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# Synthesis of Furanylalkyl Hex- and Pentenopyranosid-4-uloses

**Soro Yaya,[a]* Siaka Sorho,[a] Louis Cottier[b] and Gérard Descotes[b]**

[a]*Laboratoire des Procédés Industriels de Synthèse et d'Environement, Institut National Polytechnique Félix Houphouët-Boigny, BP 991 Yamoussoukro, Côte d'Ivoire.*
[b]*Laboratoire de Chimie Organique 2, UMR CNRS 5622, Université Claude Bernard Lyon 1, 43 Boulevard du 11 Novembre 1918, 69622-Villeurbanne, France.*

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**ABSTRACT**

**A few novel furanylalkyl hex- and pentenopyranones have been synthesized from the corresponding hexenopyranosides or hydroxymethylfurfural. In the hexose series, the reactions proceeded through monosilylation of the primary alcohol followed by oxidation of secondary alcohols. The pentenopyranones have been obtained by glycosidation of hydroxymethylfurfural oxidation product.**

**KEYWORDS**

**Hydroxymethylfurfural (HMF), silylation, oxidation, pyranone.**

## 1. Introduction

The chemical synthesis of the carbohydrate domains of saccharides and glycoconjugates is now recognized as a major frontier for organic chemistry.[1,2] Bioactive carbohydrates play a vital role in several life processes. The fundamental structural unit, the *o*-glycosidic linkage, that is present in such compounds is very labile to metabolic processes.[3]

Glycopyranosid-4-uloses, derived from glycals or hydroxymethylfurfural, are useful intermediates in many bioactive molecules such as anthracycline antibiotics[4] with proven clinical effectiveness against leukemias, lymphomas, breast carcinomas, and sarcomas.[5] They are also synthetic intermediates of sclerophylin A,[6] a unique member of the cladiellin family which manifests strong cytotoxicity against the L1210 cell line.[7]

Pyranones **1–3** (Fig. 1) seems to be the key intermediates for synthesis of iso-deoxynucleosides of type I (**4**), a rare class of nucleosides showing significant and selective anti HIV activity[8,9] as well as appearing as upstream precursors of interesting related nucleosides.[10]

It has also been shown that carbohydrate molecules possessing the enone functionality are the preferred precursors for the synthesis of branched-chain and other rare sugars.[11]

As part of the development of new unsaturated pyran-3-ones, we report the synthesis of a number of new furanylalkyl hex- and pentenopyranosid-4-uloses.

## 2. Results and Discussion

In the hexose series, the synthetic route to the furanylalkyl hexenopyranosid-4-uloses is described in Scheme 1. The starting furanylalkyl hexenopyranosides **5a–d**, as we recently reported,[12,13] were prepared by allowing 3,4,6-tri-*O*-acetyl-1,5-anhydro-2-deoxy-D-*arabino*-hex-1-enitol (tri-*O*-acetyl-D-glucal) to react with an appropriate furanyl alcohol in the presence of a catalyst *via* Ferrier rearrangement.

The acetylated compounds **5a–d** were deprotected using a mixture of methanol-water-triethylamine[11] with excellent yields (75–92%) to form **6a–d**. The $\alpha$ and $\beta$ anomers were separated by chromatography on silica gel and characterized by $^1$H and $^{13}$C NMR.

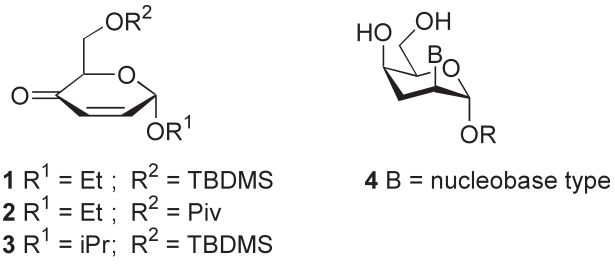


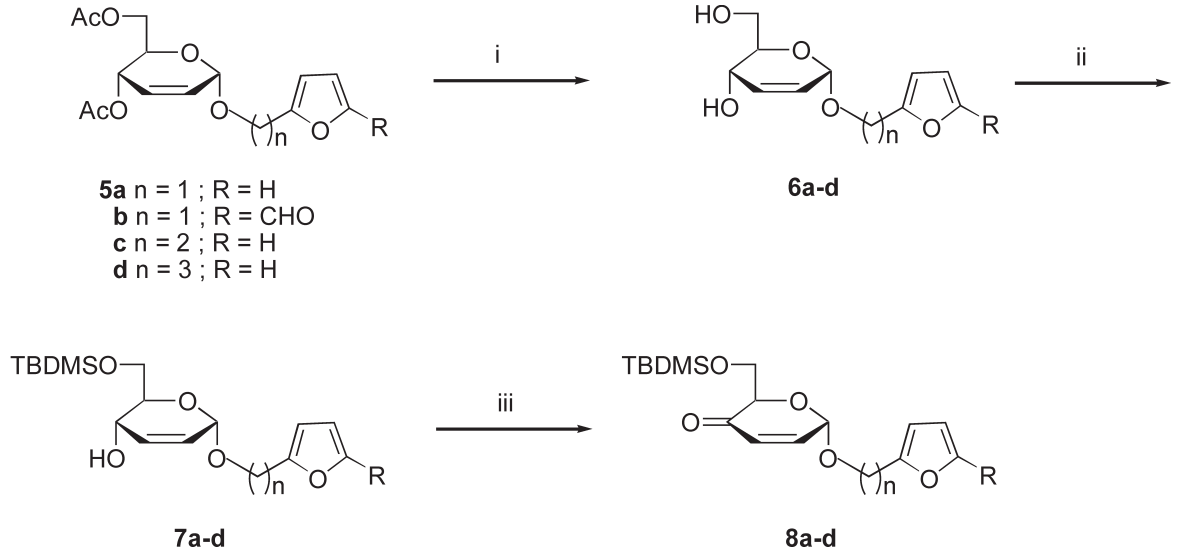

**Figure 1**

The free primary hydroxyl group of **6b–d** was then selectively protected as a *tert*-butyl dimethyl silyl ether under the silylation conditions' described by Corey and Venkateswarlu[14] to give monosilylated compounds **7b–d** with yields varying from 70 to 90%. The reaction was carried out under kinetic control to avoid *bis*-silylation. The products **7b–d** were characterized by $^1$H and $^{13}$C NMR. In the proton spectrum, the monosilylation of the primary alcohol was justified by the disappearance of the triplet at 2.36 ppm corresponding to the hydroxyl at position 6 (sugar nomenclature) in compounds **6a–d**. The secondary alcohol was detected by a doublet at 2.62 ppm present in the spectra of compounds **6a–d** and monosilylated compounds **7b–d**.

Finally, oxidation with pyridinium chlorochromate (PCC) of **7b–d** led to **8b–d** in 68 to 86% yields. The structure of the pyranones was confirmed by $^1$H NMR which showed disappearance of the doublet due to the hydroxyl at position 4 and the appearance in the $^{13}$C NMR spectra of a signal with chemical shift 194 ppm, characteristic of the carbonyl carbon of $\alpha$, $\beta$-unsaturated ketones.

In the pentose series, pyranones **11a–c** could have been prepared starting from the corresponding furanylalkyl pentenopyranosides[12] previously prepared by a similar process to the hexose series. However, we considered a direct glycosidation with 6-acetoxy-2H-pyran-3(6H)-one **10** (Scheme 2).

* To whom correspondence should be addressed: E-mail: soro_y@yahoo.fr




**Scheme 1**

(**i**) MeOH-$H_2O$-$NEt_3$, r.t., 4–6 h; (**ii**) TBDMSCI, DMF, Imidazole, 0° C to r.t., 24 h.; (**iii**) PCC. $CH_2Cl_2$, r.t., 6–24 h.

The starting compound **10** was synthesized from furfuryl alcohol **9a** using the conditions of Hoffmann *et al.*[15] The resulting compound was unstable in basic aqueous solution at room temperature and was stabilized as the acetate derivative using acetic anhydride and montmorillonite K-10, an acid catalyst known for acetylation of alcohols in carbohydrate chemistry.[16]

Reactions of **10** with various furylcarbinols **9a–c**, in the presence of a catalytic amount of ceric (IV) ammonium nitrate (CAN) in a direct glycosidation reaction, afforded **11a–c**. These reactions proceeded in yields from 64 to 30%, decreasing with the length of the alkyl chain. Racemic mixtures were obtained and their structures were established by $^1$H and $^{13}$C NMR.

In the structures of hex- and pentenopyranosid-4-uloses **8** and **11**, we note diene and dienophilic fragments. Thus, these compounds may be interesting for synthesis of tricyclic compounds via an intramolecular Diels-Alder cycloaddition. In fact Feringa *et al.*[17] have particularly shown that for pyranones **1–3**, the 6-alkoxysubstituant exerts complete stereocontrol in $\pi$ face selective additions of butadiene (Diels-Alder) or nitroethane (Michael) to this enone. Also of interest in this area, Horton's[18] and Herradon's[19] groups have discussed the total facial stereoselectivity induced by $\gamma$-substituents present on neighbouring unsaturated lactones.

## 3. Conclusion

Furanylalkyl hexenopyranosides and 6-acetoxy-2H-pyran-3(6H)-one were transformed into novel furanylalkyl hex- and pentenopyranosid-4-uloses with good yields. Their molecular structures were established using NMR methods. The prepared compounds may be of use in the synthesis of tricyclic compounds *via* intramolecular Diels-Alder cycloaddition.

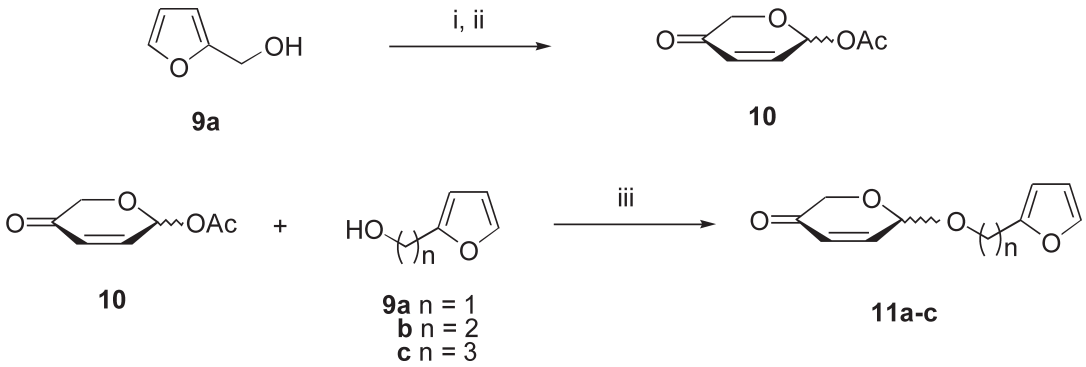
## 4. Experimental

The 200 or 300 MHz $^1$H NMR and 50 MHz $^{13}$C NMR spectra were recorded with a Bruker AC spectrometer in $CDCl_3$ with TMS as an internal standard. Elemental analysis were performed in the CNRS Analysis Department of Solaize (France). Optical rotations were measured with a Perkin-Elmer 241 polarimeter in Villeurbanne (France). Thin-layer chromatography (TLC) was carried out on plates coated with silica gel 60 (40–63 $\mu$m) followed by spraying the plates with diluted sulfuric acid (25%). Mass spectra were recorded with a Finnigan Mat 95 XL spectrometer in Villeurbanne (France).

### 4. 1. General Procedure for the Preparation of Diol 6a–d

A solution of **5** (1.38 mmol) in a mixture (6.7 mL) of methanol-water-triethylamine (5-4-1) was stirred at room temperature for 3 hours. Thin-layer chromatography (3:2 $CH_2Cl_2$-AcOEt) showed the disappearance of the starting material **5**. After filtration on celite and evaporation, the crude product was purified by silica gel column (1:2 petroleum ether-ethyl acetate) to give pure $\alpha$-anomers **6**.

From the reaction of **5a** was obtained *1′-(furan-2″-yl)methyl 2,3-dideoxy-α-D-erythro-hex-2-enopyranoside* **6a** (75%) as a light




**Scheme 2**

(**i**) mCPBA, $CH_2Cl_2$, 1 h. ; (**ii**) Montmorillonite K-10, $Ac_2O$, 0°C to r.t., 15 h ; (**iii**) CAN, $Ch_3CN$, r.t., 5–24 h.

oil; $[\alpha]_D^{20}$ +73.5 (c 1, $CHCl_3$); $R_f$ 0.2 (1:2 petroleum ether-ethyl acetate); $\delta_H$ (200 MHz, $CDCl_3$) 2.75 (1H, s, br, 6-(OH)), 3.25 (1H, s, br, 4-(OH)), 3.76 (1H, m, 5-H), 3.82 (2H, s, br, 6a-H and 6b-H), 4.17 (1H, d, br, $J_{4,5}$ 7.5 Hz, 4-H), 4.62 (1H, d, $J_{1'b,1'a}$ 13.6 Hz, 1'b-H), 4.68 (1H, d, $J_{1'a,1'b}$ 13.6 Hz, 1'a-H), 5.08 (1H, s, br, 1-H), 5.71 (1H, dt, $J_{3,1}$ and $J_{3,4}$ 2.4 Hz and $J_{3,2}$ 10.0 Hz, 3-H), 5.96 (1H, d, br, $J_{2,3}$ 10.0 Hz, 2-H), 6.35 (2H, s, br, 3"-H and 4"-H), 7.40 (1H, d, $J_{5",4"}$ 1.4 Hz, 5"-H); $\delta_C$ (50 MHz, $CDCl_3$) 61.9 (C-6), 62.5 (C-1'), 64.0 (C-4), 71.7 (C-5), 93.4 (C-1), 109.7 (C-3"), 110.5 (C-4"), 125.9 (C-3), 133.9 (C-2), 143.1 (C-5"), 151.3 (C-2"); MS (FAB) m/z 227 ($[M+H]^+$); (HRMS Found: 227.0922 ($[M+H]^+$). Calc. for $C_{11}H_{14}O_5$ (226): 227.0919 ($[M+H]^+$)).

From the reaction of **5b** was obtained *1'-(furfuraldehyde-5")methyl 2,3-dideoxy-α-D-erythro-hex-2-enopyranoside* **6b** (90%) as a light oil; $[\alpha]_D^{20}$ +49.6 (c 2, $CHCl_3$); $R_f$ 0.15 (1:2 petroleum ether-ethyl acetate); $\delta_H$ (200 MHz, $CDCl_3$) 2.95 (1H, s, br, 6-(OH)), 3.50 (1H, s, br, 4-(OH)), 3.82 (3H, m, 4-H, 6a-H and 6b-H), 4.22 (1H, m, 5-H), 4.63 (1H, d, $J_{1'b,1'a}$ 13.4 Hz, 1'b-H), 4.77 (1H, d, $J_{1'a,1'b}$ 13.4 Hz, 1'a-H), 5.08 (1H, s, br, 1-H), 5.73 (1H, dd, $J_{3,4}$ 2.4 Hz, $J_{3,2}$ 10.2 Hz, 3-H), 5.97 (1H, d, br, $J_{2,3}$ 10.2 Hz, 2-H), 6.54 (1H, d, $J_{3",4"}$ 3.5 Hz, 3"-H), 7.19 (1H, d, $J_{4",3"}$ 3.5 Hz, 4"-H), 9.59 (1H, s, CHO); $\delta_C$ (50 MHz, $CDCl_3$) 61.9 (C-6), 62.4 (C-1'), 63.9 (C-4), 71.2 (C-5), 94.7 (C-1), 111.6 (C-3"), 123.3 (C-4"), 126.4 (C-3), 130.9 (C-2), 152.3 (C-5"), 158.2 (C-2"), 177.8 (CHO); MS (FAB) m/z 255 ($[M+H]^+$); (HRMS Found: 255.0864 ($[M+H]^+$). Calc. for $C_{12}H_{14}O_6$ (M = 254): 255.0868 ($[M+H]^+$)).

From the reaction of **5c** was obtained *2'-(furan-2"-yl)ethyl 2,3-dideoxy-α-D-erythro-hex-2-enopyranoside* **6c** (92%) as a light oil; $[\alpha]_D^{20}$ +58 (c 1, $CHCl_3$); $R_f$ 0.34 (1:2 petroleum ether-ethyl acetate); $\delta_H$ (200 MHz, $CDCl_3$) 2.50 (2H, s, br, 4-(OH) and 6-(OH)), 2.95 (2H, t, $J_{2',1'a}$ and $J_{2',1'b}$ 6.8 Hz, 2'a-H and 2'b-H), 3.75 (1H, dd, $J_{1'b,2'}$ 6.8 Hz, $J_{1'b,1'a}$ 9.9 Hz, 1'b-H), 3.82 (2H, m, 4-H and 6b-H), 3.99 (1H, dd, $J_{1'a,2'}$ 6.9 Hz, $J_{1'a,1'b}$ 9.9 Hz, 1'a-H), 4.10 (1H, t, $J_{6a,5}$ and $J_{6a,\ 6b}$ 7.2 Hz, 6a-H), 4.22 (1H, m, 5-H), 4.97 (1H, s, br, 1-H), 5.72 (1H, dt, $J_{3,1}$ and $J_{3,4}$ 2.4 Hz, $J_{3,2}$ 10.2 Hz, 3-H), 5.95 (1H, d, br, $J_{2,3}$ 10.2 Hz, 2-H), 6.10 (1H, dd, $J_{3",5"}$ 0.8 Hz, $J_{3",4"}$ 3.1 Hz, 3"-H), 6.30 (1H, dd, $J_{4",5"}$ 1.8 Hz, $J_{4",3"}$ 3.1 Hz, 4"-H), 7.31 (1H, dd, $J_{5",3"}$ 0.8 Hz, $J_{5",4"}$ 1.8 Hz, 5"-H); $\delta_C$ (50 MHz, $CDCl_3$) 28.9 (C-2'), 62.3 (C-1'), 63.7 (C-4), 66.7 (C-6), 71.6 (C-5), 94.5 (C-1), 106.1 (C-3"), 110.3 (C-4"), 125.9 (C-3), 133.8 (C-2), 141.2 (C-5"), 152.8 (C-2"); MS (FAB) m/z 241 ($[M+H]^+$); (HRMS Found: 241.1077 ($[M+H]^+$). Calc. for $C_{12}H_{16}O_5$ (M = 240): 241.1076 ($[M+H]^+$)).

From the reaction of **5d** was obtained *3'-(furan-2"-yl)propyl 2,3-dideoxy-α-D-erythro-hex-2-enopyranoside* **6d** (92%) as a colourless oil; $[\alpha]_D^{20}$ +40 (c 1, $CHCl_3$); $R_f$ 0.34 (3:2 dichloromethane-ethyl acetate); $\delta_H$ (200 MHz, $CDCl_3$) 1.95 (2H, m, 2'a-H and 2'b-H), 2.36 (1H, t, $J_{(OH)6,6a}$ and $J_{(OH)6,6b}$ 5.9 Hz, 6-(OH)), 2.62 (1H, d, $J_{(OH)4,4}$ 7.5 Hz, 4-(OH)), 2.73 (2H, t, $J_{3'a,2'}$ and $J_{3'b,2'}$ 7.4 Hz, 3'a-H and 3'b-H), 3.52 (1H, ddd, $J_{1'b,2'a}$ 3.4 Hz, $J_{1'b,2'b}$ 9.6 Hz, $J_{1'b,1'a}$ 12.6 Hz, 1'b-H), 3.72 (1H, m, 1'a-H), 3.82 (3H, m, 4-H, 6a-H and 6b-H), 4.22 (1H, m, 5-H), 4.96 (1H, d, $J_{1,2}$ 0.96 Hz, 1-H), 5.75 (1H, ddd, $J_{3,4}$ 2.2 Hz, $J_{3,1}$ 2.6 Hz, $J_{3,2}$ 10.2 Hz, 3-H), 5.97 (1H, d, $J_{2,3}$ 10.2 Hz, 2-H), 6.00 (1H, dd, $J_{3",5"}$ 0.8 Hz, $J_{3",4"}$ 3.1 Hz, 3"-H), 6.28 (1H, dd, $J_{4",5"}$ 1.9 Hz, $J_{4",3"}$ 3.1 Hz, 4"-H), 7.31 (1H, dd, $J_{5",3"}$ 0.8 Hz, $J_{5",4"}$ 1.9 Hz, 5"-H); $\delta_C$ (50 MHz, $CDCl_3$) 24.6 (C-2'), 28.2 (C-3'), 62.4 (C-1'), 63.8 (C-6), 67.8 (C-4), 71.6 (C-5), 94.5 (C-1), 105.1 (C-3"), 110.2 (C-4"), 126.1 (C-3), 133.6 (C-2), 141.0 (C-5"), 155.5 (C-2"); (Found: C, 61.14; H, 7.15%. Calc. for $C_{13}H_{18}O_5$ (M = 254.25): C, 61.40; H, 7.14%).

### 4. 2. General Procedure for the Preparation of Monosilylated Compounds 7

Compound **6** (0.79 mmol) was dissolved in DMF (0.4 mL) and then imidazole (118 mg, 1.74 mmol) and TBDMSCl (130 mg, 0.87 mmol) were added at 0°C. The mixture was stirred for 24 hours at room temperature. Thin-layer chromatography (3:2 $CH_2Cl_2$-AcOEt) showed the disappearance of compound **6**. The crude product **7** was extracted with petroleum ether, washed with water, then brine and the organic layer dried on $MgSO_4$. After filtration, the organic layer was concentrated and the crude product purified by silica gel column (5:1 petroleum ether-ethyl acetate) to give pure α-anomers **7**.

From the reaction of **6b** was obtained *1'-(furfuraldehyde-5")methyl 6-O-(tertiarybutyldimethylsilyl)-2,3-dideoxy-α-D-erythro-hex-2-enopyranoside* **7b** (70%) as a yellow oil; $[\alpha]_D^{20}$ -54 (c 1, $CHCl_3$); $R_f$ 0.28 (1:1 petroleum ether-ethyl acetate); $\delta_H$ (200 MHz, $CDCl_3$) 0.11 (6H, s, $(CH_3)_2Si$), 0.91 (9H, s, $(CH_3)_3CSi$), 2.95 (1H, s, br, OH), 3.71 (1H, m, 4-H), 3.75 (1H, dd, $J_{6b,5}$ 5.5 Hz, $J_{6b,6a}$ 9.6 Hz, 6b-H), 3.88 (1H, dd, $J_{6a,5}$ 5.0 Hz, $J_{6a,6b}$ 9.6 Hz, 6a-H), 4.19 (1H, m, 5-H), 4.63 (1H, d, $J_{1'b,1'a}$ 13.4 Hz, 1'b-H), 4.78 (1H, d, $J_{1'a,1'b}$ 13.4 Hz, 1'a-H), 5.30 (1H, s, br, 1-H), 5.75 (1H, ddd, $J_{3,4}$ 2.1 Hz, $J_{3,1}$ 2.5 Hz, $J_{3,2}$ 10.2 Hz, 3-H), 6.00 (1H, d, $J_{2,3}$ 10.2 Hz, 2-H), 6.54 (1H, d, $J_{3",4"}$ 3.5 Hz, 3"-H), 7.21 (1H, d, $J_{4",3"}$ 3.5 Hz, 4"-H), 9.62 (1H, s, CHO); $\delta_C$ (50 MHz, $CDCl_3$) -5.4 ($(\mathbf{C}H_3)Si(\mathbf{C}H_3)$), 18.3 ($Me_3\mathbf{C}Si$), 25.9 ($(\mathbf{C}H_3)_3CSi$), 61.8 (C-6), 64.6 (C-1'), 65.8 (C-4), 71.1 (C-5), 93.8 (C-1), 111.5 (C-3"), 122.1 (C-4"), 125.1 (C-3), 133.8 (C-2), 152.7 (C-5"), 158.2 (C-2"), 177.8 (CHO); MS (FAB) m/z 369 ($[M+H]^+$); (HRMS Found: 369.1733 ($[M+H]^+$). Calc. for $C_{18}H_{28}O_6Si$ (M = 368): 369.1733 ($[M+H]^+$)).

From the reaction of **6c** was obtained *2'-(furan-2"-yl)ethyl 6-O-(tertiarybutyldimethylsilyl)-2,3-dideoxy-α-D-erythro-hex-2-enopyranoside* **7c** (90%) as a yellow oil; $[\alpha]_D^{20}$ +22 (c 1, $CHCl_3$); $R_f$ 0.15 (5:1 petroleum ether-ethyl acetate); $\delta_H$ (200 MHz, $CDCl_3$) 0.12 (6H, s, $(CH_3)_2Si$), 0.92 (9H, s, $(CH_3)_3CSi$), 2.85 (1H, d, $J_{(OH),4}$ 3.8 Hz, OH), 2.96 (2H, t, $J_{2',1'a}$ and $J_{2',1'b}$ 6.9 Hz, 2'a-H and 2'b-H), 3.70 (2H, dd, $J_{1'a,2'}$ and $J_{1'b,2'}$ 6.9 Hz, $J_{1'a,1'b}$ 10.6 Hz, 1'a-H and 1'b-H), 3.81 (1H, m, 4-H), 3.90 (1H, dd, $J_{6b,5}$ 4.6 Hz, $J_{6b,6a}$ 9.6 Hz, 6b-H), 4.00 (1H, dd, $J_{6a,5}$ 2.6 Hz, $J_{6a,6b}$ 9.6 Hz, 6a-H), 4.18 (1H, m, 5-H), 4.95 (1H, s, br, 1-H), 5.72 (1H, dt, $J_{3,1}$ and $J_{3,4}$ 2.2 Hz, $J_{3,2}$ 10.2 Hz, 3-H), 5.94 (1H, d, br, $J_{2,3}$ 10.2 Hz, 2-H), 6.08 (1H, d, $J_{3",4"}$ 3.0 Hz, 3"-H), 6.29 (1H, dd, $J_{4",5"}$ 2.0 Hz, $J_{4",3"}$ 3.0 Hz, 4"-H), 7.32 (1H, dd, $J_{5",3"}$ 0.7 Hz, $J_{5",4"}$ 2.0 Hz, 5"-H); $\delta_C$ (50 MHz, $CDCl_3$) -5.4 ($(\mathbf{C}H_3)Si(\mathbf{C}H_3)$), 18.3 ($Me_3\mathbf{C}Si$), 25.9 ($(\mathbf{C}H_3)_3CSi$), 28.9 (C-2'), 64.7 (C-1'), 65.9 (C-4), 66.5 (C-6), 71.0 (C-5), 94.3 (C-1), 106.0 (C-3"), 110.2 (C-4"), 125.8 (C-3), 133.2 (C-2), 141.0 (C-5"), 152.9 (C-2"); MS (FAB) m/z 355 ($[M+H]^+$); (HRMS Found: 355.1936 ($[M+H]^+$). Calc. for $C_{18}H_{30}O_5Si$ (M = 354): 355.1941 ($[M+H]^+$)).

From the reaction of **6d** was obtained *3'-(furan-2"-yl)propyl 6-O-(tertiarybutyldimethylsilyl)-2,3-dideoxy-α-D-erythro-hex-2-enopyranoside* **7d** (90%) as a yellow oil; $[\alpha]_D^{20}$ -67.4 (c 1, $CHCl_3$); $R_f$ 0.32 (5:1 petroleum ether-ethyl acetate); $\delta_H$ (200 MHz, $CDCl_3$) 0.12 (6H, s, $(CH_3)_2Si$), 0.92 (9H, s, $(CH_3)_3CSi$), 1.97 (2H, m, 2'a-H and 2'b-H), 2.74 (2H, t, $J_{3'a,2'}$ and $J_{3'b,2'}$ 7.5 Hz, 3'a-H and 3'b-H), 2.88 (1H, d, $J_{OH,4}$ 3.67 Hz, OH), 3.51 (1H, ddd, $J_{1'b,2'a}$ 3.4 Hz, $J_{1'b,2'b}$ 6.3 Hz, $J_{1'b,1'a}$ 12.4 Hz, 1'b-H), 3.78 (3H, m, 4-H, 6a-H and 6b-H), 3.91 (1H, ddd, $J_{1'a,2'a}$ 8.6 Hz, $J_{1'a,1'b}$ 12.4 Hz, 1'a-H), 4.20 (1H, m, 5-H), 4.94 (1H, d, $J_{1,3}$ 2.4 Hz, 1-H), 5.74 (1H, ddd, $J_{3,4}$ 2.3 Hz, $J_{3,1}$ 2.4 Hz, $J_{3,2}$ 10.2 Hz, 3-H), 5.95 (1H, d, $J_{2,3}$ 10.3 Hz, H-2), 6.00 (1H, dd, $J_{3",5"}$ 0.7 Hz, $J_{3",4"}$ 3.1 Hz, 3"-H), 6.28 (1H, dd, $J_{4",5"}$ 1.8 Hz, $J_{4",3"}$ 3.1 Hz, 4"-H), 7.31 (1H, dd, $J_{5",3"}$ 0.7 Hz, $J_{5",4"}$ 1.8 Hz, 5"-H); $\delta_C$ (50 MHz, $CDCl_3$) -5.44 and -5.49 ($(\mathbf{C}H_3)Si(\mathbf{C}H_3)$), 18.3 ($Me_3\mathbf{C}Si$), 24.7 ($(\mathbf{C}H_3)_3CSi$), 25.9 (C-2'), 28.3 (C-3'), 65.4 (C-1'), 67.0 (C-4), 67.6 (C-6), 70.2 (C-5), 94.3 (C-1), 105.0 (C-3"), 110.1 (C-4"), 125.9 (C-3), 132.9 (C-2), 140.9 (C-5"), 155.6 (C-2"); (Found: C, 61.40 ; H, 8.72%. Calc. for $C_{19}H_{32}O_5Si$ (M = 368.60): C, 61.85 ; H, 8.68 %).

### 4. 3. General Procedure for the Preparation of Furanic Hexenopyranosid-4-uloses 8

A solution of **7** (0.43 mmol) and pyridinium chlorochromate (278 mg, 1.29 mmol) in dichloromethane (8 mL) was stirred screened from daylight for 24 hours at room temperature. After

filtration on celite and evaporation, the crude product was purified by silica gel column (5:1 petroleum ether-ethyl acetate) to give the pure $\alpha$-anomers **8**.

From the reaction of **7b** was obtained *1′-(furfuraldehyde-5″) methyl-6-O-(tertiarybutyldimethylsilyl)-2,3-dideoxy-α-D-glycero-hex-2-enopyranosid-4-ulose* **8b** (86%) as a yellow oil; $[\alpha]_D^{20}$ -54 (c 1, $CHCl_3$); $R_f$ 0.34 (5:1 petroleum ether-ethyl acetate); $\delta_H$ (200 MHz, $CDCl_3$) 0.09 (6H, s, $(CH_3)_2Si$), 0.89 (9H, s, $(CH_3)_3CSi$), 4.06 (2H, m, 6a-H and 6b-H), 4.48 (1H, dd, $J_{5,6b}$ 3.3 Hz, $J_{5,6a}$ 4.4 Hz, 5-H), 4.75 (1H, d, $J_{1'b,1'a}$ 13.2 Hz, 1′b-H), 4.86 (1H, d, $J_{1'a,1'b}$ 13.2 Hz, 1′a-H), 5.45 (1H, d, $J_{1,2}$ 3.4 Hz, 1-H), 6.16 (1H, d, $J_{3,2}$ 10.3 Hz, 3-H), 6.59 (1H, d, $J_{3'',4''}$ 3.5 Hz, 3″-H), 6.90 (1H, dd, $J_{2,1}$ 3.4 Hz, $J_{2,3}$ 10.3 Hz, 2-H), 7.23 (1H, d, $J_{4'',3''}$ 3.5 Hz, 4″-H), 9.65 (1H, s, CHO); $\delta_C$ (50 MHz, $CDCl_3$) -5.3 ((**C**$H_3$)Si(**C**$H_3$)), 18.4 ($Me_3$**C**Si), 25.9 ((**C**$H_3$)$_3$CSi), 62.1 (C-6), 62.6 (C-1′), 76.4 (C-5), 92.7 (C-1), 112.1 (C-3″), 121.6 (C-4″), 128.7 (C-3), 143.1 (C-2), 153.0 (C-5″), 157.0 (C-2″), 177.8 (CHO), 194.2 (C-4); MS (FAB) m/z 367 ($[M+H]^+$); (HRMS Found: 367.1579 ($[M+H]^+$). Calc. for $C_{18}H_{26}O_6Si$ (M = 366): 367.1577 ($[M+H]^+$)).

From the reaction of **7c** was obtained *2′-(furan-2″-yl)ethyl 6-O-(tertiarybutyldimethylsilyl)-2,3-dideoxy-α-D-glycero-hex-2-enopyranosid-4-ulose* **8c** (68%) as a yellow oil; $[\alpha]_D^{20}$ -20 (c 1, $CHCl_3$); $R_f$ 0.33 (5:1 petroleum ether-ethyl acetate); $\delta_H$ (200 MHz, $CDCl_3$) 0.07 (6H, s, $(CH_3)_2Si$), 0.88 (9H, s, $(CH_3)_3CSi$), 2.98 (2H, t, $J_{2',1'a}$ and $J_{2',1'b}$ 6.8 Hz, 2′a-H and 2′b-H), 3.89 (1H, dd, $J_{1'b,2'}$ 6.8 Hz, $J_{1'b,1'a}$ 9.8 Hz, 1′b-H), 4.02 (2H, m, 6a-H and 6b-H), 4.10 (1H, dd, $J_{1'a,2'}$ 6.8 Hz, $J_{1'a,1'b}$ 9.9 Hz, 1′a-H), 4.36 (1H, dd, $J_{5,6a}$ 3.2 Hz, $J_{5,6b}$ 4.7 Hz, 5-H), 5.31 (1H, d, $J_{1,2}$ 3.5 Hz, 1-H), 6.00 (1H, dd, $J_{3'',5''}$ 0.7 Hz, $J_{3'',4''}$ 3.1 Hz, 3″-H), 6.10 (1H, d, $J_{3,2}$ 10.3 Hz, 3-H), 6.28 (1H, dd, $J_{4'',5''}$ 1.8 Hz, $J_{4'',3''}$ 3.1 Hz, 4″-H), 6.84 (1H, dd, $J_{2,1}$ 3.5 Hz, $J_{2,3}$ 10.3 Hz, 2-H), 7.32 (1H, dd, $J_{5'',3''}$ 0.7 Hz, $J_{5'',4''}$ 1.8 Hz, 5″-H); $\delta_C$ (50 MHz, $CDCl_3$) -5.3 ((**C**$H_3$)Si(**C**$H_3$)), 18.3 ($CH_3$**C**Si), 25.9 ((**C**$H_3$)$_3$CSi), 28.8 (C-2′), 62.6 (C-1′), 67.2 (C-6), 76.2 (C-5), 93.2 (C-1), 106.3 (C-3″), 110.3 (C-4″), 128.1 (C-3), 141.3 (C-5″), 143.8 (C-2), 152.5 (C-2″), 194.7 (C-4); MS (FAB) m/z 353 ($[M+H]^+$); (HRMS Found: 353.1783 ($[M+H]^+$). Calc. for $C_{18}H_{28}O_5Si$ (M = 352): 353.1784 ($[M+H]^+$)).

From the reaction of **7d** was obtained *3′-(furan-2″-yl)propyl 6-O-(tertiarybutyldimethylsilyl)-2,3-dideoxy-α-D-glycero-hex-2-enopyranosid-4-ulose* **8d** (68%) as a yellow oil $[\alpha]_D^{20}$ -59 (c 1.8, $CHCl_3$); $R_f$ 0.23 (5:1 petroleum ether-ethyl acetate); $\delta_H$ (200 MHz, $CDCl_3$) 0.07 (6H, s, $(CH_3)_2Si$), 0.88 (9H, s, $(CH_3)_3CSi$), 2.00 (2H, m, 2′a-H and 2′b-H), 2.73 (2H, t, $J_{3'a,2'}$ and $J_{3'b,2'}$ 7.4 Hz, 3′a-H and 3′b-H), 3.61 (1H, ddd, $J_{1'b,2'a}$ 3.3 Hz, $J_{1'b,2'a}$ 6.3 Hz, $J_{1'b,1'a}$ 12.7 Hz, 1′b-H), 3.91 (1H, ddd, $J_{1',2'}$ 3.3 Hz, $J_{1'a,2'b}$ 6.3 Hz, $J_{1'a,1'b}$ 12.7 Hz, 1′a-H), 4.04 (2H, m, 6a-H and 6b-H), 4.45 (1H, dd, $J_{5,6a}$ 3.1 Hz, $J_{5,6b}$ 4.8 Hz, 5-H), 5.31 (1H, d, $J_{1,2}$ 3.4 Hz, 1-H), 6.00 (1H, dd, $J_{3'',5''}$ 0.6 Hz, $J_{3'',4''}$ 3.1 Hz, 3″-H), 6.10 (1H, d, $J_{2,3}$ 10.3 Hz, 3-H), 6.28 (1H, dd, $J_{4'',5''}$ 1.9 Hz, $J_{4'',3''}$ 3.1 Hz, 4″-H), 6.87 (1H, dd, $J_{2,1}$ 3.4 Hz, $J_{2,3}$ 10.3 Hz, 2-H), 7.31 (1H, dd, $J_{5'',3''}$ 0.6 Hz, $J_{5'',4''}$ 1.9 Hz, 5″-H); $\delta_C$ (50 MHz, $CDCl_3$) -5.3 ((**C**$H_3$)Si(**C**$H_3$)), 18.3 ($Me_3$**C**Si), 24.7 ((**C**$H_3$)$_3$CSi), 25.9 (C-2′), 28.2 (C-3′), 62.7 (C-1′), 68.3 (C-6), 76.2 (C-5), 93.2 (C-1), 105.1 (C-3″), 110.2 (C-4″), 128.1 (C-3), 141.0 (C-5″), 144.0 (C-2), 155.3 (C-2″), 194.8 (C-4); (Found: C, 62.10 ; H, 8.26%. Calc. for $C_{19}H_{30}O_5Si$ (M = 366.52): C, 62.26 ; H, 8.25%).

### 4. 4. Synthesis of 1-*O*-acetyl-2,3-dideoxy-D-pent-2-enopyranosid-4-ulose 10

Compound **10** was prepared by the method of Hoffmann *et al.*[15] To 4.5 g (44 mmol) of furfuryl alcohol **9a**, 9.8 g (75 mmol) of metachloroperbenzoïc acid (70%) in dichloromethane was added at 0°C. The crude product was purified by silica gel column (5:0.5 dichlorométhane-ethyl acetate) to give 3.5 g of a mixture $\alpha$- and $\beta$-anomers of 6-hydroxy-2,3-dihydro-6H-pyran-3-one.

Montmorillonite K-10 (7 g) was added to a suspension of 6-hydroxy-2,3-dihydro-6H-pyran-3-one (3.5 g, 30.8 mmol) in acetic anhydride (14 mL) at 0°C and the mixture stirred at room temperature for 12 hours until the completion of the reaction. The catalyst was filtrated, washed with dichloromethane and the solvent evaporated. The crude product was purified by silica gel column (5:0.5 dichlorométhane-ethyl acetate) to give 4 g of a mixture $\alpha$- and $\beta$-anomers of *1-O-acetyl-2,3-dideoxy-D-pent-2-enopyranosid-4-ulose* **10** (58%) as a yellow crystal; $R_f$ 0.8 (5:0.5 dichlorométhane-ethyl acetate); $\delta_H$ (200 MHz, $CDCl_3$) 2.10 (3H, s, $CH_3$), 4.15 (1H, d, $J_{5b,5a}$ 17.0 Hz, 5b-H), 4.46 (1H, d, $J_{5a,5b}$ 17.0 Hz, 5a-H), 6.20 (1H, d, $J_{3,2}$ 10.4 Hz, 3-H), 6.42 (1H, d, $J_{1,2}$ 3.6 Hz, 1-H), 6.90 (1H, dd, $J_{2,1}$ 3.6 Hz, $J_{2,3}$ 10.4 Hz, 2-H); $\delta_C$ (50 MHz, $CDCl_3$) 20.8 ($CH_3$), 67.3 (C-5), 86.6 (C-1), 128.7 (C-3), 142.3 (C-2), 169.5 ($CO_2$), 193.3 (C-4). The $^1H$ and $^{13}C$ NMR spectra were in agreement with the reported data.[15]

### 4. 5. General Procedure for the Preparation of Furanylalkyl Pentenopyranosid-4-uloses 11

Ceric (IV) ammonium nitrate (140 mg; 20 mmol %) in acetonitrile (4 mL) was added to a mixture of **10** (200 mg, 1.28 mmol) and furanic alcohol **9** (3.84 mmol, 3 equiv.). The mixture was stirred at room temperature in a 10 mL round-bottom flask under nitrogen atmosphere and the reaction was followed by thin-layer chromatography (5:0.5 $CH_2Cl_2$-AcOEt). After the disappearance of the starting compound **10** (5–24 hours), the mixture was quenched with water (5 mL) and extracted with ethyl acetate (3 × 10 mL). The combined organic layers were dried over anhydrous $MgSO_4$, concentred *in vacuo* and purified by silica gel column (2:1 petroleum ether-ethyl acetate) to afford a mixture $\alpha$- and $\beta$-anomers **11**.

From the reaction of **9a** was obtained *1′-(furan-2″-yl)methyl 2,3-dideoxy-α(β-D-glycero-pent-2-enopyranosid-4-ulose* **11a** (64%) as a clear oil; $R_f$ 0.5 (5:1 petroleum ether-ethyl acetate); $\delta_H$ (200 MHz, $CDCl_3$) 4.12 (1H, d, $J_{5b,5a}$ 16.9 Hz, 5b-H), 4.50 (1H, d, $J_{5a,5b}$ 16.9 Hz, 5a-H), 4.65 (1H, d, $J_{1'b,1'a}$ 12.8 Hz, 1′b-H), 4.75 (1H, d, $J_{1'a,1'b}$ 12.8 Hz, 1′a-H), 5.31 (1H, d, $J_{1,2}$ 3.4 Hz, 1-H), 6.15 (1H, d, $J_{3,2}$ 10.3 Hz, 3-H), 6.37 (2H, m, $J_{3'',5''}$ 0.8 Hz, $J_{4'',5''}$ 1.7 Hz, $J_{3'',4''}$ 3.0 Hz, 3″-H and 4″-H), 6.88 (1H, dd, $J_{2,1}$ 3.4 Hz, $J_{2,3}$ 10.3 Hz, 2-H), 7.45 (1H, $J_{5'',3''}$ 0.8 Hz, dd, $J_{5'',4''}$ 1.7 Hz, 5″-H); $\delta_C$ (50 MHz, $CDCl_3$) 62.1 (C-1′), 66.3 (C-5), 91.8 (C-1), 110.4 (C-3″), 110.5 (C-4″), 128.0 (C-3), 143.4 (C-5″), 144.1 (C-2), 150.6 (C-2″), 194.5 (C-4); (Found: C, 61.58 ; H, 5.30%. Calc. for $C_{10}H_{10}O_4$ (M = 194.18): C, 61.85 ; H, 5.19%).

From the reaction of **9b** was obtained *2′-(furan-2″-yl)ethyl 2,3-dideoxy-α(β-D-glycero-pent-2-enopyranosid-4-ulose* **11b** (50%) as a clear oil $R_f$ 0.42 (5:1 petroleum ether-ethyl acetate); $\delta_H$ (200 MHz, $CDCl_3$) 2.98 (2H, t, $J_{2',1'a}$ and $J_{2',1'b}$ 6.6 Hz, 2′a-H and 2′b-H), 3.85 (1H, dd, $J_{1'b,2'}$ 6.6 Hz, $J_{1'b,1'a}$ 16.4 Hz, 1′b-H), 4.06 (1H, d, $J_{5b,5a}$ 16.9 Hz, 5b-H), 4.10 (1H, dd, $J_{1'a,2'}$ 6.6 Hz, $J_{1'a,1'b}$ 16.4 Hz, 1′a-H), 4.35 (1H, d, $J_{5a,5b}$ 16.9 Hz, 5a-H), 5.20 (1H, d, $J_{1,2}$ 3.4 Hz, 1-H), 6.07 (1H, d, $J_{3'',4''}$ 3.2 Hz, 3″-H), 6.15 (1H, d, $J_{3,2}$ 10.4 Hz, 3-H), 6.32 (1H, dd, $J_{4'',5''}$ 1.1 Hz, $J_{4'',3''}$ 3.2 Hz, 4″-H), 6.88 (1H, dd, $J_{2,1}$ 3.4 Hz, $J_{2,3}$ 10.4 Hz, 2-H), 7.30 (1H, dd, $J_{5'',3''}$ 0.8 Hz, $J_{5'',4''}$ 1.1 Hz, 5″-H); $\delta_C$ (50 MHz, $CDCl_3$) 28.8 (C-2′), 66.2 (C-1′), 67.3 (C-5), 93.2 (C-1), 106.4 (C-3″), 110.4 (C-4″), 127.8 (C-3), 141.3 (C-5″), 144.2 (C-2), 152.4 (C-2″), 194.6 (C-4); (Found: C, 63.23 ; H, 6.02%. Calc. for $C_{11}H_{12}O_4$ (M = 208.21): C, 63.45 ; H, 5.81%).

From the reaction of **9c** was obtained *3′-(furan-2″-yl)propyl 2,3-dideoxy-α(β-D-glycero-pent-2-enopyranosid-4-ulose* **11c** (30%) as a clear oil; $R_f$ 0.64 (5:1 petroleum ether-ethyl acetate); $\delta_H$ (300 MHz, $CDCl_3$) 1.97 (2H, m, 2′a-H and 2′b-H), 2,74 (2H, t, $J_{3',2'a}$ and $J_{3',2'b}$ 7.4 Hz, 3′a-H and 3′b-H), 3.59 (1H, ddd, $J_{1'b,2'a}$ 3.0 Hz, $J_{1'b,2'b}$ 6.3 Hz, $J_{1'b,1'a}$ 16.0 Hz, 1′b-H), 3.89 (1H, ddd, $J_{1'a,2'b}$ 3.1 Hz, $J_{1'a,2'a}$ 6.4 Hz, $J_{1'a,1'b}$ 16.0 Hz, 1′a-H), 4.10 (1H, d, $J_{5b,5a}$ 16.9 Hz, 5b-H), 4.46 (1H, d, $J_{5a,5b}$ 16.9 Hz, 5a-H), 5.20 (1H, d, $J_{1,2}$ 3.3 Hz, 1-H), 6.00 (1H, d,

$J_{3'',4''}$ 3.0 Hz, 3″-H), 6.14 (1H, d, $J_{3,2}$ 10.3 Hz, 3-H), 6.28 (1H, dd, $J_{4'',5''}$ 1.8 Hz, $J_{4'',3''}$ 3.0 Hz, 4″-H), 6.89 (1H, dd, $J_{2,1}$ 3.3 Hz, $J_{2,3}$ 10.3 Hz, 2-H), 7.30 (1H, s, br, 5″-H); $\delta_C$ (50 MHz, $CDCl_3$) 24.6 (C-2′), 28.1 (C-3′), 66.3 (C-1′), 68.5 (C-5), 93.3 (C-1), 105.2 (C-3″), 110.2 (C-4″), 127.7 (C-3), 141.0 (C-5″), 144.6 (C-2), 155.2 (C-2″), 194.7 (C-4); (Found: C, 64.54 ; H, 6.14%. Calc. for $C_{12}H_{14}O_4$ (M = 222.23): C, 64.85 ; H, 6.35%).

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## References

1 P. Collins and R. Ferrier, *Monosaccharides. Their Chemistry and their Roles in Natural Products,* (John Wiley & Sons eds.), 1st edn, Chichester, United Kingdom, 1995, pp. 317–326.
2 L. Cottier, G. Descotes and Y. Soro, *J. Carbohydr. Chem.,* 2005, **24**(1), 55–71.
3 G.V.M. Sharma, L. Hymavathi and P.R. Krishna, *Tetrahedron Lett.,* 1997, **38**(39), 6929–6932.
4 O. Achmatowicz and B. Szechner, *J. Org. Chem.,* 2003, **68**, 2389–2404.
5 J.W. Lown, *Chem. Soc. Rev.,* 1993, 165.
6 M.E. Jung and J. Pontillo, *J. Org. Chem.,* 2002, **67**, 6848–6851.
7 P. Sharma and M. Alam, *J. Chem. Soc., Perkin Trans. 1,* 1988, 2537.
8 P.J. Bolon, T.B. Sells, Z.M. Nuesca and D.F. Purdy, V. Nair, *Tetrahedron,* 1994, **50**, 7747–7764.
9 M.J. Konkel and R. Vince, *Tetrahedron,* 1996, **52**, 799–808 and references cited therein.
10 C. Hendrix and H. Rosemeyer, I. Verheggen, F. Seela, A. Van Acrshot and P. Herdewijn, *Chemistry Eur. J.,* 1997, **3**, 110–120.
11 J.R. De Freitas Filho, R.M. Srivastava, W.J.P. De Silva, L. Cottier and D. Sinou, *Carbohydr. Res.,* 2003, **338**, 673–680 and references cited therein.
12 J.R. De Freitas Filho, R.M. Srivastava, Y. Soro, L. Cottier and G. Descotes, *J. Carbohydr. Chem.*, 2001, **20 (7&8)**, 561–568.
13 Y. Soro, S. Siaka, L. Cottier and G. Descotes, *Bull. Chem. Soc. Ethiop.,* 2005, **19**(2), 233–241.
14 E.J. Corey and A. Venkateswarlu, *J. Am. Chem. Soc.,* 1972, **94**, 6190–6191.
15 H.M.R. Hoffmann, D. Kumwiede, B. Mucha, H.H. Ochlerking and G.W. Prahst, *Tetrahedron,* 1993, **49**, 8999–9018 and references cited therein.
16 P.M. Bhaskar and D. Loganathan, *Tetrahedron Lett.,* 1998, **39**, 2215–2218.
17 M. Van der Henvel, A.D. Cuper, H. Van der Deen, R.M. Kellogg and B.L. Feringa, *Tetrahedron Lett.,* 1997, **38**, 1655–1658.
18 D. Horton, D. Koh and Y. Takagi, *Carbohydr. Res.,* 1993, **250**, 261–274.
19 B. Herradon, E. Fenude, R. Bao and S. Valverde, *J. Org. Chem.,* 1996, **61**, 1143–1147.