Available online at www.sciencedirect.com
ScienceDirect
Tetrahedron 64 (2008) 1703–1710
Tetrahedron
www.elsevier.com/locate/tet

5-Deoxy glycofuranosides by carboxyl group assisted photoinduced electron-transfer deoxygenation

Andrea Bordoni, Rosa M. de Lederkremer, Carla Marino*

CIHIDECAR (CONICET), Departamento de Química Orgánica, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Pabellón II, Ciudad Universitaria, 1428 Buenos Aires, Argentina

Received 28 November 2007; accepted 4 December 2007
Available online 8 December 2007

Abstract

In connection with the development of practical methods for the synthesis of deoxy sugars, a photoinduced electron-transfer (PET) reaction using 9-methylcarbazole (MCZ) as photosensitizer was applied to a 2-*O*-(3-trifluoromethyl)benzoylated derivative of D-galacturonic acid. The carboxylic group efficiently assists α-deoxygenation, the required irradiation time being significantly shorter than that in the absence of it. The photochemical reaction was also used for the deoxygenation of D-glucurono-6,3-lactone derivatives, providing in both cases the convenient routes for the synthesis of 5-deoxy-hexofuranosides and intermediate compounds for the synthesis of natural products, avoiding the use of metal hydrides.

Keywords: PET deoxygenatin; Deoxy sugars; Galactofuranosides; Glucofuranosides

1. Introduction

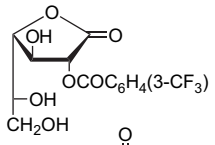
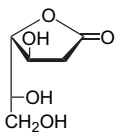
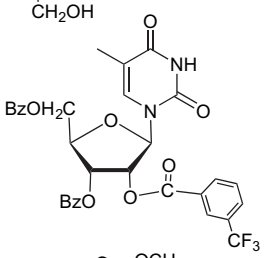
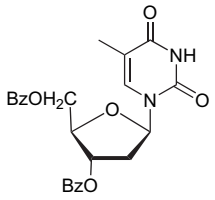
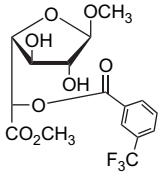
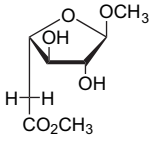
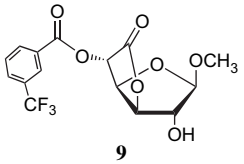
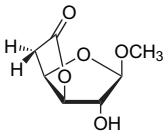
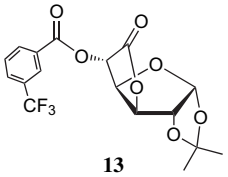
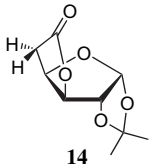
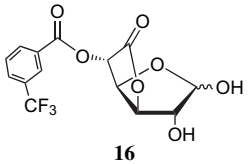
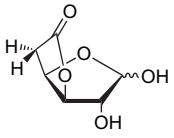
The glycobiology of galactofuranose is a topic of great interest, since galactofuranosyl residues are constituents of infectious microorganisms, but are absent in mammal glycoconjugates. The enzymes involved in the metabolism of the sugar are good targets for the development of antimicrobial agents.[1–3] As part of an ongoing project for the synthesis of compounds useful for the characterization of the enzymes,[4,5] we have developed strategies for the synthesis of galactofuranosides deoxygenated at C-2, 3, and 6 and we showed that these hydroxyls are necessary for the interaction with *exo* β-D-galactofuranosidase from *Penicillium fellutanum*.[6–8] The synthesis of 2-deoxy-D-*lyxo*-hexofuranosides ('2-deoxy-galactofuranosides') was performed via a photoinduced electron-transfer (PET) reaction on 2-*O*-(3-trifluoromethyl)benzoyl-D-galactono-1,4-lactone using 9-methylcarbazole (MCZ) as photosensitizer (Table 1, entry 1).[3] The PET reduction of hydroxyl groups was previously used for the deoxygenation of different ester derivatives under diverse conditions.[9–13] Saito et al. described that the 3-trifluoromethylbenzoyl group was an efficient group for this reaction.[11] In all the applications, several hours of irradiation were required for conversion of the starting material into the corresponding deoxygenated photoproducts. Following Rizzo's protocol,[13] we observed that the reaction conditions necessary for the deoxygenation of 2-*O*-(3-trifluoromethyl)benzoyl derivatives of aldono-1,4-lactones were extremely mild compared, for example, with those required for the synthesis of 2-deoxyribonucleosides[13] (Table 1, entries 1 and 2). The effectiveness of this reaction on lactone derivatives was attributed to the stabilization of the intermediate radical by the carbonyl group.[6] The PET deoxygenation was optimized for different derivatives of D-galactono- and D-glucono-1,4-lactones, confirming the selectivity for the reduction at the α-carbonyl position. The unique reactivity of aldonolactones allows for 9-methylcarbazole (MCZ) to turn over, so it can be used in 10 mol %.[14]

The importance of the HO-5 of galactofuranosides in the interaction with *exo* β-D-galactofuranosidase has not been reported. Therefore, we pursued the design of a methodology

* Corresponding author. Tel.: +54 11 45763352; fax: +54 11 45763346.
E-mail address: cmarino@qo.fcen.uba.ar (C. Marino).

0040-4020/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2007.12.005

Table 1
Photoinduced deoxygenation of hydroxyl groups derivatized as 3-(trifluoromethyl)benzoates

Entry	Compound	Product	Time	Conversion[a] (%)	Yield[b] (%)
1			3 min	100	73[14]
2			12–15 h	—	50–70[13]
3			3 min	60	42
	3	**4**			
4	**3**	**4**	6 min	90	66
5	**3**	**4**	8 min	100	25
6	 **9**	 **10**	6 min	100	90
7	 **13**	 **14**	3 min	78	46
8	**13**	**14**	6 min	100	90
9	 **16**	 **17**	3 min	85	27
10	**16**	**17**	6 min	100	56

The reaction was performed with a 450 W medium-pressure lamp (λ_{exc} >300 nm), at 25 °C, in 9:1 2-PrOH–H_2O in the presence of MCZ (0.075 mmol) and $Mg(ClO_4)_2$ (0.3 mM).

[a] Conversion was determined by NMR spectroscopy.

[b] Yields refer to the isolated pure products after column chromatography.

for the deoxygenation of C-5 in galactofuranosides and in general, for the synthesis of 5-deoxy-glycofuranosides.

The first synthesis of 5-deoxyhexoses was developed by Wolfrom et al. which involved the anti-Markovnikov hydration of a 5,6-alkene derivative.[15] Since that report, the same approach has been followed by several authors, and the conditions for the key step have been improved.[16,17] A three-step sequence involving the reduction of a 5,6-*O*-benzylidene derivative was used for the deoxygenation of glucofuranose, but the reaction was not regioselective, and some of the 6-deoxy sugar was obtained.[17]

We now report the successful application of the PET deoxygenation on derivatives of D-galacturonic acid and D-glucofuranosidurono-6,3-lactone for the synthesis of 5-deoxy-galacto and glucofuranosides.

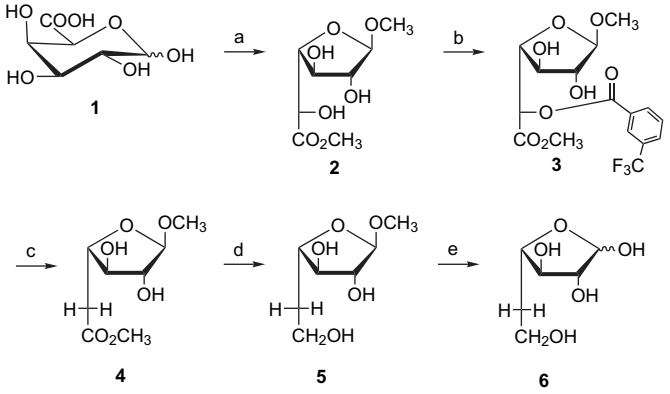
2. Results and discussion

One of the obvious approaches to 5-deoxy-L-*arabino*-hexofuranosides would be the reduction of a compound conveniently derivatized at C-5. With this aim and taking advantage of the different reactivities of the hydroxyl groups

in aldohexono-1,4-lactones, we treated 2,6-di-*O*-benzoyl-D-galactono-1,4-lactone[18] with 1.2 equiv of tosylchloride (4-toluenesulfonylchloride) in pyridine–$CHCl_2$ at 0 °C, expecting that the exocyclic 5-hydroxyl would be selectively substituted. Unfortunately, regioselective sulfonation was not achieved.

On the basis of the effectiveness of the photoinduced electron-transfer (PET) α-deoxygenation of aldonolactones,[6,14] we thought to extend it to the synthesis of 5-deoxy-galactofuranosyl derivatives. This strategy would require a derivative oxidized at C-6. Thus, we envisioned commercial D-galacturonic acid (**1**) as a convenient starting material, considering that the carboxylic group could probably facilitate the PET deoxygenation at the vicinal position by stabilization of the intermediate radical. We subsequently investigated the reactions that would lead to appropriate derivatives for the PET reaction. The preparation of methyl (methyl α-D-galactopiranosid)uronate from **1** by treatment with methanol in the presence of a cation-exchange resin (H^+ form) under reflux was earlier described. The authors pointed out that the same reaction under room temperature for 8 h led to the methyl D-galacturonate.[19] In our case, treatment of **1** with methanol in the presence of Amberlite IR-120H cation resin was performed at 35 °C for 48 h. Methyl uronate was formed during the early stages of the reaction, but after keeping the reaction for 48 h, mainly the glycosylated β-furanosic derivative **2** was obtained. Pyranose glycosides were not detected by ^{13}C NMR spectroscopy. Conditions for the stereospecific glycofuranosylation of uronic acids with long chain alcohols were also described.[20] A stereospecific three-step procedure for the preparation of **2** from D-Gal was reported,[21] but the procedure optimized here for the preparation of **2** from D-galacturonic acid is certainly easier. Subsequent reduction of the ester group constitutes a direct strategy for accessing galactofuranosides.

We considered that compound **2** could be selectively esterified at C-5 owing to the enhanced reactivity of the HO vicinal to the carboxyl group, similar to the regioselectivity observed in aldonolactones.[6,14,18] In fact, treatment of **2** with 1.2 equiv of 3-(trifluoromethyl)benzoyl chloride led to derivative **3** (Scheme 1), in 68% yield. The structure of **3** was confirmed on the basis of the NMR data. The signal of H-5 was shifted from 4.50 ppm in **2**[22] to 5.53 ppm in **3**, and the signal for C-5 was shifted from 70.0 to 72.3 ppm. Signals corresponding to C-4 and C-6 were shielded in comparison to those of compound **2**, as a result of the β-effect.



Scheme 1. Synthesis of methyl 5-deoxy-α-L-*arabino*-hexofuranoside (**5**) and 5-deoxy-L-*arabino*-hexofuranose (**6**). (a) Amberlite IR-120H, MeOH; (b) $(3\text{-}CF_3)C_4H_6COCl$, CH_2Cl_2–pyridine; (c) *hν*, MCZ, $Mg(ClO_4)_2$; (d) $NaBH_4$–I_2, THF; (e) 40 mM TFA, 100 °C.

With compound **3** in hand, conditions for the PET deoxygenation could be studied. The photochemical reaction was carried out by irradiation with a Heraeus TQ, medium-pressure Hg lamp of 450 W in the presence of 9-methylcarbazole (MCZ) at 10 mol % as photosensitizer, and 2-PrOH–water (9:1) as solvent. We have previously observed that photolysis of 2-*O*-(3-trifluoromethyl)benzoyl-D-galactono (Table 1, entry 1) and D-glucono-1,4-lactone derivatives under these conditions for 3 min led to total conversion to the corresponding 2-deoxy-aldonolactones.[14] Compound **3** was irradiated for different times in order to find the optimal conditions (Table 1, entries 3–5). On the basis of the ^{13}C NMR spectrum of the crude mixture complete disappearance of the starting material occurred after 8 min of irradiation, however, the recovery of the deoxygenated product was low. The best yield of **4** was obtained with 6 min of irradiation to give the desired product in 66% yield although some of the starting material was still present in the crude reaction mixture. This result shows that the carboxylate ester group is also effective for assisting the deoxygenation at the vicinal position, in comparison with the derivatives without a carbonyl group, which required several hours of irradiation (Table 1, entry 2).[13] As in the case of aldonolactone derivatives,[14] the reactivity enhanced by the carboxylate ester group allows for MCZ to turn over, so it can be used in sub-molar quantity.

Complex signals were observed in the ^1H NMR spectrum of **4**, as a result of long range couplings. Nevertheless, the presence of two double doublets at high field (2.86 and 2.72 ppm) with a large J_{gem} (16.0 Hz) and the signal corresponding to the deoxy function (C-5) at 38.57 ppm in the ^{13}C NMR spectrum confirmed the identity of **4**. The signal corresponding to C-6 was shifted from 168.1 ppm in **3** to 172.3 ppm in **4**, as a result of the C-5 deoxygenation, as we previously observed.[6,14]

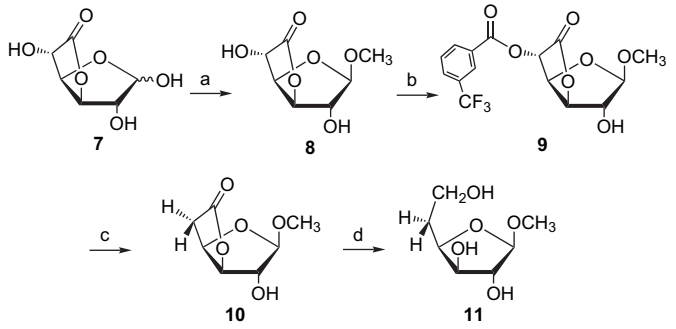
The next step was the reduction of the carboxylic ester of **4** to afford methyl glycoside **5**. Reduction of carboxylic esters with $NaBH_4$ is usually slow,[23] but in the case of **2** we observed that it could be performed by the use of an excess of reagent in methanol at room temperature. This fact could be attributed to the presence of an α-heteroatom, as it has been observed in aldonolactones.[23] Compound **4** could not be reduced under similar conditions, confirming the influence of HO at the vicinal position. Although a powerful reducing agent could be used, we were interested in using $NaBH_4$ with the aim to extend the methodology to the use of NaB^3H_4, and thus introduce a tritium label for sensitive biological assays.[4] By using the I_2–$NaBH_4$ system,[24] reduction of the carboxylic group of **6** was successfully achieved to afford glycoside **5**. Compound **5** was thus obtained in four steps from commercial D-galacturonic acid, and the physical properties were in agreement with those reported.[16] The synthetic sequence now described is shorter and more efficient in terms of yield. The NMR spectra of **5** are now completely assigned. Complex signals for H-5,

5′, 6, and 6′ were observed in the ^{1}H NMR spectrum. Signals corresponding to H-5 and 5′ were shielded from 2.86/2.72 to 1.96/1.87 ppm as a result of the reduction of the methoxycarbonyl group and appeared as complex multiplets (dddd). Also H-4 was shielded. The reduction was confirmed by the appearance of a complex signal centered at 3.72 ppm corresponding to H-6 and 6′ in the ^{1}H NMR spectrum and the signal corresponding to C-6 in the ^{13}C NMR spectra, which was shifted from 174.3 ppm in **4** to 59.0 ppm in **5**.

Glycoside **5** was hydrolyzed by treatment with dilute TFA, affording 5-deoxy-D-galactose (**6**, 5-deoxy-L-*arabino*-hexose). Compounds **4**–**6** were analyzed by high performance anion-exchange chromatography with pulse amperometric detection (HPAEC–PAD) and the conditions for good resolution were established (see Section 3). Thus, this analytical method could be useful for studies on the substrate–inhibitor properties of 5-deoxy-galactofuranoside with respect to β-D-galactofuranosidase.

Based on the results obtained with the PET deoxygenation of derivatives of D-galacturonic acid, we studied the reaction with derivatives of D-glucurono-6,3-lactone (**7**) with the aim to obtain 5-deoxygenated derivatives of D-glucose. Deoxygenated derivatives of glucose are important for the characterization of glucosidases and glucose-isomerases.[17] Recently, the synthesis of 4-deoxypyranosides from **7** has been reported.[25]

Treatment of **7** with Amberlite IR-120H in methanol at room temperature led to β-methyl glycoside **8** in good yield (Scheme 2). Although, some of the α-anomer was detected by ^{1}H NMR, pure β-anomer was obtained by crystallization from chloroform. A similar procedure, but under reflux, was earlier reported to afford the methyl glycoside as an anomeric mixture.[19]



Scheme 2. Synthesis of methyl 5-deoxy-β-D-*xylo*-hexofuranoside (**11**). (a) Amberlite IR-120H, MeOH; (b) (3-CF_3)C_6H_4COCl, CH_2Cl_2–pyridine, 0 °C; (c) *hν*, MCZ, $Mg(ClO_4)_2$; (d) $NaBH_4$–I_2, THF.

On the basis of the selectivity observed in the substitution of the HO vicinal to the carbonyl group in lactones,[6,14] we supposed that **8** could be selectively esterified at C-5. In fact, treatment of **8** with 1.2 equiv of (3-trifluoromethyl)benzoyl chloride led to derivative **9** in good yield (Scheme 2). The ^{1}H NMR spectrum of **9** clearly confirmed the regioselectivity of the benzoylation. The signal at 4.47 ppm, assigned to H-2, showed coupling with the hydroxyl group (δ 2.56 ppm, $J_{2,HO}$=4.94 Hz). On deuteration this signal disappeared and the H-2 signal collapsed into a singlet. The shielding of the signal corresponding to C-6, from 178.0 ppm in **8** to 170.1 ppm in **9** observed in the ^{13}C NMR spectrum, was also an indicative of the substitution at C-5.

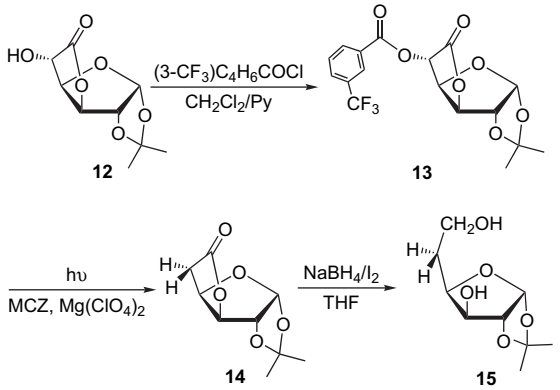
Photolysis of compound **9** afforded **10** (Table 1, entry 6). The presence of two double doublets at high fields (2.82 and 2.54 ppm) with a large J_{gem} in the ^{1}H NMR spectrum and the signal corresponding to the deoxy function (37.01 ppm, C-5) in the ^{13}C NMR spectrum were diagnostic signals for the deoxygenation. The deprotection of C-6 was similar to the effect observed in other α-deoxygenations.[6,14]

Although reduction of aldonolactones is usually achieved with $NaBH_4$, reduction of **10** failed presumably due to the absence of a heteroatom at C-α to the carboxylic group.[23] Using the $NaBH_4$–I_2 method,[24] methyl 5-deoxy glucofuranoside (**11**) was efficiently obtained.

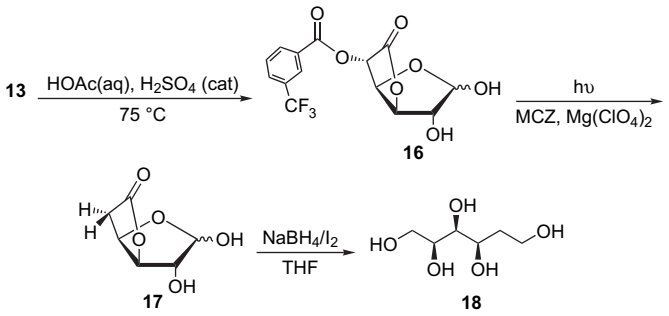
With the purpose to study the PET deoxygenation in the presence of different protective groups, we developed the reaction sequences depicted in Schemes 3 and 4, starting from acetonide **12**.[26] The free hydroxyl group of **12** was converted to its (3-trifluoromethyl)benzoyl ester **13**, as described for the preparation of **9**. Photochemical deoxygenation was more efficient in this case and compound **13** afforded **14** in 90% yield after 6 min of irradiation (Table 1, entries 6 and 7). The absence of free hydroxyls in product **14** facilitated the work up of the reaction, compared with the other derivatives. Compound **14** was previously obtained by the Barton deoxygenation method applied to the phenylthiocarbonate derivative of **12**[27] and used as intermediate for the synthesis of halichondrins[28] and (+)-cardiobutanolide.[29]

By reduction of **14** with $NaBH_4$–I_2,[24] compound **15** was obtained. The synthesis of **15** was previously reported.[16,27]

On the other hand, deisopropylidenation of **13** afforded **16**. PET deoxygenation and subsequent reduction with $NaBH_4$–I_2 of **16** was a good route to 2-deoxy-L-*xylo*-hexitol (**18**, '5-deoxy-D-glucitol', Scheme 4). During the work up of the deoxygenation reaction of **16** partial glycosylation with the solvent (2-PrOH) occurred, lowering the yield of compound **17** (Table 1, entries 9 and 10). The ^{13}C NMR spectrum of the glycosylated product showed the signals corresponding to C-1 at 109.3 ppm and those of the aglycone at 69.1, 22.7, and 20.7 ppm. We concluded that compounds **9** and **13** would be



Scheme 3. Synthesis of 1,2-di-*O*-isopropylidene-5-deoxy-D-*xylo*-hexofuranose (**15**).



Scheme 4. Synthesis of 2-deoxy-L-*xylo*-hexitol (**18**).

more convenient than **16** as starting material for 5-deoxy glucose derivatives.

The development of specific deoxygenation methods for carbohydrates is important as they are useful not only for enzymatic characterization, but also for the synthesis of natural products from carbohydrate precursors as chiral templates.[27–29] On the other hand, avoiding the use of metal hydrides is desirable from the environmental point of view.[30] For 5-deoxy sugars, several methods have been reported, all of them involving several steps to afford the appropriate furanosic derivative for the deoxygenation step.[17] We investigated here the efficiency of the PET deoxygenation on D-galacturonic acid and D-glucofuranosidurono-6,3-lactone derivatives, showing the effectiveness of the carboxylate ester group for the reduction of the vicinal position, and we used this reaction as the key step for the synthesis of 5-deoxy-D-galacto and glucofuranosides. The straightforward access to furanosyl precursors from uronic acids by the resin catalyzed glycosylation, combined with the regioselectivity on the acylation of glycuronic acids, and the easiness of the deoxygenation, significantly shorten the pathway to 5-deoxy sugars.

3. Experimental section

3.1. General

Thin layer chromatography (TLC) was performed on 0.2 mm Silica Gel 60 F_{254} (Merck) aluminum supported plates. Detection was effected by exposure to UV light and by spraying 10% (v/v) H_2SO_4 in EtOH and charring. Column chromatography was performed on Silica Gel 60 (200–400 mesh, Merck). NMR spectra were recorded with a Bruker AC 200 spectrometer at 200 MHz (^{1}H) and 50.3 MHz (^{13}C) or with a Bruker AM 500 spectrometer at 500 MHz (^{1}H) and 125.8 MHz (^{13}C). Assignments were supported by COSY and HSQC experiments. High resolution mass spectra (HRMS) were recorded on an Agilent LCTOF with Windows XP based OS and APCI/ESI ionization high resolution mass spectrometer analyzer, with Opus V3.1 and DEC 3000 Alpha Station. Melting points were determined with a Fisher–Johns apparatus and are uncorrected. Optical rotations were measured at 25 °C with a Perkin–Elmer 343 polarimeter, with a path length of 1 dm.

3.2. General procedure for PET deoxygenation

In a custom-made Pyrex reaction vessel equipped with a cold finger, a solution containing 0.75 mmol of the substrate, $Mg(ClO_4)_2$ (33 mg, 0.3 mM), and 9-methylcarbazole (13 mg, 0.075 mmol) in 500 mL of 10% deionized water–2-propanol was degassed by bubbling UHP Ar through the solution for 30 min. The solution was photolyzed with a 450 W medium-pressure lamp (λ_{exc} >300 nm), while the temperature was maintained at 25 °C with a circulating water bath. After irradiation for the times indicated in Table 1, the solvent was removed under reduced pressure and the residue was treated as described in each case.

3.2.1. Methyl (methyl β-D-galactofuranosid)uronate (*2*)

A suspension of D-galacturonic acid (1.00 g, 5.15 mmol) in MeOH (20.0 mL) with 1.0 g of Amberlite IR-120H was stirred at 35 °C for 48 h. TLC examination showed a main product with R_f 0.48 (EtOAc, twice development) and a lower moving product (R_f 0.36). After filtration and removal of the solvent under diminished pressure, the residue (1.11 g) was purified by column chromatography (EtOAc–toluene, 49:1). Fractions of R_f 0.48 afforded syrup **2β** (0.71 g, 62%), $[\alpha]_D$ −125 (*c* 1, methanol), lit.[22] $[\alpha]_D$ −112 (*c* 1.38, methanol). ^{1}H NMR (500 MHz, D_2O) δ 4.89 (d, *J*=1.9 Hz, 1H, H-1), 4.50 (d, *J*=2.7 Hz, 1H, H-5), 4.29 (dd, *J*=2.7, 6.5 Hz, 1H, H-4), 4.18 (dd, *J*=3.9, 6.5 Hz, 1H, H-3), 4.03 (dd, *J*=1.9, 3.9 Hz, 1H, H-2), 3.81 (s, 3H, OC*H*$_3$), 3.38 (s, 3H, CO_2CH_3). ^{13}C NMR (50.3 MHz, D_2O) δ 174.2 (C-6), 109.0 (C-1), 84.1, 81.0 (C-2, 4), 76.3 (C-3), 70.0 (C-5), 55.6, 53.5 (2O*C*H$_3$). Fractions of R_f 0.36 afforded methyl (methyl α-D-galactofuranosid)uronate (0.31 g, 28%) with physical and spectroscopic data identical to those reported in the literature.[22]

3.2.2. Methyl (methyl 5-O-(3-trifluoromethyl)benzoyl-β-D-galactofuranosid)uronate (*3*)

To a solution of **2** (0.50 g, 2.25 mmol) in CH_2Cl_2 (10.0 mL) containing pyridine (5 mL), cooled at 0 °C, 3-(trifluoromethyl)benzoyl chloride (0.39 mL, 2.64 mmol) diluted in CH_2Cl_2 (5.0 mL) was added in three aliquots for 1.5 h. After 1 h of stirring at 0 °C, TLC analysis showed a main product of R_f 0.63 (EtOAc–toluene, 9:1) and a minor amount of the starting material. The solution was diluted with CH_2Cl_2 and washed with HCl (5%), water, satd $NaHCO_3$, and water, dried (Na_2SO_4), and concentrated. The syrup obtained was purified by column chromatography (toluene–EtOAc, 3:2). Evaporation of the corresponding fractions afforded **3** (0.70 g, 68%), which gave $[\alpha]_D$ −66 (*c* 1, CH_3OH). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.37–7.58 (4H, C*H*$_{Ar}$), 5.53 (d, *J*=4.2 Hz, 1H, H-5), 4.92 (s, 1H, H-1), 4.48 (apparent t, *J*=4.5 Hz, 1H, H-4), 4.11 (m, 2H, H-2, 3), 3.79 (s, 3H, CO_2CH_3), 3.36 (s, 3H, OC*H*$_3$). ^{13}C NMR (125 MHz, D_2O) δ 168.1 (C-6), 164.8 (*C*OAr), 133.1–122.5 (6C, C_{Ar}), 108.6 (C-1), 83.1 (C-4), 81.1 (C-2), 77.7 (C-3), 72.3 (C-5), 55.2 (O*C*H$_3$), 53.0 (CO_2CH_3). Anal. Calcd for $C_{16}H_{17}F_3O_8$: C, 48.74; H, 4.35. Found: C, 49.01; H, 4.48.

*3.2.3. Methyl (methyl 5-deoxy-β-L-arabino-hexofuranosid)-uronate (**4**)*

Compound **4** was obtained by photolysis of **3** (0.29 g, 0.75 mmol) as described in Section 3.2. After evaporation of the solvent, the residue was partitioned between water and CH_2Cl_2. TLC examination of the aqueous layer showed the deoxygented product (R_f 0.47, EtOAc–toluene, 9:1) and faster moving components (R_f 0.95) corresponding to 9-methylcarbazole and a photoproduct of 9-methylcarbazole. After evaporation under reduced pressure the syrup obtained was purified by column chromatography (EtOAc–toluene, 97:3) to afford 0.102 g (66%) of **4**, R_f 0.40 (EtOAc–toluene, 9:1), $[\alpha]_D$ −68 (*c* 1, $CHCl_3$). ^{1}H NMR (500 MHz, D_2O) δ 4.89 (d, *J*=0.5 Hz, 1H, H-1), 4.30 (m, 1H, H-4), 4.04 (m, 1H, H-2), 3.89 (ddd, *J*=4.4, 5.3, 0.4 Hz, 1H, H-3), 3.73 (CO_2CH_3), 3.36 (OCH_3), 2.86 (dd, *J*=4.4, 16.0 Hz, 1H, H-5), 2.72 (dd, *J*=8.7, 16.0 Hz, 1H, H-5′). ^{13}C NMR (125 MHz, D_2O) δ 174.3 (C-6), 109.1 (C-1), 81.4 (C-4), 80.5 (C-2), 80.2 (C-3), 55.4 (CO_2CH_3), 53.2 (OCH_3), 38.6 (C-5). HRMS (ESI/APCI) calcd for $C_8H_{18}NO_6$: $[M+NH_4]^+$ 224.1929, found: 224.2234.

*3.2.4. Methyl 5-deoxy-α-L-arabino-hexofuranoside (**5**)*

To a suspension of $NaBH_4$ (0.126 g, 3.34 mmol) in dry THF (6.7 mL) at 0 °C under argon atmosphere, a solution of I_2 (0.34 g, 1.34 mmol) in THF (3.2 mL) was added slowly for 1 h. A solution of **4** (0.08 g, 0.38 mmol) in THF (2.0 mL) was then added and the mixture was vigorously stirred under reflux for 1.5 h. Then 5% HCl (2 mL) was carefully added and the mixture was partitioned with $CHCl_3$–H_2O. The aqueous layer was washed with $CHCl_3$ (3×15 mL) in order to remove iodine and deionized by elution with water through a column of IWT® TMD-8, mixed bed ion-exchange resin (1.0×6.0 cm). Evaporation of the solvent under reduced pressure and co-evaporation with methanol (3×5 mL) afforded **5** (0.051 g, 76%), $[\alpha]_D$ −141 (*c* 1, CH_3OH), lit.[16] $[\alpha]_D$ −137 (*c* 1, methanol). ^{1}H NMR (500 MHz, D_2O) δ 4.89 (d, *J*=1.4 Hz, 1H, H-1), 4.03 (m, 2H, H-2, 3), 3.83 (ddd, *J*=0.5, 3.4, 7.1 Hz, 1H, H-4), 3.75 (ddd, *J*=5.7, 6.9, 11.1 Hz, 1H, H-6), 3.71 (ddd, *J*=6.4, 7.4, 11.1 Hz, 1H, H-6′), 3.39 (OCH_3), 1.96 (dddd, *J*=4.8, 7.2, 9.3, 14.2 Hz, 1H, H-5), 1.87 (dddd, *J*=5.7, 6.3, 8.3, 14.2 Hz, 1H, H-5′). ^{13}C NMR (125 MHz, D_2O) δ 108.7 (C-1), 81.6, 81.3 (C-2, 3), 80.8 (C-4), 59.0 (C-6), 55.4 (OCH_3), 35.8 (C-5).

5-Deoxy-L-*arabino*-hexose (**6**) for HPAEC was obtained by hydrolysis of **5** with 40 mM TFA (100 μL) at 100 °C for 1 h, $[\alpha]_D$ −16 (*c* 1, water), lit.[16] $[\alpha]_D$ −18 (*c* 1, water).

*3.2.5. Methyl β-D-glucofuranosidurono-6,3-lactone (**8**)*

A suspension of D-glucuronic-6,3-lactone (**7**, 2.00 g, 1.14 mmol) in MeOH (15.0 mL) with Amberlite IR-120H cation resin (1.25 g) was stirred at 35 °C until TLC examination showed complete conversion of the starting material into a single faster moving product (24 h). The resin was filtered and the filtrate was evaporated under vacuum. NMR examination showed the β/α anomeric mixture in a 4:1 ratio. Recrystallization from $CHCl_3$ afforded the β-anomer **8** (1.54 g, 71%), mp 140–141 °C, $[\alpha]_D$ −52 (*c* 1.1, water), lit.[19] mp 139 °C, $[\alpha]_D$ −56 (*c* 1.4, water). ^{13}C NMR (50 MHz, D_2O) δ 178.0 (C-6), 110.0 (C-1), 84.0 (C-3), 78.6 (C-4), 76.8 (C-2), 69.6 (C-5), 55.9 (OCH_3).

*3.2.6. Methyl 5-O-(3-trifluoromethyl)benzoyl-β-D-glucofuranosidurono-6,3-lactone (**9**)*

To a solution of **8** (0.75 g, 3.96 mmol) in CH_2Cl_2 (7.0 mL) containing pyridine (7.0 mL), cooled at 0 °C, 3-(trifluoromethyl)benzoyl chloride (0.70 mL, 4.64 mmol) was added in three aliquots for 1.5 h. The solution was stirred for an additional 0.5 h at 0 °C and then for 1 h at room temperature. TLC analysis of the syrup showed a main product with R_f 0.33 (toluene–EtOAc, 7:3). The solution was diluted with CH_2Cl_2 and washed with HCl (5%), water, satd $NaHCO_3$, and water, dried ($NaSO_4$), and concentrated. The syrup obtained was purified by column chromatography (toluene–EtOAc, 4:1). Evaporation of the corresponding fractions afforded compound **9** (1.07 g, 75%), which gave $[\alpha]_D$ +33 (*c* 1, $CHCl_3$). ^{1}H NMR (200 MHz, $CDCl_3$) δ 8.44–7.68 (m, 4H, CH_{Ar}), 5.52 (d, *J*=6.8 Hz, 1H, H-5), 5.34 (dd, *J*=4.9, 6.8 Hz, 1H, H-4), 5.02 (d, *J*=4.9 Hz, 1H, H-3), 4.98 (s, 1H, H-1), 4.47 (d, *J*=4.94 Hz, 1H, H-2), 3.38 (s, 3H, OCH_3), 2.56 (d, 1H, OH). ^{13}C NMR (50 MHz, $CDCl_3$) δ 170.1 (C-6), 163.9 (*C*OAr), 133.8–127.2 (6C, Ar), 109.7 (C-1), 83.8 (C-3), 77.5 (C-4), 75.5 (C-2), 70.0 (C-5), 55.7 (OCH_3). Anal. Calcd for $C_{15}H_{13}F_3O_7$: C, 49.73; H, 3.62. Found: C, 50.03; H, 3.59.

*3.2.7. Methyl 5-deoxy-β-D-xylo-hexofuranosidurono-6,3-lactone (**10**)*

Compound **10** was obtained by photolysis of **9** (0.35 g, 0.85 mmol) as described above. After irradiation for 6.5 min, the solvent was removed under reduced pressure and the syrup obtained was purified by column chromatography (toluene–EtOAc, 2:1). Evaporation of fractions with R_f 0.45 (EtOAc) afforded compound **10** (0.16 g, 97%), $[\alpha]_D$ −53 (*c* 1, $CHCl_3$). ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.13 (dd, *J*=5.2, 7.9 Hz, 1H, H-4), 4.94 (s, 1H, H-1), 4.88 (d, *J*=5.2 Hz, 1H, H-3), 4.40 (s, 1H, H-2), 3.35 (s, 3H, OCH_3), 2.82 (dd, *J*=7.9, 18.9 Hz, 1H, H-5), 2.64 (d, *J*=18.9 Hz, 1H, H-5′). ^{13}C NMR (125 MHz, $CDCl_3$) δ 175.9 (C-6), 109.4 (C-1), 86.4 (C-3), 77.6 (C-4), 77.1 (C-2), 55.3 (OCH_3), 37.0 (C-5). HRMS (ESI/APCI) calcd for ($C_7H_{14}NO_5$): $[M+NH_4]^+$ 192.0866, found: 192.0867.

*3.2.8. Methyl 5-deoxy-β-D-xylo-hexofuranoside (**11**)*

Compound **11** was obtained from **10** (0.10 g, 0.57 mmol) by reduction as described for the preparation of **5** with 0.11 g (2.93 mmol) of $NaBH_4$ and 0.23 g (0.91 mmol) of I_2 in THF (4.0 mL). Compound **11** (0.073 g, 72%) gave $[\alpha]_D$ −69 (*c* 1, CH_3OH). ^{1}H NMR (500 MHz, D_2O) δ 4.85 (s, 1H, H-1), 4.37 (ddd, *J*=4.5, 5.7, 8.1 Hz, 1H, H-4), 4.12 (d, *J*=1.6 Hz, 1H, H-2), 4.10 (dd, *J*=1.6, 4.5 Hz, 1H, H-3), 3.75 (m, 1H, H-6), 3.73 (m, 1H, H-6′), 3.37 (s, 3H, OCH_3), 1.89 (m, 2H, H-5, 5′). ^{13}C NMR (125 MHz, D_2O) δ 109.2 (C-1), 80.5 (C-2, 4), 75.9 (C-3), 59.5 (C-6), 55.9 (OCH_3), 32.5 (C-

5). Anal. Calcd for $C_7H_{14}O_5$: C, 47.18; H, 7.92. Found: C, 47.25; H 7.82.

3.2.9. 1,2-Di-O-isopropylidene-5-O-(3-trifluoromethyl)-benzoyl-α-D-glucofuranosidurono-6,3-lactone (**13**)

Compound **13** was obtained by reacting **12** (1.30 g, 6.15 mmol)[26] with 3-(trifluoromethyl)benzoyl chloride (1.10 mL, 7.20 mmol) in CH_2Cl_2 (15.0 mL) containing pyridine (7.5 mL) at 0 °C for 1 h. After the work up as used for **9**, the syrup was purified by column chromatography (toluene–EtOAc, 95:5) and evaporation of the fractions of R_f 0.65 (hexane–EtOAc, 3:1) gave **13** (1.97 g, 82%), mp 102–103 °C, $[\alpha]_D$ +62 (*c* 1, $CHCl_3$). ^{1}H NMR (200 MHz, $CDCl_3$) δ 8.42–7.15 (4H, CH_{Ar}), 6.06 (dd, ^4J=0.5 Hz, *J*=3.7 Hz, 1H, H-1), 5.76 (d, *J*=4.4 Hz, 1H, H-5), 5.20 (ddd, ^4J=0.5 Hz, *J*=2.9, 4.4 Hz, H-4), 4.97 (d, *J*=2.9 Hz, 1H, H-3), 4.89 (d, *J*=3.7 Hz, 1H, H-2), 1.52, 1.36 (2s, 6H, C(CH_3)$_2$). ^{13}C NMR (50.3 MHz, $CDCl_3$) δ 169.2 (C-6), 165.5 (COAr), 113.6 (*C*(CH$_3$)$_2$), 107.0 (C-1), 82.6, 82.3 (C-2, 3), 77.0 (C-4), 70.6 (C-5), 26.9, 26.5 (C(*C*H$_3$)$_2$). Anal. Calcd for $C_{17}H_{15}F_3O_7$: C, 52.58; H, 3.89. Found: C, 52.46; H, 4.05.

3.2.10. 1,2-Di-O-isopropylidene-5-deoxy-α-D-xylo-hexofuranosidurono-6,3-lactone (**14**)

Compound **14** was obtained by photolysis of **13** (0.29 g, 0.75 mmol) as described in Section 3.2. After evaporation of the solvent, the syrup obtained was purified by column chromatography (toluene–EtOAc, 8:1). Evaporation of fractions with R_f 0.60 (hexane–EtOAc, 1:1) afforded compound **14** (0.09 g, 90%), mp 89–90 °C, $[\alpha]_D$ +73 (*c* 1, $CHCl_3$), lit.[28] mp 90–92 °C. ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.97 (d, *J*=3.8 Hz, 1H, H-1), 5.00 (dd, *J*=3.3, 4.2 Hz, 1H, H-4), 4.84 (d, *J*=3.8 Hz, 1H, H-2), 4.81 (d, *J*=3.3 Hz, 1H, H-3), 2.75 (d, *J*=18.0 Hz, 1H, H-5), 2.70 (dd, *J*=4.2, 18.0 Hz, 1H, H-5′), 1.52, 1.35 (2s, 6H, C(CH_3)$_2$). ^{13}C NMR (125 MHz, $CDCl_3$) δ 174.2 (C-6), 112.7 (*C*(CH$_3$)$_2$), 106.2 (C-1), 85.5 (C-3), 82.4 (C-2), 77.9 (C-4), 35.8 (C-5), 26.9, 26.5 (C(*C*H$_3$)$_2$). HRMS (ESI/APCI) calcd for ($C_9H_{16}NO_5$): $[M+NH_4]^+$ 218.1023, found: 218.1025.

3.2.11. 1,2-Di-O-isopropylidene-5-deoxy-D-xylo-hexofuranose (**15**)

Compound **14** (0.16 g, 0.80 mmol) was reduced with the I_2–$NaBH_4$ system,[24] as described for the synthesis of **5**, using 0.076 g (2.0 mmol) of $NaBH_4$ and 0.203 g (0.8 mmol) of I_2 in THF (5.0 mL). After the work up, compound **15** (0.104 g, 64%) was obtained, $[\alpha]_D$ −10 (*c* 1, water), mp 91–92 °C, lit.[9] $[\alpha]_D$ −10.5 (*c* 1.7, chloroform), mp 93–94.5 °C. ^{1}H NMR (500 MHz, D_2O) δ 5.98 (d, *J*=3.9 Hz, 1H, H-1), 4.68 (d, *J*=3.9 Hz, 1H, H-2), 4.30 (apparent dt, *J*=2.6, 6.8 Hz, 1H, H-4), 4.14 (d, *J*=2.6 Hz, 1H, H-3), 3.71 (m, 2H, H-6, 6′), 1.88 (q, *J*=6.7 Hz, 2H, H-5, 5′), 1.51, 1.35 (2s, 6H, C(CH_3)$_2$). ^{13}C NMR (125 MHz, D_2O) δ 112.9 (*C*(CH$_3$)$_2$), 104.6 (C-1), 85.2 (C-2), 78.8 (C-4), 75.1 (C-3), 59.3 (C-6), 30.6 (C-5), 26.0, 25.6 (C(*C*H$_3$)$_2$).

3.2.12. 5-O-[3-(Trifluoromethyl)benzoyl]-β-D-glucofuranosidurono-6,3-lactone (**16β**)

A solution of **13** (2.07 g, 5.33 mmol) in AcOH–H_2O (4:1, 15 mL) with H_2SO_4 (72 μL, 1.3 mmol) was heated under reflux for 1.5 h. The mixture was concentrated under diminished pressure and the syrup obtained was crystallized from water. It was filtered and thoroughly washed. ^{1}H NMR spectrum of this product showed the β-anomer with traces of the α-anomer. Recrystallization from $CHCl_3$ gave pure **16β** (1.15 g, 87%), mp 162–164 °C, $[\alpha]_D$ +64 (*c* 1, acetone). ^{1}H NMR (500 MHz, DMSO-d_6) δ 6.74 (d, *J*=4.0 Hz, 1H, OH), 5.75 (d, *J*=6.8 Hz, 1H, H-5), 5.71 (d, *J*=4.0 Hz, 1H, OH), 5.18 (d, J=4.0 Hz, 1H, H-1), 5.04 (dd, *J*=4.8, 6.8 Hz, 1H, H-4), 4.92 (d, *J*=4.8, 1H, H-3), 4.07 (d, *J*=4.0 Hz, 1H, H-2). ^{13}C NMR (50.3 MHz, DMSO-d_6) δ 171.3 (C-6), 163.8 (COAr), 103.6 (C-1), 85.1 (C-3), 77.5 (C-4), 75.6 (C-2), 70.8(C-5). Anal. Calcd for $C_{14}H_{11}F_3O_7$: C, 48.29; H, 3.18. Found: C, 48.34; H, 3.26.

3.2.13. 5-Deoxy-α,β-D-xylo-hexofuranosidurono-6,3-lactone (**17**)

Compound **17** was obtained by photolysis of **16** (0.26 g, 0.75 mmol) as described in Section 3.2. After evaporation of the solvent, the residue was partitioned between water and CH_2Cl_2. The aqueous layer was concentrated and purified by column chromatography (EtOAc–toluene, 99:1) to afford 0.078 g (65%) of **17** (R_f 0.38, 9:1 EtOAc–toluene) as a β/α mixture in 5:1 ratio. ^{1}H NMR (500 MHz, D_2O) data for **17β** δ 5.42 (s, 1H, H-1), 5.18 (dd, *J*=5.3, 7.7 Hz, 1H, H-4), 4.04 (d, *J*=5.3 Hz, 1H, H-3), 4.37 (s, 1H, H-2), 3.06 (dd, *J*=7.7, 19.2 Hz, 1H, H-5), 2.75 (d, *J*=19.2 Hz, 1H, H-5′). Selected signals for the α-anomer δ 5.50 (d, *J*=4.0 Hz, 1H, H-1), 3.01 (dd, *J*=6.5, 18.9 Hz, 1H, H-5), 2.71 (d, *J*=18.9 Hz, 1H, H-5′). ^{13}C NMR (125 MHz, D_2O) for **17β** δ 180.1 (C-6), 102.8 (C-1), 87.8 (C-3), 78.6, 77.2 (C-2, 4), 38.1 (C-5). For **17α** δ 179.7 (C-6), 97.5 (C-1), 89.2 (C-3), 75.9, 75.6 (C-2, 4), 36.1 (C-5). HRMS (ESI/APCI) calcd for ($C_6H_4NO_5$): $[M+NH_4]^+$ 178.0715, found: 178.0714.

3.2.14. 2-Deoxy-L-xylo-hexitol (**18**, '5-deoxy-β-D-glucitol')

Compound **17** (0.10 g) was reduced with $NaBH_4$ (0.12 g, 3.08 mmol) and I_2 (0.31 g, 1.23 mmol) in THF (5.0 mL) as described for the preparation of **4**. After the work up compound **18** (0.066 g, 63%) gave R_f 0.33 (*n*-PrOH–NH_3–H_2O, 7:0.5:0.5), $[\alpha]_D$ +14 (*c* 1, CH_3OH). ^{1}H NMR (500 MHz, D_2O) δ 3.81 (m, 2H, H-2, 4), 3.70 (m, 3H, H-1, 6, 6′), 3.62 (dd, *J*=6.8, 11.7 Hz, 1H, H-1′), 3.49 (t, *J*=4.5 Hz, 1H, H-3), 1.78 (m, 2H, H-5, 5′). ^{13}C NMR (125 MHz, D_2O) δ 74.1 (C-4), 72.6 (C-5), 69.3 (C-3), 63.3 (C-6), 59.1 (C-1), 35.8 (C-2). Anal. Calcd for $C_6H_{14}O_5$: C, 43.37; H, 8.49. Found: C, 43.18; H, 8.63.

3.2.15. HPAEC–PAD analysis

Analysis by HPAEC–PAD was performed using a Dionex DX 300 HPLC system with pulse amperometric detection (PAD), set at 30 nA and E_1=+0.05 V, E_2=+0.60 V, and E_3=−0.60 V. The column used was a CarboPac MA-10

anion-exchange analytical column (4×250 mm), equipped with a guard column MA-10 (4×50 mm). The separations were performed isocratically at 0.6 M NaOH, at a flow rate of 0.4 mL min^{-1}: t_r for **4**=28.8 min; t_r for **5**=13.7 min, t_r for **6**=24.1 min.

Acknowledgements

This work was supported by grants from Fundación Antorchas, Universidad de Buenos Aires, Agencia Nacional de Promoción Científica y Tecnológica and CONICET. R.M.L. and C.M. are research members of CONICET, and A.B. was supported by a fellowship from CONICET.

Supplementary data

Copies of the ^{1}H and ^{13}C NMR spectra for all new compounds. Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2007.12.005.

References and notes

1. Lederkremer, R. M.; Colli, W. *Glycobiology* **1995**, *5*, 547–552.
2. Houseknecht, J. B.; Lowary, T. L. *Curr. Opin. Chem. Biol.* **2003**, *7*, 677–682.
3. Pedersen, L. L.; Turco, S. J. *Cell. Mol. Life Sci.* **2003**, *60*, 259–266.
4. Mariño, K.; Marino, C.; Lima, C.; Baldoni, L.; Lederkremer, R. M. *Eur. J. Org. Chem.* **2005**, 2958–2964.
5. Mariño, K.; Baldoni, L.; Marino, C. *Carbohydr. Res.* **2006**, *341*, 2286–2289 and references therein.
6. Chiocconi, A.; Marino, C.; Otal, E.; Lederkremer, R. M. *Carbohydr. Res.* **2002**, *337*, 2119–2126.
7. Marino, C.; Chiocconi, A.; Varela, O.; Lederkremer, R. M. *Carbohydr. Res.* **1998**, *311*, 183–189.
8. Chiocconi, A.; Marino, C.; Lederkremer, R. M. *Carbohydr. Res.* **2000**, *323*, 7–13.
9. Klausener, A.; Müller, E.; Runsink, J.; Scharf, H.-D. *Carbohydr. Res.* **1983**, *116*, 295–302.
10. Portella, C.; Deshayes, H.; Pete, J. P.; Scholler, D. *Tetrahedron* **1984**, *40*, 3635–3644.
11. Saito, I.; Ikehira, H.; Kasatani, R.; Watanabe, M.; Matsuura, T. *J. Am. Chem. Soc.* **1997**, *62*, 8257–8260.
12. Jütten, P.; Scharf, H.-D. *J. Carbohydr. Chem.* **1990**, *5*, 675–681.
13. Park, M.; Rizzo, C. J. *J. Org. Chem.* **1996**, *61*, 6092–6093; Prudhomme, D. R.; Wang, Z.; Rizzo, C. J. *J. Org. Chem.* **1997**, *62*, 8257–8260; Wang, Z.; Prudhomme, D. R.; Buck, J. R.; Park, M.; Rizzo, C. J. *J. Org. Chem.* **2000**, *65*, 5969–5985.
14. Bordoni, A.; Lederkremer, R. M.; Marino, C. *Carbohydr. Res.* **2006**, *341*, 1788–1795.
15. Wolfrom, M. L.; Matsuda, K.; Komitsky, F., Jr.; Whiteley, T. E. *J. Org. Chem.* **1963**, *28*, 3551–3553.
16. Szarek, W. A.; Ritchie, R. G. S.; Vyas, D. M. *Carbohydr. Res.* **1978**, *62*, 89–103.
17. Lederkremer, R. M.; Marino, C. *Adv. Carbohydr. Chem. Biochem.* **2007**, *61*, 143–216.
18. Lederkremer, R. M.; Marino, C.; Varela, O. *Carbohydr. Res.* **1990**, *200*, 227–235.
19. Cadotte, J. E.; Smith, F.; Spriestersbach, D. *J. Am. Chem. Soc.* **1952**, *74*, 1501–1504.
20. Bertho, J. N.; Ferrières, V.; Plusquellec, D. *J. Chem. Soc., Chem. Commun.* **1995**, 1391–1393; Ferrières, V.; Bertho, J.-N.; Plusquellec, D. *Carbohydr. Res.* **1998**, *311*, 25–35.
21. Choudhury, A. K.; Roy, N. *Synlett* **1997**, 105–106.
22. Matsuhiro, B.; Zanlungo, A. B.; Dutton, G. G. S. *Carbohydr. Res.* **1981**, *97*, 11–18.
23. Banfi, L.; Narisano, E.; Riva, R. *Handbook of Reagents for Organic Synthesis. Oxidizing and Reducing Agents*; Burke, S. D., Danheiser, R. L., Eds.; Wiley and Sons: Chichester, UK, 1999; pp 394–400.
24. Bhanu Prasad, S.; Bhaskar Kanth, J. V.; Periasamy, M. *Tetrahedron* **1992**, *48*, 4623–4628.
25. Stanford, D.; Stachulski, A. V. *Tetrahedron Lett.* **2007**, *48*, 2361–2364.
26. Bashyal, B. P.; Chow, H.-F.; Fellows, L. E.; Fleet, G. W. J. *Tetrahedron* **1987**, *43*, 415–422.
27. Ye, J.; Bhatt, R. K.; Falk, J. R. *Tetrahedron Lett.* **1993**, *34*, 8007–8010.
28. Choi, H.-w.; Demeke, D.; Kang, F.-A.; Kishi, Y.; Nakajima, K.; Nowak, P.; Wan, Z.-K.; Xie, C. *Pure Appl. Chem.* **2003**, *75*, 1–17.
29. Matsuura, D.; Takabe, K.; Yoda, H. *Tetrahedron Lett.* **2006**, *47*, 1371–1374.
30. Spiegel, D. A.; Wiberg, K. B.; Schacherer, L. N.; Madeiros, M. R.; Wood, J. L. *J. Am. Chem. Soc.* **2005**, *127*, 12513–12515.