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# 1-*O*-Vinyl Glycosides via Tebbe Olefination, Their Use as Chiral Auxiliaries and Monomers

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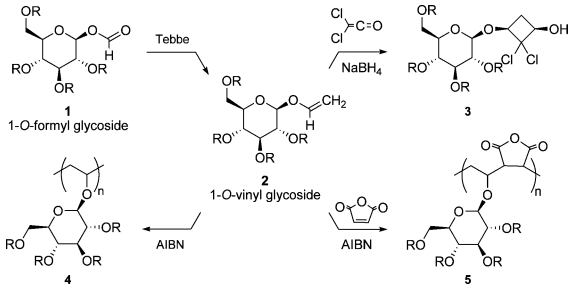


A series of anomerically pure 1-*O*-formyl glycosides **1** was prepared and converted into the corresponding 1-*O*-vinyl glycosides **2** by Tebbe olefination. The unsubstituted vinyl glycosides were obtained as anomerically pure compounds in good yields, and the method of preparation was compatible with the presence of a variety of functional groups. Remarkably, the anomeric formate group was regioselectively converted into the corresponding olefin in the presence of acetate and benzoate protecting groups. With the perspective to use the 1-*O*-vinyl glycosides as monomers for the preparation of glycosylated poly(vinyl alcohol) derivatives with controlled tacticity, their scope as chiral auxiliaries for a stereodifferentiation in addition reactions to the olefin function was investigated by using the [2+2] cycloaddition to dichloroketene as a model reaction. In particular, vinyl 2,3,4,6-tetra-*O*-benzoyl-α-D-mannopyranoside (**2i**) exhibited excellent diastereoselectivity. Finally, the 1-*O*-vinyl glycosides were successfully subjected to radical homopolymerization in bulk or used as electron-rich comonomers in radical copolymerizations with maleic anhydride, yielding alternating, glycosylated poly(vinyl alcohol-*alt*-maleic anhydride).

## Introduction

Synthetic glycopolymers,[1] i.e., hybrid materials of carbohydrates and synthetic polymers, are attracting increasing interest as potentially biomimetic materials, because carbohydrates play an important role in biomaterials and cell signaling. Nevertheless, while improving biocompatibility by derivatization, modification, or coating of synthetic polymers with specific peptide sequences has been thoroughly explored in recent years, comparably few investigations deal with similar approaches utilizing carbohydrates.[2]

Early examples of polymers with sugar residues attached to the backbone via their anomeric functions are copolymers of acryl amide and allyl glycosides.[3] Isopropylidene protected sugars attached to methacrylate or styrene groups as well as glycosylated HEMA were polymerized by different protocols,[4] including, more recently, the preparation of block and brush copolymers as well as hyperbranched polymers by living radical polymerization methods.[5] Glycosylated polymers and their block copolymers were also obtained by living cationic polymerization of (2-vinyloxy ethyl) derivatives of D-glucofuranose as well as D-glucosamine.[6] Recently, 6-*O*-vinyladipoyl-D-glucopyranose was polymerized with the RAFT protocol without the use of protecting groups.[7] Roy et al. prepared copolymers of acryl amide with 4-acrylamidophenyl $\beta$-lactoside and the analogous $GM_3$ trisaccharide acryl amide monomers aimed at lectin

(1) (a) Ladmiral, V.; Melia, E.; Haddleton, D. M. *Eur. Polym. J.* **2004**, *40*, 431−449. (b) Wulff, G.; Schmid, J.; Venhoff, T. *Macromol. Chem. Phys.* **1996**, *197*, 259−274.

(2) (a) Leeuwenburgh, M. A.; van der Marel, G. A.; Overkleeft, H. S. *Curr. Opin. Chem. Biol.* **2003**, *7*, 757−765. (b) Kodokawa, J.; Tagaya, H.; Chiba, K. *Synlett* **1999**, 1845−1856. (c) Roy, R. *Curr. Opin. Struct. Biol.* **1996**, *6*, 692−702.

(3) Horejsi, V.; Smolek, P.; Kocourek, J. *Biochim. Biophys. Acta* **1978**, *538*, 293−298.

(4) (a) Ambrosi, M.; Batsanov, A. S.; Cameron, N. R.; Davis, B. G.; Howard, J. A. K.; Hunter, R. *J. Chem. Soc., Perkin Trans. 1* **2002**, 45−52. (b) Loykulnant, S.; Yamashiro, M.; Hirao, A. *Macromol. Chem. Phys.* **2001**, *202*, 1791−1798. (c) Wulff, G.; Zhu, L.; Schmidt, H. *Macromolecules* **1997**, *30*, 0, 4533−4539.

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binding,[8] as well as copolymers containing 3′-sulfo-Lewis$^X$-Glc residues.[9] Yoshida et al. reported the synthesis of poly(methacrylate)s bearing sulfated maltoheptaose side chains which exhibited anti-HIV activity.[10]

We were interested in preparing poly(vinyl glycoside)s and their copolymers, i.e., glycosylated poly(vinyl alcohol) derivatives, with the glycosyl residues directly attached to the backbone via their anomeric function without a spacer. Such homo- and copolymers represent the most simple glycosylated polymers with an all-carbon backbone; they may allow for tacticity control during polymerization and exhibit secondary structure formation; and finally, they may be interesting materials in terms of both biocompatibility and biodegradability. For this purpose, we needed a fast, efficient, and versatile route toward 1-*O*-vinyl glycoside derivatives that is compatible with various carbohydrate substrates and common protecting group schemes. Vinyl glycosides have been prepared via (i) transvinylation reactions catalyzed by mercury salts[11] or palladium complexes,[12] (ii) elimination reactions such as Hofmann degradation,[13] selenoxide pyrolysis,[14] or decomposition of mixed acetals,[15] and (iii) photolysis of oxopentyl glycosides.[16] The available routes are typically plagued by poor yields, poor anomeric selectivity, toxic reactants, or tedious substrate preparation. Methyl-substituted 1-*O*-vinyl glycosides (1-*O*-isopropenyl glycosides) were also synthesized from 1-*O*-acetyl glycosides via Tebbe or Petasis olefination[17,18] while a Wittig olefination of 1-*O*-formyl glycosides had reportedly failed.[19]

**SCHEME 1. Synthesis of 1-*O*-Vinyl Glycosides 2 via Tebbe Olefination (A), Their Use as Chiral Auxiliaries in a [2+2] Cycloaddition (B), and Their Polymerization to Poly(vinyl glycoside) Homo- and Copolymers 4 and 5 (C,D)**

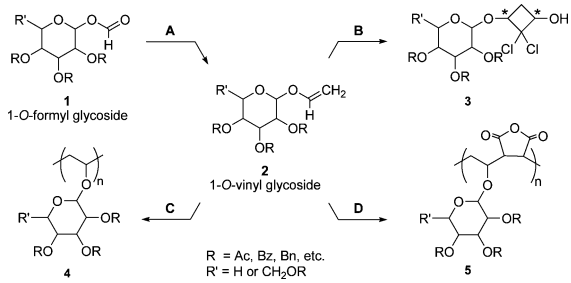



**TABLE 1. Preparation of 1-*O*-Formyl Glycosides (and Carbohydrate Formyl Esters) 1a−m and Their Conversion into the Corresponding 1-*O*-Vinyl Glycosides (and Vinyl Ethers) 2a−m**

| formyl sugar | method[a] | α: β[b] | yield,[c] % | vinyl sugar | α: β[b] | yield,[c] % |
|---|---|---|---|---|---|---|
| **1a** | A | 1:5 | 51 | **2a** | 0:100[g] | 63 |
| **1b** | B | 20:1 | 69 | **2b** | 100:0[g] | 60 |
| **1c** | A | 1:70 | 60 | **2c** | 0:100[g] | 64 |
| **1d** | B | 99:1 | 86 | **2d** | 100:0[g] | 83 |
| **1e** | A | 9:1 | 64 | **2e** | 100:0[g] | 67 |
| **1f** | A | 1:90 | 100[d] | **2f** | n.d.[e] | 73[f] |
| **1g** | B | 1:90 | 59 | **2g** | 0:100 | 68 |
| **1h** | A | 1:22 | 100[d] | **2h** | n.d.[e] | 46[f] |
| **1i** | A | 5:1 | 100[d] | **2i** | n.d.[e] | 53[f] |
| **1k** | A | 1:11 | 90[d] | **2k** | n.d.[e] | 43[f] |
| **1*l*** | C | n.a.[h] | 76 | **2*l*** | n.a.[h] | 89 |
| **1m** | C | n.a.[h] | 69 | **2m** | n.a.[h] | 87 |

[a] Method A: glycosyl bromide, HCOOH, $AgNO_3$. Method B: ethyl 1-thioglycoside, HCOOH, TfOH, NIS. Method C: ROH, HCOOH, EDCI, DPTS. [b] Anomeric ratio in the crude product mixture, determined by $^1$H NMR spectroscopy. [c] Isolated yield of anomerically pure product. [d] Yield of crude product. [e] NMR spectrum of the crude mixture did not allow for an unambiguous assignment. [f] Isolated yield of anomerically pure 1-*O*-vinyl glycoside over two steps starting from the glycosyl bromide. [g] Crude 1-*O*-vinyl glycoside was anomerically pure (within the error of determination by $^1$H NMR spectroscopy). [h] Not applicable because the product was not a 1-*O*-formyl or a 1-*O*-vinyl glycoside.

We report here the successful synthesis and olefination of 1-*O*-formyl glycosides **1** via the Tebbe reaction (Scheme 1), which furnished the desired 1-*O*-vinyl glycosides **2** as anomerically pure compounds in good yields, including derivatives with ester protecting groups. Furthermore, we studied the propensity of different 1-*O*-vinyl glycosides toward stereodifferentiation in a [2+2] cycloaddition to the olefin function. Finally, we investigated the polymerizability of the 1-*O*-vinyl glycosides in order to prepare poly(vinyl glycoside) homo- and copolymers **4** and **5**.

## Results and Discussion

**Synthesis of Formyl and Vinyl Glycosides.** To investigate the scope of the Tebbe reaction in the synthesis of unsubstituted vinyl glycosides, various 1-*O*-formyl glycosides **1** were synthesized by using either Koenigs-Knorr conditions (method A) or NIS promoted reactions of thioglycosides (method B) (Table 1). The 1-*O*-formyl glycosides, including mono- and disaccharides, substrates with different anomeric configurations, as well as different protecting group patterns, were obtained in good yields and with high anomeric diastereoselectivity. While they appeared to be air and moisture stable compounds, they turned out to be easily anomerized or hydrolyzed during column chromatography with both silica gel and aluminum oxide as the column materials. Therefore, they were typically obtained in anomerically pure form by recrystallization.

(5) (a) Bernard, J.; Hao, X.; Davis, T. P.; Barner-Kowollik, C.; Stenzel, M. H. *Biomacromolecules* **2006**, *7*, 232−238. (b) Albertin, L.; Stenzel, M. H.; Barner-Kowollik, C.; Foster, L. J. R.; Davis, T. P. *Macromolecules* **2005**, *38*, 9075−9084. (c) Albertin, L.; Stenzel, M.; Barner-Kowollik, C.; Foster, L. J. R.; Davis, T. P. *Macromolecules* **2004**, *37*, 7530−7537. (d) Muthukrishnan, S.; Jutz, G.; Andre, X.; Mori, H.; Müller, A. H. E. *Macromolecules* **2005**, *38*, 9−18. (e) Muthukrishnan, S.; Mori, H.; Müller, A. H. E. *Macromolecules* **2005**, *38*, 3108−3119. (f) Muthukrishnan, S.; Zhang, M.; Burkhardt, M.; Drechsler, M.; Mori, H.; Müller, A. H. E. *Macromolecules* **2005**, *38*, 7926−7934.

(6) (a) Yamada, K.; Minoda, M.; Fukuda, T.; Miyamoto, T. *J. Polym. Sci., Part A*: *Polym. Chem.* **2001**, *39*, 459−467. (b) Yamada, K.; Minoda, M.; Miyamoto, T. *Macromolecules* **1999**, *32*, 3553−3558. (c) Yamada, K.; Yamaoka, K.; Minoda, M.; Miyamoto, T. *J. Polym. Sci., Part A*: *Polym. Chem.* **1997**, *35*, 255−261. (d) Yamada, K.; Minoda, M.; Miyamoto, T. *J. Polym. Sci., Part A*: *Polym. Chem.* **1997**, *35*, 751−757.

(7) Albertin, L.; Kohlert, C.; Stenzel, M.; Foster, L. J. R.; Davis, T. P. *Biomacromolecules* **2004**, *5*, 255−260.

(8) Cao, S.; Roy, R. *Tetrahedron Lett.* **1996**, *37*, 3421−3424.

(9) Roy, R.; Park, W. K. C.; Srivastava, O. P.; Foxall, C. *Bioorg. Med. Chem. Lett.* **1996**, *6*, 1399−1402.

(10) Yoshida, T.; Akasaka, T.; Choi, Y.; Hattori, K.; Yu, B.; Mimura, T.; Kaneko, Y.; Nakashima, H.; Aragaki, E.; Premanathan, M.; Yamamoto, N.; Uryu, T. *J. Polym. Sci., Part A*: *Polym. Chem.* **1999**, *37*, 789−800.

(11) (a) Dettinger, H. M.; Lehmann, J.; Wallenfels, K. *Carbohydr. Res.* **1980**, *87*, 63−70. (b) De Raadt, A.; Ferrier, R. J. *Carbohydr. Res.* **1991**, *216*, 93−107.

(12) Handerson, S.; Schlaf, M. *Org. Lett.* **2002**, *4*, 407−409.

(13) Perrine, T. D.; Glaudemans, C. P. J.; Ness, R. K.; Kyle, J.; Fletcher, H. G., Jr. *J. Org. Chem.* **1967**, *32*, 664−669.

(14) Rollin, P.; Bencomo, V. V.; Sinay, P. *Synthesis* **1984**, 134−135.

(15) (a) Edathil, J.; Nguyen, J.; Hughes, K.; Boyko, W. J.; Giuliano, R. M. *J. Carbohydr. Chem.* **2001**, *20*, 81−85. (b) Hughes, K. D.; Nguyen, T.-L. N.; Dyckman, D.; Dulay, D.; Boyko, W. J.; Giuliano, R. M. *Tetrahedron*: *Asymmetry* **2005**, *16*, 273−282.

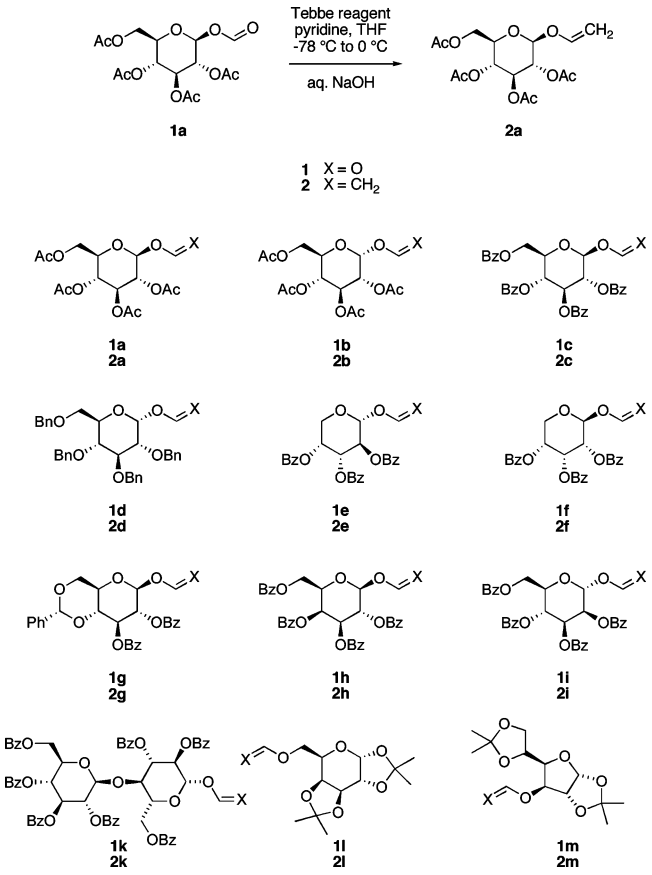
(16) Cottier, L.; Remy, G.; Descotes, G. *Synthesis* **1979**, 711−712.

(17) Marra, A.; Esnault, J.; Veyrieres, A.; Sinay, P. *J. Am. Chem. Soc.* **1992**, *114*, 6354−6360.

(18) Chenault, H. K.; Castro, A.; Chafin, L. F.; Yang, J. *J. Org. Chem.* **1996**, *61*, 5024−5031.

(19) Larsen, D. S.; Stoodley, R. J. *J. Chem. Soc., Perkin Trans. 1* **1989**, 1841−1852.

**SCHEME 2. Preparation of 1-*O*-Vinyl Glycosides (and Vinyl Ethers) 2a−m by Tebbe Olefination of 1-*O*-Formyl Glycosides (and Carbohydrate Formyl Esters) 1a−m**




The formyl ester derivatives **1*l*** and **1m** were prepared from the corresponding alcohol derivatives and included in the present study as comparative compounds.

The methylenation of the formyl functions of compounds **1a**−**m**, leading to the 1-*O*-vinyl glycosides **2a**−**k** and the vinyl ethers **2*l*** and **2m**, respectively, was achieved via Tebbe olefination (Scheme 2). In a typical procedure, the 1-*O*-formyl glycoside was dissolved in THF and pyridine at −78 °C. The solution was treated with 2 equiv of Tebbe reagent, which was added dropwise, maintaining the temperature in the reaction mixture at −78 °C. The mixture was then allowed to warm to 0 °C, and finally quenched by the addition of a 15% solution of NaOH. A crucial parameter for a successful reaction turned out to be the very careful and slow addition of the NaOH solution over a time period of at least 30 min, waiting after each drop for the gas evolution to cease. Furthermore, while the Tebbe reagent can reportedly be stored for weeks at room temperature, we found it advantageous to use it within the first 5 days after preparation.

The 1-*O*-vinyl glycosides **2a**−**k** as well as the vinyl ether **2*l*** and **2m** were obtained in acceptable or good yields in all cases (Table 1). The substrates **1a**−**m** were straightforwardly accessible in pure form on a large scale, and the Tebbe reactions could easily be performed on a reaction scale of up to 5 g of the carbohydrate substrate. No anomerization occurred under the reaction conditions applied, as confirmed by $^1$H NMR spectra of the crude products. Hence, anomerically pure vinyl glycosides were obtained whenever anomerically pure formyl glycosides had been used as the starting material. This is a definite advantage over the transvinylation methods[11,12] which produce anomeric mixtures and do not allow for the selective synthesis of one desired diastereomer, and likewise, the elimination protocols[13−15] which give rise to anomerization as a consequence of the reaction conditions applied.

Furthermore, the Tebbe olefination was successfully performed in the presence of other functional groups including ether, acetal, as well as, most notably, ester groups. Thus, in the cases of **1a**−**c** and **1e**−**k**, the anomeric formate group was regioselectively converted into the corresponding olefin without affecting the sterically more demanding acetate or benzoate groups, in agreement with previous investigations concerning the regioselectivity of Tebbe or Petasis reagents.[18,20]

The isolated yield was slightly better in the case of the benzyl ether protected glycoside **1d**, but the anomeric formyl group of acetylated or benzoylated substrates such as **1a**−**c**, **1e**, and **1g** was found to be selectively converted with an acceptable yield. Overall, the formyl esters **1*l*** and **1m** appeared to react slightly better than the formyl glycosides **1a**−**k**, which may, however, also just be a consequence of the absence of other ester functions. The somewhat poorer yields in the cases of **1f** and **1h**−**k** can be attributed to the fact that in these cases, all recrystallization attempts had failed. Therefore, the compounds were subjected to the Tebbe olefination as anomeric mixtures, and the yields were determined as the isolated yields of anomerically pure 1-*O*-vinyl glycosides over two steps.

**Vinyl Glycosides as Chiral Auxiliaries.** As the vinyl glycosides were to serve as chiral monomers in the preparation of glycosylated poly(vinyl alcohol) derivatives with the aim to control polymer tacticity, we attempted to investigate their propensity to stereodifferentiation in a typical addition reaction to the olefin function. While cycloadditions of tetracyanoethylene, methyl 2-pyrone-3-carboxylate, and ethyl diazoacetate had worked well for vinyl ether derivatives used as test substrates, they failed in our hands when applied to vinyl glycosides. Therefore, we finally resorted to the [2+2] addition of dichloroketene.[21] This reaction had been reported to show efficient diastereofacial differentiation in the synthesis of various natural products, using optically pure 2-phenylcyclohexanol as the chiral auxiliary,[22] and had also been studied in the enantioselective synthesis of chiral cyclobutanol derivatives, using carbohydrates as chiral auxiliaries.[23]

The acetylated $\beta$- and $\alpha$-D-glucopyranosides **2a** and **2b**, the benzoylated $\beta$-D-glucopyranoside **2c**, the $\beta$-D-ribopyranoside **2f**, as well as the $\alpha$-D-mannopyranoside **2i** were chosen as the substrates in order to study the influence of different carbohydrate residues, anomeric configurations, and protecting group schemes. The vinyl glycosides were reacted with dichloroketene generated in situ by dehalogenation of trichloroacetyl chloride with Zn−Cu (Scheme 3).[21] As the obtained dichlorocyclobutanone derivatives turned out to decompose during workup, they were reduced to the corresponding dichlorocyclobutanol derivatives in situ with $NaBH_4$ in 2-propanol.[23] Consistent with results reported in the literature, the two cis diastereomers were obtained exclusively in all cases (within the error of determination from

(20) Hartley, R. C.; McKiernan, G. J. *J. Chem. Soc., Perkin Trans. 1* **2002**, 2763−2793.

(21) (a) Brady, W. T.; Watts, R. D. *J. Org. Chem.* **1980**, *45*, 3525−3527. (b) Brady, W. T. *Tetrahedron* **1981**, *37*, 2949−2966.

(22) (a) Greene, A. E.; Charbonnier, F.; Luche, M. J.; Moyano, A. *J. Am. Chem. Soc.* **1987**, *109*, 4752−4753. (b) De Azevedo, M. B. M.; Murta, M. M.; Greene, A. E. *J. Org. Chem.* **1992**, *57*, 4567−4569.

(23) Ganz, I.; Kunz, H. *Synthesis* **1994**, 1353−1358.

**SCHEME 3. Dichloroketene Addition to the 1-*O*-Vinyl Glycoside 2 Followed by Reduction**

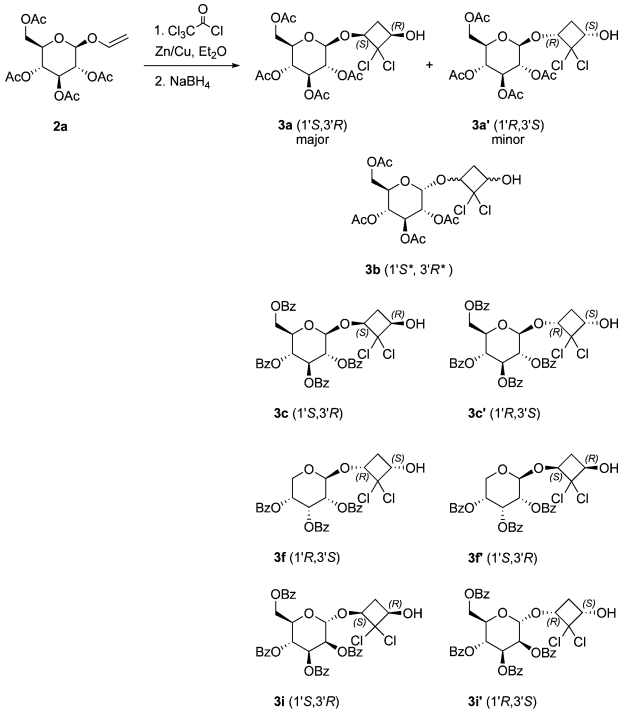



**TABLE 2. Results of the Dichloroketene Addition to 1-*O*-Vinyl Glycosides 2 and Subsequent Reduction**

| 1-*O*-cyclobutyl glycoside diastereomers | | diastereomeric ratio | | |
|---|---|---|---|---|
| major | minor | $^1$H NMR | LC-MS | yield,[a] % |
| **3a** (1′*S*,3′*R*) | **3a′** (1′*R*,3′*S*) | 100:0[b] | 2.4:1 | 53 |
| **3b** (1′*S*,3′*R*)* [c] | | 3.0:1[c] | 1.8:1 | 56[a] |
| **3c** (1′*S*,3′*R*) | **3c′** (1′*R*,3′*S*) | 3.3:1 | 2.1:1 | 48 |
| **3f** (1′*R*,3′*S*) | **3f′** (1′*S*,3′*R*) | 10.1:1 | 4.9:1 | 67 |
| **3i** (1′*S*,3′*R*) | **3i′** (1′*R*,3′*S*) | 100: 0[b] | 100:0[b] | 60 |

[a] Isolated yield of diastereomerically pure major product (except **3b**, which was isolated as a mixture of diastereomers). [b] Just one diastereomer was visible in the $^1$H NMR spectra, or in LC-MS, respectively. [c] The absolute configuration could not be assigned.

$^1$H NMR spectra), indicating that the reduction proceeded diastereospecifically. The ratio of the obtained two diastereomers resulting from the cycloaddition was determined both from the $^1$H NMR spectra and via an LC-MS analysis of the crude product mixtures (Table 2).

The crude products **3** were then purified by silica gel chromatography. Thus, the pure major diastereomers of **3a**, **3f**, and **3i** were obtained, and both major and minor diastereomers **3c** and **3c′** could be isolated in pure form. Recrystallization of the major diastereomer of the $\beta$-D-glucopyranoside derivative **3a** afforded crystals suitable for X-ray structure analysis (Figure 1), which allowed us to assign the absolute stereoconfiguration as (1′*S*,3′*R*)-2′,2′-dichloro-3′-hydroxycyclobutyl 2,3,4,6-tetra-*O*-acetyl-$\beta$-D-glucopyranoside. The absolute stereoconfigurations of the other major diasteromers were then unambiguously deduced from the known stereoconfiguration of **3a** as (1′*S*,3′*R*) for **3c**, (1′*R*,3′*S*) for **3f**, and (1′*S*,3′*R*) for **3i** by chemical derivatization (Scheme 4). Unfortunately, neither recrystallization nor separation by column chromatography was successful in the case of **3b** so that the absolute stereoconfiguration of the two obtained diastereomers could not be assigned.

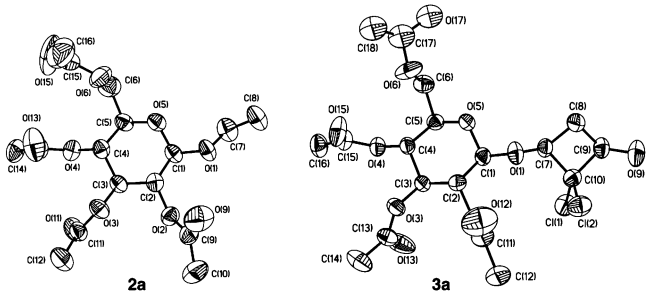



**FIGURE 1.** Single-crystal structures of the 1-*O*-vinyl glycoside **2a** (left) and the corresponding product of dichloroketene addition **3a** (right).

In summary, in all cases with the exception of **3f**, the major diastereomer resulted from an addition of the dichloroketene from the *Si* side of the olefin in the 1-*O*-vinyl glycoside **2.** The observed diastereoselectivities (Table 2) were only moderate for the glucopyranoside **2a**−**c**. However, good diastereoselectivities were found for the $\beta$-D-ribopyranoside **2f**, and, in particular, for the α-D-mannopyranoside **2i**. In the latter case, only one diastereomer was observed both in the $^1$H NMR spectra and by LC-MS.

Attempting to rationalize the observed diastereoselectivities, we found the glucopyranoside derivatives **2a**−**c** and the α-D-mannopyranoside **2i** to exist preferably in the $^4C_1$(D) conformation, while the $\beta$-D-ribopyranoside **2f** was more stable in the $^1C_4$(D) conformation. This was confirmed by $^1$H NMR spectra which revealed coupling constants of $^3J_{12} = 7.8$ Hz for **2a** and **2c**, $^3J_{12} = 2.5$ Hz for **2f**, and $^3J_{12} = 1.8$ Hz for **2i**, all in agreement with previous studies.[24] Furthermore, we expected the EGT conformers[25] of **2a** and **2c** as well as the AGT conformers of **2f** and **2i** to be most favorable (Figure 2).[26] Assuming that rotation around the O1−C7 bond is hindered to a certain extent, two conformers remain, one of which is supposedly preferred due to steric interactions (Figure 2). The above analysis coincides with the conformation of the vinyl group observed in single crystalline **2a** (Figure 1), which may, of course, just be the result of packing considerations in the solid state. For substrates **2a** and **2c**, the experimentally observed preferred *Si* addition may then be explained in terms of a competitive shielding of the olefin function by both the protecting groups on O(6) and O(2), leading to a favored addition from the *Si* side and a better diastereoselectivity in the case of the smaller acetyl group on O(2) in the case of **2a**. In the cases of **2f** and **2i**, shielding of the addition trajectory by the sugar backbone should lead to a strong preference of addition from the *Re* and the *Si* side, respectively. Of course, the above model has many variables and is, thus, just to be regarded as an attempted rationalization post facto rather than a model with predictive power.

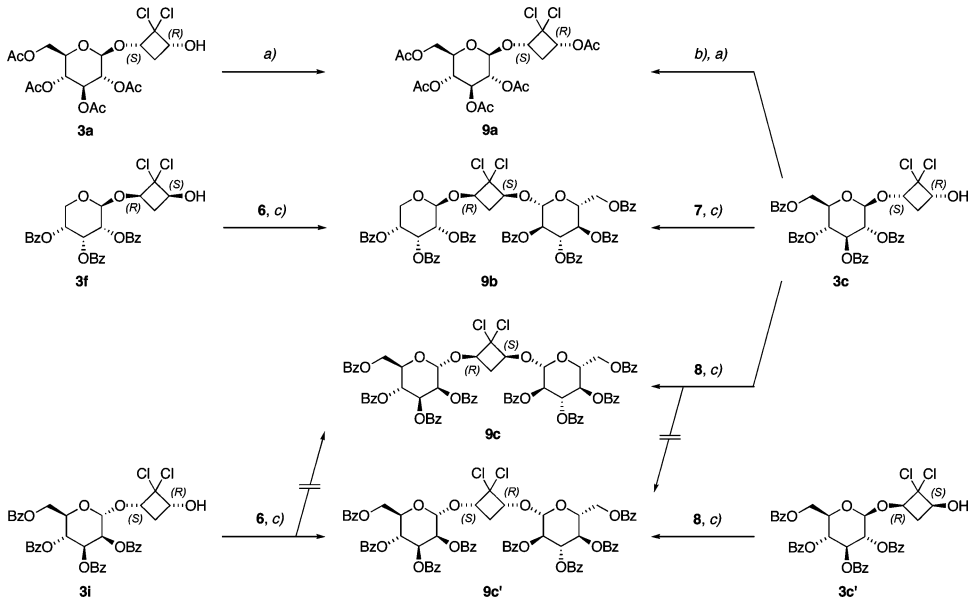
**Polymerization of the Vinyl Glycosides.** In our initial attempts to polymerize the obtained vinyl glycoside derivatives, 2,3,4,6-tetra-*O*-acetyl-$\beta$-D-glucopyranoside (**2a**) and 1-*O*-vinyl 2,3,4,6-tetra-*O*-benzoyl-α-D-mannopyranoside (**2i**) were chosen as the monomers because they are both easily available from

(24) (a) James, V. J.; Stevens, J. D. *Carbohydr. Res.* **1972**, *21*, 334−335. (b) Horton, D.; Durette, P. L. *Carbohydr. Res.* **1971**, *18*, 57−80.

(25) The three-letter code refers to the orientation of the anomeric group (*equatorial* or *axial*) and the conformation (*gauche* or *trans*) of the anomeric group in relation to O-5 and C-2, respectively.

(26) (a) Tvaroska, I.; Kozar, T. *J. Am. Chem. Soc.* **1980**, *102*, 6929−6936. (b) Tvaroska, I.; Kozar, T. *Carbohydr. Res.* **1981**, *90*, 173−185.

**SCHEME 4. Deduction of the Absolute Configuration of 3c, 3c′, 3f, and 3i from the Known Stereoconfiguration of 3a**[a]




[a] Reactants: ethyl 2,3,4,6-tetra-*O*-benzoyl-1-thio-*β*-D-glucoside **6**, phenyl 2,3,4-tri-*O*-benzoyl-1-thio-*β*-D-riboside **7**, ethyl 2,3,4,6-tetra-*O*-benzoyl-1-thio-*β*-D-mannoside **8**. Reaction conditions: (a) $Ac_2O$, pyridine, rt; (b) NaOMe, MeOH, rt; (c) TfOH, NIS, DCM, 0 °C.

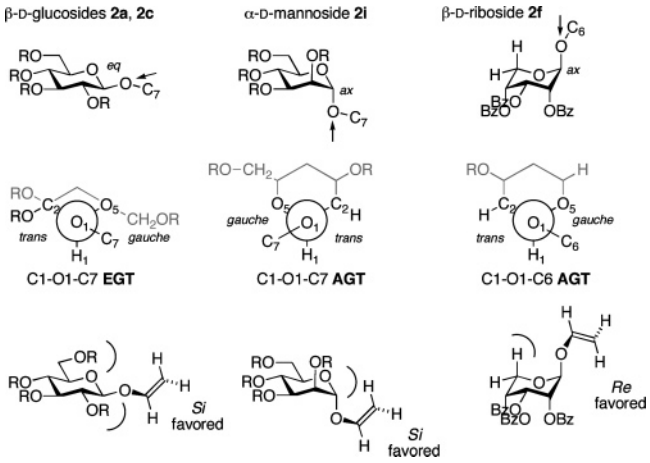



**FIGURE 2.** Attempted rationalization of the observed diastereoselectivities.

commercial substrates in a few steps in good yield on a multigram scale. In addition, **2i** had exhibited a very good diastereoselectivity in the [2+2] cycloaddition of dichloroketene that we used as a test reaction for the stereodifferentiation (vide supra). All attempts to polymerize vinyl glycosides **2a** or **2i** with different cationic initiators failed in our hands, which may not be too surprising given the fact that 1-*O*-isopropenyl glycosides have successfully been used as glycosyl donors.[17,18] Preliminary free radical polymerization experiments produced relatively low molecular weight poly(vinyl glycoside)s **4i** in poor yields. These results are consistent with investigations by Ringsdorf et al., who reported that cationic polymerizations of simple vinyl acetals were unsuccessful, and radical homopolymerizations failed or proceeded only sluggishly.[27] On the other hand, some examples of radical polymerizations of vinyl acetals have been reported in the literature.[28] One important factor to consider in this context is the substantial steric demand of the 1-*O*-vinyl glycoside monomers which may even be comparable to highly sterically hindered dendronized monomers.[29] Work on improved homopolymerization protocols is in progress.

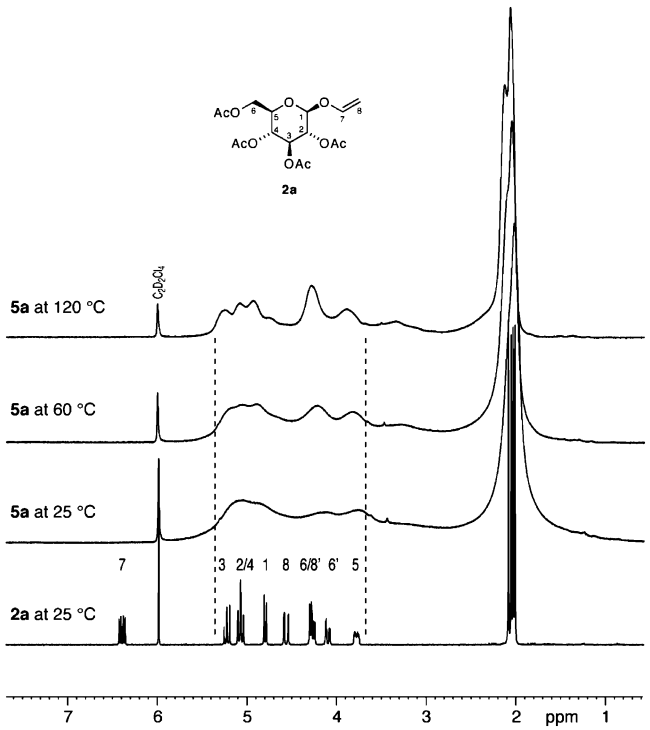



**FIGURE 3.** $^1H$ NMR spectra of copolymer **5a**, recorded in $C_2D_2Cl_4$ at different temperatures.

Assuming that the 1-*O*-vinyl glycosides are electron-rich vinyl monomers, we investigated their radical copolymerization with the electron-poor maleic anhydride (MA). Thus, radical copolymerizations of **2a** and **2i** in solution initiated by AIBN at 60 °C were performed successfully, leading to the copolymers **5a**

(27) Beyer, U.; Müller, F. H.; Ringsdorf, H. *Makromol. Chem.* **1967**, *101*, 74−90.

(28) (a) Tsukino, M.; Kunitake, T. *Polym. J.* **1979**, *11*, 437−447. (b) Tsukino, M.; Kunitake, T. *Polym. J.* **1985**, *17*, 943−951.

(29) (a) Schlüter, A. D.; Rabe, J. P. *Angew. Chem., Int. Ed.* **2000**, *39*, 864−883. (b) Frauenrath, H. *Prog. Polym. Sci.* **2005**, *30*, 325−384.

**SCHEME 5. Copolymerization of the 1-*O*-Vinyl Glycosides 2 with Maleic Anhydride**

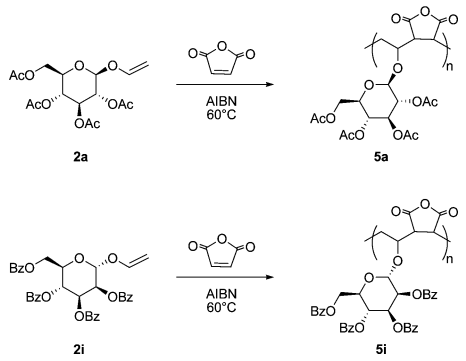



**TABLE 3. Results of the Radical Copolymerization of 2a and 2i with Maleic Anhydride with AIBN as the Initiator at 60 °C**

| entry | vinyl glycoside (mmol) | MA, mmol | AIBN, $10^{-3}$ mmol | solvent (mL) | time, h | copolymers **5a**, **5i** $M_n$[a] | PDI[a] | yield,[b] % |
|---|---|---|---|---|---|---|---|---|
| 1 | **2a** (0.40) | 0.41 | 48 | toluene (0.15) | 12 | 25 900 | 2.23 | 63 |
| 2 | **2a** (0.40) | 0.82 | 24 | toluene (0.15) | 12 | 25 100 | 2.86 | 68 |
| 3 | **2a** (0.37) | 0.61 | 6 | $CHCl_3$ (0.15) | 12 | 14 400 | 1.94 | 94 |
| 4 | **2a** (0.37) | 0.37 | 6 | $CHCl_3$ (0.08) | 12 | 7 700 | 2.35 | 95 |
| 5 | **2i** (0.36) | 0.18 | 6 | toluene (0.10) | 36 | 22 000 | 2.84 | 98 |
| 6 | **2i** (0.11) | 0.22 | 6 | toluene (0.08) | 36 | 93 700 | 2.25 | 80 |
| 7 | **2i** (0.14) | 0.14 | 6 | toluene (0.08) | 36 | 49 900 | 2.09 | 73 |

[a] Determined by GPC vs PS standards with triple detection. [b] Isolated yield of the polymer after repricipitation, with respect to the monomer present in minor concentration (i.e., the vinyl glycoside, except entry 5).

and **5i** (Scheme 5, Table 3). Polymer yields seemed to improve with lower AIBN concentration, and molecular weights obtained in toluene as the solvent were higher than those in $CHCl_3$, which may be expected from the respective typical chain transfer rates of the solvents. Overall, the α-mannoside **2i** appeared to give better results as compared to the *β*-glucoside **2a** in terms of both yield and molecular weight. This result is particularly interesting because **2i** had also exhibited the better diastereoselectivity in the cycloaddition test reactions. Furthermore, an excess of MA furnished the best results, so that, in one case, copolymer **5i** with a molecular weight of $M_n = 93\,700$ (PDI = 2.25) was obtained. This result may be rationalized by assuming that the more reactive vinyl glycoside centered radical chain ends are more prone to chain transfer or termination reactions which are, hence, suppressed to some extent by an excess of the MA comonomer.

As a homopolymerization of MA is not possible and its copolymerization with electron-rich vinyl monomers typically leads to strictly alternating copolymers,[30] we expected to obtain an alternating glycosylated poly(vinyl alcohol-*alt*-maleic anhydride). Accordingly, the polymer yield was near quantitative with respect to MA, when the vinyl glycoside was used in excess (Table 3, entry 5) and vice versa (Table 3, entries 3 and 6). The residual comonomer was quantitatively recovered in both cases. In all polymerization attempts, irrespective of the ratio of vinyl glycoside and maleic anhydride in the feed, elemental analyses of the copolymers were found to be consistent with a 1:1 ratio of vinyl glycoside and maleic anhydride repeating units. Unfortunately, a direct determination of the structure of copolymers **5a** and **5i** turned out to be infeasible on the basis of $^1$H NMR spectra (Figure 3). Despite its excellent solubility in $CDCl_3$ and other chlorinated solvents such as $C_2D_2Cl_4$, the $^1$H NMR spectra of the copolymer **5a** exhibited extremely broad peaks at room temperature. While the resolution improved to some extent when the NMR spectra were measured at elevated temperatures, the lines were still too broad to allow for a simple structure determination. In our eyes, this feature of the $^1$H NMR spectra does not have its origin in the polydispersity of the polymer alone but may point to a reduced segmental mobility of the macromolecules, indicating a rigidification of the backbone similar to that of dendronized polymers.[29] Neither the solution nor the solid phase $^{13}$C NMR spectra could be used to assess the polymer tacticity for the same reason.

## Conclusions

In conclusion, the Tebbe olefination proved to be a versatile method for the preparation of various unsubstituted 1-*O*-vinyl glycosides **2**. The 1-*O*-formyl glycosides **1** used as the substrates were easily prepared in pure form on the multigram scale. The products were obtained as anomerically pure compounds in good yields, and the reaction was found to be compatible with different functional groups, most notably, ester protecting groups. Thus, the anomeric formate group was regioselectively converted into the corresponding olefin in the presence of acetate or benzoate groups. The application of the 1-*O*-vinyl glycosides as chiral auxiliaries for a stereodifferentiation in addition reactions to the olefin function was investigated by using the [2+2] cycloaddition of dichloroketene and subsequent reduction as a test reaction. All vinyl glycosides showed diastereofacial differentiation, and, in particular, 1-*O*-vinyl 2,3,4,6-tetra-*O*-benzoyl-α-D-mannopyranoside **2i** was found to exhibit excellent diastereoselectivity. Finally, the *β*-D-glucopyranoside **2a** and the α-D-mannopyranoside **2i** were successfully used as the monomers in free radical homopolymerizations as well as alternating copolymerizations with maleic anhydride. For example, the alternating poly(vinyl α-D-mannopyranoside-*alt*-maleic anhydride) **5i** with a molecular weight of $M_n = 93\,700$ (PDI = 2.25) was obtained in 80% yield. Such copolymers may combine the features of alternating maleic anhydride copolymers and synthetic glycopolymers and, therefore, be a promising platform for new biomaterials or biocompatible surface modifications.

## Experimental Section

**General Procedure for the Preparation of the Tebbe Reagent.** A solution of the Tebbe reagent in toluene was prepared according to a modified literature procedure.[31] Thus, titanocene dichloride (3.74 g, 15 mmol, 1 equiv) and $AlMe_3$ (2.0 M solution in toluene; 15 mL, 30 mmol, 2 equiv) were dissolved in dry toluene (30 mL). The solution was stirred at room temperature for 72 h prior to use. The Tebbe reagent can reportedly be stored for weeks at room temperature, but we found it to be advantageous to use it within the first 5 days after preparation.

**General Procedure for the Preparation of Formyl Glycosides from Glycosyl Bromides (Procedure A).** The glycosyl bromide (typically 10 mmol) is dissolved in a large excess of formic acid (25 mL/g of glycosyl bromide). $AgNO_3$ (typically 2 equiv) is added, the mixture is stirred for 1 h at room temperature, diluted with DCM (10 mL/g of glycosyl bromide), and filtered over Celite. The filtrate is washed three times with saturated aqueous $NaHCO_3$ solution and once with brine. The pure products are obtained by flash column chromatography or recrystallization.

(30) (a) Baldwin, M. G. *J. Polym. Sci.* **1965**, *3*, 703−710. (b) Hallensleben, M. L. *Makromol. Chem.* **1971**, *144*, 267−281. (c) Hao, X.-J.; Fujimori, K.; Henry, P. C. *Macromol. Rapid Commun.* **2001**, *22*, 111−113.

(31) Tebbe, F. N.; Parshall, G. W.; Reddy, G. S. *J. Am. Chem. Soc.* **1978**, *100*, 3611−3613.

**General Procedure for the Preparation of α Formyl Glycosides from Ethylthio Glycosides (Procedure B).** The ethylthio glycoside (typically 10 mmol), 4 Å molecular sieves, and DCM (20 mL/g of ethylthio glycoside) are placed in a dried Schlenk flask under a nitrogen atmosphere. The mixture is cooled to 0 °C, and formic acid (typically 2.2 equiv), *N*-iodosuccinimide (1.2 equiv), and TfOH (0.9 equiv) are added. After 3−120 min of stirring, depending on the substrate, the reaction is quenched with triethylamine (large excess). The solution is diluted with DCM (approximately 100 mL/g of ethylthio glycoside) and filtered through Celite. It is washed two times each with 1 M HCl and saturated aqueous $NaHCO_3$ solution and once with brine, dried over $MgSO_4$, filtered, and evaporated to dryness. The pure products are obtained by flash column chromatography, followed by recrystallization in some cases.

**General Procedure for the Preparation of Formyl Esters of Sugar Alcohols (Procedure C).** The alcohol (typically 20 mmol), DPTS (41 mmol), and EDCI (41 mmol) are dissolved in DCM (typically 50 mL) and HCOOH (40 mmol). The reaction is stirred at room temperature for 3 h. Then the solution is washed with saturated aqueous $NaHCO_3$ solution as well as brine and dried over $MgSO_4$. The pure products are obtained by flash column chromatography followed by recrystallization in some cases.

**General Procedure for the Preparation of Vinyl Glycosides via Tebbe Olefination of Formyl Glycosides (Procedure D).** The formyl glycoside (typically 0.5 mmol) is dissolved in THF (20 mL/g of formyl glycoside) and pyridine (4 mL/g of formyl glycoside), and the reaction mixture is cooled to −78 °C. After 20 min, a solution of the Tebbe reagent (0.333 M in toluene, 2 equiv) is added very slowly, maintaining the temperature in the reaction mixture at −78 °C. The mixture is stirred for 15 min, then allowed to warm to 0 °C, and stirred for an additional 15 min. A 15% solution of NaOH (1 equiv) is added dropwise very carefully and slowly over a time period of at least 30 min, waiting after each drop for the gas evolution to cease. The mixture is then diluted with DCM (200 mL/g of formyl glycoside), and the blue-green precipitate formed during the addition of NaOH is filtered off over Celite. The filtrate is washed with aqueous 1 M HCl, saturated aqueous $NaHCO_3$ solution, and brine, dried over $MgSO_4$, filtered, and evaporated to dryness. The pure products are obtained by flash column chromatography, followed by recrystallization in some cases.

**General Procedure for the Cycloadditon of Dichloroketene to the Vinyl Glycosides 2 (Procedure E).** Zn/Cu was freshly prepared by stirring zinc powder (1.0 g) in a solution of $CuSO_4 \cdot 5H_2O$ (100 mg/30 mL of water) for 1 h, washing with water, acetone, and diethyl ether, and drying in high vacuum. It was then added to a solution of the vinyl glycoside (typically 0.5 mmol) in diethyl ether (50 mL/g of vinyl glycoside). A solution of trichloroacetyl chloride (0.2 mL, 1.8 mmol typically 3−4 equiv) in 5 mL of diethyl ether was added at room temperature over a time period of 3 h. After additional stirring for 12 h, the mixture was diluted with 100 mL of diethyl ether then washed three times with saturated aqueous $NaHCO_3$ solution and once with brine. The organic phase was dried over $MgSO_4$, filtered, and evaporated to dryness in high vacuum. $NaBH_4$ (2.6 mmol, typically 5 equiv) was added to an ice-cold solution of the crude product (0.5 mmol) in 2-propanol (20 mL). The mixture was stirred for 3 h, diluted with 100 mL of diethyl ether, and washed with brine. The organic layer was separated, dried, and concentrated in a vacuum. The pure products were obtained by flash column chromatography, followed by recrystallization in some cases.

**General Procedure for the Glycosylation of the 1-*O*-(2′,2′-Dichloro-3′-hydroxycyclobutyl) Glycosides 3 (Procedure F).** The alcohol **3** (typically 0.1 mmol) and the ethylthio or phenylthio glycoside (typically 5 equiv), 4 Å molecular sieves, and DCM (50 mL/g of ethylthio glycoside) are placed in a dried Schlenk flask under a nitrogen atmosphere. The mixture is cooled to 0 °C, and *N*-iodosuccinimide (5 equiv) and TfOH (5 equiv) are added. After 3 min, the reaction is quenched with triethylamine (large excess). The solution is diluted with diethyl ether (500 mL/g of substrate), washed with 1 M HCl, saturated aqueous $NaHCO_3$ solution, and brine, dried over $MgSO_4$, filtered, and evaporated to dryness. The pure products are obtained by flash column chromatography, followed by recrystallization in some cases.

**Copolymerization of Vinyl Glycosides and Maleic Anhydride.** Maleic anhydride, the vinyl glycoside, AIBN, and dry toluene or chloroform were placed in a Schlenk flask and carefully degassed with 3 freeze−pump−thaw cycles. The mixture was then heated to 60 °C and kept at that temperature for 12−36 h. The crude product mixture was dissolved in DCM, and the pure copolymer was obtained by precipitation in MeOH, filtered off, and dried in high vacuum.

**Formyl 2,3,4,6-Tetra-*O*-acetyl-β-D-glucopyranoside (1a).** The product was prepared according to procedure A, using 2,3,4,6-tetra-*O*-acetyl-D-glucopyranosyl bromide (3.4 g, 8.3 mmol), formic acid (85 mL, 2.3 mol), and $AgNO_3$ (1.6 g, 9.4 mmol, 1.1 equiv). After recrystallization from ethyl acetate/hexane, **1a** (1.6 g, 51%) was obtained as a white crystalline solid. $^1$H NMR ($CDCl_3$, 500 MHz) $\delta$ 8.00 (s, 1H), 5.78 (d, 1H, $J$ = 8.2 Hz), 5.22 (dd, 1H, $J$ = 9.4, 8.4 Hz), 5.11 (dd, 1H, $J$ = 8.4, 8.2 Hz), 5.05 (dd, 1H, $J$ = 9.7, 9.4 Hz), 4.23 (dd, 1H, $J$ = 12.5, 4.6 Hz), 4.06 (dd, 1H, $J$ = 12.5, 2.3 Hz), 3.84 (ddd, 1H, $J$ = 9.7, 4.6, 2.3 Hz), 2.01 (s, 3H), 1.97 (s, 6H), 1.94 (s, 3H); $^{13}$C NMR ($CDCl_3$, 125 MHz) $\delta$ 170.4, 169.9, 169.3, 169.1 (4C), 158.6, 91.1, 72.8, 72.5, 70.0, 67.6, 61.3, 20.6−20.4 (4C). Anal. Calcd for $C_{15}H_{20}O_{11}$: C, 47.88; H, 5.36. Found: C, 47.85; H, 5.55. MS (ESI) $m/z$ 399.1 ([M + Na]$^+$). $R_f$ 0.53 (ethyl acetate/hexane 1:1).

**Formyl 2,3,4,6-Tetra-*O*-acetyl-α-D-glucopyranoside (1b).** The product was prepared according to procedure B, using ethyl 2,3,4,6-tetra-*O*-acetyl-1-thio-β-D-glucopyranoside (5 g, 12.7 mmol), 50 mL of DCM, formic acid (0.79 mL, 21 mmol, 1.7 equiv), *N*-iodosuccinimide (3.44 g, 15.3 mmol, 1.2 equiv), and TfOH (0.91 mL, 10.2 mmol, 0.8 equiv). The reaction mixture was stirred for 2 h at 0 °C before it was quenched with triethylamine (5 mL, 36 mmol, 2.8 equiv). After purification by flash column chromatography (silica gel, ethyl acetate/hexane 1:5, 0.5% of formic acid) and recrystallization from ethyl acetate/hexane, **1b** (3.3 g, 69%) was obtained as a white crystalline solid. $^1$H NMR ($CDCl_3$, 500 MHz) $\delta$ 8.10 (s, 1H), 6.38 (d, 1H, $J$ = 3.7 Hz), 5.42 (t, 1H, $J$ = 10.0 Hz), 5.09 (t, 1H, $J$ = 10.0 Hz), 5.05 (dd, 1H, $J$ = 10.0, 3.7 Hz), 4,21 (dd, 1H, $J$ = 12.5, 4.4 Hz), 4.12−4.08 (m, 1H), 4.04 (dd, 1H, $J$ = 12.5, 2.2 Hz), 2.03 (s, 3H), 1.98 (s, 3H), 1.97 (s, 3H), 1.96 (s, 3H). $^{13}$C NMR ($CDCl_3$, 125 MHz) $\delta$ 170.3−169.2 (4C), 158.4, 88.8, 70.0, 69.4, 69.0, 67.5, 61.2, 20.4−20.2 (4C). Anal. Calcd for $C_{15}H_{20}O_{11}$: C, 47.88; H, 5.36. Found: C, 48.05; H, 5.45. MS (ESI) $m/z$ 399.0 ([M + Na]$^+$). $R_f$ 0.53 (ethyl acetate/hexane 1:1).

**Formyl 2,3,4,6-Tetra-*O*-benzoyl-β-D-glucopyranoside (1c).** The product was prepared according to procedure A, using 2,3,4,6-tetra-*O*-benzoyl-D-glucopyranosyl bromide (3.0 g, 4.6 mmol), formic acid (85 mL, 1.8 mol), and $AgNO_3$ (1.5 g, 8.8 mmol, 1.9 equiv). After purification by flash column chromatography (silica gel, ethyl acetate/hexane 1:6, 0.5% of formic acid) and recrystallization from ethyl acetate/hexane, **1c** (1.7 g, 60%) was obtained as a white crystalline solid. $^1$H NMR ($CDCl_3$, 500 MHz) $\delta$ 8.10−7.26 (m, 21H), 6.26 (d, 1H, $J$ = 8.1 Hz), 6.04 (t, 1H, $J$ = 9.6 Hz), 5.86−5.75 (m, 2H), 4.70 (dd, 1H, $J$ = 12.4, 2.9 Hz), 4.54 (dd, 1H, $J$ = 12.4, 4.9 Hz), 4.43−4.36 (m, 1H); $^{13}$C NMR ($CDCl_3$, 125 MHz) $\delta$ 166.0−164.9 (4C), 158.5, 133.5−128.2 (24C), 91.5, 73.3, 72.7, 70.6, 68.5, 62.5. Anal. Calcd for $C_{35}H_{28}O_{11}$: C, 67.30; H, 4.52. Found: C, 67.17; H, 4.56. MS (ESI) $m/z$ 646.7 ([M + Na]$^+$), 618.7 ([M + Na − CHO]$^+$). $R_f$ 0.53 (ethyl acetate/hexane 1:1).

**Formyl 2,3,4,6-Tetra-*O*-benzyl-α-D-glucopyranoside (1d).** The product was prepared according to procedure B, using ethyl 2,3,4,6-tetra-*O*-benzyl-1-thio-β-D-glucopyranoside (0.23 g, 0.39 mmol), 20 mL of DCM, formic acid (0.10 mL, 2.6 mmol, 6.7 equiv), *N*-iodosuccinimide (100 mg, 0.44 mmol, 1.1 equiv), and TfOH (0.03 mL, 0.34 mmol, 0.9 equiv). The reaction mixture was stirred for

30 min at 0 °C before it was quenched with triethylamine (5 mL, 36 mmol). After purification by flash column chromatography (silica gel, ethyl acetate/hexane 1:6, 0.5% of formic acid), **1d** (0.19 g, 86%) was obtained as a white crystalline solid. $^1$H NMR ($CDCl_3$, 500 MHz) $\delta$ 8.19 (s, 1H), 7.40−7.20 (m, 20H), 6.47 (d, 1H, $J$ = 3.4 Hz), 5.01−3.68 (m, 14H); $^{13}$C NMR ($CDCl_3$, 125 MHz) $\delta$ 159.3, 138.5−127.5 (24C), 90.1, 81.6, 78.6, 76.7, 75.6, 75.0, 73.4, 73.3, 73.0, 70.0. Anal. Calcd for $C_{35}H_{36}O_7$: C, 73.92; H, 6.38. Found: C, 73.68; H, 6.44. MS (EI) $m/z$ 591.2 ([M + Na]$^+$). $R_f$ 0.65 (ethyl acetate/hexane 1:1).

**Formyl 2,3,4-Tri-*O*-benzoyl-α-D-arabinopyranoside (1e).** The product was prepared according to procedure A, using 2,3,4-tri-*O*-benzoyl-D-arabinopyranosyl bromide (3.0 g, 5.7 mmol), formic acid (50 mL, 1.3 mol), and $AgNO_3$ (2.0 g, 11.8 mmol, 2.1 equiv). After purification by flash column chromatography (silica gel, ethyl acetate/hexane 1:6, 0.5% of formic acid) and recrystallization from ethyl acetate/hexane, **1e** (1.8 g, 64%) was obtained as a crystalline white solid. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 8.17 (s, 1H), 8.13−7.95 (m, 6H), 7.63−7.33 (m, 9H), 6.22 (d, 1H, $J$ = 6.1 Hz), 5.91 (dd, 1H, $J$ = 7.9, 6.1 Hz), 5.85−5.77 (m, 2H), 4.41 (dd, 1H, $J$ = 12.7, 4.5 Hz), 4.14 (dd, 1H, $J$ = 12.7, 2.3 Hz); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 165.5, 165.4, 165.0, 158.9, 133.7−128.5 (18 C) 91.6, 70.1, 68.8, 67.7, 63.4. Anal. Calcd for $C_{27}H_{22}O_9$: C, 66.12; H, 4.52. Found: C, 66.05; H, 4.51. MS (ESI) $m/z$ 513.0 ([M + Na]$^+$), 484.9 ([M + Na − CHO]$^+$). $R_f$ 0.49 (ethyl acetate/hexane 1:1).

**Formyl 2,3-Di-*O*-benzoyl-4,6-*O*-benzylidene-β-D-glucopyranoside (1g).** The product was prepared according to procedure B, using ethyl 2,3-di-*O*-benzoyl-4,6-*O*-benzylidene-1-thio-β-D-glucopyranoside (1.3 g, 2.5 mmol), DCM (50 mL), formic acid (0.15 mL, 3.9 mmol, 1.6 equiv), *N*-iodosuccinimide (0.67 g, 3.0 mmol, 1.2 equiv), and TfOH (0.22 mL, 2.5 mmol, 1.0 equiv). The reaction was quenched with triethylamine (5 mL, 36 mmol) after 3 min. After purification by flash column chromatography (silica gel, ethyl acetate/hexane 1:6, 0.5% of formic acid) and recrystallization from ethyl acetate and hexane, **1g** (0.74 g, 59%) was obtained as a crystalline white solid. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 8.09 (s, 1H), 8.05−7.32 (m, 15H), 6.18 (d, 1H, $J$ = 8.1 Hz), 5.90 (t, 1H, $J$ = 9.3 Hz), 5.70 (dd, 1H, $J$ = 9.3, 8.1 Hz), 5.60 (s, 1H), 4.49 (dd, 1H, $J$ = 15.6, 9.9 Hz), 4.05 (t, 1H, $J$ = 9.3 Hz), 3.97−3.85 (m, 2H); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 165.5, 165.2, 158.7, 136.6−126.2 (18C), 101.7, 92.0, 78.4, 72.0, 71.3, 68.4, 67.6. Anal. Calcd for $C_{28}H_{24}O_9$: C, 66.66; H, 4.80. Found: C, 66.69; H, 4.86. MS (ESI) $m/z$ 526.8 ([M + Na]$^+$), 542.7 ([M + K]$^+$). $R_f$ 0.68 (ethyl acetate/hexane 1:1).

**6-*O*-Formyl-1,2:3,4-di-*O*-isopropylidene-α-D-galactopyranose (1*l*).** The product was prepared according to procedure C, using 1,2:3,4-di-*O*-isopropylidene-α-D-galactopyranose (5 g, 19 mmol), DPTS (12.0 g, 41 mmol, 2.2 equiv), EDCI (7.9 g, 41 mmol, 2.2 equiv), and HCOOH (1.5 mL, 40 mmol, 2.0 equiv). After flash column chromatography (silica gel, ethyl acetate/hexane 1:8), **1*l*** (4.2 g, 76%) was obtained as a crystalline white solid. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 7.94 (s, 1H), 5.37 (d, 1H, $J$ = 5.1 Hz), 4.48 (dd, 1H, $J$ = 7.9, 2.6 Hz), 4.21−3.85 (m, 5H), 1.35 (s, 3H), 1.29 (s, 3H), 1.18 (s, 3H), 1.17 (s, 3H); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 160.6, 109.3, 108.4, 96.0, 70.7, 70.4, 70.1, 65.6, 62.6, 25.7−24.2 (4C). Anal. Calcd for $C_{13}H_{20}O_7$: C, 54.16; H, 6.99. Found: C, 53.96; H, 6.94. MS (ESI) $m/z$ 311.1 ([M + Na]$^+$). $R_f$ 0.71 (ethyl acetate/hexane 1:1).

**3-*O*-Formyl-1,2:5,6-di-*O*-isopropylidene-α-D-glucofuranose (1m).** The product was prepared according to procedure C, using 1,2:5,6-di-*O*-isopropylidene-α-D-glucofuranose (2.1 g, 8.1 mmol), DPTS (4.6 g, 16 mmol, 2.0 equiv), EDCI (3.1 g, 16 mmol, 2.0 equiv), and HCOOH (0.6 mL, 16 mmol, 2.0 equiv). After flash column chromatography (silica gel, ethyl acetate/hexane 1:8), **1m** (1.6 g, 69%) was obtained as a colorless syrup. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 8.01 (s, 1H), 5.80 (d, 1H, $J$ = 3.8 Hz), 5.24 (d, 1H, $J$ = 2.3 Hz), 4.44 (d, 1H, $J$ = 3.8 Hz), 4.17−4.06 (m, 2H), 4.00 (dd, 1H, $J$ = 8.8, 5.5 Hz), 3.91 (dd, 1H, $J$ = 8.8, 4.0 Hz), 1.42 (s, 3H), 1.31 (s, 3H), 1.22 (s, 6H); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 159.5, 112.2, 109.3, 104.9, 83.1, 79.5, 75.6, 72.1, 67.2, 26.8, 26.6, 26.1, 25.0. Anal. Calcd for $C_{13}H_{20}O_7$: C, 54.16; H, 6.99. Found: C, 53.99; H, 7.09. MS (ESI) $m/z$ 311.2 ([M + Na]$^+$). $R_f$ 0.56 (ethyl acetate/hexane 1:1).

**Vinyl 2,3,4,6-Tetra-*O*-acetyl-β-D-glucopyranoside (2a).** The product was prepared according to procedure D, using **1a** (0.30 g, 0.8 mmol), Tebbe reagent (4.8 mL, 1.6 mmol, 2.0 equiv), and aqueous NaOH solution (0.21 mL, 0.8 mmol, 1.0 equiv). After flash column chromatography (silica gel, ethyl acetate/hexane 1:6) and recrystallization from ethyl acetate/hexane, **2a** (0.19 g, 63%) was obtained as a white crystalline solid. $^1$H NMR ($CDCl_3$, 500 MHz) $\delta$ 6.38 (dd, 1H, $J$ = 14.1, 6.4 Hz), 5.17 (t, 1H, $J$ = 9.4 Hz), 5.05 (dd, 1H, $J$ = 9.4, 7.5 Hz), 5.03 (dd, 1H, $J$ = 9.4, 7.8 Hz), 4.75 (d, 1H, $J$ = 7.8 Hz), 4,50 (dd, 1H, $J$ = 14.1, 2.1 Hz), 4.21 (dd, 1H, $J$ = 6.4, 2.1 Hz), 4.19 (dd, 1H, $J$ = 12.4, 2.5 Hz), 4.07 (dd, 1H, $J$ = 12.4, 5.1 Hz), 3.72 (m, 1H), 1.99 (s, 3H), 1.96 (s, 3H), 1.94 (s, 3H), 1.92 (s, 3H); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 170.4, 170.0, 169.2, 169.0, 148.6, 98.8, 92.9, 72.5, 72.0, 70.7, 68.0, 61.7, 20.5−20.4 (4C). Anal. Calcd for $C_{16}H_{22}O_{10}$: C, 51.34; H, 5.92. Found: C, 51.32; H, 5.86. MS (ESI) $m/z$ 397.1 ([M + Na]$^+$). $R_f$ 0.59 (ethyl acetate/hexane 1:1). HRMS (MALDI) $m/z$ calcd for $C_{16}H_{22}O_{10}$ ([M + Na]$^+$) 397.1105, found 397.1105.

**Vinyl 2,3,4,6-Tetra-*O*-acetyl-α-D-glucopyranoside (2b).** The product was prepared according to procedure D, using **1b** (0.30 g, 0.8 mmol), Tebbe reagent (4.8 mL, 1.6 mmol, 2.0 equiv), and aqueous NaOH solution (0.21 mL, 0.8 mmol, 1.0 equiv). After flash column chromatography (silica gel, ethyl acetate/hexane 1:6) and recrystallization from ethyl acetate/hexane, **2b** (0.18 g, 60%) was obtained as a white crystalline solid. $^1$H NMR ($CDCl_3$, 500 MHz) $\delta$ 6.31 (dd, 1H, $J$ = 14.0, 6.4 Hz), 5.48 (t, 1H, $J$ = 9.7 Hz), 5.33 (d, 1H, $J$ = 3.7 Hz), 5.05 (dd, 1H, $J$ = 10.2, 9.7 Hz), 4.89 (dd, 1H, $J$ = 10.2, 3.7 Hz), 4.61 (dd, 1H, $J$ = 14.0, 1.9 Hz), 4.24 (dd, 1H, $J$ = 6.6, 1.9 Hz), 4.20 (dd, 1H, $J$ = 12.5, 4.4 Hz), 4.03 (dd, 1H, $J$ = 12.5, 2.2 Hz), 3.97−3.93 (m, 1H), 2.03 (s, 3H), 2.02 (s, 3H), 1.98 (s, 3H), 1.97 (s, 3H); $^{13}$C NMR ($CDCl_3$, 125 MHz) $\delta$ 170.5−169.5 (4C), 147.9, 94.5, 93.5, 70.2, 70.0, 68.2, 67.9, 61.5, 20.6, 20.6, 20.6, 20.5. Anal. Calcd for $C_{16}H_{22}O_{10}$: C, 51.34; H, 5.92. Found: C, 51.33; H, 5.84. MS (ESI) $m/z$ 397.1 ([M + Na]$^+$). $R_f$ 0.63 (ethyl acetate/hexane 1:1).

**Vinyl 2,3,4,6-Tetra-*O*-benzoyl-β-D-glucopyranoside (2c).** The product was prepared according to procedure D, using **1c** (0.3 g, 0.48 mmol), Tebbe reagent (2.9 mL, 0.96 mmol, 2.0 equiv), and aqueous NaOH solution (0.13 mL, 0.48 mmol, 1.0 equiv). After purification by column chromatography (silica gel, ethyl acetate/hexane 1:6) and recrystallization from ethyl acetate/hexane, **2c** (0.19 g, 64%) was obtained as a white crystalline solid. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 8.10−7.25 (m, 20H), 6.50 (dd, 1H, $J$ = 14.0, 6.5 Hz), 6.04 (t, 1H, $J$ = 9.6 Hz), 5.82−5.71 (m, 2H), 5.27 (d, 1H, $J$ = 7.8 Hz), 4.72 (dd, 1H, $J$ = 12.3, 3.0 Hz), 4.64 (dd, 1H, $J$ = 14.0, 2.1 Hz), 4.59 (dd, 1H, $J$ = 12.3, 5.6 Hz), 4.35 (m, 1H), 4.29 (dd, 1H, $J$ = 6.5, 2.1 Hz); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 166.1−165.1 (4C), 148.7, 133.6−128.4 (24C), 99.3, 93.3, 72.8, 72.7, 71.5, 69.5, 63.2. Anal. Calcd for $C_{36}H_{30}O_{10}$: C, 69.45; H, 4.86. Found: C, 69.23; H, 4.95. MS (ESI) $m/z$ 644.8 ([M + Na]$^+$). $R_f$ 0.59 (ethyl acetate/hexane 1:1).

**Vinyl 2,3,4,6-Tetra-*O*-benzyl-α-D-glucopyranoside 2d.** The product was prepared according to procedure D, using **1d** (1.1 g, 1.93 mmol), Tebbe reagent (11.6 mL, 3.87 mmol, 2.0 equiv), and aqueous NaOH solution (0.51 mL, 1.9 mmol, 1.0 equiv). After purification by column chromatography (silica gel, ethyl acetate/hexane 1:10) and recrystallization from ethyl acetate/hexane, **2d** (0.91 g, 83%) was obtained as a white crystalline solid. $^1$H NMR ($CDCl_3$, 500 MHz) $\delta$ 7.46−7.02 (m, 20), 6.43 (dd, 1H, $J$ = 14.0, 6.5 Hz), 5.15 (d, 1H, $J$ = 3.4 Hz), 5.07 (d, 1H, $J$ = 11.0 Hz), 4.92 (d, 1H, $J$ = 11.0 Hz), 4.91 (d, 1H, $J$ = 11.0 Hz), 4.86 (d, 1H, $J$ = 12.0 Hz), 4.73 (d, 1H, $J$ = 12.0 Hz), 4.70 (dd, 1H, $J$ = 14.0, 2.1 Hz), 4.67 (d, 1H, $J$ = 12.0 Hz), 4.55 (d, 1H, $J$ = 11.0 Hz), 4.50 (d, 1H, $J$ = 12.0 Hz), 4.28 (dd, 1H, $J$ = 6.5, 2.1 Hz), 4.13 (t, 1H, $J$ = 9.0 Hz), 3.87−3.65 (m, 5H); $^{13}$C NMR ($CDCl_3$, 125 MHz) $\delta$ 148.4,

138.7−127.6 (24 C), 96.2, 92.5, 81.9, 79.2, 77.2, 75.7, 75.0, 73.3, 73.2, 70.7, 68.0. Anal. Calcd for $C_{36}H_{38}O_6$: C, 76.30; H, 6.76. Found: C, 76.02; H, 6.77. MS (ESI) *m/z* 588.7 ([M + Na]$^+$). $R_f$ 0.69 (ethyl acetate/hexane 1:1). HRMS (MALDI) *m/z* calcd for $C_{36}H_{38}O_6$ ([M + Na]$^+$) 589.2561, found 589.2550.

**Vinyl 2,3,4-Tri-*O*-benzoyl-α-D-arabinopyranoside (2e).** The product was prepared according to procedure D, using **1e** (0.24 g, 0.49 mmol), Tebbe reagent (3.3 mL, 1 mmol, 2.0 equiv), and aqueous NaOH solution (0.12 mL, 0.45 mmol, 0.9 equiv). After purification by column chromatography (silica gel, ethyl acetate/hexane 1:6) and recrystallization from ethyl acetate/hexane, **2e** (0.16 g, 67%) was obtained as a white crystalline solid. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 8.10−7.99 (m, 6H), 7.63−7.33 (m, 9H), 6.51 (dd, 1H, $J$ = 13.8, 6.6 Hz), 5.84−5.70 (m, 3H), 5.17 (d, 1H, $J$ = 5.1 Hz), 4.67 (dd, 1H, $J$ = 13.8, 1.9 Hz), 4.39 (dd, 1H, $J$ = 12.3, 5.1 Hz), 4.31 (dd, 1H, $J$ = 6.6, 1.9 Hz), 4.01 (dd, 1H, $J$ = 12.3, 2.5 Hz); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 165.7−165.2 (3C), 148.7, 133.6−128.5 (18C), 98.6, 93.1, 69.9, 69.4, 67.7, 61.8. Anal. Calcd for $C_{28}H_{24}O_8$: C, 68.85; H, 4.95. Found: C, 68.56; H, 4.78. MS (ESI) *m/z* 511.0 ([M + Na]$^+$). $R_f$ 0.54 (ethyl acetate/hexane 1:1).

**Vinyl 2,3,4-Tri-*O*-benzoyl-β-D-ribopyranoside (2f).** The product was prepared according to procedure D, using the crude formyl 2,3,4-tri-*O*-benzoyl-β-D-ribopyranoside (**1f**; 0.30 g) [prepared from 2,3,4-tri-*O*-benzoyl-β-D-ribopyranosyl bromide (0.31 g, 0.59 mmol), $AgNO_3$ (0.32 g, 1.9 mmol), and HCOOH (20 mL, 0.53 mol) following procedure A], Tebbe reagent (5.0 mL, 1.7 mmol), and aqueous NaOH solution (0.16 mL, 0.6 mmol). After purification by column chromatography (silica gel, ethyl acetate/hexane 1:7), **2f** (0.21 g, 73% over two steps) was obtained as a white solid. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 8.12−7.29 (m, 15H), 6.51 (dd, 1H, $J$ = 14.1, 6.5 Hz), 5.92 (t, 1H, $J$ = 3.9 Hz), 5.72−5.67 (m, 1H), 5.66−5.62 (m, 1H), 5.50 (d, 1H, $J$ = 2.5 Hz), 4.75 (dd, 1H, $J$ = 14.1, 2.1 Hz), 4.37 (dd, 1H, $J$ = 6.5, 2.1 Hz), 4.32 (dd, 1H, $J$ = 13.2, 2.1 Hz), 4.16 (dd, 1H, $J$ = 13.2, 2.4 Hz); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 166.3−165.2 (3C), 147.9, 133.4−128.5 (18C), 97.4, 93.5, 68.1, 67.5, 65.9, 61.8. Anal. Calcd for $C_{28}H_{24}O_8$: C, 68.85; H, 4.95. Found: C, 68.70; H, 5.07. MS (ESI) *m/z* 511.0 ([M + Na]$^+$). $R_f$ 0.56 (ethyl acetate/hexane 1:1).

**Vinyl 2,3-Di-*O*-benzoyl-4,6-*O*-benzylidene-β-D-glucopyranoside (2g).** The product was prepared according to procedure D, using **1g** (190 mg, 0.38 mmol), Tebbe reagent (2.3 mL, 0.77 mmol, 2.0 equiv), and aqueous NaOH solution (0.1 mL, 0.38 mmol, 1.0 equiv). After flash column chromatography (silica gel, ethyl acetate/hexane 1:7) and recrystallization from ethyl acetate/hexane, **2g** (130 mg, 68%) was obtained as a white crystalline solid. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 8.06−7.31 (m, 15H), 6.45 (dd, 1H, $J$ = 13.8, 6.3 Hz), 5.85 (t, 1H, $J$ = 9.3 Hz), 5.62 (dd, 1H, $J$ = 9.3, 7.8 Hz), 5.59 (s, 1H), 5.15 (d, 1H, $J$ = 7.8 Hz), 4.63 (dd, 1H, $J$ = 13.8, 2.1 Hz), 4.49 (dd, 1H, $J$ = 10.2, 4.8 Hz), 4.29 (dd, 1H, $J$ = 6.3, 2.1 Hz), 4.03 (t, 1H, $J$ = 9.3 Hz), 3.95 (t, 1H, $J$ = 10.2 Hz), 3.81 (dt, 1H, $J$ = 9.4, 4.8 Hz); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 165.7, 165.2, 148.9, 136.8−126.2 (18C) 101.6, 100.0, 93.5, 78.6, 72.1, 72.1, 68.6, 67.0. Anal. Calcd for $C_{29}H_{26}O_8$: C, 69.31; H, 5.21. Found: C, 69.42; H, 5.23. MS (ESI) *m/z* 525.0 ([M + Na]$^+$). $R_f$ 0.74 (ethyl acetate/hexane 1:1). HRMS (MALDI) *m/z* calcd for $C_{29}H_{26}O_8$ ([M + Na]$^+$) 525.1520, found 525.1529.

**Vinyl 2,3,4,6-Tetra-*O*-benzoyl-β-D-galactopyranoside (2h).** The product was prepared according to procedure D, using the crude formyl 2,3,4,6 tetra-*O*-benzoyl-β-D-galactopyranoside (**1h**; 0.80 g) [prepared from 2,3,4,6-tetra-*O*-benzoyl-β-D-galactopyranosyl bromide (0.85 g,1.3 mmol), $AgNO_3$ (0.45 g, 2.6 mmol) ,and HCOOH (50 mL, 1.3 mmol) following procedure A], Tebbe reagent (8.0 mL, 2.7 mmol), and aqueous NaOH solution (0.35 mL, 1.3 mmol). After flash column chromatography (silica gel, ethyl acetate/hexane 1:6), **2h** (0.37 g, 46% over two steps) was obtained as a white solid. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 8.19−7.23 (m, 20H), 6.55 (dd, 1H, $J$ = 14.1, 6.5 Hz), 6.11 (d, 1H, $J$ = 3.3 Hz), 6.00 (dd, 1H, $J$ = 10.2, 7.8 Hz), 5.74 (dd, 1H, $J$ = 10.2, 3.3 Hz), 5.24 (d, 1H, $J$ = 7.8 Hz), 4.79−4.46 (m, 4H), 4.32 (dd, 1H, $J$ = 6.5, 2.2 Hz); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 166.1−165.2 (4C), 148.9, 133.7−128.4 (24C), 99.7, 93.3, 71.8, 71.7, 69.3, 68.0, 62.1. Anal. Calcd for $C_{36}H_{30}O_{10}$: C, 69.45; H, 4.86. Found: C, 69.31; H, 5.01. MS (ESI) *m/z* 644.8 ([M + Na]$^+$). $R_f$ 0.53 (ethyl acetate/hexane 1:1).

**Vinyl 2,3,4,6-Tetra-*O*-benzoyl-α-D-mannopyranoside (2i).** The product was prepared according to procedure D, using the crude formyl 2,3,4,6-tetra-*O*-benzoyl-α-D-mannopyranoside (**1i**; 2.8 g) [prepared from 2,3,4,6-tetra-*O*-benzoyl-α-D-mannopyranosyl bromide (3 g, 4.5 mmol), $AgNO_3$ (2 g, 11.7 mmol), and HCOOH (50 mL, 1.3 mmol) following procedure A], Tebbe reagent (27 mL, 9.0 mmol), and aqueous NaOH solution (1.2 mL, 4.5 mmol). After purification by column chromatography (silica gel, ethyl acetate/hexane 1:6), **2i** (1.51 g, 53% over two steps) was obtained as a white solid. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 8.17−7.28 (m, 20H), 6.54 (dd, 1H, $J$ = 14.1, 6.7 Hz), 6.22 (t, 1H, $J$ = 10.1 Hz), 6.03 (dd, 1H, $J$ = 10.1, 3.2 Hz), 5.83 (dd, 1H, $J$ = 3.2, 1.8 Hz), 5.50 (d, 1H, $J$ = 1.8 Hz), 4.83 (dd, 1H, $J$ = 14.1, 2.1 Hz), 4.78−4.70 (m, 1H), 4.56−4.45 (m, 2H), 4.40 (dd, 1H, $J$ = 6.7, 2.1 Hz); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 166.2−165.4 (4C), 147.6, 133.7−128.4 (24C), 96.4, 93.9, 69.9, 69.9, 69.5, 66.6, 62.6. Anal. Calcd for $C_{36}H_{30}O_{10}$: C, 69.45; H, 4.86. Found: C, 69.47; H, 4.97. MS (ESI) *m/z* 644.8 ([M + Na]$^+$). $R_f$ 0.58 (ethyl acetate/hexane 1:1).

**Vinyl 2,3,6,8,9,10,12-Hepta-*O*-benzoyl-β-D-cellobioside (2k).** The product was prepared according to procedure D, using the crude formyl 2,3,6,8,9,10,12-hepta-*O*-benzoyl-β-D-cellobioside (**1k**; 0.60 g) [prepared from 2,3,6,8,9,10,12-hepta-*O*-benzoyl-β-D-cellobiosyl bromide (0.69 g, 0.61 mmol), $AgNO_3$ (0.50 g, 2.9 mmol), and HCOOH (20 mL, 0.53 mol) following procedure A], Tebbe reagent (4.0 mL, 1.33 mmol), and aqueous NaOH solution (0.15 mL, 0.56 mmol). After flash column chromatography (silica gel, ethyl acetate/hexane 1:4), **2k** (0.29 g, 43% over two steps) was obtained as a white solid. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 8.15−7.18 (m, 35H), 6.35 (dd, 1H, $J$ = 14.1, 6.7 Hz), 5.86 (t, 1H, $J$ = 9.2 Hz), 5.77 (t, 1H, $J$ = 9.6 Hz), 5.56 (dd, 1H, $J$ = 9.4, 7.8 Hz), 5.55 (dd, 1H, $J$ = 9.9, 7.8 Hz), 5.41 (t, 1H, $J$ = 9.6 Hz), 5.03, 4.98 (d, d, 2H, $J$ = 7.8 Hz), 4.64 (dd, 1H, $J$ = 12.4, 2.1 Hz), 4.52 (dd, 1H, $J$ = 14.1, 2.1 Hz), 4.50 (dd, 1H, $J$ = 12.3, 5.1 Hz), 4.31 (t, 1H, $J$ = 9.6 Hz), 4.19 (dd, 1H, $J$ = 6.7, 2.1 Hz), 4.10 (dd, 1H, $J$ = 11.5, 2.5 Hz), 4.00−3.75 (m, 3H); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 165.8−164.9 (7C), 148.8, 133.5−128.4 (42C), 101.0, 99.1, 93.1, 76.3, 73.5, 72.9, 72.7, 72.6, 72.0, 71.5, 69.5, 62.7, 62.5. Anal. Calcd for $C_{63}H_{52}O_{18}$: C, 68.97; H, 4.78. Found: C, 68.70; H, 4.92. MS (ESI) *m/z* 1119.2 ([M + Na]$^+$). $R_f$ 0.49 (ethyl acetate/hexane 1:1).

**1,2:3,4-Di-*O*-isopropylidene-6-*O*-vinyl-α-D-galactopyranose (2*l*).** The product was prepared according to procedure D, using **1*l*** (1 g, 3.5 mmol), Tebbe reagent (21 mL, 7 mmol, 2.0 equiv), and 15% solution of NaOH (0.85 mL, 3.2 mmol, 0.9 equiv). After flash column chromatography (silica gel, ethyl acetate/hexane 1:10), **2*l*** (0.89 g, 89%) was obtained as a colorless syrup. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 6.45 (dd, 1H, $J$ = 14.4, 6.8 Hz), 5.50 (d, 1H, $J$ = 4.8 Hz), 4.58 (dd, 1H, $J$ = 8.0, 2.4 Hz), 4.28 (dd, 1H, $J$ = 4.8, 2.4 Hz), 4.23 (dd, 1H, $J$ = 7.8, 1.8 Hz), 4.18 (dd, 1H, $J$ = 14.4, 2.4 Hz), 4.04 (m, 1H), 3.98 (dd, 1H, $J$ = 6.8, 2.4 Hz), 3.88−3.75 (m, 2H), 1.49 (s, 3H), 1.41 (s, 3H), 1.30 (s, 3H), 1.29 (s, 3H); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 151.6, 109.3, 108.6, 96.3, 86.7, 71.0, 70.6, 70.5, 66.5, 66.1, 26.0−24.4 (4C). Anal. Calcd for $C_{14}H_{22}O_6$: C, 58.73; H, 7.74. Found: C, 59.00; H, 7.71. MS (ESI) *m/z* 309.2 ([M + Na]$^+$), $R_f$ 0.76 (ethyl acetate/hexane 1:1).

**1,2:5,6-Di-*O*-isoproplidene-3-*O*-vinyl-α-D-glucofuranose (2m).** The product was prepared according to procedure D, using **1m** (0.40 g, 1.4 mmol), Tebbe reagent (8.4 mL, 2.8 mmol, 2.0 equiv), and 15% solution of NaOH (0.36 mL, 1.4 mmol, 1.0 equiv). After flash column chromatography (silica gel, ethyl acetate/hexane 1:8), **2m** (0.35 g, 87%) was obtained as a colorless syrup. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 6.35 (dd, 1H, $J$ = 14.1, 6.6 Hz), 5.83 (d, 1H, $J$ = 3.8 Hz), 4.54 (d, 1H, $J$ = 3.8 Hz), 4.35 (dd, 1H, $J$ = 14.1, 2.3 Hz), 4.30 (d, 1H, $J$ = 3.0 Hz), 4.29−4.22 (m, 1H), 4.14 (dd, 1H, $J$ = 7.7, 3.0 Hz), 4.11 (dd, 1H, $J$ = 6.6, 2.3 Hz), 4.04 (dd, 1H, $J$ = 8.9, 6.2 Hz), 3.97 (dd, 1H, $J$ = 8.5, 5.3 Hz), 1.47 (s, 3H), 1.38 (s, 3H),

1.29 (s, 3H), 1.27 (s, 3H); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 150.1, 111.9, 109.1, 105.2, 89.4, 82.1, 80.4, 80.4, 72.2, 67.1, 26.9−25.3 (4C). Anal. Calcd for $C_{14}H_{22}O_6$: C, 58.73; H, 7.74. Found: C, 58.82; H, 7.62. MS (ESI) *m/z* 309.2 ([M + Na]$^+$). $R_f$ 0.62 (ethyl acetate/hexane 1:1).

**(1′*S*,3′*R*)-2′,2′-Dichloro-3′-hydroxycyclobutyl 2,3,4,6-Tetra-*O*-acetyl-$\beta$-D-glucopyranoside (3a).** The product was prepared according to procedure E, using **2a** (130 mg, 0.35 mmol) and trichloroacetyl chloride (0.1 mL, 0.89 mmol, 2.5 equiv), as well as $NaBH_4$ (80 mg, 2 mmol, 5.7 equiv). $^1$H NMR spectra of the crude product were consistent with the presence of only one diastereomer. After flash column chromatography (silica gel, ethyl acetate/hexane 1:5) and recrystallization from ethyl acetate/hexane, **3a** (91 mg, 53%) was obtained as a white crystalline solid. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 5.26 (t, 1H, $J$ = 9.4 Hz), 5.09 (t, 1H, $J$ = 9.4 Hz), 5.04 (dd, 1H, $J$ = 9.4, 7.8 Hz), 4.84 (d, 1H, $J$ = 7.8 Hz), 4.41 (t, 1H, $J$ = 8.5 Hz), 4.29−4.12 (m, 3H), 3.74 (ddd, 1H, $J$ = 9.8, 4.5, 2.6 Hz), 3.13 (d, 1H, $J$ = 9.6 Hz), 2.70 (dt, 1H, $J$ = 11.7, 7.8 Hz), 2.09 (s, 3H), 2.07 (s, 3H), 2.03 (s, 3H), 2.01 (s, 3H), 1.93 (dt, 1H, $J$ = 11.7, 9.2 Hz); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 170.8−169.6 (4C), 98.8, 90.6, 74.4, 72.6, 72.3, 71.7, 71.0, 68.3, 61.78, 35.6, 20.8−20.6 (4C). Anal. Calcd for $C_{18}H_{24}Cl_2O_{11}$: C, 44.37; H, 4.96; Cl, 14.55. Found: C, 44.54; H, 5.09; Cl, 14.53. MS (ESI) *m/z* 508.8 ([M + Na]$^+$). $R_f$ 0.26 (ethyl acetate/hexane 1:1).

**(1′*S**,3′*R**)-2′,2′-Dichloro-3′-hydroxycyclobutyl 2,3,4,6-Tetra-*O*-acetyl-$\alpha$-D-glucopyranoside (3b).** The product was prepared according to procedure E, using **2b** (98 mg, 0.26 mmol) and trichloroacetyl chloride (0.1 mL, 0.89 mmol, 3.4 equiv), as well as $NaBH_4$ (40 mg, 1 mmol, 3.8 equiv). $^1$H NMR spectra of the crude product showed the presence of two diastereomers in a ratio of 3.0:1. After flash column chromatography (silica gel, ethyl acetate/hexane 1:4), an inseparable diastereomeric mixture of **3b** (71 mg, 56%) was obtained as a colorless syrup. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 5.53 (t, 1H, $J$ = 9.9 Hz), 5.41 (d, 1H, $J$ = 3.9 Hz, minor), 5.22 (d, 1H, $J$ = 3.9 Hz, major), 5.14 (t, 1H, $J$ = 9.9 Hz), 4.91 (dd, 1H, $J$ = 9.9, 3.9 Hz, minor), 4.88 (dd, 1H, $J$ = 9.9, 3.9 Hz, major), 4.45−4.02 (m, 5H), 2.95 (d, 1H, $J$ = 9.8 Hz, major), 2.93 (d, 1H, $J$ = 9.8 Hz, minor), 2.72 (dt, 1H, $J$ = 11.7, 7.8 Hz), 2.11 (s, 3H), 2.07 (s, 3H), 2.06 (s, 3H), 2.04 (s, 3H), 1.99 (dt, 1H, $J$ = 11.7, 9.0 Hz); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 170.80−169.65 (4C, major and minor), 96.9 (major), 94.5 (minor), 91.3 (major), 90.5 (minor), 78.0 (major), 73.6 (minor), 71.7 (minor), 71.4 (major), 70.8 (major), 69.9 (major), 68.4 (major), 68.0 (major), 70.2 (minor), 69.6 (minor), 68.4 (minor), 67.9 (minor), 61.7 (minor), 61.5 (major), 36.0 (major), 35.5 (minor), 20.8−20.6 (4C, major and minor). $R_f$ 0.23 (ethyl acetate/hexane 1:1). HRMS (MALDI) *m/z* calcd for $C_{18}H_{24}Cl_2O_{11}$ ([M + Na]$^+$) 509.0588, found 509.0579.

**(1′*S*,3′*R*)-2′,2′-Dichloro-3′-hydroxycyclobutyl 2,3,4,6-Tetra-*O*-benzoyl-$\beta$-D-glucopyranoside (3c) and (1′*R*,3′*S*)-2′,2′-Dichloro-3′-hydroxycyclobutyl 2,3,4,6-Tetra-*O*-benzoyl-$\beta$-D-glucopyranoside (3c′).** The product was prepared according to procedure E, using **2c** (0.55 g, 0.88 mmol) and trichloroacetyl chloride (0.3 mL, 2.7 mmol, 3.1 equiv), as well as $NaBH_4$ (100 mg, 2.6 mmol, 3.0 equiv). $^1$H NMR spectra of the crude product showed the presence of two diastereomers in a ratio of 3.3:1. After flash column chromatography (silica gel, ethyl acetate/hexane 1:5) and recrystallization from ethyl acetate/hexane, the major and the minor diastereomer **3c** (0.31 g, 48%) and **3c′** (0.11 g, 17%), respectively, were isolated as a white crystalline solids.

Analytical data for **3c** (major diastereomer): $^1$H NMR ($CDCl_3$, 500 MHz) $\delta$ 8.12−7.29 (m, 20H), 5.98 (t, 1H, $J$ = 9.6 Hz), 5.71 (t, 1H, $J$ = 9.6 Hz), 5.60 (dd, 1H, $J$ = 9.6, 7.8 Hz), 5.23 (d, 1H, $J$ = 7.8 Hz), 4.67 (dd, 1H, $J$ = 12.2, 2.9 Hz), 4.56−4.50 (m, 2H), 4.23 (ddd, 1H, $J$ = 10.1, 5.2, 2.9 Hz), 4.10 (t, 1H, $J$ = 8.4 Hz), 2.65 (dt, 1H, $J$ = 11.7, 7.8 Hz), 2.52 (s, 1H), 1.86 (dt, 1H, $J$ = 11.7, 9.2 Hz); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 166.3−165.2 (4C), 133.6−128.4 (24C), 98.8, 90.5, 73.9, 72.9, 72.8, 71.7, 71.6, 69.6, 63.0, 35.6. Anal. Calcd for $C_{38}H_{32}Cl_2O_{11}$: C, 62.05; H, 4.38; Cl, 9.64. Found: C, 61.79; H, 4.41; Cl, 9.67. MS (ESI) *m/z* 756.9 ([M + Na]$^+$). $R_f$ 0.47 (ethyl acetate/hexane 1:1).

Analytical data for **3c′** (minor diastereomer): $^1$H NMR ($CDCl_3$, 500 MHz) $\delta$ 8.12−7.29 (m, 20H), 5.91 (t, 1H, $J$ = 9.6 Hz), 5.73 (t, 1H, $J$ = 9.6 Hz), 5.63 (dd, 1H, $J$ = 9.6, 7.8 Hz), 4.94 (d, 1H, $J$ = 7.8 Hz), 4.66 (dd, 1H, $J$ = 12.0, 3.6 Hz), 4.57 (dd, 1H, $J$ = 12.0, 4.8 Hz), 4.23 (ddd, 1H, $J$ = 9.6, 4.8, 3.6 Hz), 4.16 (t, 1H, $J$ = 8.4 Hz), 4.10 (t, 1H, $J$ = 8.4 Hz), 2.62 (dt, 1H, $J$ = 12.0, 7.5 Hz), 1.86 (dt, 1H, $J$ = 12.0, 9.0 Hz), 1.7 (s, 1H); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 166.3−165.1 (4C), 133.6−128.4 (24C), 100.9, 91.2, 78.2, 72.9, 72.7, 72.0, 71.8, 69.7, 63.2, 36.1. Anal. Calcd for $C_{38}H_{32}Cl_2O_{11}$: C, 62.05; H, 4.38; Cl, 9.64. Found: C, 61.87; H, 4.34; Cl, 9.81. MS (ESI) *m/z* 756.8 ([M + Na]$^+$). $R_f$ 0.38 (ethyl acetate/hexane 1:1).

**(1′*R*,3′*S*)-2′,2′-Dichloro-3′-hydroxycyclobutyl 2,3,4-Tri-*O*-benzoyl-$\beta$-D-ribopyranoside (3f).** The product was prepared according to procedure E, using **2f** (207 mg, 0.42 mmol) and trichloroacetyl chloride (0.15 mL, 1.3 mmol, 3.1 equiv), as well as $NaBH_4$ (50 mg, 1.3 mmol, 3.1 equiv). $^1$H NMR spectra of the crude product showed the presence of two diastereomers in a ratio of 10.1:1. After purification by column chromatography (silica gel, ethyl acetate/hexane 1:5), the major diastereomer **3f** (172 mg, 67%) was obtained as a white solid. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 8.10−7.29 (m, 15H), 5.87 (t, 1H, $J$ = 3.9 Hz), 5.73−5.69 (m, 1H), 5.62−5.59 (m, 1H), 5.24 (d, 1H, $J$ = 1.8 Hz), 4.63 (dd, 1H, $J$ = 13.3, 1.9 Hz), 4.28−4.15 (m, 3H), 2.83 (dt, 1H, $J$ = 11.7, 7.5 Hz, major), 2.70 (dt, 1H, $J$ = 11.4, 7.5 Hz, minor), 2.63 (d, 1H, $J$ = 10.7 Hz), 2.07 (dt, 1H, $J$ = 11.7, 9.3 Hz, major), 1.88 (dt, 1H, $J$ = 11.4, 9.3 Hz, minor); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 166.4−165.3 (3 C), 133.4−128.4 (18 C), 99.1, 91.4, 77.1, 71.6, 68.3, 67.5, 65.9, 62.3, 36.26. Anal. Calcd for $C_{30}H_{26}Cl_2O_9$: C, 59.91; H, 4.36. Found: C, 60.31; H, 4.59. MS (ESI) *m/z* 622.9 ([M + Na]$^+$). $R_f$ 0.44 (ethyl acetate/hexane 1:1). HRMS (MALDI) *m/z* calcd for $C_{30}H_{26}Cl_2O_9$ ([M + Na]$^+$) 623.0846, found 623.0835.

**(1′*S*,3′*R*)-2′,2′-Dichloro-3′-hydroxycyclobutyl 2,3,4,6-Tetra-*O*-benzoyl-$\alpha$-D-mannopyranoside (3i).** The product was prepared according to procedure E, using **2i** (128 mg, 0.2 mmol) and trichloroacetyl chloride (0.1 mL, 0.89 mmol, 4.5 equiv), as well as $NaBH_4$ (40 mg, 1 mmol, 5.0 equiv). $^1$H NMR spectra of the crude product were consistent with the presence of only one diastereomer. After purification by column chromatography (silica gel, ethyl acetate/hexane 1:5), **3i** (91 mg, 60%) was obtained as a white solid. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 8.25−7.25 (m, 20H), 6.28 (t, 1H, $J$ = 10.0 Hz), 5.97 (dd, 1H, $J$ = 10.0, 3.1 Hz), 5.80 (dd, 1H, $J$ = 3.1, 0.5 Hz), 5.24 (d, 1H, $J$ = 0.5 Hz), 4.87−4.80 (m, 2H), 4.53 (dd, 1H, $J$ = 9.6, 3.9 Hz), 4.30−4.19 (m, 2H), 2.85 (dt, 1H, $J$ = 11.7, 7.8 Hz), 2.67 (d, 1H, $J$ = 9.9 Hz), 2.14 (dt, 1H, $J$ = 11.7, 9.2 Hz); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 166.4−165.6 (4C), 133.8−128.5 (24C), 98.7, 91.6, 71.7, 70.3−70.1 (4C), 66.3, 62.6, 36.6. $R_f$ 0.38 (ethyl acetate/hexane 1:1). HRMS (MALDI) *m/z* calcd for $C_{38}H_{32}Cl_2O_{11}$ ([M + Na]$^+$) 757.1214, found 757.1201.

**Phenyl 2,3,4-Tri-*O*-benzoyl-1-thio-$\beta$-D-ribopyranoside (7).** PhSH (0.5 mL) was added at room temperature to a stirred solution of 2,3,4-tri-*O*-benzoyl-D-ribopyranosyl bromide (630 mg, 1.2 mmol) and 2 mL of $NEt_3$ in dry $CH_3CN$. The reaction mixture was stirred overnight, diluted with $Et_2O$ and washed with 1 M HCl, saturated aqueous $NaHCO_3$ solution, and brine, dried over $MgSO_4$, filtered, and evaporated to dryness. After purification by flash column chromatography (silica gel, ethyl acetate/hexane 1:10), **7** (72 mg, 11%) was obtained as a colorless syrup. $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 8.05−7.29 (m, 20H), 5.95 (t, 1H, $J$ = 3.6 Hz), 5.65 (d, 1H, $J$ = 4.8 Hz), 5.63−5.56 (m, 2H), 4.62 (dd, 1H, $J$ = 12.3, 3.3 Hz,), 4.17 (dd, 1H, $J$ = 12.3, 5.4 Hz); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 165.8−165.2 (3C), 133.4−128.2 (24 C), 85.2, 69.4, 67.5 (2C), 63.3. Anal. Calcd for $C_{32}H_{26}O_7S$: C, 69.30; H, 4.72. Found: C, 69.03; H, 4.76. $R_f$ 0.66 (ethyl acetate/hexane 1:1). HRMS (MALDI) *m/z* calcd for $C_{32}H_{26}O_7S$ ([M + Na]$^+$) 577.1291, found 577.1281.

**(1′*S*,3′*R*)-3′-Acetoxy-2′,2′-dichlorocyclobutyl 2,3,4,6-Tetra-*O*-acetyl-$\beta$-D-glucopyranoside (9a). (i) Preparation Starting from**

**3a.** $Ac_2O$ (3 mL, large excess) was added to a solution of **3a** (100 mg, 0.2 mmol) in 5 mL of pyridine via a syringe over a time period of 3 h. The reaction mixture was stirred at room temperature for another 3 h and then diluted with $Et_2O$. The organic phase was washed with 1 M HCl, saturated aqueous $NaHCO_3$ solution as well as brine, and dried over $MgSO_4$. After flash column chromatography, **9a** (97 mg, 92%) was obtained as a colorless syrup.

**(ii) Preparation Starting from 3c. 3c** (150 mg, 0.2 mmol) was dissolved in 10 mL of methanol, and NaOMe (50 mg, 0.9 mmol) was added. The reaction mixture was stirred at room temperature for about 20 min and followed by TLC until the conversion was complete. Then, Amberlite IR-120 (H+) (500 mg, 2.2 mmol) was added into the reaction mixture. After 3 min, when the pH value of the reaction mixture reached 7−8, the Amberlite was filtered off. The solution was concentrated and dried in high vacuum for 12 h. Pyridine (5 mL) was added, and then $Ac_2O$ (3 mL, large excess) was added slowly via a syringe over a time period of 3 h. The reaction mixture was stirred at room temperature for another 3 h and then diluted with $Et_2O$. The organic phase was washed with 1 M HCl, saturated aqueous $NaHCO_3$ solution as well as brine, and dried over $MgSO_4$. After purification by column chromatography, **9a** (103 mg, 97%) was obtained as a colorless syrup.

The analytical data for the products obtained via both pathways were identical within experimental error. $[\alpha]^{25}_D$ −14.6 (*c* 0.9, $CHCl_3$). $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 5.25 (t, 1H, $J$ = 9.6 Hz), 5.12−4.99 (m, 3H), 4.83 (d, 1H, $J$ = 7.8 Hz), 4.51 (m, 1H), 4.26 (dd, 1H, $J$ = 12.6, 4.8 Hz), 4.17 (dd, 1H, $J$ = 12.6, 2.4 Hz), 3.74 (ddd, 1H, $J$ = 10.0, 4.8, 2.4 Hz), 2.73 (dt, 1H, $J$ = 12.0, 7.8 Hz), 2.19−2.12 (m, 4H), 2.08 (s, 3H), 2.06 (s, 3H), 2.02 (s, 3H), 2.00 (s, 3H); $^{13}$C NMR ($CDCl_3$, 300 MHz) $\delta$ 170.5−169.3 (5C), 98.6, 87.5, 75.0, 72.5, 72.3, 70.9 (2C), 68.2, 61.7, 32.0, 20.7−20.3 (5C). Anal. Calcd for $C_{20}H_{26}Cl_2O_{12}$: C, 45.38; H, 4.95; Cl, 13.40. Found: C, 45.51; H, 5.08; Cl, 13.62. MS (ESI) *m*/*z* 550.8 ([M + Na]$^+$). $R_f$ 0.35 (ethyl acetate/hexane 1:1). HRMS (MALDI) *m*/*z* calcd for $C_{20}H_{26}Cl_2O_{12}$ ([M + Na]$^+$) 551.0694, found 551.0684.

**(1′*S*,3′*R*)-2′,2′-Dichloro-3′-(2″,3″,4″-tri-*O*-benzoyl-β-D-ribopyranosyl)oxycyclobutyl 2,3,4,6-Tetra-*O*-benzoyl-β-D-glucopyranoside (9b). (i) Preparation Starting from 3f.** The product was prepared according to procedure F, using ethyl 2,3,4,6-tetra-*O*-benzoyl-1-thio-β-D-glucopyranoside (**6**; 500 mg, 0.78 mmol), **3f** (111 mg, 0.18 mmol), *N*-iodosuccinimide (175 mg, 0.78 mmol), and TfOH (0.07 mL, 0.78 mmol). After 3 min, the reaction was quenched with triethylamine (1 mL, 7.2 mmol). After flash column chromatography (silica gel, ethyl acetate/hexane 1:4), **9b** (195 mg, 92%) was obtained as a white solid.

**(ii) Preparation Starting from 3c.** The product was prepared according to procedure F, using phenyl 2,3,4-tetra-*O*-benzoyl-1-thio-β-D-ribopyranoside (**7**; 60 mg, 0.11 mmol), **3c** (25 mg, 0.034 mmol), *N*-iodosuccinimide (34 mg, 0.15 mmol), and TfOH (0.01 mL, 0.11 mmol). After 3 min, the reaction was quenched with triethylamine (1 mL, 7.2 mmol). After flash column chromatography (silica gel, ethyl acetate/hexane 1:4), **9b** (28 mg, 70%) was obtained as a white solid.

The analytical data for the products obtained via both pathways were identical within experimental error. $[\alpha]^{25}_D$ −30.7 (*c* 0.25, $CHCl_3$). $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 8.15−7.25 (m, 35H), 6.03 (t, 1H, $J$ = 9.6 Hz), 5.80−5.53 (m, 5H), 5.30 (d, 1H, $J$ = 7.8 Hz), 5.20 (d, 1H, $J$ = 1.8 Hz), 4.71 (dd, 1H, $J$ = 12.0, 3.0 Hz), 4.63−4.52 (m, 3H), 4.31−4.23 (m, 1H), 4.19−4.10 (m, 2H), 2.72 (dt, 1H, $J$ = 11.7, 7.8 Hz), 2.20 (dt, 1H, $J$ = 11.7, 9.6 Hz); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 166.3−165.2 (7C), 133.6−128.4 (42C), 99.4, 98.7, 88.6, 77.3, 73.7, 73.0, 72.9, 71.5, 69.6, 68.3, 67.5, 66.0, 63.0, 62.4, 33.1. Anal. Calcd for $C_{64}H_{52}Cl_2O_{18}$: C, 65.14; H, 4.44. Found: C, 65.19; H, 4.52. $R_f$ 0.51 (ethyl acetate/hexane 1:1). HRMS (MALDI) *m*/*z* calcd for $C_{64}H_{52}Cl_2O_{18}$ ([M + Na]$^+$) 1201.2423, found 1201.2438.

**(1′*S*,3′*R*)-2′,2′-Dichloro-3′-(2″,3″,4″,6″-tetra-*O*-benzoyl-α-D-mannopyranosyl)oxycyclobutyl 2,3,4,6-Tetra-*O*-benzoyl-β-D-glucopyranoside (9c) and (1′*R*,3′*S*)-2′,2′-Dichloro-3′-(2″,3″,4″,6″-tetra-*O*-benzoyl-α-D-mannopyranosyl)oxycyclobutyl 2,3,4,6-Tetra-*O*-benzoyl-β-D-glucopyranoside (9c′). (i) Preparation Starting from 3c.** The product was prepared according to procedure F, using ethyl 2,3,4,6-tetra-*O*-benzoyl-1-thio-α-D-mannopyranoside (**8**; 150 mg, 0.23 mmol), 4 Å molecular sieves, **3c** (71 mg, 0.097 mmol), *N*-iodosuccinimide (60 mg, 0.27 mmol), and TfOH (0.022 mL, 0.25 mmol). After 3 min, the reaction was quenched with triethylamine (1 mL, 7.2 mmol). After flash column chromatography (silica gel, ethyl acetate/hexane 1:4), **9c** (93 mg, 73%) was obtained as a white solid.

**(ii) Preparation Starting from 3c′.** The product was prepared according to procedure F, using ethyl 2,3,4,6-tetra-*O*-benzoyl-1-thio-α-D-mannopyranoside (**8**; 300 mg, 0.47 mmol), **3c′** (90 mg, 0.12 mmol), *N*-iodosuccinimide (110 mg, 0.49 mmol), and TfOH (0.04 mL, 0.45 mmol). After 3 min, the reaction was quenched with triethylamine (1 mL, 7.2 mmol). After flash column chromatography (silica gel, ethyl acetate/hexane 1:4), **9c′** (130 mg, 82%) was obtained as a white solid.

**(iii) Preparation Starting from 3i.** The product was prepared according to procedure F, using ethyl 2,3,4,6-tetra-*O*-benzoyl-1-thio-β-D-glucopyranoside (**6**; 200 mg, 0.31 mmol), **3i** (70 mg 0.095 mmol), *N*-iodosuccinimide (70 mg, 0.31 mmol), and TfOH (0.027 mL, 0.31 mmol). After 3 min, the reaction was quenched with triethylamine (1 mL, 7.2 mmol). After flash column chromatography (silica gel, ethyl acetate/hexane 1:4), **9c′** (73 mg, 58%) was obtained as a white solid.

Analytical data for **9c**: $[\alpha]^{25}_D$ −20.7 (*c* 1.7, $CHCl_3$). $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 8.20−7.20 (m, 40H), 6.14 (t, 1H, $J$ = 10.0 Hz), 6.02 (t, 1H, $J$ = 9.6 Hz), 5.88 (dd, 1H, $J$ = 10.0, 3.3 Hz), 5.80 (dd, 1H, $J$ = 3.3, 1.8 Hz), 5.75 (t, 1H, $J$ = 9.6 Hz), 5.66 (dd, 1H, $J$ = 9.6, 8.1 Hz), 5.36 (d, 1H, 1.8 Hz), 5.28 (d, 1H, $J$ = 8.1 Hz), 4.71 (dd, 2H, $J$ = 12.6, 2.7 Hz), 4.62−4.49 (m, 3H), 4.42−4.36 (m, 2H), 4.30−4.23 (m, 1H), 2.73 (dt, 1H, $J$ = 11.7, 7.8 Hz), 2.27 (dt, 1H, $J$ = 11.7, 9.3 Hz); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 166.2−165.3 (8C), 133.7−128.4 (48C), 98.6, 96.5, 87.5, 77.4, 74.0, 73.8, 73.0, 72.9, 71.5, 69,9, 69.7, 69.6, 66.9, 63.0, 62.8, 32.6. $R_f$ 0.51 (ethyl acetate/hexane 1:1). HRMS (MALDI) *m*/*z* calcd for $C_{72}H_{58}Cl_2O_{20}$ ([M + Na]$^+$) 1335.2791, found 1335.2765.

Analytical data for **9c′**: $[\alpha]^{25}_D$ −14.0 (*c* 0.8, $CHCl_3$). $^1$H NMR ($CDCl_3$, 300 MHz) $\delta$ 8.20−7.28 (m, 40H), 6.29 (t, 1H, $J$ = 10.0 Hz), 5.98 (t, 1H, $J$ = 9.6 Hz), 5.93 (dd, 1H, $J$ = 10.0, 3.3 Hz), 5.83−5.75 (m, 2H), 5.72 (dd, 1H, $J$ = 9.6, 7.8 Hz), 5.21 (d, 1H, 1.8 Hz), 5.04 (d, 1H, $J$ = 7.8 Hz), 4.85−4.61 (m, 4H), 4.48 (dd, 1H, $J$ = 12.6, 3.0 Hz), 4.34−4.15 (m, 3H), 2.70 (dt, 1H, $J$ = 11.7, 7.8 Hz), 2.29 (dt, 1H, $J$ = 11.7, 9.6 Hz); $^{13}$C NMR ($CDCl_3$, 75 MHz) $\delta$ 166.2−165.1 (8C), 133.7−128.4 (48C), 100.8, 98.9, 89.4, 78.0 (2C), 73.0, 72.7, 71.9, 70.3, 70.2, 70.1, 69.8, 66.2, 63.2, 62.4, 33.5. Anal. Calcd for $C_{72}H_{58}Cl_2O_{20}$: C, 65.81; H, 4.45; Cl, 5.40. Found: C, 65.52; H, 4.71; Cl, 5.37. MS (ESI) *m*/*z* 1335.5 ([M + Na]$^+$). $R_f$ 0.46 (ethyl acetate/hexane 1:1). HRMS (MALDI) *m*/*z* calcd for $C_{72}H_{58}Cl_2O_{20}$ ([M + Na]$^+$) 1335.2791, found 1335.2766.

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**Supporting Information Available:** General experimental methods, $^1$H and $^{13}$C NMR spectra of **1a**, **1b**, **1c**, **1d**, **1e**, **1g**, **1l**, **1m**, **2a-2k**, **3a**, **3b**, **3c**, **3c′**, **3f**, **3i**, **7**, **9a**, **9b**, **9c**, and **9c′**; ORTEP representations and complete crystallographic data (CIF) of **2a** and **3a**; representative GPC result of a copolymer **5i**. This material is available free of charge via the Internet at http://pubs.acs.org.

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