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Photoinduced electron-transfer α-deoxygenation of aldonolactones. Efficient synthesis of 2-deoxy-D-*arabino* hexono-1,4-lactone

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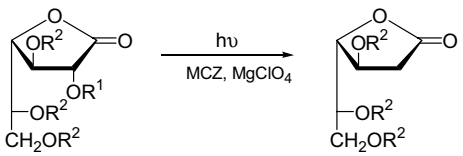
Abstract—A photoinduced electron-transfer (PET) reaction was used for the deoxygenation at C-2 of aldonolactones derivatized as 2-*O*-[3-(trifluoromethyl)benzoyl] or benzoyl esters. By irradiation of different D-galactono- and D-glucono-1,4-derivatives, with a 450 W lamp, using 9-methylcarbazole as photosensitizer, the corresponding 2-deoxy-D-*lyxo*- and 2-deoxy-D-*arabino*-hexono-1,4-lactones were efficiently obtained.

Keywords: Deoxy sugars; Aldonolactone photodeoxygenation; 2-Deoxy-D-*arabino*-1,4-lactone; 2-Deoxy-D-*lyxono*-1,4-lactone

1. Introduction

In connection with our project on the specificity of the enzyme, *exo*-β-D-galactofuranosidase, we developed strategies for the synthesis of 2-, 3-, and 6-deoxygenated galactofuranosides in order to establish the importance of each hydroxyl group in the interaction with the enzyme.[1–3] We showed that the *exo*-β-D-galactofuranosidase (EC 3.2.1.146) from *Penicillium fellutanum* has a strict selectivity for the glycon structure and that the hydroxyl groups at C-2, C-3, and C-6 of the substrate are essential for the interaction with the enzyme. For the synthesis of the deoxygenated analogues, we have used D-galactono-1,4-lactone, a convenient precursor of the furanosic sugar, which offers the possibility of regioselective acylation.[4,5] Particularly, for the synthesis of 2-deoxy-D-*lyxo*-hexofuranosides (2-deoxy-D-galactofuranosides), the deoxygenation step was performed via a photoinduced electron-transfer (PET) reaction on 2-*O*-[3-(trifluoromethyl)benzoyl]-D-galactono-1,4-lactone (**1a**) using 9-methylcarbazole as the photosensitizer (Scheme 1).[1] This reaction was first used for the synthesis of 2-deoxyribonucleosides[6–8] and for the deoxygenation of a disaccharide analogue of moenomycin A.[9] Surprisingly, the reaction conditions necessary for the deoxygenation of compound **1a** were extremely mild compared with those required for the ribonucleosides. While such derivatives needed several hours of irradiation at 400 W,[6,8] the lactone derivative **1a** was deoxygenated in 1 h using a 120-W medium-pressure lamp.[1] The effectiveness of this reaction on lactone derivatives should be due to the stabilization of the intermediate radical by the vicinal carbonyl group.



1a $R^1 = COC_6H_4(3\text{-}CF_3)$, $R^2 = H$
1b $R^1 = COC_6H_4(3\text{-}CF_3)$, $R^2 = Bz$
1c $R^1 = R^2 = Bz$

2a $R^2 = H$
2b $R^2 = Bz$

Scheme 1.

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The development of specific deoxygenation methods for sugars is important for the preparation of biologically important sugars from readily available precursors. Among a variety of methods for carbohydrate deoxygenation, tin radical cleavage of thiono esters developed by Barton and McCombie has been widely used.[10] However, avoiding the use of reagents based on tin hydrides and thiocarbonyl compounds is desirable from the environmental and economical point of view, and an alternative procedure has been recently developed.[11]

We have now optimized the PET reaction for other derivatives of D-galactono- and extended the reaction to derivatives of D-glucono-1,4-lactone with the aim to establish an efficient protocol for deoxygenation at C-2.

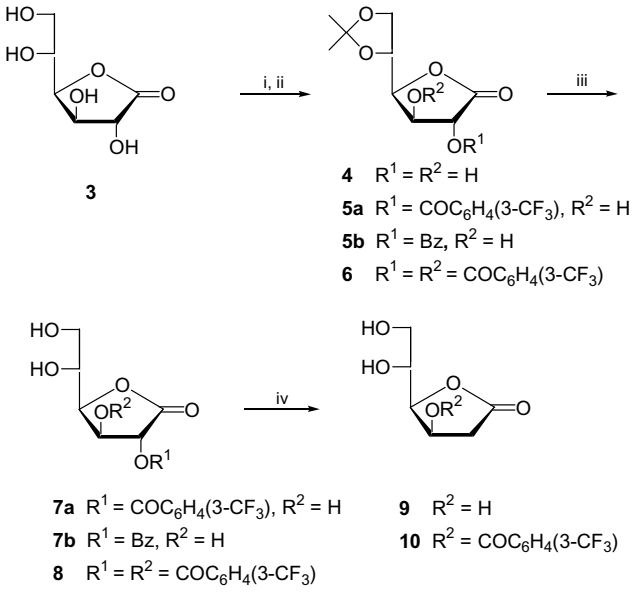
2. Result and discussion

2.1. Preparation of partially acylated derivatives of D-galactono- and D-glucono-1,4-lactones

D-Galactono-1,4-lactone derivatives **1a**–**c** (Scheme 1) were prepared as previously reported.[1,12] The photochemical deoxygenation of partially protected derivatives of D-glucono-1,5-lactone was unsuccessful because complex mixtures were obtained in which open-chain, and 1,4- and 1,5-lactone derivatives were present, as observed by FTIR and NMR spectroscopy. The contraction to the1,4-lactone isomers was the predominant reaction. We then studied the photoinduced deoxygenation reaction using derivatives of the more stable 1,4-lactone **3**, obtained by refluxing a solution of commercial 1,5-lactone in 2-methoxyethanol–HCl.[13]

All the derivatives of lactone **3** were prepared at low temperature, and acylations were performed under mildly basic conditions in order to minimize β-elimination reactions.[14] For the synthesis of monoacylated derivatives **7a** and **7b** (Scheme 2), the sequence previously used for analogue **1a** was applied.[1] Treatment of lactone **3** with 2,2-dimethoxypropane in acetone with H_2SO_4 as catalyst gave a better yield (85%) than that previously reported for compound **4** (Scheme 2).[13] Treatment of **4** with 1.2 equiv of either 3-(trifluoromethyl)benzoyl or benzoylchloride afforded compounds **5a** or **5b**, while with an excess of reagent, compound **6** was obtained. NMR spectroscopic data for compounds **5a**,**b** and **6** are shown in Tables 1 and 2. Doublets corresponding to H-2 are the lowest field signals for **5a**,**b**. For compound **6**, the signal corresponding to H-3 was shifted from 4.74 to 6.11 ppm, in comparison with **5a**, as effect of acylation at HO-3.

Treatment of **5a**,**b** and **6** with acetic acid led to compounds **7a**,**b** and **8** (Scheme 2). The corresponding upfield shift of the signals for H-6, 6′, and 5 were observed in the ^{1}H NMR spectra (Table 1).



Scheme 2. Reagents and conditions: (i) 2,2-dimethoxypropane–acetone, H^+; (ii) $(3\text{-}CF_3)C_6H_4COCl$ or BzCl, Py, 0 °C; (iii) 4:1 AcOH–H_2O, 65 °C; (iv) 9-methylcarbazole, $Mg(ClO_4)_2$, 9:1 *n*-PrOH–H_2O, *hv*.

The 2,6-disubtituted derivatives of aldohexonolactones are easily obtained due to the enhanced reactivity of the HO-6, primary, and the HO-2, activated by the vicinal carbonyl lactone group.[4] Thus, treatment of **3** with 2.2 equiv of 3-(trifluoromethyl)benzoyl chloride led to derivative **11** (Scheme 3), isolated from the crude mixture as a crystalline product from toluene in 51% yield. The structure of **11** was confirmed on the basis of the NMR data (Tables 1 and 2). The signal for H-2 was shifted downfield (4.52 to 5.65 ppm) in comparison to that of lactone **3**.

Signals for C-2 and C-6 were shifted downfield with respect to those of lactone **3**, and signals corresponding to the β-carbon atoms (C-1,3 and 5) were shifted upfield on acylation of HO-2 and 6, in accordance with previous reports.[4]

Compound **11** was acetylated to afford **12**. The ^{1}H NMR spectrum of **12** showed significant downfield shifts (>1 ppm) for the H-3,5 signals with respect to **11**, as expected for acylation of HO-3 and HO-5.

Treatment of **3** with an excess of 3-(trifluoromethyl)benzoylchloride led to peracylated derivative **15** (Scheme 4). The ^{1}H NMR spectrum of **15** was completely assigned and resembled that of the per-O-acetylated analogue. The signal for H-3 was the lowest-field signal (Table 1), as previously observed.[15]

2.2. Photoinduced deoxygenation of aldonolactone derivatives

Saito et al. have studied the photoinduced electron-transfer (PET) deoxygenation of alcohols derivatized

Table 1. ^{1}H NMR (500 MHz) chemical shifts and $J_{H,H}$ coupling constants value for compounds **5**–**16**

Compd	H-2	H-2′		H-3	H-4	H-5	H-6	H-6′
	($J_{2,3}$)	($J_{2',3}$)	($J_{2,2}$)	($J_{3,4}$)	($J_{4,5}$)	($J_{5,6}$)	($J_{6,6'}$)	($J_{5,6'}$)
5a[a]	5.42			4.74	4.65	4.51	4.22	4.11
	(4.6)			(6.0)	(7.3)	(6.5)	(9.1)	(4.6)
5b[a]	5.42			4.69	4.65	4.49	4.20	4.10
	(3.8)			(5.7)	(7.2)	(6.3)	(9.1)	(4.9)
6[a]	5.99			6.11	4.90	4.51	4.21	4.06
	(6.6)			(6.8)	(8.1)	(6.5)	(9.1)	(5.1)
7a[a]	5.62			4.86[d]	4.73[d]	4.18	3.93	3.88
	(5.6)			—	—	(3.7)	(11.6)	(5.1)
7b[b]	5.29			3.99[d]	3.77[d]	4.14	3.73	3.66
	(8.8)					(2.2)	(12.4)	(3.1)
8[a]	5.90			6.07	5.02	(4.12)	(3.85)	3.89
	(4.9)			(6.0)	(7.6)	(3.6)	(11.1)	(5.1)
9[c]	3.01	2.53		4.66	4.44	3.98	3.80	3.66
	(5.3)	(<0.5)	(18.3)	(3.6)	(9.2)	(2.7)	(12.2)	(5.3)
10[a]	3.07	2.79		5.92	4.62	3.98	3.92	3.85
	(5.4)	(<0.5)	(18.3)	(3.6)	(9.4)	(2.8)	(11.7)	(4.5)
11[a]	5.65			4.89	4.79	4.47	4.72	4.68
	(5.9)			(6.9)	(~6.2)	(3.7)	(12.1)	(6.1)
12[a]	5.52			5.84	5.17	5.60	4.87	4.47
	(3.7)			(5.8)	(8.2)	(2.9)	(12.4)	(5.5)
13[a]	2.76	2.63		4.76	4.81	4.58	4.39[e]	4.39[e]
	(5.9)	(0.5)	(17.9)	(2.6)	(12.3)	(4.9)	(—)	(4.9)
14[a]	2.94	2.60		5.67	4.74	5.49	4.89	4.43
	(5.5)	(<0.5)	(18.3)	(3.6)	(9.5)	(2.2)	(12.5)	(5.2)
15[a]	5.96			6.26	5.49	5.97	5.06	4.66
	(6.04)			(6.8)	(9.3)	(2.9)	(12.5)	(5.1)
16[a]	3.14	2.86		5.99	5.11	5.91	5.05	4.98
	(5.9)	(1.2)	(18.6)	(4.2)	(7.6)	(2.6)	(12.6)	(4.9)

[a] $CDCl_3$.
[b] Me_2SO-d_6.
[c] D_2O.
[d] Interchangeable.
[e] Center of a complex multiplet.

as benzoate esters using 9-methylcarbazole (MCZ) in stoichiometric amounts as photosensitizer.[16] The reaction took place efficiently with 3-(trifluoromethyl)benzoates as substrates in 9:1 *i*-PrOH–H_2O as solvent. The reaction mechanism, the influence of the solvent, and the role of $MgClO_4$, have been studied.[6–8,16]

The reaction was successfully used for the deoxygenation of ribonucleosides at positions 2′ or 3′, depending on the derivative used, and it has been used as the key step in a stereocontrolled de novo synthesis of 2′-deoxynucleosides.[6] Irradiation times between 7 and 15 h were required for conversion of the starting material into the deoxygenated photoproducts, which were isolated from the photolysis reaction in 44–73% yield. They improved the method by using synthetic 3,6-dimethyl-9-ethylcarbazole (DMECZ) as the electron donor. This photosensitizer showed both turnover and improved reactivity. When used at levels of 10–15 mol %, the deoxygenated products resulted after 2 h of irradiation.[7]

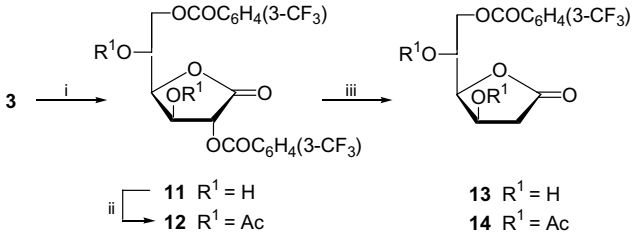
In our previous work for the synthesis of 2-deoxy-D-*lyxo*-hexono-1,4-lactone (**2a**, Scheme 1), derivative **1a** was irradiated during 1 h with a 120-W lamp in the presence of MCZ at 10 mol %. Compound **2a** was obtained in 88% yield (Table 3, entry 1). Deoxygenation of the peracylated derivative **1b**, required 3 h of irradiation for consumption of the starting lactone (as monitored by TLC). However, a complex reaction mixture was obtained due to the long reaction time, from which compound **2b** was isolated by column chromatography in low yield (Table 3, entry 2).[1]

The reaction was improved by using a 450-W lamp, which allowed one to diminish the irradiation time, minimizing decomposition. Under these conditions, we observed complete disappearance of the starting lactones

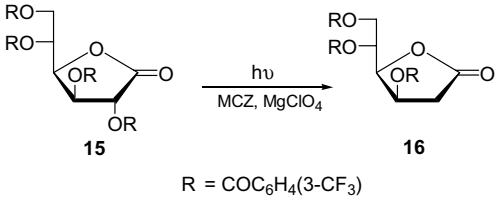
Table 2. ^{13}C NMR chemical shifts (125 or 50 MHz) for compounds **5**–**16**

Compd	C-1	C-2	C-3	C-4	C-5	C-6
5a[a]	169.7	75.5	73.4[d]	79.9	72.2[d]	66.6
5b[a]	170.2	75.4	73.3[d]	80.3	72.2[d]	66.6
6[a]	168.1	73.3	72.7[d]	77.6	71.8[d]	66.6
7a[a]	170.7	75.2	72.1[d]	79.2	71.2[d]	62.9
7b[b]	171.5	74.4	72.2[d]	79.9	71.4[d]	62.5
8[a]	168.8	73.8	72.3	77.6	71.0	62.8
9[c]	180.1	39.5	68.6[d]	83.5	68.4[d]	63.7
10[a]	173.8	36.8	71.4[d]	80.4	68.0[d]	63.4
11[a]	169.2	76.1	73.1[d]	78.1	70.3[d]	66.3
12[a]	169.1	72.7	70.8[d]	76.4	67.6[d]	63.2
13[a]	171.5	38.3	67.9[d]	81.4	66.9[d]	60.5
14[a]	172.9	36.4	68.3[d]	78.3	67.0[d]	63.6
15[a]	170.6	72.4	71.8[d]	74.6	69.0[d]	63.2
16[a]	172.3	36.2	69.9[d]	78.0	68.6[d]	63.6

[a] $CDCl_3$.
[b] Me_2SO-d_6.
[c] D_2O.
[d] Interchangeable.



Scheme 3. Reagents and conditions: (i) 2.2 equiv $(3\text{-}CF_3)C_6H_4COCl$, Py, 0 °C; (ii) 1:1 Ac_2O, Py, 0 °C; (iii) 9-methylcarbazole, $Mg(ClO_4)_2$, 9:1 *n*-PrOH–H_2O, *hν*.



Scheme 4.

in 3 min. Thus, photolysis of compound **1b** afforded selectively **2b** in 73% yield (Table 3, entry 3), and complete deoxygenation of **1a** occurred in a comparable yield (Table 3, entry 4).

With the purpose of comparing the efficiency between benzoyl and 3-(trifluoromethyl)benzoyl groups as subtituents for the deoxygenation reaction, derivative **1c**[12] (Scheme 1) was also irradiated. Entry 5 (Table 3) shows that the reaction requires longer irradiation times with benzoyl than with 3-(trifluoromethyl)benzoyl esters. However, the less expensive benzoyl esters can be satisfactorily used to obtain derivatives like **2b**.

For deoxygenation of the 2-O-benzoylated derivative **7b** (Scheme 2), more than 6 min were required (Table 3, entries 6 and 7), whereas the 3-(trifluoromethyl)-benzoyl analogue **7a** showed total conversion to **9** in 3 min (Table 3, entry 8). Lactone **9** was previously prepared in several steps from tri-*O*-acetyl-D-glucal,[17] and later it was isolated in very low yield from the γ-radiolysis products of D-glucose.[18]

Saito et al. reported that secondary OH could be selectively reduced in the presence of primary OH, upon 15 h irradiation of the corresponding 3-(trifluoromethyl)benzoyl esters at 400 W.[16] In lactone derivatives, we now observed that the 2,6-substituted derivative **11** was selectively deoxygenated at C-2 upon only 3 min of irradiation due to the assistance of the carbonyl group (Scheme 3 and Table 3, entry 9). Recovery of compound **13** from the column chromatography was low (23%); thus acetylation was performed (compound **12**) previous to photodeoxygenation, which considerably improved the yield (**14**, 67%, Table 3, entry 10).

The carbonyl-assisting effect for the PET reaction on secondary hydroxyl groups could be confirmed by selective deoxygenation at C-2 of derivative **8** to give **10** (Scheme 3 and Table 3, entry 11). Moreover, when the other secondary OH groups are substituted as in compound **15**, the 2-*O*-(3-trifluoromethyl)benzoyl group is selectively deoxygenated (Table 3, entry 12). This feature of the PET reaction is not shared by the Barton–McCombie deoxygenation, by which a bis-xanthate would give a C-2–C-3 olefin.[19]

The identity of compounds **9**, **10**, **13**, **14**, and **16** was established on the basis of their NMR spectra. The presence of two doublets of doublets at high fields (δ 3.00 and 2.50, Table 1), with a large J_{gem} (~18.0 Hz) in the ^1H NMR spectra, and the signal corresponding to the deoxy function (C-2) at ~39.0 ppm in the ^{13}C NMR spectra (Table 2), were diagnostic for deoxygenation.

Table 3. Photoinduced deoxygenation of aldono-1,4-lactone derivatives

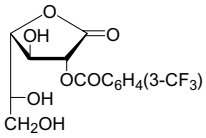
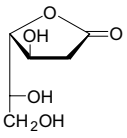
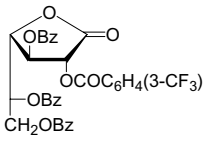
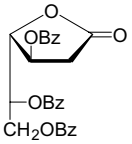
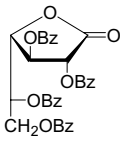
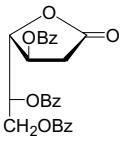
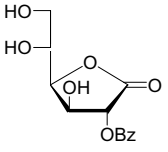
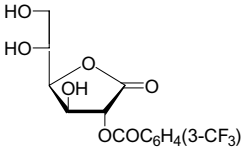
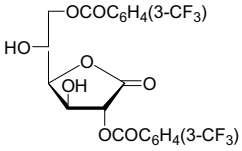
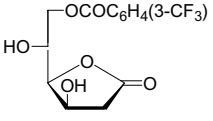
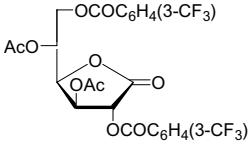
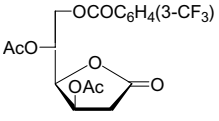
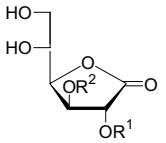
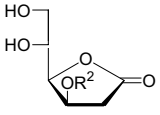
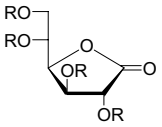
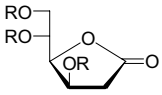
Entry	Compd	Product	Watts	Time (min)	Conversion[a] (%)	Yield[b] (%)
1	 **1a**	 **2a**	120	60	100	88[l]
2	 **1b**	 **2b**	120	180	100	20[l]
3	**1b**	**2b**	450	3	100	73
4	**1a**	**2a**	450	3	100	76
5	 **1c**	 **2b**	450	10	68	36
6	 **7b**	**9**	450	3	16	10
7	**7b**	**9**	450	6	68	46
8	 **7a**	**9**	450	3	100	70
9	 **11**	 **13**	450	3	100	23
10	 **12**	 **14**	450	3	100	67

Table 3 (*continued*)

Entry	Compd	Product	Watts	Time (min)	Conversion[a] (%)	Yield[b] (%)
11	 **8** R = $COC_6H_4(3\text{-}CF_3)$	 **10**	450	3	100	59
12	 **15** R = $COC_6H_4(3\text{-}CF_3)$	 **16**	450	3	100	78

[a] Conversion was determined by NMR spectroscopy.
[b] Yield refers to isolated pure products after column chromatography.

In conclusion, the PET deoxygenation reaction on aldonolactones that are conveniently derivatized allows selective deoxygenation at C-2. Conditions for the deoxygenation of D-glucono and D-galactono-1,4-lactone derivatives were optimized, and the selectivity for the vicinal position to the carbonyl group was confirmed. The effectiveness of this strategy lies in the easy preparation of partially substituted aldonolactones, together with the carbonyl-assisting effect for the PET reaction. The unique reactivity of the aldonolactone allows for the 9-methylcarbazole (MCZ) to turn over, and it can be used in 10 mol %. The 2-deoxy-aldonolactones are good precursors for the synthesis of 2-deoxy sugar derivatives that are useful for studies on enzyme inhibition.[1]

3. Experimental

3.1. General procedures

Thin-layer chromatography (TLC) was performed on 0.2-mm Silica Gel 60 F_{254} (Merck) aluminum-backed plates. Detection was effected by exposure to UV light and by spraying with 10% (v/v) H_2SO_4 in EtOH, and charring. Column chromatography was performed on Silica Gel 60 (200–400 mesh, E. Merck). NMR spectra were recorded with a Bruker AC 200 spectrometer at 200 MHz (^1H) and 50 MHz (^{13}C) or with a Bruker AM 500 spectrometer at 500 MHz (^1H) and 125 MHz (^{13}C). The assignments are listed in Tables 1 and 2. High-resolution mass spectra (HRMS) were recorded on a VG ZAB2SE (1996) high-resolution mass spectrometer, outfitted with an Opus V3.1 and DEC 3000 Alpha Station. Melting points were determined with a Fisher–Johns apparatus and are uncorrected. Optical rotations were measured with a Perkin–Elmer 343 polarimeter, using cells with a path length of 1 dm.

3.2. Materials

D-Glucono-1,5-lactone and 3-(trifluoromethyl)benzoylchloride were purchased from Sigma–Aldrich. D-Glucono-1,4-lactone was prepared by refluxing D-glucono-1,5-lactone in HCl–2-methoxyethanol as described,[13] although the use of basic lead carbonate for the neutralization was avoided; mp 134–135 °C, lit.[13] 131–134 °C, $[\alpha]_D$ +67 (*c* 1, water); lit.[13] +65.5. 5,6-Di-*O*-isopropylidene-D-glucono-1,4-lactone (**4**) was obtained in 83% yield by treatment of lactone **3** with 2,2-dimethoxypropane and sulfuric acid as catalyst: mp 108–110; lit.[13] 107–110 °C; $[\alpha]_D$ +80 (*c* 1, acetone); lit.[13] +84.

3.3. 5,6-Di-*O*-isopropylidene-2-*O*-[3-(trifluoromethyl)-benzoyl]-D-glucono-1,4-lactone (5a)

To a solution of 5,6-di-*O*-isopropylidene-D-glucono-1,4-lactone (**4**, 1.28 g, 5.86 mmol) in CH_2Cl_2 (20 mL) containing pyridine (2 mL), cooled to 0 °C, was added 3-(trifluoromethyl)benzoylchloride (1.06 mL, 7.01 mmol) in four aliquots during 2 h. The solution was stirred for an additional 0.5 h at 0 °C, and then for 1 h at rt. The solution was diluted with CH_2Cl_2 and washed with HCl (5%), water, $NaHCO_3$ (ss), and water, dried ($NaSO_4$), and concentrated. TLC analysis of the syrup showed a main product of R_f 0.41 (3:1 toluene–EtOAc), which was purified by column chromatography (20:1 toluene–EtOAc). Evaporation of the corresponding fractions afforded compound **5a** (1.64, 72%) that gave $[\alpha]_D$ +55 (*c* 1, $CHCl_3$). Anal. Calcd for $C_{17}H_{17}F_3O_7$: C 52.31; H 4.39. Found C 52.27, H 4.34.

3.4. 5,6-Di-*O*-isopropylidene-2,3-di-*O*-[3-(trifluoromethyl)benzoyl]-D-glucono-1,4-lactone (6)

Compound **6** was synthesized as described for **5a**, but using 17.6 mmol (2.65 mL) of 3-(trifluoromethyl)benzoylchloride for 1.28 g (5.86 mmol) of compound **4**. The syrup obtained (2.99 g, 98%) gave $[\alpha]_D$ +96 (*c* 1, Cl_3CH). Anal. Calcd for $C_{25}H_{20}F_6O_8$: C 52.67; H 2.56. Found: C 52.86; H 2.89.

3.5. 2-*O*-[3-(Trifluoromethyl)benzoyl]-D-glucono-1,4-lactone (7a)

Crude compound **5a** (2.24 g, 5.74 mmol) was treated with 4:1 AcOH–water (41 mL) for 1.5 h at 65 °C. The solvent was evaporated under reduced pressure, and the acid was eliminated by several coevaporations with water and toluene. The syrup obtained was purified by column chromatography (10:1 toluene–EtOAc) and fractions of R_f 0.55 (EtOAc) (1.45 g, 72%) gave $[\alpha]_D$ +76 (*c* 1, acetone). Anal. Calcd for $C_{14}H_{13}F_3O_7$ C 48.01, H 3.74. Found: C 48.25; H 3.93.

3.6. 2-*O*-Benzoyl-D-glucono-1,4-lactone (7b)

5,6-Di-*O*-isopropylidene-D-glucono-1,4-lactone (**4**, 1.28 g, 5.86 mmol) was treated with benzoyl chloride (0.81 mL, 7.01 mmol) as described for the preparation of **5a**, and immediately after the workup, the crude product was treated with 4:1 AcOH–water (41 mL) for 1.5 h at 65 °C. After the evaporation of the solvent and several coevaporations with water and toluene, the syrup obtained was crystallized from 7:3 EtOAc–toluene. Recrystallization from the same solvent gave 0.95 g (58%) of 2-*O*-benzoyl-D-glucono-1,4-lactone (**7b**): mp 130–131.5 °C, $[\alpha]_D$ +89 (*c* 1, acetone). Anal. Calcd for $C_{13}H_{14}O_7$: C 55.32; H 5.00. Found: C 55.33; H 5.09.

3.7. 2,3-Di-*O*-[3-(trifluoromethyl)benzoyl]-D-glucono-1,4-lactone (8)

Compound **8** was obtained from **6** as described for **7a**; R_f 0.38 (1:1 toluene–EtOAc), 85% yield. Anal. Calcd for $C_{22}H_{16}F_6O_8$: C 50.59; H 3.09. Found: C 50.64; H 3.38.

3.8. 2,6-Di-*O*-[3-(trifluoromethyl)benzoyl]-D-glucono-1,4-lactone (11)

Compound **11** was prepared as previously described for 2,6-di-*O*-benzoyl-D-galactono-1,4-lactone.[4] To a stirred solution of D-glucono-1,4-lactone (0.63 g, 3.5 mmol) in dry pyridine (5.0 mL), cooled in an ice-water bath, 3-(trifluoromethyl)benzoyl chloride (1.30 mL, 8.6 mmol) was added in four aliquots during 2 h and treated as usual. Treatment of the syrup with toluene gave crystalline compound **11** (0.93 g, 51%) chromatographically homogeneous (R_f 0.55, 3:2 toluene–EtOAc). By recrystallization from $CHCl_3$, compound **11** gave mp 141–142 °C, $[\alpha]_D$ +77 (*c* 1, acetone). Anal. Calcd for $C_{22}H_{16}F_6O_8$: C 50.59; H 3.09. Found C 50.52; H 3.24.

3.9. 3,5-Di-*O*-acetyl-2,6-di-*O*-[3-(trifluoromethyl)-benzoyl]-D-glucono-1,4-lactone (12)

To a solution of **11** (0.30 g, 0.59 mmol) in dried pyridine (0.5 mL), cooled at 0 °C, Ac_2O (0.5 mL) was added. After 1.5 h of stirring at 0 °C, the solution was poured into ice-water and treated as usual. Compound **12** was obtained as a homogeneous syrup (0.34 g, 94%) of R_f 0.49 (9:1.5 toluene–EtOAc). After purification by column chromatography (toluene) it gave $[\alpha]_D$ +70 (*c* 1, acetone). Anal. Calcd for $C_{26}H_{20}F_6O_{10}$: C 51.50; H 3.32. Found: C 51.35; H 3.20.

3.10. 2,3,5,6-Tetra-*O*-[3-(trifluoromethyl)benzoyl]-D-glucono-1,4-lactone (15)

To a solution of D-glucono-1,4-lactone (**3**, 0.60 g, 3.37 mmol) in CH_2Cl_2 (6.0 mL), pyridine (3.0 mL), and 3-(trifluoromethyl)benzoyl chloride (2.54 mL, 16.8 mmol) were added, and the solution was stirred for 2 h at 0 °C. The solution was diluted with CH_2Cl_2 and treated as usual. After column chromatography (9:1 toluene–EtOAc), fractions of R_f 0.53 were evaporated and characterized as compound **15** (1.17 g, 40%), $[\alpha]_D$ +16 (*c* 1, $CHCl_3$). Anal. Calcd for $C_{38}H_{20}F_{12}O_{10}$: C 52.67; H 2.56. Found: C 52.86; H 2.89.

3.11. Photochemical deoxygenation. General procedure

In a custom-made Pyrex reaction vessel equipped with a cold finger, a solution containing 0.75 mmol of the substrate, $Mg(ClO_4)_2$ (66 mg, 0.3 mM), and 9-methylcarbazole (13 mg, 0.075 mmol) in 500 mL of 10% deionized water–2-PrOH was degassed by bubbling UHP Ar through the solution for 30 min. The solution was photolyzed with a 450-W, medium-pressure lamp ($\lambda_{exc} > 300$ nm), while the temperature was maintained at 25 °C with a circulating water bath. Alternatively, a 120-W lamp was used. After irradiation for the times indicated in Table 3 the solvent was removed under reduced pressure and the residue was treated as described in each case. TLC examination showed the deoxygenated product, and faster moving components (R_f 0.95 and 0.65, 1:1 toluene–EtOAc) corresponding to 9-methylcarbazole and a photoproduct of 9-methylcarbazole.

2-Deoxy-D-*lyxo*-hexono-1,4-lactone (**2a**) and 3,5,6-tri-*O*-benzoyl-2-deoxy-D-*lyxo*-hexono-1,4-lactone (**2b**) were obtained as previously reported,[1] but using a 400-W lamp (Table 3).

The following compounds were obtained.

3.11.1. 2-Deoxy-D-*arabino*-hexono-1,4-lactone (9). The photolyzed solution from **7a** (0.26 g) was evaporated, partitioned between water and CH_2Cl_2, and the aqueous phase was concentrated. Column chromatography purification afforded 0.08 g (70%) of 2-deoxy-D-*arabino*-hexono-1,4-lactone (**9**), R_f 0.32 (9:1 EtOAc–MeOH), $[\alpha]_D$ +58 (*c* 1, water), lit.[17] +68. HRFABMS (positive ion): calcd for $C_6H_{10}O_5$, $[M+NH_4]^+$, *m*/*z* 180.0914, found *m*/*z* 180.0878.

Compound **9** was also obtained from **7b** (0.21g) in 46% yield.

3.11.2. 2-Deoxy-3-*O*-[3-(trifluoromethyl)benzoyl]-D-*arabino*-hexono-1,4-lactone (10). The photolyzed solution from compound **8** (0.39 g) was purified by column chromatography (6:4 toluene–EtOAc), and fractions of R_f 0.23 (1:2 toluene–EtOAc) afforded 0.15 g (59%) of 2-deoxy-3-*O*-[3-(trifluoromethyl)benzoyl]-D-*arabino*-hexono-1,4-lactone (**10**): $[\alpha]_D$ +3 (*c* 1, acetone). HRFABMS (positive ion): calcd for $C_{14}H_{13}F_3O_6$, $[M+H]^+$, *m*/*z* 352.1002, found *m*/*z* 352.1014.

3.11.3. 2-Deoxy-6-*O*-[(3-trifluoromethyl)benzoyl]-D-*arabino*-hexono-1,4-lactone (13). The photolyzed solution from **11** (0.39 g) was evaporated and purified by column chromatography (2:1 to 1:1 toluene–EtOAc). Fractions of R_f 0.27 were evaporated, and recrystallized from chloroform, affording 2-deoxy-6-*O*-[(3-trifluoromethyl)-benzoyl]-D-*arabino*-hexono-1,4-lactone (**13**, 0.06 g, 23%); mp 121–124 °C; $[\alpha]_D$ +42 (*c* 1, acetone). Anal. Calcd for $C_{14}H_{13}F_3O_6{\cdot}0.5H_2O$: C 48.99; H 4.11. Found: C 49.33; H 3.82.

3.11.4. 3,5-Di-*O*-acetyl-2-deoxy-6-*O*-[(3-trifluoromethyl)-benzoyl]-D-*arabino*-hexono-1,4-lactone (14). The photolyzed solution from compound **12** (0.45 g) was evaporated and partitioned between water and CH_2Cl_2. The organic layer was dried (Na_2SO_4), and evaporated and the crude product was purified by column chromatography. Fractions of R_f 0.33 (5:2 hexane–EtOAc) were evaporated and recrystallized from MeOH, affording 3,5-di-*O*-acetyl-2-deoxy-6-*O*-[(3-trifluoromethyl)benzoyl]-D-*arabino*-hexono-1,4-lactone (**14**, 0.21g, 67%): mp 110–113 °C; $[\alpha]_D$ +70 (*c* 1, $CHCl_3$). Anal. Calcd for $C_{18}H_{17}F_3O_8$: C 51.68; H 4.10. Found: C 51.27; H 4.36.

3.11.5. 2-Deoxy-3,5,6-tri-*O*-[(3-trifluoromethyl)benzoyl]-D-*arabino*-hexono-1,4-lactone (16). The photolyzed solution from compound **15** (0.65 g) was evaporated and partitioned between water and CH_2Cl_2. The organic layer was dried (Na_2SO_4), and evaporated, and the crude product was purified by column chromatography (96:4 toluene–EtOAc). Fractions of R_f 0.36 (9:1 toluene–EtOAc) were evaporated and afforded 2-deoxy-3,5,6-tri-*O*-[(3-trifluoromethyl)benzoyl]-D-*arabino*-hexono-1,4-lactone (**16**) in 78% yield (0.40 g), $[\alpha]_D$ −83 (*c* 1, $CHCl_3$). HRFABMS (positive ion): calcd for $C_{30}H_{19}F_9O_8$ $[M+H]^+$, *m*/*z* 679.1009; found, *m*/*z* 679.1018.

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Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.carres.2006.04.012.

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