C-1), 126.7, 128.4, 128.7 and 138.7 (Carom); Anal. calcd for C\(_{12}\)H\(_{14}\)O\(_4\): C, 64.85; H, 6.35. Found: C, 64.94; H, 6.28.

(6-O-tert-Butyldimethylsilyl-2,3-anhydro-β-D-allopyranosyl)benzene (10). Yield 50%, oil, \( R_f \) 0.32 (petroleum ether-diethyl ether 2:1), \([\alpha]_D^{20} +100 \) (c 0.9, CHCl\(_3\)); \(^1\)H-NMR (CDCl\(_3\)) \( \delta \) 0.10 (s, 6H, SiMe), 0.93 (s, 9H, CMe\(_3\)), 3.32 (d, 1H, \( J = 3.9 \) Hz, OH), 3.44 (d, 1H, \( J = 4.3 \) Hz, H-2), 3.57 (dd, 1H, \( J = 4.3, 2.2 \) Hz, H-3), 3.60 (ddd, 1H, \( J = 9.0, 6.9, 4.9 \) Hz, H-5), 3.79 (dd, 1H, \( J = 10.1, 6.9 \) Hz, H-6), 3.96 (dd, 1H, \( J = 10.1, 4.9 \) Hz, H-6), 4.19 (ddd, 1H, \( J = 9.0, 3.9, 2.2 \) Hz, H-4), 4.91 (s, 1H, H-1), 7.38 (m, 5H, Harm); \(^13\)C-NMR (CDCl\(_3\)) \( \delta \) -1.3 (2xSiMe), 18.7 (CMe\(_3\)), 26.3 (CMe\(_3\)), 55.2 and 57.7 (C-2, C-3), 65.0 (C-6), 67.6 (C-4), 71.4 (C-5), 72.1 (C-1), 127.0, 128.1, 128.8 and 138.8 (Carom); Anal. calcd for C\(_{18}\)H\(_{28}\)O\(_4\)Si: C, 64.25; H, 8.39. Found: C, 64.28; H, 8.79.

General procedure for the bis-hydroxylation.

A solution of the unsaturated carbohydrate (1 mmol), \( N \)-methylmorpholine oxide (470 mg, 4 mmol), and OsO\(_4\) (5 mg, 0.02 mmol, 2%) in acetone/water (4 mL/1 mL) was stirred at rt until all the starting carbohydrate has disappeared as shown by TLC. Na\(_2\)SO\(_3\) (500 mg) was then added, and the solution was stirred at rt for 0.5 h. After addition of brine (10 mL), the mixture was extracted with ethyl acetate (3x10 mL). Evaporation of the solvent under reduced pressure gave a residue that was purified by column chromatography on silica using the corresponding eluent for the silylated products. When starting from dihydroxy compounds 2a and 2b, the crude mixture was directly acetylated using a standard procedure, and the tetraacetates were purified by chromatography.

(4,6-Di-O-tert-butyldimethylsilyl-α-D-mannopyranosyl)benzene (11). Yield 70%, oil, \( R_f \) 0.40 (petroleum ether-diethyl acetate 4:1), \([\alpha]_D^{20} +17 \) (c 1.0, CHCl\(_3\)); \(^1\)H-NMR (CDCl\(_3\)) \( \delta \) 0.04 (s, 3H, SiMe), 0.06 (s, 3H, SiMe), 0.08 (s, 3H, SiMe), 0.10 (s, 3H, SiMe), 0.85 (s, 9H, CMe\(_3\)), 2.25 (bs, 1H, OH), 2.25 (d, 1H, \( J = 7.4 \) Hz, OH), 3.60 (ddd, 1H, \( J = 5.9, 5.0, 3.7 \) Hz, H-5), 3.74 (ddd, 1H, \( J = 7.4, 6.6, 2.9 \) Hz, H-3), 3.80 (dd, 1H, \( J = 11.0, 5.0 \) Hz, H-6), 3.96 (dd, 1H, \( J = 6.6, 5.9 \) Hz, H-4), 4.03 (dd, 1H, \( J = 11.0, 3.7 \) Hz, H-6), 4.27 (bddd, 1H, \( J = 5.9, 2.9 \) Hz, H-2), 4.90 (d, 1H, \( J = 5.9 \) Hz, H-1), 7.40 (m, 5H, Harm); \(^13\)C-NMR (CDCl\(_3\)) \( \delta \) -5.0 (SiMe), -4.9 (SiMe), -4.5 (SiMe), -4.0 (SiMe), 18.5 (CMe\(_3\)), 18.7 (CMe\(_3\)), 26.2 (2xCMe\(_3\)), 64.4 (C-6), 70.8, 71.2 and 72.2 (C-1, C-4, C-5), 77.6, and 77.7 (C-2, C-3), 127.3, 128.3, 129.0 and 138.7 (Carom); Anal. calcd for C\(_{24}\)H\(_{44}\)O\(_5\)Si\(_2\): C, 61.50; H, 8.97. Found: C, 61.50; H, 8.79.

(2,3,4,6-Tetra-O-acetyl-α-D-mannopyranosyl)benzene (12). Yield 43%, white solid, m.p. 136 °C, \( R_f \) 0.60 (petroleum ether-diethyl acetate 1:1), \([\alpha]_D^{20} +46 \) (c 1.0, CHCl\(_3\)); \(^1\)H-NMR (CDCl\(_3\)) \( \delta \) 2.01 (s, 3H, Me), 2.06 (s, 3H, Me), 2.13 (s, 3H, Me), 2.17 (s, 3H, Me), 3.77 (ddd, 1H, \( J = 8.8, 6.1, 2.6 \) Hz, H-5), 4.14 (dd, 1H, \( J = 12.0, 6.1 \) Hz, H-6), 4.38 (dd, 1H, \( J = 12.0, 2.6 \) Hz, H-6), 5.12 (d, 1H, \( J = 2.9 \) Hz, H-
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1), 5.17 (dd, 1H, J = 9.1, 3.1 Hz, H-3), 5.35 (dd, 1H, J = 9.1, 8.8 Hz, H-4), 6.20 (dd, 1H, J = 3.1, 2.9 Hz, H-2), 7.35-7.55 (m, 5H, H_arom); $^{13}$C-NMR (CDCl$_3$) $\delta$ 21.1 (2xMe), 21.2 (Me), 21.4 (Me), 62.8 (C-6), 67.2 (C-4), 69.6 (C-2), 70.1 (C-3), 71.5 (C-5), 76.2 (C-1), 126.8, 128.9, 129.5 and 135.6 (C_arom), 170.0 (CO), 170.3 (CO), 170.7 (CO), 171.1 (CO). All the data are in agreement with the literature [21].

(4,6-Di-O-tert-butylidimethylsilyl-β-D-mannopyranosyl)benzene (13) (as a mixture with 14). Yield 56%, oil, $R_f$ 0.45 (petroleum ether-ethyl acetate 4:1); $^1$H-NMR (CDCl$_3$) $\delta$ 0.10 (s, 3H, SiMe), 0.14 (s, 3H, SiMe), 0.15 (s, 3H, SiMe), 0.19 (s, 3H, SiMe), 0.93 (s, 9H, CMe$_3$), 0.94 (s, 9H, CMe$_3$), 1.70 (bs, 1H, OH), 2.40 (bs, 1H, OH), 3.31 (dd, 1H, J = 9.2, 5.5, 2.9 Hz, H-5), 3.66 (dd, 1H, J = 8.8, 3.3 Hz, H-3), 3.88 (dd, 1H, J = 9.2, 8.8 Hz, H-4), 3.93 (m, 2H, H-6), 4.06 (d, 1H, J = 3.3 Hz, H-2), 4.60 (s, 1H, H-1), 7.28 (m, 5H, H_arom); $^{13}$C-NMR (CDCl$_3$) $\delta$ -5.1 (CH$_3$), -5.0 (CH$_3$), -4.8 (CH$_3$), -4.0 (CH$_3$), 18.4 (CMe$_3$), 18.5 (CMe$_3$), 26.0 (CMe$_3$), 26.1 (CMe$_3$), 62.3 (C-6), 69.1, 73.1, and 76.3 (C-1, C-4, C-5), 79.4 and 81.5 (C-2, C-3), 126.0, 127.7, 128.4 and 138.0 (C_arom); Anal. calcd for C$_{24}$H$_{44}$O$_5$Si$_2$ (mixture 13 + 14): C, 61.50; H, 9.47. Found: C, 61.86; H, 9.31.

(4,6-Di-O-tert-butylidimethylsilyl-β-D-allopyranosyl)benzene (14) (as a mixture with 13). Yield 14%, oil, $R_f$ 0.45 (petroleum ether-ethyl acetate 4:1); $^1$H-NMR (CDCl$_3$) $\delta$ 0.00 (s, 3H, SiMe), 0.03 (s, 3H, SiMe), 0.07 (s, 3H, SiMe), 0.16 (s, 3H, SiMe), 0.90 (s, 9H, CMe$_3$), 0.93 (s, 9H, CMe$_3$), 1.50 (bs, 1H, OH), 2.60 (bs, 1H, OH), 3.50 (dd, 1H, J = 9.9, 2.9 Hz, H-2), 3.61 (dd, 1H, J = 9.5, 2.9, 1.5 Hz, H-5), 3.80 (dd, 1H, J = 11.4, 2.9 Hz, H-6), 3.87 (dd, 1H, J = 11.4, 1.5 Hz, H-6), 4.01 (dd, 1H, J = 9.5, 2.9 Hz, H-4), 4.20 (dd, 1H, J = 2.9, 2.9 Hz, H-3), 4.50 (d, 1H, J = 9.9 Hz, H-1), 7.40 (m, 5H, H_arom); $^{13}$C-NMR (CDCl$_3$) $\delta$ -5.2 (CH$_3$), -5.0 (CH$_3$), -4.8 (CH$_3$), -4.5 (CH$_3$), 18.0 (CMe$_3$), 18.2 (CMe$_3$), 25.8 (CMe$_3$), 26.0 (CMe$_3$), 62.2 (C-6), 67.8, 71.5 and 73.1 (C-1, C-4, C-5), 76.1 and 77.6 (C-2, C-3), 127.4, 128.0, 128.2 and 137.0 (C_arom).

(2,3,4,6-Tetra-O-acetyl-β-D-mannopyranosyl)benzene (15) (as a mixture with 16). Yield 19%, oil, $R_f$ 0.30 (petroleum ether-ethyl acetate 1:1); $^1$H-NMR (CDCl$_3$) $\delta$ 2.00 (s, 3H, Me), 2.03 (s, 3H, Me), 2.11 (s, 3H, Me), 2.20 (s, 3H, Me), 2.23 (s, 3H, Me), 2.20 (s, 3H, Me), 2.23 (s, 3H, Me), 3.83 (dd, 1H, J = 9.5, 5.9, 2.6 Hz, H-5), 4.21-4.30 (s, 3H, H-6), 4.35 (dd, 1H, J = 12.5, 5.9 Hz, H-6), 4.79 (d, 1H, J = 1.1 Hz, H-1), 5.25 (dd, 1H, J = 10.2, 3.3 Hz, H-3), 5.33 (dd, 1H, J = 10.2, 9.5 Hz, H-4), 5.55 (dd, 1H, J = 3.3, 1.1 Hz, H-2), 7.30 (m, 5H, H_arom); $^{13}$C-NMR (CDCl$_3$) $\delta$ 20.2 (Me), 20.3 (Me), 20.8 (Me), 21.0 (Me), 60.4 (C-6), 66.6 (C-4), 73.1 (C-2), 77.3 (C-3), 77.4 (C-5), 81.8 (C-1), 127.2, 128.7, 129.2, and 136.3 (C_arom), 168.7 (CO), 168.9 (CO), 169.2 (CO), 170.6 (CO). All data are in agreement with the literature [21].

(2,3,4,6-Tetra-O-acetyl-β-D-allopyranosyl)benzene (16) (as a mixture with 15). Yield 56%, oil, $R_f$ 0.30 (petroleum ether-ethyl acetate 1:1); $^1$H-NMR (CDCl$_3$) $\delta$ 1.80 (s, 3H, Me), 2.03 (s, 3H, Me), 2.11 (s, 3H, Me), 2.20 (s, 3H, Me), 2.23 (s, 3H, Me), 4.15-4.27 (m, 3H, H-5, H-6), 4.71 (d, 1H, J = 10.3 Hz, H-1), 5.03 (dd, 1H, J = 10.3, 2.9 Hz, H-2), 5.12 (dd, 1H, J = 9.9, 2.6 Hz, H-4), 5.73 (dd, 1H, J = 2.9, 2.6 Hz, H-3), 7.35-7.43 (m, 5H, H_arom); $^{13}$C-NMR (CDCl$_3$) $\delta$ 20.4 (Me), 20.6 (Me), 20.8 (Me), 21.4 (Me), 62.8 (C-6), 66.6 (C-4), 68.5 (C-2), 70.6 (C-3), 71.4 (C-5), 76.2 (C-1), 126.9, 127.2, 128.4 and 136.9 (C_arom), 168.8 (CO), 169.2 (CO), 170.0 (CO), 170.8 (CO).
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*Sample Availability:* Available from the authors

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