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Cerium(IV)-mediated C–C bond formations in carbohydrate chemistry

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ABSTRACT

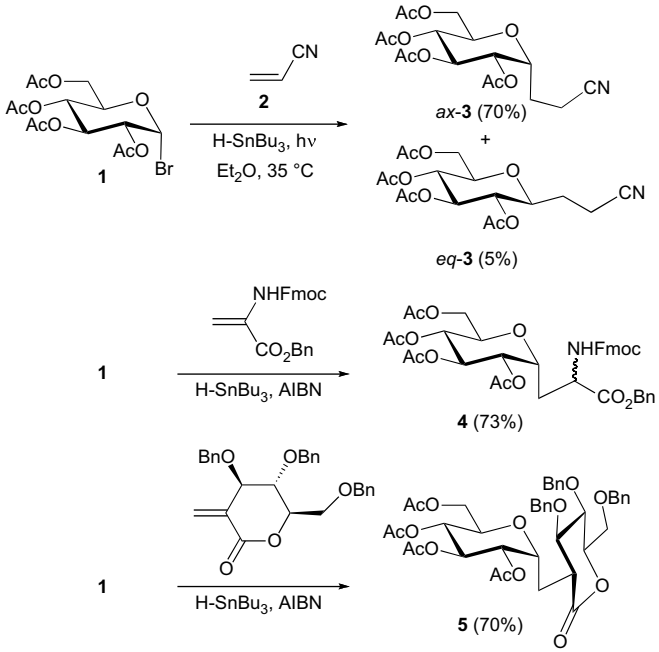
We provide a comprehensive study on the addition of radicals to unsaturated carbohydrates in the presence of cerium(IV) ammonium nitrate (CAN). The method is applicable to hexoses, pentoses, and disaccharides, tolerates different protecting groups, and is characterized by mild reaction conditions. Best substrates are malonates and glycals, which afford 2-*C*-branched carbohydrates in high yields and stereoselectivities. For the first time, the anomeric radicals were trapped with nucleophiles after oxidation and thus the 1- and 2-position of glucose were functionalized in one step. Nitro compounds are suitable CH acidic radical precursors as well, offering an easy access to *C*-analogs of glycosamines in moderate to good yields. Finally, selective reductions demonstrate the synthetic potential of cerium(IV)-mediated radical reactions in carbohydrate chemistry.

1. Introduction

Radical reactions have become a convenient and versatile tool in organic synthesis during the last decades.[1] Mild conditions and high stereoselectivities have enabled numerous applications in natural product chemistry, with special emphasis on carbon–carbon bond formations. The importance of radical reactions is reflected in many reviews every year, and various new methodologies have been described very recently.[2] For instance, the first enantioselective organocatalysis in radical chemistry was published merely one year ago.[3]

Despite such new developments, the generation of radicals from alkyl halides and their addition to electron-poor alkenes in the presence of tri-*n*-butylstannane is still one of the most prominent methods for the formation of C–C bonds.[1] The pioneering work of Giese was essential for the understanding of orbital interactions in radical reactions and led to many applications of the 'tin hydride method'.[4] Exactly 25 years ago, the breakthrough in carbohydrate chemistry was published by the same group, with the successful synthesis of C-1 analogs **3** from acetobromo-α-D-glucose (**1**) and acrylonitrile (**2**) (Scheme 1).[5]

Orbital interactions and a preferred boat-like conformation of the anomeric radical are responsible for the remarkably high stereoselectivity. Additionally, the reactions are characterized by mild conditions, good yields, and easily available starting materials, and are nowadays well established in carbohydrate and natural product chemistry. Especially the formation of C–C bonds at the 1-position offers a convenient entry point to biologically interesting *C*-glycosides. Two selected examples are the amino acid analog **4**[6] and the *C*-disaccharide **5**,[7] available in one step from the same simple radical precursor **1** (Scheme 1). The only disadvantage is the high toxicity of



Scheme 1. Synthesis of *C*-glycosides **3**–**5** from easily available acetobromo-α-D-glucose (**1**).

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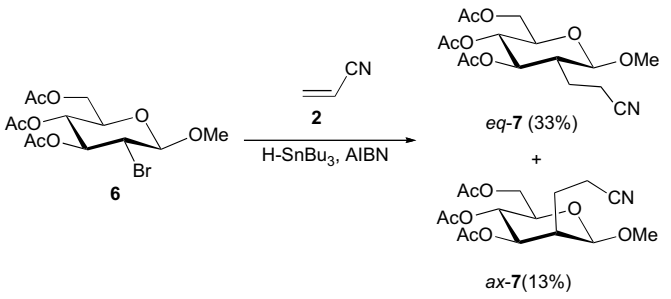
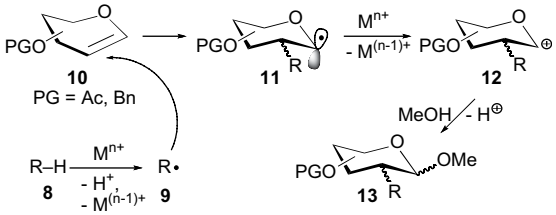
tin reagents, but silanes are suitable substitutes as hydrogen atom donors.[8]

In contrast to the easy formation of carbon–carbon bonds at the anomeric center via the 'tin hydride method', other positions of the carbohydrate are more difficult to functionalize. For instance, synthesis of the radical precursor **6** is tedious and the *C*-analogs **7** can only be isolated in moderate yields and steroeselectivities (Scheme 2).[9]



Scheme 2. Synthesis of 2-*C*-branched carbohydrates **7**.

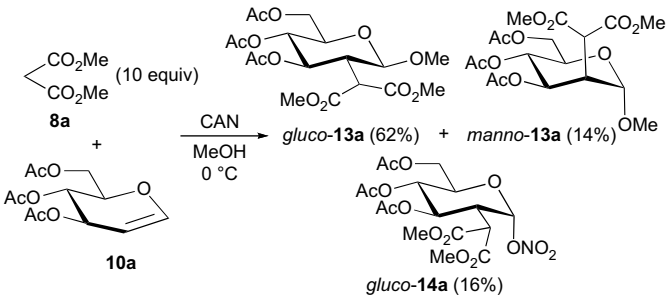
More than 10 years ago, we developed a new entry to 2-*C*-branched saccharides by a different strategy (Scheme 3). In this case the carbohydrate is not the precursor, but the unsaturated radical acceptor, with the advantage that such glycals **10** can be easily synthesized on a large scale or are nowadays commercially available.[10] However, for a successful addition, the radicals **9** must have electrophilic character due to the electron-rich double bond. If this is the case, orbital interactions should favor the attack at the 2-position,[4] affording 2-*C*-branched carbohydrates.



Scheme 3. Concept for the synthesis of 2-*C*-branched carbohydrates **13**.

The generation of electrophilic radicals **9** can be best accomplished by the oxidation of CH acidic precursors **8** (e.g., ketones, malonates or nitro compounds) in the presence of manganese(III) acetate or cerium(IV) ammonium nitrate (CAN). Besides reductive methods,[11] such oxidative transition-metal-mediated radical reactions have found many applications during the last two decades.[12] Another advantage is the subsequent oxidation of the adduct radicals **11** into cations **12** under the reaction conditions, directly affording glycosides **13** after trapping with the nucleophilic solvent (Scheme 3).

We have been interested in transition-metal-mediated radical reactions with simple precursors for many years.[13] Our first successful application of such reactions in carbohydrate chemistry was the addition of dimethyl malonate (**8a**) to tri-*O*-acetyl-D-glucal (**10a**) in the presence of CAN (Scheme 4).[14] Ten equivalents of the precursor **8a** were necessary for an efficient radical generation, but we were able to remove the excess by distillation after complete conversion. Importantly, the 2-*C*-analogs were obtained with exclusive regioselectivity by an orbital controlled addition. Furthermore, the methyl glycosides **13a** and the nitrate **14a** were isolated in high yields and stereoselectivities in analytically pure form. Although the addition of azide radicals to glycals in the presence of CAN was known for many years,[15] this was the first example of a cerium(IV)-mediated C–C bond formation in carbohydrate chemistry.



Scheme 4. Synthesis of 2-*C*-branched carbohydrates **13** and **14**.

We were able to extend our methodology to other unsaturated saccharides and malonates[16] and very recently to benzyl-protected glycals[17] with even higher stereoselectivities. Furthermore, the undesired formation of nitrates **14** was suppressed completely with anhydrous cerium(IV) ammonium nitrate. We applied the addition of malonates to 1-substituted glycals[18] and in the total synthesis of natural products.[19] However, other CH acidic radical precursors were less suitable for the synthesis of branched-chain carbohydrates, and we described the successful reaction with glycals in two communications only recently.[20]

Herein we present a comprehensive study on the scope and limitations of cerium(IV)-mediated C–C bond formations in carbohydrate chemistry. For the first time, the anomeric radicals were trapped with nucleophiles after oxidation. This enabled the functionalization of the 1- and 2-position of glucose in only one step. Nitro compounds were applied as CH acidic radical precursors, which reacted less efficiently but provided high regio- and stereoselectivities. Thus, 2-*C*-branched carbohydrates with nitrogen substituents were isolated in moderate to good yields. Finally, the C-2 side-chains were modified by reductions, affording interesting amines and amino acids, demonstrating the synthetic potential of CAN-mediated radical reactions in carbohydrate chemistry.

2. Results and discussion

2.1. Malonates as radical precursors and nucleophilic trapping at the anomeric center

The addition of dimethyl malonate (**8a**) to various glycals **10** proceeded efficiently in the presence of cerium(IV) ammonium nitrate (CAN) in methanol.[14,16] Methyl glycosides **13** were isolated in high yields and stereoselectivities by trapping of the intermediary anomeric cations **12** with the nucleophilic solvent (Scheme 3). To functionalize the 1- and 2-position in the same reaction step, the radical addition had to be performed in a non-nucleophilic solvent in the presence of an external nucleophile **15**. However, CAN is only soluble in polar solvents, which additionally influence the oxidation potential of this transition-metal complex.[1d,21] Thus, the generation of malonyl radicals might have proceeded less efficiently, and therefore the reaction conditions had to be carefully optimized.

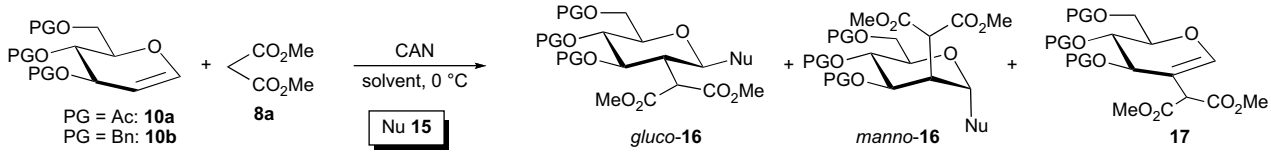
We selected tri-*O*-acetyl- (**10a**) and tri-*O*-benzyl-D-glucal (**10b**) as suitable unsaturated radical acceptors, since they can be synthesized on a large scale[10] and afford *gluco*-configured addition products, which represent biologically interesting 2-*C*-analogs. Furthermore, the protecting groups can be easily removed after the radical reactions. We tested a broad variety of nucleophiles **15**, with special emphasis on new pathways to disaccharides. First experiments were conducted in water, to obtain the hemiacetals **16a** (Table 1, entries 1 and 2). Although tri-*O*-acetyl-D-glucal (**10a**) was slightly soluble in this solvent, the oxidation potential of CAN was

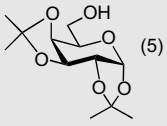
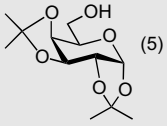
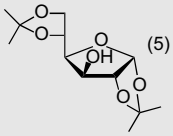
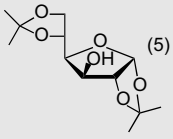
not sufficient to generate malonyl radicals and no conversion was observed. On the other hand, we could not employ the *O*-benzyl-protected carbohydrate **10b**, which was completely insoluble in water. Therefore, non-nucleophilic solvents were required, in order to dissolve the carbohydrates and allow the external addition of nucleophiles **15**. *N*,*N*-Dimethylformamide (DMF) and acetonitrile were applied in transition-metal-mediated radical reactions previously,[12] and indeed, the addition of 25 equiv of water (**15a**) afforded the hemiacetals **16a** in moderate yields as anomeric mixtures (entries 3–5). Acetonitrile was superior to DMF and was employed in all further additions, with *gluco*/*manno* ratios in the range from 4:1 to 5:1. These selectivities are independent from the trapping nucleophile **15** and can be explained by unfavorable steric interactions of the attacking malonyl radicals with the *O*-acetyl group in the 3-position, in accordance to our previous studies.[16]

Next, we became interested in the synthesis of anomeric acetates, since such compounds represent interesting glycosyl donors. Acetic acid was not suitable as nucleophile, due to acid-catalyzed Ferrier rearrangements.[22] However, with potassium acetate (**15b**), the requested 2-*C*-anologs **16b** were isolated in moderate to good yields (Table 1, entries 6 and 7). Interestingly, unsaturated carbohydrates **17** were isolated as by-products, which can be rationalized by the mechanism outlined in Scheme 5.

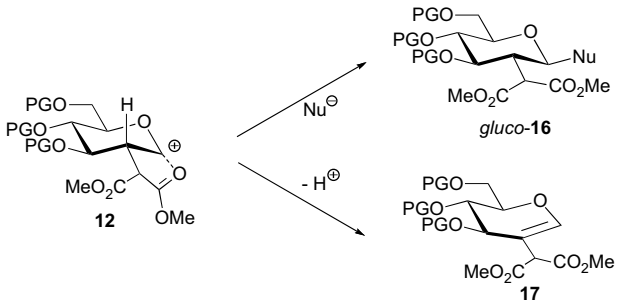
If a good nucleophile **15** is present (e.g., solvent methanol), the intermediary cations **12** (compare Scheme 3) are trapped, affording addition products **16**. A neighboring group participation of the malonyl side-chain is responsible for the exclusive formation of β-glucosides and α-mannosides. On the other hand, if this bimolecular reaction is too slow (bad nucleophile and/or low concentrations), deprotonation of the 2-position competes and elimination products **17** are obtained in some reactions (Table 1). Glycosyl

Table 1
Addition of dimethyl malonate (**8a**) to glucals **10** in the presence of nucleophiles **15**



Entry	Glycal	PG	Solvent	Nu **15** (equiv)	*gluco*/*manno*[a]	*gluco*-**16** (%)[b]	*manno*-**16** (%)[b]	**17** (%)[b]
1	**10a**	Ac	H_2O	—	—[c]	—	—	—
2	**10b**	Bn	H_2O	—	—[c]	—	—	—
3	**10a**	Ac	DMF	**15a**:H_2O (25)	5:1	26[d]	—[e]	—
4	**10a**	Ac	CH_3CN	**15a**:H_2O (25)	5:1	57[d]	12[d]	—
5	**10b**	Bn	CH_3CN	**15a**: H_2O (25)	5:1	56[d]	9[d]	—
6	**10a**	Ac	CH_3CN	**15b**: KOAc (10)	4:1	40	10	24
7	**10b**	Bn	CH_3CN	**15b**: KOAc (10)	4:1	54	13	18
8	**10a**	Ac	CH_3CN	**15c**: LiCl (10)	—[f]	—	—	—
9	**10b**	Bn	CH_3CN	**15d**: EtOH (10)	5:1	68	11	—
10	**10a**	Ac	CH_3CN	**15e**: $H_{17}C_8OH$ (10)	4:1	59	12	—
11	**10b**	Bn	CH_3CN	**15e**: $H_{17}C_8OH$ (10)	4:1	64	14	—
12	**10b**	Bn	CH_3CN	**15f**: $H_{25}C_{12}OH$ (10)	4:1	53	9	—
13	**10a**	Ac	CH_3CN	**15g**: *i*-PrOH (10)	5:1	51	12	16
14	**10b**	Bn	CH_3CN	**15g**: *i*-PrOH (10)	5:1	68	9	10
15	**10a**	Ac	CH_3CN	**15h**: $PhCH_2OH$ (10)	—[g]	—	—	—
16	**10a**	Ac	CH_3CN	**15i**: *t*-BuOH (10)	5:1	21	—[e]	32
17	**10a**	Ac	CH_3CN	**15j**:  (5)	5:1	31	5	28
18	**10b**	Bn	CH_3CN	**15j**:  (5)	5:1	29	6	31
19	**10a**	Ac	CH_3CN	**15k**:  (5)	5:1	7	—[e]	35
20	**10b**	Bn	CH_3CN	**15k**:  (5)	5:1	6	—[e]	37

[a] Ratios determined by ^1H NMR analysis of the crude product (300 MHz).
[b] Yields of isolated products after column chromatography.
[c] No conversion was observed.
[d] Isolated as an anomeric mixture.
[e] Due to the low yield, no *manno* isomer was isolated.
[f] Addition of chlorine from oxidation of chloride by CAN.
[g] Oxidation of benzyl alcohol (**15h**) to benzaldehyde by CAN.



Scheme 5. Formation of the unsaturated carbohydrates **17**.

chlorides **16c** would be even more attractive glycosyl donors than the acetates **16b**, but lithium chloride (**15c**) was oxidized to chlorine by CAN, which after addition to the double bond afforded 1,2-dichlorides in low yields in accordance to the literature (entry 8).[23]

The reactions with alcohols as nucleophiles **15** proceeded very efficiently and the 2-*C*-branched saccharides **16d–g** were isolated in moderate to good yields in analytically pure form (Table 1, entries 9–14). Assembly of long chains at the anomeric center was achieved with 1-octanol (**15e**) and 1-dodecanol (**15f**), affording interesting amphiphilic carbohydrate structures. Even the sterically more demanding 2-propanol (**15g**) was a suitable nucleophile. Although glycal **17** was obtained as by-product, the isopropyl glycosides **16g** were isolated in 63–77% yield (entries 13 and 14). The limit of trapping with alcohols was reached with benzyl alcohol (**15h**), which was oxidized to benzaldehyde by CAN under the reaction conditions (entry 15). Finally, *tert*-butanol (**15i**) afforded the glycoside *gluco*-**16i** in only 21% yield and elimination to the glycal **17** was the major pathway (entry 16, Scheme 5), which can be explained by unfavorable steric interactions.

Trapping of the intermediary cations **12** with another carbohydrate seemed to be very attractive, since disaccharides **16** would be accessible in only one step. We investigated 1,2:3,4-di-*O*-isopropylidene-D-galactose (**15j**) and diacetone-D-glucose (**15k**) as nucleophiles, which have only one reactive hydroxy group. Yields with the sterically demanding secondary alcohol **15k** were very low, but the main *gluco* isomer **16k** could be isolated (entries 19 and 20). The primary alcohol **15j** reacted more efficiently, affording the disaccharides **16j** in moderate yields (entries 17 and 18). Since malonates can be added to maltal and lactal as well,[17b] we established a possibility to introduce carbon side-chains in the 2-position of both sugar units of disaccharides in only one step.

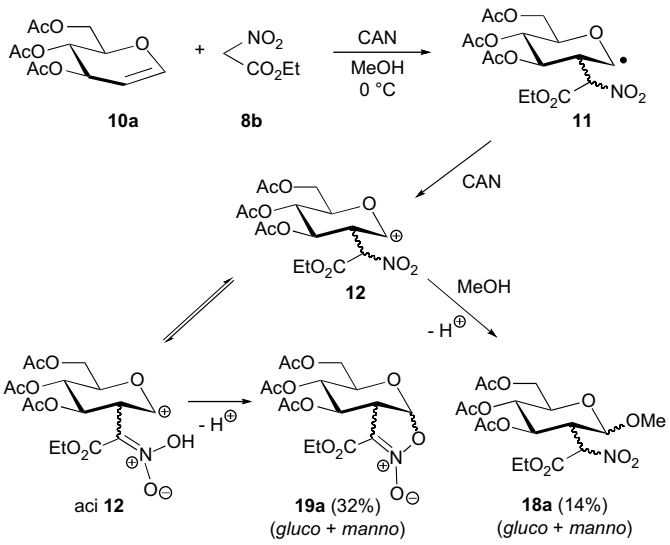
In summary, we extended the scope of cerium(IV)-mediated C–C bond formations in carbohydrate chemistry by simple functionalization of the anomeric position. Acetonitrile was the ideal solvent, providing sufficient solubility and allowing the generation of malonyl radicals. The intermediary cations at the anomeric position were trapped by external addition of nucleophiles, such as water, acetate, and various alcohols. All reactions proceeded with high regio- and good stereoselectivities in favor of the β-configured *gluco* isomers. With less reactive nucleophiles, deprotonation at the 2-position competed, affording glycals as by-products. The anomeric center was trapped with free OH groups of carbohydrates, providing simple access to disaccharides in moderate yields. Although radical reactions with CAN proceed in methanol more efficiently than in acetonitrile, we succeeded in the functionalization of the 1- and 2-position of carbohydrates in one reaction step, affording interesting *C*-analogs for further transformations.

2.2. Nitro compounds as radical precursors

The generation of radicals by cerium(IV) ammonium nitrate (CAN) requires CH acidic precursors **8**.[12] In our previous studies, dimethyl malonate (**8a**) was the best substrate for the addition to various glycals **10**, affording carbohydrate *C*-analogs **13** and **14** in good to excellent yields (Scheme 4).[14,16–19] To gain access to further functionalized 2-*C*-branched saccharides, we became interested in radical precursors with nitro groups. Although the generation of nitroalkyl radicals by oxidative transition-metal-mediated reactions is known for many years,[12,24] we published their application in carbohydrate chemistry in two communications only very recently.[20] Herein we describe the synthetic and mechanistic details, explaining the different product distributions and stereoselectivities.

For the initial experiment, tri-*O*-acetyl-D-glucal (**10a**) and the radical precursor ethyl nitroacetate (**8b**) were selected as commercially available starting materials. The reaction was performed in the presence of CAN in methanol as solvent. However, the expected methyl glycosides **18a** were isolated in only low yields as complex mixtures of diastereomers together with the isoxazoline *N*-oxides **19a**. The formation of such bicyclic 2-*C*-branched carbohydrates is interesting from a mechanistic point of view (Scheme 6). After the addition of the nitroalkyl radicals, the anomeric radical **11** is oxidized to the cations **12**, and subsequent trapping by the solvent affords the methyl glycosides **18a**. Due to the generation of three new stereocenters, a complex mixture of isomers results.

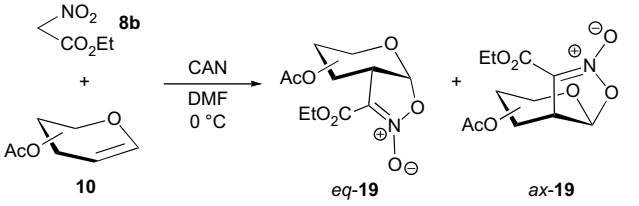
The isoxazoline *N*-oxides **19a** are presumably formed via the tautomers aci **12**, which can attack the anomeric cation and afford the bicycles after deprotonation. Cyclization of the anomeric radical **11** by intramolecular attack of the nitro group and subsequent oxidation might be possible as well, but the corresponding reaction of nitromethane (**8c**) did not give any bicyclic products at all (see below).



Scheme 6. Formation of the 2-*C*-branched carbohydrates **18** and **19**.

To suppress the formation of methyl glycosides **18**, which make product separation much more difficult, we applied non-nucleophilic solvents. Best results were obtained with *N*,*N*-dimethylformamide (DMF), and the reactions proceeded smoothly with various glycals **10** at 0 °C. The isoxazoline *N*-oxides **19** were isolated in moderate yields in analytically pure form, and the method was suitable for hexoses, pentoses, and disaccharides (Scheme 7). The exclusive formation of 1,2-cis-bicyclic products was established by the coupling constants in the ^{1}H NMR spectra and is due to the intramolecular trapping of the anomeric cations. High to excellent stereoselectivities at the 2-position were obtained as well, resulting from an *anti* attack of the radicals to the 3-*O*-acetyl group, in accordance with the addition of malonates.[16,17] Although yields of isoxazoline *N*-oxides **19** are somewhat lower compared to other 2-*C*-branched carbohydrates **13** or **16**, the addition of ethyl nitroacetate (**8b**) to glycals **10** offers an easy one-step entry to unnatural

bicyclic carbohydrates, which can be transferred into interesting *C*-glycosylated amino acids (Section 2.3).

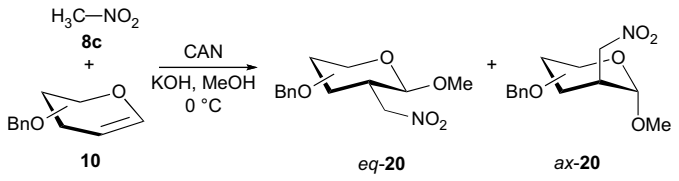


tri-*O*-acetyl-D-glucal (**10a**)	*gluco*-**19a** (45%)[a]	*manno*-**19a** (13%)[a]
tri-*O*-acetyl-D-galactal (**10c**)	*galacto*-**19c** (52%)[a]	*talo*-**19c** (4%)[a]
di-*O*-acetyl-D-xylal (**10d**)	*xylo*-**19d** (54%)[a]	–
di-*O*-acetyl-D-arabinal (**10e**)	–	*arabino*-**19e** (51%)[a]
hexa-*O*-acetyl-D-maltal (**10f**)	*malto*-**19f** (64%)[a]	–
hexa-*O*-acetyl-D-lactal (**10g**)	*lacto*-**19g** (53%)[a]	–

[a] Yield of isolated pure product.

Scheme 7. Synthesis of isoxazoline *N*-oxides **19**.

The reaction of nitromethane (**8c**) with glycals **10** seemed to be very attractive, since a C1 building block with an additional functional group could be introduced at the 2-position by this radical methodology. However, in comparison to dimethyl malonate (**8a**) and ethyl nitroacetate (**8b**) the CH acidity of this reagent is lower. Thus, the generation of radicals by CAN proceeds less efficiently and is only possible under basic conditions.[24] Therefore, *O*-acetylated glycals were unsuitable substrates, due to the lability of the functional groups. Very recently, we succeeded in the first cerium(IV)-mediated C–C bond formation with nitromethane (**8c**) in carbohydrate chemistry.[20b] Per *O*-benzylated glycals **10b**,**h**–**l** reacted smoothly at 0 °C in the presence of potassium hydroxide as base, and the 2-*C*-nitromethyl-pyranosides **20** were isolated in moderate to good yields in analytically pure form (Scheme 8). Pentoses **10i**–**j** were oxidized by CAN to by-products, but the radical addition worked well with disaccharides **20k**,**l**. Interestingly, in contrast to the reaction of ethyl nitroacetate (**8b**), nitromethane (**8c**) afforded no bicyclic isoxazoline *N*-oxides. This result proves the mechanism outlined in Scheme 6, with an intramolecular trapping of the cation **12** and not of the radical **11**. In a radical pathway, both CH acidic precursors **8b** and **8c** would cyclize, which is obviously not the case. Thus, the aci form of **12**, which due to the ester group is much more stabilized with **8c**, is responsible for the formation of isoxazoline *N*-oxides **19**. During the addition of nitromethane (**8c**) this tautomeric form is less favored, and thus a cyclization cannot compete with the intramolecular reaction with the solvent methanol, affording exclusively methyl glycosides **20**.



tri-*O*-benzyl-D-glucal (**10b**)	*gluco*-**20b** (59%)[a]	*manno*-**20b** (12%)[a]
tri-*O*-benzyl-D-galactal (**10h**)	*galacto*-**20h** (55%)[a]	*talo*-**20h** (10%)[a]
di-*O*-benzyl-D-xylal (**10i**)	*xylo*-**20i** (28%)[a]	*lyxo*-**20i** (20%)[a]
di-*O*-benzyl-D-arabinal (**10j**)	*ribo*-**20j** (8%)[a]	*arabino*-**20j** (31%)[a]
hexa-*O*-benzyl-D-maltal (**10k**)	*malto*-**20k** (58%)[a]	*epi-malto*-**20k** (12%)[a]
hexa-*O*-benzyl-D-lactal (**10l**)	*lacto*-**20l** (59%)[a]	*epi-lacto*-**20l** (9%)[a]

[a] Yield of isolated pure product.

Scheme 8. Synthesis of 2-*C*-nitromethyl-pyranosides **20**.

Interestingly, selectivities at the newly formed stereocenter at the 2-position are lower with nitromethane compared to malonates or nitroesters. Thus, *ribo*, *lyxo*, *epi-malto*, and *epi-lacto* isomers **20i**–**l** were isolated as by-products (Scheme 8), whereas precursors with two acceptor groups afforded exclusively the *xylo*-, *arabino*-, *malto*-, and *lacto*-configured isoxazoline *N*-oxides **19** (Scheme 7). This can be rationalized by reduced steric interactions between the attacking radicals and the functional groups at the carbohydrate. Additionally, the nitromethyl radicals are less electrophilic than malonyl radicals, resulting in an earlier transition state and lower selectivities.

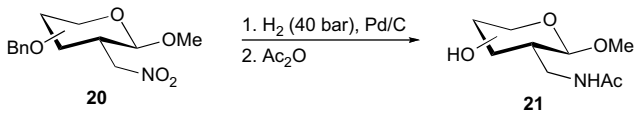
In summary, we were able to demonstrate the applicability of CH acidic radical precursors with nitro groups in cerium(IV)-mediated C–C bond formations in carbohydrate chemistry. Ethyl nitroacetate and nitromethane were suitable substrates for the addition to various glycals, affording bicyclic isoxazoline *N*-oxides or 2-*C*-nitromethyl-pyranosides in moderate to good yields. This difference in product distribution was rationalized by an intramolecular trapping of the anomeric cations with the aci form of the nitro compound, which should be interesting for the mechanism of other transition-metal-mediated radical reactions.

From the synthetic point of view, the additions of the new radical precursors proceeded less efficiently than the established reactions of malonates, but the convenient procedure allowed the formation of C–C bonds and the introduction of nitro groups in only one step. The regioselectivities were excellent, due to the electrophilic character of the nitroalkyl radicals, and good to high stereoselectivities were realized. The method was applicable to hexoses, pentoses, and disaccharides and the glycal and nitro alkane precursors are commercially available or can be synthesized on a large scale. Finally, the nitro group allows various further transformations like reductions to amino acids or amines (Section 2.3), and the 2-*C*-nitromethyl-pyranosides may even serve as precursors for the synthesis of *C*-disaccharides.[25]

2.3. Reduction of the nitro compounds

Nitro groups can be transferred into various other functional groups and the reduction to amines is one of the most prominent methods.[26] However, only few applications in carbohydrate chemistry exist, and the labile protecting groups and stereocenters require mild reaction conditions. Very recently, we described the reduction of the 2-*C*-nitromethyl-pyranosides **20** with lithium aluminum hydride, which afforded *O*-benzyl-2-*C*-branched glycosamines.[20b] Catalytic hydrogenation was even more attractive, since the protecting groups could be removed in the same reaction step. Thus, after acetylation, the free C-2 branched glycosamines **21** were isolated in good yields in analytically pure form (Scheme 9).

Next, we became interested in the reduction of isoxazoline *N*-oxides **19**, since carbohydrate-linked unnatural amino acid derivatives, which are stable toward enzymatic cleavage and possess

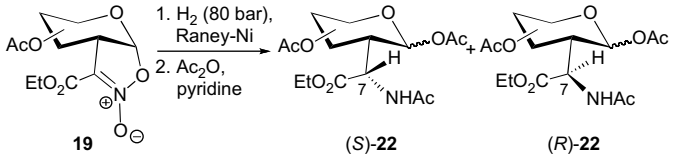


gluco-**20b**	*gluco*-**21b** (82%)[a]
galacto-**20h**	*galacto*-**21h** (77%)[a]
xylo-**20i**	*xylo*-**21i** (78%)[a]
arabino-**20j**	*arabino*-**21j** (75%)[a]
malto-**20k**	*malto*-**21k** (71%)[a]
lacto-**20l**	*lacto*-**21l** (73%)[a]

[a] Yield of isolated pure product.

Scheme 9. Synthesis C-2 branched glycosamines **21**.

Table 2
Reduction of isoxazoline *N*-oxides **19** to *C*-glycosylated amino acids **22**



Entry	Isoxazoline *N*-oxide	*S*:*R*[a]	α:β[a]	(*S*)-**22**[b]	(*R*)-**22**[b]
1	*gluco*-**19a**	>95:5	35:65	74	—
2	*galacto*-**19c**	>95:5	30:70	68	—
3	*xylo*-**19d**	>95:5	30:70	78	—
4	*arabino*-**19e**	<5:95	80:20	—	62
5	*malto*-**19f**	>95:5	30:70	71	—
6	*lacto*-**19g**	>95:5	35:65	65	—

[a] Ratios determined by ^{1}H NMR analysis of the crude product (300 MHz).
[b] Yields of isolated *C*-glycosylated amino acids **22**. Main anomers were separated by column chromatography and afforded analytically pure products.

antibiotic activities,[27] are potentially accessible in only one step. However, two new stereogenic centers, at the anomeric position and α to the amino group, are formed during this transformation, and thus the control of selectivity was a challenging task. Indeed, in our previous studies, reduction with aluminum amalgam afforded all four possible isomers.[20a] Therefore, we investigated catalytic hydrogenations with various catalysts. Although Pd, Pd/C, PdO, and $Pd(OH)_2$ gave no conversion, Raney-Ni was the metal of choice and after acetylation the *C*-glycosylated amino acids **22** were isolated in moderate to good overall yield (Table 2). High pressure of hydrogen gas was necessary, since the ethyl ester group reduces the reactivity of the isoxazoline *N*-oxides and resulted in slow heterogenous reactions.

On the other hand, due to the steric hindrance of the carbohydrate residue, excellent *R*/*S* selectivities were obtained. The NMR spectra of the crude products showed the exclusive formation of one isomer at the newly formed stereocenter at C-7. Only a mixture of α and β anomers resulted after acetylation of the intermediary hemiacetals. The main isomer of all *C*-glycosylated amino acids **22** had the 1,2-diequatorial configuration of substituents, which was unequivocally proven by large coupling constants ($J_{1,2}$ 9–10 Hz) in the ^{1}H NMR spectra. Finally, the anomers were separated by column chromatography and main products **22** were isolated in analytically pure form.

Interestingly, most isoxazoline *N*-oxides **19** gave exclusively the *S*-configured amino acids (*S*)-**22**, whereas *arabino*-**19e** reacted selectively to (*R*)-**22e** (entry 4). This result is important from the mechanistic point of view and can be rationalized by the preferred configurations and conformations of the bicyclic starting materials (Fig. 1).

The *gluco*, *galacto*, *xylo*, *malto*, and *lacto* isomers (*eq*-**19a**,**c**,**d**,**f**,**g**), which all have the C-2 substituent equatorially aligned, were attacked by the catalyst exclusively from the *Re* face. Thus, the sugar ring efficiently shields one side of the isoxazoline, irrespective of the configuration of the carbohydrate. On the other hand, *arabino*-**19e** is the only isomer with an axial substituent at the 2-position. Now the other side of the isoxazoline is blocked and hydrogenation occurs

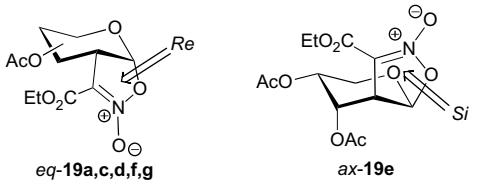


Figure 1. Facial selective hydrogenation of isoxazoline *N*-oxides **19**.

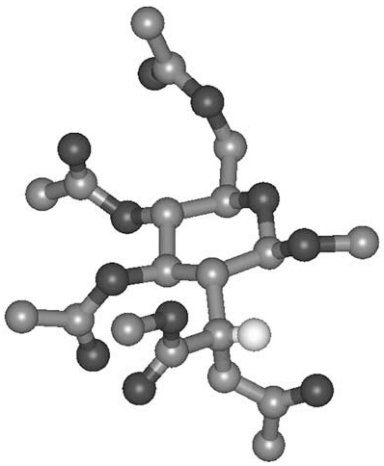


Figure 2. X-ray crystal structure of the *gluco* isomer (*S*)-**22a**.[20a]

exclusively from the *Si* face. Thus, all heterogenous reductions proceed from the convex side of bicycles **19**, with excellent facial selectivity.

Although α and β anomers were easily distinguishable by the $J_{1,2}$ coupling constant, the determination of the configuration at C-7 was more difficult. Comparison of NMR spectra clearly showed the analogy of all *S*-configured products (*S*)-**22** with small $J_{2,7}$ coupling constants of 1.2–1.7 Hz, whereas the *R*-configured *arabino* isomer **22e** exhibits a remarkably larger coupling ($J_{2,7}$=8.5 Hz). However, due to the fast rotation of the C–C single bond, the NMR data were not completely indicative. Finally, we succeeded in the crystallization of the main *gluco* isomer **22a**, which was assigned unequivocally as the *S*-configured product by X-ray analysis (Fig. 2).[20a]

In summary, reduction of the nitro compounds proceeded smoothly by catalytic hydrogenation. The method was applicable to hexoses, pentoses, and disaccharides. 2-*C*-Nitromethyl-pyranosides afforded C-2 branched glycosamines in high yields, and the protecting groups were removed in the same reaction step. Isoxazoline *N*-oxides were reduced by Raney-Ni in moderate yields but with excellent stereoselectivities. This opened an easy entry to carbohydrate-linked unnatural amino acid derivatives.

3. Conclusions

Cerium(IV)-mediated C–C bond formations are a valuable tool for the synthesis of 2-*C*-branched carbohydrates. We investigated the scope and limitations of such highly regioselective radical reactions, which are characterized by easily available precursors, mild reaction conditions, and non-toxic reagents. For the first time, the anomeric radicals were trapped with nucleophiles after oxidation to cations by CAN. This enabled the functionalization of the 1- and 2-position of glucose in only one step. Furthermore, free OH groups of carbohydrates were suitable external nucleophiles, providing simple access to disaccharides in moderate yields. Nitro compounds were applied as commercially available CH acidic radical precursors, which reacted less efficiently but with high regio- and stereoselectivities. Thus, nitromethane afforded 2-*C*-nitromethyl-pyranosides, representing interesting substrates for the synthesis of *C*-disaccharides. On the other hand, with ethyl nitroacetate, bicyclic isoxazoline *N*-oxides were isolated in moderate to good yields. This difference in product distribution was rationalized by an intramolecular trapping of the anomeric cations with the aci form of the nitro compound, which might be interesting for the mechanism of other transition-metal-mediated radical reactions. Finally, the C-2 side-chains of the carbohydrates were selectively reduced by catalytic hydrogenation. 2-*C*-Nitromethyl-pyranosides

afforded C-2 branched glycosamines in high yields and the protecting groups were removed in the same step. Best conditions for the reduction of isoxazoline *N*-oxides were found with Raney-Ni, providing *C*-glycosylated amino acids in moderate yields but with excellent stereoselectivities. This opened a convenient entry to carbohydrate-linked amino acid derivatives, which are interesting substrates for future applications in biology and medicine. Overall, easily available starting materials, high selectivities, and few reaction steps demonstrate the synthetic potential of CAN-mediated radical reactions in carbohydrate chemistry.

4. Experimental

4.1. General

All reactions were carried out under argon by using standard Schlenk techniques. Solvents and commercially available chemicals were purified by standard methods or used as purchased. Excess of malonate was removed by a Kugelrohrofen (GKR-50, Büchi). TLC was performed on aluminum sheets silica gel $60F_{254}$ (Merck, Darmstadt). Silica gel (63–200 μm, Woelm, Erlangen) was used for column chromatography. Optical rotations were measured on a JASCO P-1020 polarimeter and melting points on a Büchi SMP 20 apparatus (uncorrected). IR spectra were recorded on a Perkin–Elmer 1600 FT-IR spectrometer. NMR spectra were recorded either on a Bruker AM 250, AC 300, Avance 500 or DMX 600 with $CDCl_3$ as the solvent and internal standard. Elemental analyses were performed on an ELEMENTAR Vario EL III analyser.

4.2. General procedure for the radical additions in the presence of nucleophiles 15

A solution of tri-*O*-acetyl-D-glucal (**10a**) (545 mg, 2.0 mmol) or tri-*O*-benzyl-D-glucal (**10b**) (830 mg, 2.0 mmol), dimethyl malonate (**8a**) (2.64 g, 20 mmol, 10 equiv), sodium hydrogen carbonate (670 mg, 8 mmol, 4 equiv), and the nucleophile **15** (5–25 equiv, Table 1) in dry acetonitrile (10 mL) was cooled to 0 °C under an argon atmosphere. At this temperature, a solution of cerium(IV) ammonium nitrate (CAN) (2.2–4.4 g, 2–4 equiv), which was dried in a desiccator under high vacuum overnight, in acetonitrile (20 mL) was added dropwise over a period of 4–6 h until TLC showed complete conversion of the starting material. After stirring for 30 min at 0 °C, an ice-cold diluted solution of sodium thiosulfate (50 mL) was added, and the mixture was extracted with dichloromethane (4×100 mL). The combined organic extracts were dried (Na_2SO_4) and concentrated, and the excess of malonate was removed at 0.01 mbar in a Kugelrohrofen. The crude product was purified by column chromatography (cyclohexane/ethyl acetate) and the glycosides **16** were isolated in analytically pure form. Complete characterization of all nucleophilic trapping products **16** is provided in Supplementary data. Elimination products **17** were isolated in analytically pure form in the yields depicted in Table 1.

4.2.1. 3,4,6-Tri-O-acetyl-2-C-[bis-(methoxycarbonyl)-methyl]-D-glucal (acetyl-**17**)

Colorless syrup; R_f=0.37 (cyclohexane/ethyl acetate 1:1); $[\alpha]_D^{20}$ +58.9 (*c* 1.01, $CHCl_3$); ^{1}H NMR (600 MHz, $CDCl_3$): δ=2.00, 2.06, 2.09 (3s, 3H each, OAc), 3.74, 3.75 (2s, 3H each, COOMe), 3.94 (s, 1H, 7-H), 4.20 (dd, *J*=12.2, 3.2 Hz, 1H, 6-H), 4.31 (ddd, *J*=7.6, 5.9, 3.2 Hz, 1H, 5-H), 4.39 (dd, *J*=12.2, 5.9 Hz, 1H, 6′-H), 5.19 (dd, *J*=7.6, 5.5 Hz, 1H, 4-H), 5.71 (d, *J*=5.5 Hz, 1H, 3-H), 6.64 (s, 1H, 1-H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=20.5, 20.6, 20.7 (3q, OAc), 47.9 (d, C-7), 52.7, 52.8 (2q, COO*Me*), 61.2 (t, C-6), 67.2, 67.8 (2d, C-4, C-5), 73.8 (d, C-3), 103.9 (s, C-2), 146.6 (d, C-1), 167.8, 168.3, 169.6, 170.2, 170.4 (5s, OAc, *C*OOMe); IR ($CDCl_3$): ν=3065, 2986, 1752, 1664, 1425, 1286 cm^{-1}. Anal. Calcd (%) for $C_{17}H_{22}O_{11}$ (402.40): C, 50.74; H, 5.51. Found: C, 50.46; H, 5.63.

4.2.2. 3,4,6-Tri-O-benzyl-2-C-[bis-(methoxycarbonyl)-methyl]-D-glucal (benzyl-**17**)

Colorless syrup; R_f=0.38 (cyclohexane/MTB 2:1); $[\alpha]_D^{20}$+ 43.1 (*c* 0.90, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$): δ=3.49 (s, 3H, COOMe), 3.68 (dd, *J*=10.7, 3.4 Hz, 1H, 6-H), 3.71 (s, 3H, COOMe), 3.81 (dd, *J*=10.7, 5.4 Hz, 1H, 6′-H), 3.94 (dd, *J*=6.6, 5.1 Hz, 1H, 4-H), 4.01 (s, 1H, 7-H), 4.24 (ddd, *J*=9.7, 5.4, 3.4 Hz, 1H, 5-H), 4.40 (d, *J*=5.1 Hz, 1H, 3-H), 4.50 (d, *J*=11.2 Hz, 1H, C*H*$_2$–Ph), 4.55 (d, *J*=11.5 Hz, 1H, C*H*$_2$–Ph), 4.58 (d, *J*=11.2 Hz, 1H, C*H*$_2$–Ph), 4.61 (d, *J*=11.2 Hz, 1H, C*H*$_2$–Ph), 4.64 (d, *J*=11.5 Hz, 1H, C*H*$_2$–Ph), 4.74 (d, *J*=11.5 Hz, 1H, C*H*$_2$–Ph), 6.50 (s, 1H, 1-H), 7.22–7.34 (m, 15H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=51.2 (d, C-7), 52.3, 52.4 (2q, COO*Me*), 68.0 (t, C-6), 72.4, 72.9, 73.4 (3t, *C*H$_2$–Ph), 74.0, 74.8, 76.6 (3d, C-3, C-4, C-5), 106 (q, C-2), 127.6, 127.7, 127.8, 128.1, 128.2, 128.3, 128.4, 128.6, 128.9 (9d, arom. *C*-H), 137.8, 137.9, 138.1 (3s, arom. *C*–CH$_2$O), 144.8 (d, C-1), 168.6, 169.0 (2s, *C*OOMe); IR ($CDCl_3$): ν=3030, 2961, 1734, 1453, 1145, 1069, 736, 697, 600 cm^{-1}. Anal. Calcd (%) for $C_{32}H_{34}O_8$ (546.61): C, 70.32; H, 6.27. Found: C, 70.30; H, 6.25.

4.3. General procedure for the synthesis of isoxazoline *N*-oxides 19

A solution of the per-*O*-acetylated-D-glycal **10** (3.0 mmol), ethyl nitroacetate (**8b**) (3.99 g, 30 mmol, 10 equiv), and sodium hydrogen carbonate (2.02 g, 24 mmol, 8 equiv) in DMF (10 mL) was cooled to 0 °C under an argon atmosphere. At this temperature, a solution of cerium(IV) ammonium nitrate (CAN) (9.87 g, 18 mmol, 6 equiv) in DMF (20 mL) was added dropwise over a period of 4–6 h until TLC showed complete conversion of the starting material. After stirring for 30 min at 0 °C, an ice-cold diluted solution of sodium thiosulfate (50 mL) was added, and the mixture was extracted with dichloromethane (4×100 mL). The combined organic extracts were dried (Na_2SO_4) and concentrated, and the excess of nitroacetate was removed at 0.01 mbar in a Kugelrohrofen. The crude product was purified by column chromatography (cyclohexane/ethyl acetate) and the isoxazoline *N*-oxides **19** were isolated in analytically pure form.

4.3.1. gluco-Isoxazoline N-oxide (gluco-***19a***)

Colorless syrup (545 mg, 45%); R_f=0.47 (hexane/ethyl acetate 1:1); $[\alpha]_D^{26}$ −97.2 (*c* 1.03, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$): δ=1.34 (t, *J*=7.1 Hz, 3H, $CO_2CH_2CH_3$), 1.99, 2.07, 2.11 (3s, 3H each, 3OAc), 4.00 (ddd, *J*=7.0, 5.9, 3.3 Hz, 1H, 5-H), 4.07 (ddd, *J*=8.3, 3.3, 1.4 Hz, 1H, 2-H), 4.21 (dd, *J*=12.0, 5.9 Hz, 1H, 6-H), 4.27 (dd, *J*=12.0, 3.3 Hz, 1H, 6′-H), 4.33 (q, *J*=7.1 Hz, 2H, $CO_2CH_2CH_3$), 4.96 (ddd, *J*=7.0, 2.0, 1.4 Hz, 1H, 4-H), 5.59 (dd, *J*=3.3, 2.0 Hz, 1H, 3-H), 6.05 (d, *J*=8.3 Hz, 1H, 1-H); ^{13}C NMR (125 MHz, $CDCl_3$): δ=14.1 (q, $CO_2CH_2CH_3$), 20.4, 20.6, 20.8 (3q, 3OAc), 43.2 (d, C-2), 62.2 (t, $CO_2CH_2CH_3$), 63.6 (t, C-6), 66.6, 67.4, 69.1 (3d, C-3, C-4, C-5), 93.7 (d, C-1), 106.7 (s, C-7), 157.9 (s, *C*O$_2$Et), 168.8, 169.0, 170.4 (3s, 3OAc); IR (neat): ν=2988, 1747, 1634, 1373, 1232, 1041, 876 cm^{-1}. Anal. Calcd (%) for $C_{16}H_{21}NO_{11}$ (403.34): C, 47.65; H, 5.25; N, 3.47. Found: C, 47.82; H, 5.50; N, 3.32.

4.3.2. manno-Isoxazoline N-oxide (manno-***19a***)

Colorless oil (160 mg, 13%); R_f=0.38 (hexane/ethyl acetate 1:1); $[\alpha]_D^{20}$ +19.0 (*c* 0.93, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ=1.29 (t, *J*=7.1 Hz, 3H, $CO_2CH_2CH_3$), 2.03, 2.07, 2.11 (3s, 3H each, 3OAc), 3.95 (ddd, *J*=6.9, 5.4, 2.7 Hz, 1H, 5-H), 4.18 (dd, *J*=11.7, 6.9 Hz, 1H, 6-H), 4.25 (dd, *J*=11.7, 5.4 Hz, 1H, 6′-H), 4.26 (q, *J*=7.1 Hz, 2H, $CO_2CH_2CH_3$), 4.23–4.32 (m, 1H, 2-H), 4.98 (dd, *J*=4.6, 2.7 Hz, 1H, 4-H), 5.45 (dd, *J*=6.3, 4.6 Hz, 1H, 3-H), 5.79 (d, *J*=6.7 Hz, 1H, 1-H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=14.0 (t, $CO_2CH_2CH_3$), 20.5, 20.6, 20.7 (3q, 3OAc), 45.1 (d, C-2), 62.3 (t, $CO_2CH_2CH_3$), 63.6 (t, C-6), 64.9, 65.7, 74.9 (3d, C-3, C-4, C-5), 93.4 (d, C-1), 105.8 (s, C-7), 158.3 (s, *C*O$_2$Et), 168.9, 169.1, 170.5 (3s, 3OAc); IR (neat): ν=2988, 1746, 1638, 1376, 1236, 1048, 890 cm^{-1}. Anal. Calcd (%) for $C_{16}H_{21}NO_{11}$ (403.34): C, 47.65; H, 5.25; N, 3.47. Found: C, 47.53; H, 5.42; N, 3.39.

*4.3.3. galacto-Isoxazoline N-oxide (galacto-**19c**)*

White crystals (630 mg, 52%); R_f=0.36 (hexane/ethyl acetate 1:1); mp 140 °C; $[\alpha]_D^{25}$ −27.8 (*c* 1.02, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$): δ=1.30 (t, *J*=7.1 Hz, 3H, $CO_2CH_2CH_3$), 2.05, 2.08, 2.17 (3s, 3H each, 3OAc), 3.60 (ddd, *J*=8.5, 6.2, 1.4 Hz, 1H, 2-H), 4.16 (d, *J*=6.5 Hz, 2H, 6-H), 4.28 (q, *J*=7.1 Hz, 2H, $CO_2CH_2CH_3$), 4.42 (td, *J*=6.5, 1.4 Hz, 1H, 5-H), 5.39 (dd, *J*=8.5, 3.0 Hz, 1H, 3-H), 5.38–5.45 (m, 1H, 4-H), 6.16 (d, *J*=6.2 Hz, 1H, 1-H); ^{13}C NMR (125 MHz, $CDCl_3$): δ=14.1 (q, $CO_2CH_2CH_3$), 20.4, 20.5, 20.6 (3q, 3OAc), 42.3 (d, C-2), 61.4 (t, $CO_2CH_2CH_3$), 62.3 (t, C-6), 64.4, 68.9, 70.4 (3d, C-3, C-4, C-5), 98.0 (d, C-1), 112.7 (s, C-7), 158.4 (s, CO_2Et), 169.6, 169.7, 170.4 (3s, 3OAc); IR (neat): ν=2973, 1748, 1731, 1607, 1366, 1218, 1159, 1079, 1037, 890 cm^{-1}. Anal. Calcd (%) for $C_{16}H_{21}NO_{11}$ (403.34): C, 47.65; H, 5.25; N, 3.47. Found: C, 47.48; H, 5.20; N, 3.30.

*4.3.4. talo-Isoxazoline N-oxide (talo-**19c**)*

Colorless oil (50 mg, 4%); R_f=0.34 (hexane/ethyl acetate 1:1); $[\alpha]_D^{25}$ +8.9 (*c* 0.97, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ=1.33 (t, *J*=7.1 Hz, 3H, $CO_2CH_2CH_3$), 2.04, 2.07, 2.16 (3s, 3H each, 3OAc), 3.61 (dd, *J*=8.1, 6.2 Hz, 1H, 2-H), 4.17 (dd, *J*=6.4 Hz, 2H, 6-H), 4.30 (q, *J*=7.1 Hz, 1H, $CO_2CH_2CH_3$), 4.31 (q, *J*=7.1 Hz, 1H, $CO_2CH_2CH_3$), 4.41 (td, *J*=6.4, 1.2 Hz, 1H, 5-H), 5.39 (dd, *J*=8.1, 3.3 Hz, 1H, 3-H), 5.42 (dd, *J*=3.3, 1.2 Hz, 1H, 4-H), 6.15 (d, *J*=6.2 Hz, 1H, 1-H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=14.1 (q, $CO_2CH_2CH_3$), 20.5, 20.6, 20.7 (3q, 3OAc), 42.4 (d, C-2), 61.4, 62.3 (2t, C-6, $CO_2CH_2CH_3$), 64.4, 68.9, 70.5 (3d, C-3, C-4, C-5), 89.5 (d, C-1), 98.0 (s, C-7), 158.3 (s, CO_2Et), 169.7, 169.8, 170.3 (3s, 3OAc); IR (neat): ν=2986, 1749, 1619, 1559, 1376, 1230, 1044, 925, 862 cm^{-1}. Anal. Calcd (%) for $C_{16}H_{21}NO_{11}$ (403.34): C, 47.65; H, 5.25; N, 3.47. Found: C, 47.32; H, 5.07; N, 3.35.

*4.3.5. xylo-Isoxazoline N-oxide (xylo-**19d**)*

Colorless oil (540 mg, 54%); R_f=0.51 (hexane/ethyl acetate 1:1); $[\alpha]_D^{27}$ −118.8 (*c* 1.03, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ=1.36 (t, *J*=7.1 Hz, 3H, $CO_2CH_2CH_3$), 2.00, 2.14 (2s, 3H each, 2OAc), 3.81 (dd, *J*=13.1, 4.6 Hz, 1H, 5-H), 3.92 (ddd, *J*=6.3, 2.8, 1.0 Hz, 1H, 2-H), 4.14 (dd, *J*=13.1, 4.8 Hz, 1H, 5′-H), 4.35 (q, *J*=7.1 Hz, 2H, $CO_2CH_2CH_3$), 4.87 (dddd, *J*=4.8, 4.6, 2.7, 1.0 Hz, 1H, 4-H), 5.74 (dd, *J*=2.8, 2.7 Hz, 1H, 3-H), 5.90 (d, *J*=6.3 Hz, 1H, 1-H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=14.1 (q, $CO_2CH_2CH_3$), 20.5, 20.7 (2q, 2OAc), 44.9 (d, C-2), 61.0 (t, $CO_2CH_2CH_3$), 62.2 (t, C-5), 65.2, 66.2 (2d, C-3, C-4), 93.4 (d, C-1), 106.4 (s, C-6), 158.3 (s, CO_2Et), 168.9, 169.2 (2s, OAc); IR (neat): ν=2988, 2942, 1754, 1628, 1374, 1234, 1063, 1044 cm^{-1}. Anal. Calcd (%) for $C_{13}H_{17}NO_9$ (331.28): C, 47.13; H, 5.17; N, 4.23. Found: C, 47.20; H, 5.33; N, 4.02.

*4.3.6. arabino-Isoxazoline N-oxide (arabino-**19e**)*

Colorless oil (510 mg, 51%); R_f=0.46 (hexane/ethyl acetate 1:1); $[\alpha]_D^{27}$ +49.6 (*c* 1.02, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ=1.37 (t, *J*=7.1 Hz, 3H, $CO_2CH_2CH_3$), 2.10, 2.12 (2s, 3H each, 2OAc), 3.79 (dd, *J*=5.9, 5.7 Hz, 1H, 2-H), 3.93 (dd, *J*=12.3, 5.6 Hz, 1H, 5-H), 4.07 (dd, *J*=12.3, 3.9 Hz, 1H, 5′-H), 4.33 (q, *J*=7.1 Hz, 2H, $CO_2CH_2CH_3$), 5.11 (ddd, *J*=5.6, 3.9, 3.3 Hz, 1H, 4-H), 5.76 (dd, *J*=5.9, 3.3 Hz, 1H, 3-H), 5.95 (d, *J*=5.7 Hz, 1H, 1-H); ^{13}C NMR (125 MHz, $CDCl_3$): δ=14.0 (q, $CO_2CH_2CH_3$), 20.6, 20.7 (2q, 2OAc), 45.5 (d, C-2), 61.9 (t, $CO_2CH_2CH_3$), 62.4 (t, C-5), 65.1, 66.4 (2d, C-3, C-4), 95.8 (d, C-1), 108.8 (s, C-6), 158.3 (s, CO_2Et), 169.6, 169.6 (2s, 2OAc); IR (neat): ν=2988, 1748, 1623, 1377, 1239, 1093, 1052, 1017, 874 cm^{-1}. Anal. Calcd (%) for $C_{13}H_{17}NO_9$ (331.28): C, 47.13; H, 5.17; N, 4.23. Found: C, 47.01; H, 5.04; N, 4.31.

*4.3.7. malto-Isoxazoline N-oxide (malto-**19f**)*

Colorless oil (1.33 g, 64%); R_f=0.36 (hexane/ethyl acetate 1:2); $[\alpha]_D^{27}$ −16.8 (*c* 1.02, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ=1.38 (t, *J*=7.1 Hz, 3H, $CO_2CH_2CH_3$), 1.97, 2.02, 2.03, 2.07, 2.10, 2.14 (6s, 3H each, 6OAc), 3.65 (ddd, *J*=7.9, 1.4, 0.8 Hz, 1H, 4-H), 3.96 (ddd, *J*=10.0, 5.0, 2.2 Hz, 1H, 5′-H), 4.06 (dd, *J*=12.2, 5.0 Hz, 1H, 6′$_a$-H), 4.11 (q, *J*=7.1 Hz, 2H, $CO_2CH_2CH_3$), 4.11 (ddd, *J*=8.3, 2.7, 1.4 Hz, 1H, 2-H), 4.34–4.46 (m, 1H, 5-H), 4.37 (dd, *J*=12.2, 2.2 Hz, 1H, 6′$_b$-H), 4.38 (dd, *J*=10.8, 7.1 Hz, 1H, 6$_a$-H), 4.50 (dd, *J*=10.8, 7.1 Hz, 1H, 6$_b$-H), 4.84 (dd, *J*=10.2, 4.1 Hz, 1H, 2′-H), 4.98 (dd, *J*=10.0, 9.6 Hz, 1H, 4′-H), 5.17 (dd, *J*=10.2, 9.6 Hz, 1H, 3′-H), 5.20 (d, *J*=4.1 Hz, 1H, 1′-H), 5.54 (dd, *J*=2.7, 0.8 Hz, 1H, 3-H), 6.02 (d, *J*=8.3 Hz, 1H, 1-H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=14.0 (q, $CO_2CH_2CH_3$), 20.4, 20.5, 20.6, 20.7, 20.8, 20.9 (6q, 6OAc), 43.6 (d, C-2), 61.9 (t, $CO_2CH_2CH_3$), 62.7, 63.4 (2t, C-6, C-6′), 68.1, 68.2, 68.5, 69.5, 69.6, 70.1, 76.9 (7d, C-3, C-4, C-5, C-2′, C-3′, C-4′, C-5′), 93.2, 98.5 (2d, C-1, C-1′), 105.8 (s, C-7), 158.1 (s, CO_2Et), 169.4, 169.5, 169.6, 170.3, 170.4, 170.5 (6s, 6OAc); IR (neat): ν=2960, 1748, 1705, 1636, 1420, 1371, 1228, 1039 cm^{-1}. Anal. Calcd (%) for $C_{28}H_{37}NO_{19}$ (691.59): C, 48.63; H, 5.39; N, 2.03. Found: C, 48.41; H, 5.10; N, 2.28.

*4.3.8. lacto-Isoxazoline N-oxide (lacto-**19g**)*

White crystals (1.10 g, 53%); R_f=0.37 (hexane/ethyl acetate 1:2); mp 200 °C; $[\alpha]_D^{27}$ −35.0 (*c* 1.05, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ=1.41 (t, *J*=7.1 Hz, 3H, $CO_2CH_2CH_3$), 1.96, 2.03, 2.04, 2.11, 2.12, 2.13 (6s, 3H each, OAc), 3.76 (ddd, *J*=7.7, 1.5, 0.9 Hz, 1H, 4-H), 3.90 (ddd, *J*=7.7, 6.0, 2.8 Hz, 1H, 5-H), 3.98 (td, *J*=6.8, 0.8 Hz, 1H, 5′-H), 4.07 (ddd, *J*=8.4, 2.9, 1.5 Hz, 1H, 2-H), 4.12 (dd, *J*=12.1, 6.0 Hz, 1H, 6$_a$-H), 4.15 (d, *J*=6.8 Hz, 2H, 6′-H), 4.24 (d, *J*=12.0, 2.8 Hz, 1H, 6$_b$-H), 4.38 (q, *J*=7.1 Hz, 2H, $CO_2CH_2CH_3$), 4.64 (d, *J*=6.2 Hz, 1H, 1′-H), 4.98 (m, 1H, 4′-H), 5.01 (dd, *J*=6.2, 2.9 Hz, 1H, 2′-H), 5.37 (dd, *J*=2.9, 0.8 Hz, 1H, 3′-H), 5.87 (dd, *J*=2.9, 0.9 Hz, 1H, 3-H), 6.00 (d, *J*=8.4 Hz, 1H, 1-H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=14.1 (q, $CO_2CH_2CH_3$), 20.3, 20.4, 20.5, 20.6, 20.7, 20.8 (6q, 6OAc), 43.5 (d, C-2), 60.8, 62.1, 63.7 (3t, C-6, C-6′, $CO_2CH_2CH_3$), 66.9, 67.6, 68.6, 69.1, 70.9, 71.1, 75.8 (7d, C-3, C-4, C-5, C-2′, C-3′, C-4′, C-5′), 93.4 (d, C-1), 102.0 (d, C-1′), 106.0 (d, C-7), 157.6 (s, CO_2Et), 169.1, 169.2, 169.9, 170.0, 170.3, 170.5 (6s, 6OAc); IR (neat): ν=2984, 1748, 1641, 1568, 1422, 1373, 1235, 1136, 1063, 950, 911 cm^{-1}. Anal. Calcd (%) for $C_{28}H_{37}NO_{19}$ (691.59): C, 48.63; H, 5.39; N, 2.03. Found: C, 48.44; H, 5.51; N, 1.85.

4.4. General procedure for the radical addition of nitromethane (8c)

A solution of the per-*O*-benzylated-D-glycal **10** (2.0 mmol), potassium hydroxide (225 mg, 4.0 mmol, 2 equiv), and nitromethane (**8c**) (1.22 g, 20 mmol, 10 equiv) in methanol (10 mL) was cooled to 0 °C under an argon atmosphere. At this temperature, a solution of cerium(IV) ammonium nitrate (CAN) (4.39 g, 8 mmol, 4 equiv) in methanol (20 mL) was added dropwise over a period of 2 h until TLC showed complete conversion of the starting material. After stirring for 30 min at 0 °C, an ice-cold diluted solution of sodium bisulfate (50 mL) and ammonium chloride (20 mL) was added, and the mixture was extracted with dichloromethane (3×100 mL). The combined organic extracts were dried (Na_2SO_4) and concentrated. The crude product was purified by column chromatography (cyclohexane/ethyl acetate), affording the 2-deoxy-2-*C*-nitromethyl-pyranosides **20** in analytically pure form.

*4.4.1. Methyl 3,4,6-tri-O-benzyl-2-deoxy-2-C-nitromethyl-β-D-glucopyranoside (gluco-**20b**)*

Colorless oil (600 mg, 59%); R_f=0.32 (cyclohexane/ethyl acetate 2:1); $[\alpha]_D^{20}$ +10.4 (*c* 1.02, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$): δ=2.21 (dddd, *J*=13.1, 11.2, 8.6, 4.4 Hz, 1H, 2-H), 3.37 (ddd, *J*=11.3, 8.3, 4.3 Hz, 1H, 5-H), 3.40 (s, 3H, OMe), 3.54 (dd, *J*=11.3, 2.4 Hz, 1H, 6-H), 3.62 (dd, *J*=9.1, 4.3 Hz, 1H, 4-H), 3.65 (dd, *J*=11.3, 2.3 Hz, 1H, 6′-H), 3.68 (dd, *J*=9.1, 8.6 Hz, 1H, 3-H), 4.29 (d, *J*=8.6 Hz, 1H, 1-H), 4.44 (d, *J*=11.0 Hz, 1H, C*H*$_2$–Ph), 4.45 (dd, *J*=11.2, 5.8 Hz, 1H, 7-H), 4.46 (dd, *J*=12.6, 4.4 Hz, 1H, 7′-H), 4.52 (d, *J*=11.0 Hz, 1H, C*H*$_2$–Ph), 4.54 (d, *J*=11.0 Hz, 1H, C*H*$_2$–Ph), 4.56 (d, *J*=12.0 Hz, 1H, C*H*$_2$–Ph), 4.69 (d, *J*=11.0 Hz, 1H, C*H*$_2$–Ph), 4.83 (d, *J*=11.0 Hz, 1H, C*H*$_2$–Ph), 7.09–7.26 (m, 15H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=46.6 (d, C-2),

57.1 (q, OMe), 68.6 (t, C-6), 72.1 (t, CH_2–NO_2), 73.5, 74.7 (2t, CH_2–Ph), 75.1 (d, C-3), 75.1 (t, CH_2–Ph), 75.6, 79.6, 80.4, 101.9 (3d, C-4, C-5, C-1), 127.6, 127.7, 127.8, 127.9, 127.9, 128.0, 128.4, 128.5, 128.6 (9d, arom. C–H), 137.7, 137.8, 138.0 (3s, arom. *C*–CH_2O); IR (neat): ν=3030, 2914, 1555, 1496, 1453, 1380, 1209, 1093, 911, 738, 698, 617, 463 cm^{-1}. Anal. Calcd (%) for $C_{29}H_{33}NO_7$ (507.58): C, 68.62; H, 6.55; N, 2.76. Found: C, 68.49; H, 6.67; N, 2.80.

4.4.2. Methyl 3,4,6-tri-O-benzyl-2-deoxy-2-C-nitromethyl-α-D-mannopyranoside (manno-**20b**)

Colorless oil (120 mg, 12%); R_f=0.35 (cyclohexane/ethyl acetate 2:1); $[\alpha]_D^{20}$ +68.0 (*c* 1.00, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ=2.76 (dddd, *J*=13.7, 8.6, 4.6, 3.4 Hz, 1H, 2-H), 3.35 (s, 3H, OMe), 3.74 (ddd, *J*=11.3, 5.4, 4.5 Hz, 1H, 5-H), 3.81 (dd, *J*=9.2, 5.4 Hz, 1H, 4-H,), 4.18 (dd, *J*=9.2, 5.5 Hz, 1H, 3-H), 4.37 (dd, *J*=13.3, 4.5 Hz, 1H, 6-H), 4.39 (d, *J*=8.6 Hz, 1H, 1-H), 4.48 (dd, *J*=13.3, 4.6 Hz, 1H, 6′-H), 4.56 (d, *J*=12.0 Hz, 1H, CH_2–Ph), 4.66 (d, *J*=12.0 Hz, 1H, CH_2–Ph), 4.68 (d, *J*=12.0 Hz, 1H, CH_2–Ph), 4.70 (d, *J*=12.0 Hz, 1H, CH_2–Ph), 4.74 (d, *J*=12.0 Hz, 1H, CH_2–Ph), 4.79–4.83 (m, 2H, 7-H, 7′-H), 4.93 (d, *J*=12.0 Hz, 1H, CH_2–Ph), 7.16–7.4 (m, 15H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=44.6 (d, C-2), 55.1 (q, OMe), 68.4 (t, C-6), 70.9 (d, C-3), 73.5 (t, CH_2–NO_2), 73.6, 74.8, 75.1 (3t, CH_2–Ph), 77.8, 79.5, 98.0 (3d, C-4, C-5, C-1), 127.7, 127.7, 127.8, 127.8, 127.9, 128.0, 128.1, 128.4, 128.6 (m, arom. C–H), 137.7, 137.9, 137.9 (3s, arom. *C*–CH_2O); IR (film): ν=3030, 2911, 1551, 1496, 1453, 1377, 1206, 1097, 1063, 988, 911, 734, 695, 675, 621, 572 cm^{-1} Anal. Calcd (%) for $C_{29}H_{33}NO_7$ (507.58): C, 68.62; H, 6.55; N, 2.76. Found: C, 68.51; H, 6.56; N, 2.48.

4.4.3. Methyl 3,4,6-tri-O-benzyl-2-deoxy-2-C-nitromethyl-β-D-galactopyranoside (galacto-**20h**)

White needles (560 mg, 55%); R_f=0.54 (cyclohexane/ethyl acetate 2:1); mp 127–128 °C; $[\alpha]_D^{20}$ +8.4 (*c* 0.98, $CHCl_3$); ^1H NMR (500 MHz, $CDCl_3$): δ=2.71 (dddd, *J*=12.7, 9.3, 8.8, 4.1 Hz, 1H, 2-H), 3.50 (s, 3H, OMe), 3.56 (dd, *J*=8.7, 5.9 Hz, 1H, 6-H), 3.59 (dd, *J*=8.5, 5.6 Hz, 1H, 6′-H), 3.63 (dd, *J*=8.8, 2.3 Hz, 1H, 3-H), 3.69 (dd, *J*=8.7, 5.6, 1.0 Hz, 1H, 5-H), 4.02 (dd, *J*=2.3, 1.0 Hz, 1H, 4-H), 4.39 (d, *J*=11.5 Hz, 1H, CH_2–Ph), 4.40 (d, *J*=8.8 Hz, 1H, 1-H), 4.43 (d, *J*=11.5, Hz, 1H, CH_2–Ph), 4.44 (d, *J*=11.5 Hz, 1H, CH_2–Ph), 4.49 (d, *J*=11.5 Hz, 1H, CH_2–Ph), 4.58 (d, *J*=11.5 Hz, 1H, CH_2–Ph), 4.70–4.73 (m, 2H, 7-H, 7′-H), 4.86 (d, *J*=11.5 Hz, 1H, CH_2–Ph), 7.27–7.37 (m, 15H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=42.3 (d, C-2), 57.4 (q, OMe), 69.1 (t, C-6), 71.0 (d, C-3), 72.2 (t, CH_2–NO_2), 72.6 (t, CH_2–Ph), 73.9 (d, C-4), 74.0, 74.9 (2t, CH_2–Ph), 78.3, 102.0 (2d, C-5, C-1), 128.0, 128.2, 128.3, 128.4, 128.5, 128.6, 128.9, 130.0 (m, arom. C–H), 138.0, 138.3, 138.6 (3s, arom. *C*–CH_2O); IR (KBr): ν=3031, 2862, 1549, 1495, 1451, 1352, 1205, 1159, 1095, 1066, 1025, 1000, 910, 750, 696, 640, 596 cm^{-1}. Anal. Calcd (%) for $C_{29}H_{33}NO_7$ (507.58): C, 68.62; H, 6.55; N, 2.76. Found: C, 68.59; H, 6.51; N, 2.77.

4.4.4. Methyl 3,4,6-tri-O-benzyl-2-deoxy-2-C-nitromethyl-α-D-talopyranoside (talo-**20h**)

Colorless oil (100 mg, 10%); R_f=0.62 (cyclohexane/ethyl acetate 2:1); $[\alpha]_D^{20}$ +26.5 (*c* 1.00, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ=3.01 (dddd, *J*=9.5, 8.7, 5.2, 4.2 Hz, 1H, 2-H), 3.37 (s, 3H, OMe), 3.61 (dd, *J*=9.3, 6.4 Hz, 6-H), 3.66 (dd, *J*=9.3, 6.5 Hz, 1H, 6′-H), 3.85 (dd, *J*=2.7, 1.2 Hz, 1H, 4-H), 3.94 (ddd, *J*=7.5, 6.5, 1.2 Hz, 1H, 5-H), 4.06 (dd, *J*=5.2, 2.7 Hz, 1H, 3-H), 4.47 (d, *J*=12.0 Hz, 1H, CH_2–Ph), 4.52 (d, *J*=11.3 Hz, 1H, CH_2–Ph), 4.56 (d, *J*=12.0 Hz, 1H, CH_2–Ph), 4.61 (d, *J*=12.0 Hz, 1H, CH_2–Ph), 4.70 (d, *J*=12.0 Hz, 1H, CH_2–Ph), 4.80–4.83 (m, 2H, 7-H, 7′-H), 4.84 (d, *J*=8.7 Hz, 1H, 1-H), 4.85 (d, *J*=11.3 Hz, 1H, CH_2–Ph), 7.26–7.40 (m, 15H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=40.9 (d, C-2), 55.6 (q, OMe), 69.4 (t, C-6), 69.7 (d, C-3), 71.2 (t, CH_2–NO_2), 73.8, 74.0 (2t, CH_2–Ph), 74.3, 74.4 (2d, C-4, C-5), 75.3 (t, CH_2-Ph), 100.1 (d, C-1), 127.8, 128.1, 128.2, 128.2, 128.3, 128.8, 128.8, 130.0 (m, arom. C–H), 138.1, 138.4, 138.7 (3s, arom. *C*–CH_2O); IR (neat): ν=3030, 2910, 1547, 1496, 1453, 1357, 1205, 1096, 1051, 1026, 959, 806, 733, 695, 601, 596 cm^{-1}. Anal. Calcd (%) for $C_{29}H_{33}NO_7$ (507.58): C, 68.62; H, 6.55; N, 2.76. Found: C, 68.59; H, 6.82; N, 2.63.

4.4.5. Methyl 3,4-di-O-benzyl-2-deoxy-2-C-nitromethyl-β-D-xylopyranoside (xylo-**20i**)

Colorless oil (220 mg, 28%); R_f=0.41 (cyclohexane/ethyl acetate 2:1); $[\alpha]_D^{20}$ +45.7 (*c* 0.98, $CHCl_3$); ^1H NMR (500 MHz, $CDCl_3$): δ=2.24 (dddd, *J*=12.5, 10.5, 8.1, 4.5 Hz, 1H, 2-H), 3.25 (dd, *J*=11.8, 5.8 Hz, 1H, 5-H), 3.46 (s, 3H, OMe), 3.57 (dd, *J*=9.5, 8.1 Hz, 1H, 3-H), 3.66 (ddd, *J*=9.5, 5.8, 4.9 Hz, 1H, 4-H), 4.03 (dd, *J*=11.8, 4.9 Hz, 1H, 5′-H), 4.36 (d, *J*=8.1 Hz, 1H, 1-H), 4.57–4.60 (m, 2H, 6-H, 6′-H), 4.63 (d, *J*=11.5 Hz, 1H, CH_2–Ph), 4.64 (d, *J*=11.5 Hz, 1H, CH_2–Ph), 4.67 (d, *J*=11.5 Hz, 1H, CH_2–Ph), 4.94 (d, *J*=11.5 Hz, 1H, CH_2–Ph), 7.25–7.36 (m, 10H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=45.9 (d, C-2), 57.3 (q, OMe), 63.6 (t, C-5), 73.0 (t, CH_2–NO_2), 73.2, 75.1 (2t, CH_2–Ph), 77.9, 79.8, 102.2 (3d, C-3, C-4, C-1), 128.2, 128.4, 128.4, 128.5, 128.9, 130.0 (m, arom. C–H), 138.2, 138.3 (2s, arom. *C*–CH_2O); IR (film): ν=3030, 2875, 1552, 1453, 1378, 1206, 1070, 1027, 997, 901, 734, 696, 620, 587 cm^{-1}. Anal. Calcd (%) for $C_{21}H_{25}NO_6$ (387.43): C, 65.10; H, 6.50; N, 3.62. Found: C, 64.95; H, 6.61; N, 3.49.

4.4.6. Methyl 3,4-di-O-benzyl-2-deoxy-2-C-nitromethyl-α-D-lyxopyranoside (lyxo-**20i**)

Colorless oil (155 mg, 20%); R_f=0.62 (cyclohexane/ethyl acetate 2:1); $[\alpha]_D^{20}$ +52.7 (*c* 0.99, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ=2.65 (dddd, *J*=9.7, 8.4, 4.7, 3.3 Hz, 1H, 2-H), 3.34 (s, 3H, OMe), 3.56 (ddd, *J*=9.7, 8.2, 5.4 Hz, 1H, 4-H), 3.65 (dd, *J*=9.7, 4.7 Hz, 1H, 3-H), 3.70 (dd, *J*=8.2, 4.0 Hz, 1H, 5-H), 3.94 (dd, *J*=5.4, 2.0 Hz, 1H, 5′-H), 4.40 (dd, *J*=13.4, 8.4 Hz, 1H, 6-H), 4.52 (d, *J*=4.7 Hz, 1H, 1-H), 4.57 (dd, *J*=11.0, 3.3 Hz, 1H, 6′-H), 4.65 (d, *J*=11.5 Hz, 1H, CH_2–Ph), 4.68 (d, *J*=11.5 Hz, 1H, CH_2–Ph), 4.70 (d, *J*=11.5 Hz, 1H, CH_2–Ph), 4.94 (d, *J*=11.5 Hz, 1H, CH_2–Ph), 7.27–7.39 (m, 10H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=44.0 (d, C-2), 57.2 (q, OMe), 60.3 (t, C-5), 72.8 (t, CH_2–NO_2), 73.5, 74.9 (2t, CH_2–Ph), 76.5, 79.2, 98.2 (3d, C-3, C-4, C-1), 127.7, 127.8, 128.0, 128.0, 128.4, 128.5 (m, arom. C–H), 137.9, 138.0 (2s, arom. *C*–CH_2O); IR (neat): ν=3030, 2932, 1550, 1453, 1377, 1265, 1204, 1092, 1045, 1027, 952, 735, 696 cm^{-1}. Anal. Calcd (%) for $C_{21}H_{25}NO_6$ (387.43): C, 65.10; H, 6.50; N, 3.62. Found: C, 64.97; H, 6.42; N, 3.29.

4.4.7. Methyl 3,4-di-O-benzyl-2-deoxy-2-C-nitromethyl-α-D-arbinopyranoside (arabino-**20j**)

White crystals (240 mg, 31%); R_f=0.41 (cyclohexane/ethyl acetate 2:1); mp 128 °C; $[\alpha]_D^{20}$ −46.1 (*c* 1.01, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ=2.72 (dddd, *J*=15.5, 12.5, 8.5, 4.1 Hz, 1H, 2-H), 3.31 (dd, *J*=13.0, 1.0 Hz, 1H, 5-H), 3.51 (s, 3H, OMe), 3.58 (dd, *J*=8.5, 2.7 Hz, 1H, 3-H), 3.75 (ddd, *J*=2.7, 2.2, 1.0 Hz, 1H, 4-H), 4.19 (dd, *J*=13.0, 2.2 Hz, 1H, 5′-H), 4.35 (d, *J*=11.2 Hz, 1H, CH_2–Ph), 4.36 (d, *J*=8.5 Hz, 1H, 1-H), 4.54 (d, *J*=11.2 Hz, 1H, CH_2–Ph), 4.63 (d, *J*=12.3 Hz, 1H, CH_2–Ph), 4.70 (dd, *J*=12.9, 4.1 Hz, 1H, 6-H), 4.74 (dd, *J*=12.5, 4.9 Hz, 1H, 6′-H), 4.75 (d, *J*=12.3 Hz, 1H, CH_2–Ph), 7.27–7.40 (m, 10H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=42.4 (d, C-2), 57.4 (q, OMe), 63.8 (t, C-5), 69.9 (d, C-3), 71.5, 71.5 (2t, CH_2–Ph), 72.5 (t, CH_2–NO_2), 76.4, 102.3 (2d, C-4, C-1), 128.2, 128.4, 128.4, 128.8, 128.9 (m, arom. C–H), 138.2, 138.4 (2s, arom. *C*–CH_2O); IR (KBr): ν=3029, 2867, 1535, 1453, 1380, 1350, 1255, 1225, 1122, 1093, 1001, 878, 796, 740, 696, 649, 619, 564, 492, 425 cm^{-1}. Anal. Calcd (%) for $C_{21}H_{25}NO_6$ (387.43): C, 65.10; H, 6.50; N, 3.62. Found: C, 65.12; H, 6.58; N, 3.66.

4.4.8. Methyl 3,4-di-O-benzyl-2-deoxy-2-C-nitromethyl-β-D-ribopyranoside (ribo-**20j**)

Colorless oil (60 mg, 8%); R_f=0.54 (cyclohexane/ethyl acetate 2:1); $[\alpha]_D^{20}$ −60.7 (*c* 0.98, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ=2.86 (dddd, *J*=10.3, 7.8, 4.8, 2.8 Hz, 1H, 2-H), 3.38 (s, 3H, OMe), 3.69 (dd, *J*=5.8, 2.2 Hz, 1H, 5-H), 3.74 (ddd, *J*=3.4, 2.2, 1.0 Hz, 1H, 4-H), 3.82 (dd, *J*=12.1, 3.4 Hz, 1H, 5′-H), 4.03 (dd, *J*=7.8, 1.0 Hz, 1H, 3-H), 4.58

(d, J=12.0 Hz, 1H, CH_2–Ph), 4.62–4.68 (m, 2H, 6-H, 6′-H), 4.69 (d, J=12.0 Hz, 1H, CH_2–Ph), 4.73 (d, J=12.0 Hz, 1H, CH_2–Ph), 4.75 (d, J=12.0 Hz, 1H, CH_2–Ph), 4.78 (d, J=4.8 Hz, 1H, 1-H), 7.27–7.40 (m, 10H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=41.7 (d, C-2), 55.6 (q, OMe), 60.9 (t, C-5), 71.6 (t, CH_2–NO_2), 72.0 (t, CH_2–Ph), 72.5 (d, C-3), 73.3 (t, CH_2–Ph), 73.9, 99.8 (2d, C-4, C-1), 127.5, 127.6, 127.7, 127.8, 128.5, 128.5 (m, arom. C–H), 137.9, 138.1 (2s, arom. C–CH_2O); IR (neat): ν=3030, 2872, 1546, 1452, 1379, 1355, 1268, 1127, 1053, 939, 905, 733, 696, 634, 595 cm^{-1}. Anal. Calcd (%) for $C_{21}H_{25}NO_6$ (387.43): C, 65.10; H, 6.50; N, 3.62. Found: C, 65.02; H, 6.72; N, 3.24.

4.4.9. Methyl 3,6,8,9,10,12-hexa-O-benzyl-2-deoxy-2-C-nitromethyl-β-D-maltopyranoside (malto-**20k**)

Colorless oil (1.09 g, 58%); R_f=0.50 (cyclohexane/ethyl acetate 2:1); $[\alpha]_D^{20}$ +41.2 (c 1.00, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$): δ=2.44 (dddd, J=12.6, 9.9, 8.8, 5.2 Hz, 1H, 2-H), 3.48 (s, 3H, OMe), 3.51 (dd, J=10.1, 2.4 Hz, 1H, 12-H), 3.54 (ddd, J=9.6, 5.3, 4.1 Hz, 1H, 5-H), 3.60 (dd, J=10.7, 3.6 Hz, 1H, 12′-H), 3.64 (dd, J=10.7, 9.6 Hz, 1H, 4-H), 3.75 (dd, J=10.7, 8.8 Hz, 1H, 9-H), 3.77 (ddd, J=10.2, 3.6, 2.4 Hz, 1H, 11-H), 3.84 (dd, J=10.2, 8.8 Hz, 1H, 10-H), 3.92 (dd, J=10.7, 3.8 Hz, 1H, 8-H), 3.96 (dd, J=11.4, 4.1 Hz, 1-H, 6-H), 4.10 (d, J=8.2 Hz, 1H, 1-H), 4.36–4.38 (m, 2H, 13-H, 13′-H), 4.45 (dd, J=11.2, 5.3 Hz, 1H, 6′-H), 4.47 (dd, J=10.7, 8.8 Hz, 1H, 3-H), 4.52 (d, J=12.0 Hz, 1H, CH_2–Ph), 4.52 (d, J=11.2 Hz, 1H, CH_2–Ph), 4.53 (d, J=12.0 Hz, 1H, CH_2–Ph), 4.54 (d, J=12.0 Hz, 1H, CH_2–Ph), 4.55 (d, J=12.0 Hz, 1H, CH_2–Ph), 4.57 (d, J=11.2 Hz, 1H, CH_2–Ph), 4.62 (d, J=12.0 Hz, 1H, CH_2–Ph), 4.78 (d, J=11.2 Hz, 1H, CH_2–Ph), 4.80 (d, J=11.2 Hz, 1H, CH_2–Ph), 4.82 (d, J=11.2 Hz, 1H, CH_2–Ph), 4.87 (d, J=11.2 Hz, 1H, CH_2–Ph), 5.00 (d, J=11.2 Hz, 1H, CH_2–Ph), 5.28 (d, J=3.6 Hz, 1H, 7-H), 7.13–7.30 (m, 30H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=45.3 (d, C-2), 56.9 (q, OMe), 68.5, 69.2 (2t, C-6, C-12), 71.2 (d, C-3), 72.4 (t, CH_2–NO_2), 72.5, 73.3, 73.4, 73.5, 75.0 (5t, CH_2–Ph), 75.5 (d, C-4), 75.5 (t, CH_2–Ph), 75.6, 77.8, 78.7, 79.7, 82.0, 97.4, 101.4 (7d, C-5, C-8, C-9, C-10, C-11, C-7, C-1), 127.5, 127.6, 127.7, 127.8, 127.9, 128.0, 128.3, 128.3, 128.4, 128.4 (m, arom. C–H), 137.8, 137.8, 138.0, 138.3, 138.3, 138.6 (6s, arom. C–CH_2O); IR (neat): ν=3031, 2873, 1540, 1487, 1402, 1394, 1209, 1087, 976, 738, 687, 632, 543, 521 cm^{-1}. Anal. Calcd (%) for $C_{56}H_{61}NO_{12}$ (940.09): C, 71.55; H, 6.54; N, 1.49. Found: C, 71.67; H, 6.98; N, 1.62.

4.4.10. Methyl 3,6,8,9,10,12-hexa-O-benzyl-2-deoxy-2-epi-2-C-nitromethyl-α-D-maltopyranoside (epi-malto-**20k**)

Colorless oil (225 mg, 12%); R_f=0.55 (cyclohexane/ethyl acetate 2:1); $[\alpha]_D^{20}$ +61.6 (c 0.99, $CHCl_3$); ^{1}H NMR (500 MHz, $CDCl_3$): δ=2.80 (dddd, J=10.5, 8.2, 5.8, 3.8 Hz, 1H, 2-H), 3.31 (s, 3H, OMe), 3.50 (ddd, J=9.8, 6.4, 3.6 Hz, 1H, 5-H), 3.58 (dd, J=10.7, 5.7 Hz, 1H, 12-H), 3.63 (dd, J=9.4, 9.8 Hz, 1H, 4-H), 3.66 (dd, J=10.8, 3.3 Hz, 1H, 12′-H), 3.74 (ddd, J=11.4, 5.7, 3.3 Hz, 1H, 11-H), 3.77 (dd, J=10.1, 8.6 Hz, 1H, 9-H), 3.93 (dd, J=9.3, 8.6 Hz, 1H, 10-H), 4.03 (dd, J=10.1, 3.5 Hz, 1H, 8-H), 4. 11 (dd, J=9.4, 3.4 Hz, 1H, 3-H), 4.31 (dd, J=13.4, 3.8 Hz, 1H, 13-H), 4.34 (dd, J=13.4, 3.8 Hz, 1H, 13′-H), 4.38–4.39 (m, 2H, 6-H, 6′-H), 4.41 (d, J=8.2 Hz, 1H, 1-H), 4.46 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.47 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.50 (d, J=12.3 Hz, 1H, CH_2–Ph), 4.52 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.53 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.56 (d, J=12.3 Hz, 1H, CH_2–Ph), 4.59 (d, J=12.3 Hz, 1H, CH_2–Ph), 4.76 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.77 (d, J=12.3 Hz, 1H, CH_2–Ph), 4.82 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.87 (d, J=11.5 Hz, 1H, CH_2–Ph), 5.00 (d, J=11.5 Hz, 1H, CH_2–Ph), 5.30 (d, J=3.5 Hz, 1H, 7-H), 7.14–7.32 (m, 30H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=43.7 (d, C-2), 55.2 (q, OMe), 68.7, 69.0 (2t, C-6, C-12), 70.9, 71.2 (2d, C-3, C-4), 73.1 (t, CH_2–NO_2), 73.2, 73.3, 73.3, 73.4, 75.0, 75.5 (6t, CH_2–Ph), 76.1, 77.7, 77.8, 79.9, 81.9, 97.5, 97.7 (7d, C-5, C-8, C-9, C-10, C-11, C-1, C-7), 127.4, 127.5, 127.6, 127.6, 127.7, 127.8, 127.8, 128.0, 128.3, 128.3, 128.5 (m, arom. C–H), 137.9, 138.0, 138.0, 138.3, 138.3, 138.6 (6s, arom. C–CH_2O); IR (neat): ν=3030, 2862, 1571, 1462, 1441, 1372, 1237, 1075, 976, 731, 696, 654, 543 cm^{-1}. Anal. Calcd (%) for $C_{56}H_{61}NO_{12}$ (940.09): C, 71.55; H, 6.54; N, 1.49. Found: C, 71.43; H, 6.86; N, 1.65.

4.4.11. Methyl 3,6,8,9,10,12-hexa-O-benzyl-2-deoxy-2-C-nitromethyl-β-D-lactopyranoside (lacto-**20l**)

Colorless oil (1.11 g, 59%); R_f=0.51 (cyclohexane/ethyl acetate 2:1); $[\alpha]_D^{20}$ +8.1 (c 1.01, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ=2.13 (dddd, J=15.3, 12.7, 8.4, 4.1 Hz, 1H, 2-H), 3.27 (dd, J=11.3, 3.4 Hz, 1H, 12-H), 3.29 (dd, J=6.8, 2.4 Hz, 1H, 4-H), 3.32 (ddd, J=6.8, 4.4, 1.4 Hz, 1H, 5-H), 3.42 (s, 3H, OMe), 3.40–3.52 (m, 1H, 11-H), 3.58 (dd, J=11.3, 8.5 Hz, 1H, 12′-H), 3.61 (dd, J=10.8, 1.4 Hz, 1-H, 6-H), 3.70 (dd, J=9.7, 2.2 Hz, 1H, 10-H), 3.80 (dd, J=11.0, 4.4 Hz, 1-H, 6′-H), 3.83 (dd, J=5.3, 2.4 Hz, 1H, 9-H), 3.96 (dd, J=9.0, 2.4 Hz, 1H, H-8), 4.17 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.28 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.32 (dd, J=8.4, 2.4 Hz, 1H, H-3), 4.33–4.38 (m, 2H, 13-H, 13′-H), 4.36 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.43 (d, J=8.4 Hz, 1H, 1-H), 4.46 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.52 (d, J=12.1 Hz, 1H, CH_2–Ph), 4.55 (d, J=12.1 Hz, 1H, CH_2–Ph), 4.59 (d, J=12.1 Hz, 1H, CH_2–Ph), 4.66 (d, J=12.1 Hz, 1H, CH_2–Ph), 4.71 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.75 (d, J=12.1 Hz, 1H, CH_2–Ph), 4.87 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.89 (d, J=11.5 Hz, 1H, CH_2–Ph), 5.12 (d, J=10.2 Hz, 1H, 7-H), 7.05–7.25 (m, 30H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=46.5 (d, C-2), 57.0 (q, OMe), 67.9, 68.1 (2t, C-6, C-12), 72.3 (t, CH_2–NO_2), 72.7, 73.1 (2t, CH_2–Ph), 73.1 (d, C-3), 73.4 (t, CH_2–Ph), 73.7 (d, C-4), 74.7, 74.9 (2t, CH_2–Ph), 75.3 (d, C-5), 75.3 (t, CH_2–Ph), 77.2, 77.4, 80.0, 82.4, 101.4, 102.6 (6d, C-8, C-9, C-10, C-11, C-1, C-7), 127.3, 127.4, 127.5, 127.5, 127.6, 127.7, 127.8, 127.9, 128.0, 128.1, 128.2, 128.3, 128.4 (m, arom. C–H), 138.1, 138.2, 138.4, 138.5, 138.7, 139.0 (6s, arom. C–CH_2O); IR (neat): ν=3028, 2862, 1555, 1495, 1452, 1361, 1207, 1046, 909, 731, 694, 600, 568, 555 cm^{-1}. Anal. Calcd (%) for $C_{56}H_{61}NO_{12}$ (940.09): C, 71.55; H, 6.54; N, 1.49. Found: C, 71.32; H, 6.81; N, 1.60.

4.4.12. Methyl 3,6,8,9,10,12-hexa-O-benzyl-2-deoxy-2-epi-2-C-nitromethyl-α-D-lactopyranoside (epi-lacto-**20l**)

Colorless oil (170 mg, 9%); R_f=0.52 (cyclohexane/ethyl acetate 2:1); $[\alpha]_D^{20}$ +19.6 (c 0.99, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ=3.03 (dddd, J=9.5, 8.1, 5.9, 3.5 Hz, 1H, 2-H), 3.37 (s, 3H, OMe), 3.37 (ddd, J=4.6, 3.8, 2.8 Hz, 1H, 5-H), 3.42 (dd, J=4.6, 3.1 Hz, 1H, 4-H), 3.48 (dd, J=10.8, 5.4 Hz, 1H, 12-H), 3.52 (ddd, J=9.2, 5.9, 2.3 Hz, 1H, 11-H), 3.58 (dd, J=10.8, 2.0 Hz, 1H, 12′-H), 3.68 (dd, J=9.2, 4.0 Hz, 1H, 10-H), 3.76 (dd, J=8.7, 9.8 Hz, 1H, H-8), 3.82 (dd, J=11.0, 3.8 Hz, 1-H, 6-H), 3.90 (dd, J=11.0, 2.8 Hz, 1H, 6′-H), 4.02 (dd, J=8.1, 3.1 Hz, 1H, H-3), 4.26 (d, J=11.8 Hz, 1H, CH_2–Ph), 4.30 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.32 (d, J=8.1 Hz, 1H, 1-H), 4.33 (d, J=11.8 Hz, 1H, CH_2–Ph), 4.35 (dd, J=8.7, 4.0 Hz, 1H, 9-H), 4.40 (d, J=12.1 Hz, 1H, CH_2–Ph), 4.54 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.57 (d, J=12.1 Hz, 1H, CH_2–Ph), 4.58 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.62 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.65–4.73 (m, 2H, 13-H, 13′-H), 4.75 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.81 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.85 (d, J=11.5 Hz, 1H, CH_2–Ph), 4.97 (d, J=11.5 Hz, 1H, CH_2–Ph), 5.16 (d, J=10.7 Hz, 1H, 7-H), 7.21–7.36 (m, 30H, arom. H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=42.4 (d, C-2), 57.2 (q, OMe), 68.4 (t, C-6), 68.7 (t, C-12), 71.0 (d, C-3), 72.7 (t, CH_2–NO_2), 72.7, 72.9, 73.3, 73.5 (4t, CH_2–Ph), 73.5 (d, C-4), 73.8 (d, C-5), 74.5 (d, C-8), 74.6, 75.2 (2t, CH_2–Ph), 75.4 (d, C-9), 80.0 (d, C-10), 82.4 (d, C-11), 98.9 (d, C-1), 103.3 (d, C-7), 127.4, 127.6, 127.7, 127.8, 128.1, 128.2, 128.3 (m, arom. C–H), 138.1, 138.2, 138.4, 138.5, 138.8, 138.8 (6s, arom. C–CH_2O); IR (neat): ν=3033, 2799, 1547, 1487, 1465, 1321, 1256, 1135, 967, 721, 687, 643, 554 cm^{-1}. Anal. Calcd (%) for $C_{56}H_{61}NO_{12}$ (940.09): C, 71.55; H, 6.54; N, 1.49. Found: C, 71.93; H, 6.59; N, 1.74.

4.5. General procedure for the catalytic hydrogenation of the nitromethyl-pyranosides 20

The 2-deoxy-2-C-nitromethyl-pyranoside **20** (1.0 mmol) was dissolved in methanol (5 mL) and palladium on carbon (10%) (120 mg) was added. The reaction mixture was stirred in an autoclave under H_2 atmosphere (40 bar) for 1 h and TLC showed complete conversion. The mixture was filtered over Celite, concentrated, and acetylated with acetic anhydride (0.5 mL) for

30 min. After concentration in vacuum, the crude product was purified by column chromatography (ethyl acetate/methanol 8: 2), affording the branched-chain glycosamines **21** in analytically pure form.

*4.5.1. Methyl 2-acetamidomethyl-2-deoxy-β-D-glucopyranoside (gluco-**21b**)*

Colorless syrup (200 mg, 82%); R_f=0.50 (ethyl acetate/methanol 8:2); $[\alpha]_D^{20}$ −8.1 (*c* 0.99, H_2O); ^{1}H NMR (300 MHz, D_2O): δ=1.51 (dddd, *J*=12.1, 10.6, 8.8, 5.6 Hz, 1H, 2-H), 1.91 (s, 3H, Ac), 3.18–3.26 (m, 1H, 5-H), 3.27 (dd, *J*=8.8, 4.6 Hz, 1H, 4-H), 3.29 (dd, *J*=10.9, 5.4 Hz, 1H, 6-H), 3.38 (dd, *J*=8.8, 4.5 Hz, 1H, 3-H), 3.43 (s, OMe), 3.47 (dd, *J*=14.1, 3.1 Hz, 1H, 6′-H), 3.62 (dd, *J*=12.2, 5.6 Hz, 1H, 7-H), 3.82 (dd, *J*=12.1, 1.5 Hz, 1H, 7′-H), 4.29 (d, *J*=8.8 Hz, 1H, 1-H), 4.69 (s, 3H, OH); ^{13}C NMR (75 MHz, D_2O): δ=22.3 (q, Ac), 36.4 (t, CH_2–NH), 48.0 (d, C-2), 57.4 (q, OMe), 61.4 (t, C-6), 71.1, 72.5, 76.1 (3d, C-3, C-4, C-5), 103.2 (d, C-1), 174.6 (s, Ac); IR (neat): ν=3276, 2867, 1627, 1552, 1451, 1370, 1210, 1069, 1024, 733, 696, 604, 573 cm^{-1}; HRMS (ES) ($C_{10}H_{19}NO_6$): calcd for [M+Na]: 272.1110, found: 272.1128.

*4.5.2. Methyl 2-acetamidomethyl-2-deoxy-β-D-galactopyranoside (galacto-**21h**)*

Colorless syrup (193 mg, 77%); R_f=0.44 (ethyl acetate/methanol 8:2); $[\alpha]_D^{20}$ −4.9 (*c* 1.00, H_2O); ^{1}H NMR (300 MHz, D_2O): δ=1.64–1.74 (m, 1H, 2-H), 1.90 (s, 3H, Ac), 3.24 (ddd, *J*=12.6, 7.3, 1.7 Hz, 1H, 5-H), 3.43 (s, OMe), 3.44 (dd, *J*=12.6, 4.7 Hz, 1H, 3-H), 3.47–3.55 (m, 2H, 6-H, 6′-H), 3.64 (dd, *J*=11.8, 4.7 Hz, 1H, 4-H), 3.71–3.74 (m, 2H, 7-H, 7′-H), 4.21 (d, *J*=8.9 Hz, 1H, 1-H), 4.69 (s, 3H, OH); ^{13}C NMR (75 MHz, D_2O): δ=22.3 (q, Ac), 36.4 (t, CH_2–NH), 43.2 (d, C-2), 57.4 (q, OMe), 61.7 (t, C-6), 67.8, 69.7, 75.3 (3d, C-3, C-4, C-5), 103.7 (d, C-1), 174.6 (s, Ac); IR (neat): ν=3304, 2936, 1735, 1633, 1556, 1371, 1234, 1032, 776, 588 cm^{-1}; HRMS (ES) ($C_{10}H_{19}NO_6$): calcd for [M+Na]: 272.1110, found: 272.1120.

*4.5.3. Methyl 2-acetamidomethyl-2-deoxy-β-D-xylopyranoside (xylo-**21i**)*

Colorless syrup (170 mg, 78%); R_f=0.60 (ethyl acetate/methanol 8:2); $[\alpha]_D^{20}$ −20.1 (*c* 1.00, H_2O); ^{1}H NMR (300 MHz, D_2O): δ=1.44–1.53 (m, 1H, 2-H), 1.90 (s, 3H, Ac), 3.15 (dd, *J*=10.1, 11.6 Hz, 1H, 5-H), 3.23–3.35 (m, 2H, 6-H, 6′-H), 3.39 (s, OMe), 3.44 (dd, *J*=5.3, 9.2 Hz, 1H, 4-H), 3.51 (dd, *J*=5.3, 8.8 Hz, 1H, 3-H), 3.86 (dd, *J*=5.2, 11.6 Hz, 1H, 5′-H), 4.25 (d, *J*=8.6 Hz, 1H, H-1), 4.69 (s, 2H, OH); ^{13}C NMR (75 MHz, D_2O): δ=22.3 (q, Ac), 36.4 (t, CH_2–NH), 47.5 (d, C-2), 57.3 (q, OMe), 65.2 (t, C-5), 70.5, 72.2 (2d, C-3, C-4), 103.8 (d, C-1), 174.6 (s, Ac); IR (neat): ν=3296, 2913, 1626, 1552, 1437, 1297, 1214, 1155, 1043, 1001, 943, 639, 599 cm^{-1}; HRMS (ES) ($C_9H_{17}NO_5$): calcd for [M+Na]: 242.1004, found: 242.1016.

*4.5.4. Methyl 2-acetamidomethyl-2-deoxy-α-D-arabinopyranoside (arabino-**21j**)*

Colorless syrup (165 mg, 75%); R_f=0.53 (ethyl acetate/methanol 8:2); $[\alpha]_D^{20}$ −4.2 (*c* 1.00, H_2O); ^{1}H NMR (300 MHz, D_2O): δ=1.00–1.08 (m, 1H, 2-H), 1.90 (s, 3H, Ac), 3.17 (s, OMe), 3.30 (dd, *J*=10.2, 6.6 Hz, 1H, 3-H), 3.38–3.51 (m, 2H, 6-H, 6′-H), 3.54 (dd, *J*=10.2, 6.9, 1.1 Hz, 1H, 4-H), 3.62 (dd, *J*=12.2, 3.4 Hz, 1H, 5-H), 3.80 (dd, *J*=12.8, 3.1 Hz, 1H, 5′-H), 4.17 (d, *J*=8.2 Hz, 1H, 1-H), 4.69 (s, 2H, OH); ^{13}C NMR (75 MHz, D_2O): δ=22.3 (q, Ac), 36.6 (t, CH_2–NH), 43.6 (d, C-2), 57.2 (q, OMe), 66.0 (t, C-5), 67.2, 69.1 (2d, C-3, C-4), 103.6 (d, C-1), 174.8 (s, Ac); IR (neat): ν=3324, 2943, 1654, 1492, 1417, 1287, 1153, 1049, 967, 587 cm^{-1}; HRMS (ES) ($C_9H_{17}NO_5$): calcd for [M+Na]: 242.1004, found: 242.1002.

*4.5.5. Methyl 2-acetamidomethyl-2-deoxy-β-D-maltopyranoside (malto-**21k**)*

Colorless syrup (290 mg, 71%); R_f=0.54 (ethyl acetate/methanol 7:3); $[\alpha]_D^{20}$ −12.8 (*c* 1.01, H_2O); ^{1}H NMR (300 MHz, D_2O): δ=1.97 (s, Ac), 2.06 (dddd, *J*=11.6, 8.6, 6.3, 4.3 Hz, 1H, 2-H), 2.80 (dd, *J*=11.0, 8.5 Hz, 1H, 13-H), 3.28 (s, OMe), 3.34 (dd, *J*=11.6, 6.3 Hz, 1H, 13′-H), 3.42 (dd, *J*=11.4, 4.4 Hz, 1H, 12-H), 3.48 (ddd, *J*=9.3, 5.4, 3.3 Hz, 1H, 5-H), 3.53 (dd, *J*=11.0, 2.9 Hz, 1H, 12′-H), 3.70 (ddd, *J*=10.7, 5.9, 2.4 Hz, 1H, 11-H), 3.76 (dd, *J*=8.7, 7.0 Hz, 1H, 4-H), 3.78 (dd, *J*=9.0, 6.4 Hz, 1H, 10-H), 3.83 (dd *J*=9.3, 8.6 Hz, 1H, 3-H), 4.01 (dd, *J*=12.0, 6.6 Hz, 1H, 6-H), 4.06 (dd, *J*=9.3, 8.6 Hz, 1H, 9-H), 4.20 (dd, *J*=12.0, 6.2 Hz, 1H, 6′-H), 4.32 (dd, *J*=8.6, 3.5 Hz, 1H, 8-H), 4.69 (s, 6H, OH), 4.70 (d, *J*=8.6 Hz, 1H, 1-H), 4.83 (d, *J*=3.5 Hz, 1H, 7-H); ^{13}C NMR (75 MHz, D_2O): δ=20.6 (q, Ac), 36.8 (t, CH_2–NH), 47.8 (d, C-2), 54.9 (q, OMe), 61.0, 61.2 (2t, C-6, C-12), 69.2, 69.8, 71.1, 72.3, 73.1, 73.4, 79.4 (7d, C-3, C-4, C-5, C-8, C-9, C-10, C-11), 97.1, 103.1 (2d, C-1, C-7), 171.6 (s, Ac); IR (neat): ν=3345, 2982, 1732, 1564, 1427, 1286, 1144, 1053, 981, 562 cm^{-1}; HRMS (ES) ($C_{16}H_{29}NO_{11}$): calcd for [M+Na]: 434.1638, found: 434.1642.

*4.5.6. Methyl 2-acetamidomethyl-2-deoxy-β-D-lactopyranoside (lacto-**21l**)*

Colorless syrup (300 mg, 73%); R_f=0.59 (ethyl acetate/methanol 7:3); $[\alpha]_D^{20}$ −5.4 (*c* 0.99, H_2O); ^{1}H NMR (300 MHz, D_2O): δ=2.00 (s, 3H, Ac), 2.35 (dddd, *J*=11.0, 8.8, 6.8, 4.6 Hz, 1H, 2-H), 3.28 (dd, *J*=11.1, 6.8 Hz, 1H, 13-H), 3.36 (dd, *J*=11.7, 2.0 Hz, 1H, 12-H), 3.43 (s, OMe), 3.46 (dd, *J*=11.1, 3.4 Hz, 1H, 13′-H), 3.52 (ddd, *J*=8.8, 6.9, 3.5 Hz, 1H, 5-H), 3.58 (ddd, *J*=10.1, 7.6, 3.7 Hz, 1H, 11-H), 3.60 (dd, *J*=9.8, 3.2 Hz, 1H, 9-H), 3.65 (dd, *J*=8.8, 3.4 Hz, 1H, 3-H), 3.70 (dd, *J*=8.4, 3.4 Hz, 1H, 4-H), 3.75 (dd, *J*=12.4, 5.1 Hz, 1H, 6-H), 3.82 (dd, *J*=9.6, 3.2 Hz, 1H, 10-H), 3.91 (dd, *J*=12.2, 2.0 Hz, 1H, 12′-H), 4.38 (d, *J*=7.7 Hz, 1H, 7-H), 4.49 (d, *J*=8.8 Hz, 1H, 1-H), 4.62 (dd, *J*=13.1, 6.2 Hz, 1H, 6′-H), 4.69 (s, 6H, OH), 4.72 (dd, *J*=9.8, 7.7 Hz, 1H, H-8); ^{13}C NMR (75 MHz, D_2O): δ=20.6 (q, Ac), 36.2 (t, CH_2–NH), 47.9 (d, C-2), 57.5 (q, OMe), 61.0, 61.4 (2t, C-6, C-12), 69.8, 72.1, 72.8, 73.1, 73.3, 74.8, 75.0 (7d, C-3, C-4, C-5, C-8, C-9, C-10, C-11), 100.2, 103.1 (2d, C-1, C-7), 171.7 (s, Ac); IR (neat): ν=3334, 2930, 2493, 1724, 1562, 1372, 1241, 1028, 893, 779, 597 cm^{-1}; HRMS (ES) ($C_{16}H_{29}NO_{11}$): calcd for [M+Na]: 434.1638, found: 434.1662.

4.6. General procedure for the catalytic hydrogenation of the isoxazoline *N*-oxides 19

The isoxazoline *N*-oxide **19** (1.0 mmol) was dissolved in methanol (5 mL) and Raney nickel (50% in H_2O, 600 mg) was added. The reaction mixture was stirred in an autoclave under H_2 atmosphere (80 bar) for 1–2 days until TLC showed complete conversion. The mixture was filtered over Celite, washed with methanol (10 mL), concentrated, and acetylated with pyridine (5.0 mL) and acetic anhydride (10 mL) for 1 day. After concentration in vacuum, the diastereomeric ratios were determined by ^{1}H NMR (500 MHz) on the crude products. Purification by column chromatography (hexane/ethyl acetate 1: 2) afforded the *C*-glycosylated amino acids **22** as an anomeric mixture in the yields depicted in Table 2. The 1,2-diequatorially configured main products were isolated by MPLC (medium pressure liquid chromatography) (hexane/ethyl acetate 1: 2) in analytically pure form.

*4.6.1. gluco-Amino acid (S-**22a**)*

Colorless oil; R_f=0.35 (hexane/ethyl acetate 1:2); $[\alpha]_D^{20}$ +72.6 (*c* 1.00, $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ=1.34 (t, *J*=7.2 Hz, 3H, OCH_2CH_3), 1.96, 2.01, 2.05, 2.07 (4s, 3H each, 4OAc), 2.21 (s, 3H, NHAc), 2.71 (ddd, *J*=11.4, 9.2, 1.4 Hz, 1H, 2-H), 3.73 (ddd, *J*=10.0, 4.4, 2.1 Hz, 1H, 5-H), 4.06 (dd, *J*=12.5, 2.1 Hz, 1H, 6-H), 4.26 (q, *J*=7.2 Hz, 2H, OCH_2CH_3), 4.29 (dd, *J*=12.5, 4.4 Hz, 1H, 6′-H), 4.98 (dd, *J*=8.8, 1.4 Hz, 1H, 7-H), 5.05 (dd, *J*=10.0, 9.2 Hz, 1H, 4-H), 5.21 (dd, *J*=11.4, 9.2 Hz, 1H, 3-H), 5.39 (d, *J*=9.2 Hz, 1H, 1-H), 6.19 (d, *J*=8.8 Hz, 1H, NHAc); ^{13}C NMR (75 MHz, $CDCl_3$): δ=14.2 (q, OCH_2CH_3), 20.4, 20.5, 20.7, 20.8 (4q, 4OAc), 23.1 (q, NHAc), 47.4, 48.0 (2d, C-2, C-7), 61.7 (t, OCH_2CH_3), 62.7 (d, C-6), 68.8, 69.9, 72.4 (3d, C-3, C-4, C-5), 91.7 (d,

C-1), 168.7 (s, CO_2Et), 169.6, 170.5, 170.6, 170.8, 170.9 (5s, 4OAc, NHAc); IR (neat): ν=3417, 2963, 1749, 1688, 1525, 1443, 1373, 1261, 1026, 801 cm^{-1}. Anal. Calcd (%) for $C_{20}H_{29}NO_{12}$ (475.44): C, 50.53; H, 6.15; N, 2.95. Found: C, 49.98; H, 6.48; N, 2.88.

*4.6.2. galacto-Amino acid (S-**22c**)*

Colorless oil; R_f=0.52 (hexane/ethyl acetate 1:5); $[\alpha]_D^{20}$ −53.2 (*c* 1.04, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ=1.32 (t, *J*=7.1 Hz, 3H, OCH_2CH_3), 2.02, 2.03, 2.10, 2.10 (4s, 3H each, 3OAc, 1NHAc), 2.90 (ddd, *J*=12.0, 9.4, 1.6 Hz, 1H, 2-H), 3.93 (ddd, *J*=6.8, 6.3, 0.8 Hz, 1H, 5-H), 4.05 (dd, *J*=11.3, 6.3 Hz, 1H, 6-H), 4.12–4.19 (m, 1H, $CO_2CH_2CH_3$), 4.13 (dd, *J*=11.3, 6.8 Hz, 1H, 6′-H), 4.20–4.28 (m 1H, 4-H), 4.25 (dq, *J*=10.8, 7.1 Hz, 1H, $CO_2CH_2CH_3$), 4.97 (dd, *J*=8.5, 1.6 Hz, 1H, 7-H), 5.06 (dd, *J*=12.0, 3.2 Hz, 1H, 3-H), 5.39 (d, *J*=9.4 Hz, 1H, 1-H), 6.24 (d, *J*=8.5 Hz, 1H, NHAc); ^{13}C NMR (75 MHz, $CDCl_3$): δ=14.1 (q, OCH_2CH_3), 20.3, 20.4, 20.5, 20.7 (4q, 4OAc), 23.0 (q, NHAc), 42.9, 47.9 (2d, C-2, C-7), 61.2 (t, OCH_2CH_3), 61.8 (d, C-6), 65.9, 68.3, 71.2 (3d, C-3, C-4, C-5), 91.9 (d, C-1), 168.7, 170.0, 170.1, 170.3, 170.7, 171.1 (6s, 4OAc, CO_2Et, NHAc); IR (neat): ν=3415, 2961, 1738, 1692, 1523, 1443, 1365, 1268, 1029, 805 cm^{-1}. Anal. Calcd (%) for $C_{20}H_{29}NO_{12}$ (475.44): C, 50.53; H, 6.15; N, 2.95. Found: C, 49.88; H, 6.23; N, 2.83.

*4.6.3. xylo-Amino acid (S-**22d**)*

Colorless oil; R_f=0.62 (hexane/ethyl acetate 1:5); $[\alpha]_D^{20}$ +6.5 (*c* 0.96, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ=1.32 (t, *J*=7.1 Hz, 3H, $CO_2CH_2CH_3$), 1.98, 2.01, 2.05 (3s, 3H each, OAc), 2.19 (s, 3H, NHAc), 2.65 (ddd, *J*=11.5, 9.0, 1.7 Hz, 1H, 2-H), 3.38 (dd, *J*=11.8, 9.7 Hz, 1H, 5-H), 4.08 (dd, *J*=11.8, 5.5 Hz, 1H, 5′-H), 4.11 (q, *J*=7.1 Hz, 2H, $CO_2CH_2CH_3$), 4.92–5.01 (m, 1H, 4-H), 4.98 (dd, *J*=8.8, 1.7 Hz, 1H, 6-H), 5.18 (dd, *J*=11.5, 9.1 Hz, 1H, 3-H), 5.35 (d, *J*=9.0 Hz, 1H, 1-H), 6.25 (d, *J*=8.8 Hz, 1H, NHAc); ^{13}C NMR (75 MHz, $CDCl_3$): δ=14.1 (q, $CO_2CH_2CH_3$), 20.5, 20.6, 20.7 (3q, 3OAc), 23.1 (q, NHAc), 46.9 (d, C-2), 48.1 (d, C-6), 62.0 (t, $CO_2CH_2CH_3$), 63.4 (t, C-5), 69.4, 69.8 (2d, C-3, C-4), 92.3 (d, C-1), 168.9 (s, CO_2Et), 169.9, 170.5, 170.9, 171.0 (4s, NHAc, 3OAc); IR (neat): ν=3342, 2948, 1749, 1685, 1543, 1438, 1372, 1215, 1013, 937 cm^{-1}. Anal. Calcd (%) for $C_{17}H_{25}NO_{10}$ (403.38): C, 50.62; H, 6.25; N, 3.47. Found: C, 50.45; H, 6.12; N, 3.27.

*4.6.4. arabino-Amino acid (R-**22e**)*

Colorless oil; R_f=0.67 (hexane/ethyl acetate 1:5); $[\alpha]_D^{20}$ +55.7 (*c* 1.01, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ=1.28 (t, *J*=7.1 Hz, 3H, $CO_2CH_2CH_3$), 1.95, 2.04, 2.12, 2.20 (4s, 3H each, 3OAc, NHAc), 2.95 (ddd, *J*=11.7, 9.3, 1.6 Hz, 1H, 2-H), 3.72 (dd, *J*=13.4, 0.9 Hz, 1H, 5-H), 4.00 (dd, *J*=13.5, 1.8 Hz, 1H, 5′-H), 4.17 (dq, *J*=10.8, 7.1 Hz, 1H, $CO_2CH_2H_3$), 4.27 (dq, *J*=10.8, 7.1 Hz, 1H, $CO_2CH_2H_3$), 5.00 (dd, *J*=8.5, 1.6 Hz, 1H, 6-H), 5.09 (dd, *J*=11.7, 3.3 Hz, 1H, 3-H), 5.13–5.16 (m, 1H, 4-H), 5.32 (d, *J*=9.2 Hz, 1H, 1-H), 6.14 (d, *J*=8.5 Hz, 1H, NHAc); ^{13}C NMR (75 MHz, $CDCl_3$): δ=14.2 (q, $CO_2CH_2CH_3$), 20.5, 20.7, 20.8, 23.1 (4q, 3OAc, NHAc), 43.4 (d, C-2), 48.1 (d, C-6), 61.7 (t, $CO_2CH_2CH_3$), 65.1 (t, C-5), 67.0, 67.9 (2d, C-3, C-4), 92.4 (d, C-1), 168.9, 170.2, 170.3, 170.4, 170.6 (5s, CO_2Et, 3OAc, NHAc); IR (neat): ν=3407, 2926, 1745, 1663, 1542, 1442, 1374, 1235, 1034, 974 cm^{-1}. Anal. Calcd (%) for $C_{17}H_{25}NO_{10}$ (403.38): C, 50.62; H, 6.25; N, 3.47. Found: C, 51.03; H, 5.98; N, 3.04.

*4.6.5. malto-Amino acid (S-**22f**)*

Colorless oil; R_f=0.32 (hexane/ethyl acetate 1:5); $[\alpha]_D^{20}$ +142.2 (*c* 1.03, $CHCl_3$); ^1H NMR (300 MHz, $CDCl_3$): δ=1.46 (t, 3H, *J*=7.1 Hz, $CO_2CH_2CH_3$), 1.97, 2.01, 2.02, 2.04, 2.07, 2.09, 2.11, 2.12 (8q, 3H each, 7OAc, NHAc), 2.65 (ddd, *J*=11.4, 9.2, 1.5 Hz, 1H, 2-H), 3.73 (ddd, *J*=9.3, 4.1, 2.5 Hz, 1H, 5-H), 3.91 (ddd, *J*=10.4, 2.5, 2.2 Hz, 1H, 5′-H), 3.93 (dd, *J*=9.3, 8.8 Hz, 1H, 4-H), 4.06 (dd, *J*=12.2, 2.2 Hz, 1H, $6'_a$-H), 4.10–4.22 (m, 3H, 6_a-H, $CO_2CH_2CH_3$), 4.24 (dd, *J*=11.9, 4.1 Hz, 1H, 6_b-H), 4.43 (dd, *J*=12.2, 2.5 Hz, 1H, $6'_b$-H), 4.90 (dd, *J*=10.6, 3.8 Hz, 1H, 2′-H), 5.04 (dd, *J*=10.4, 9.4 Hz, 1H, 4′-H), 5.05 (dd, *J*=9.6, 1.5 Hz, 1H, 7-H), 5.26 (d, *J*=3.8 Hz, 1H, 1′-H), 5.27 (dd, *J*=11.4, 8.8 Hz, 1H, 3-H), 5.32 (dd, *J*=10.6, 9.4 Hz, 1H, 3′-H), 5.38 (d, *J*=9.2 Hz, 1H, 1-H), 6.36 (d, *J*=9.6 Hz, 1H, NHAc); ^{13}C NMR (75 MHz, $CDCl_3$): δ=14.1 (q, $CO_2CH_2CH_3$), 20.3, 20.4, 20.5, 20.6, 20.7, 20.8, 20.9, 23.1 (8q, 7OAc, NHAc), 474, 47.6 (2d, C-2, C-7), 61.4, 61.9, 62.8 (3t, C-6, C-6′, $CO_2CH_2CH_3$), 67.9, 68.6, 69.2, 69.9, 72.2, 73.0, 73.9 (7d, C-3, C-4, C-5, C-2′, C-3′, C-4′, C-5′), 91.3, 95.8 (2d, C-1, C-1′), 168.5, 169.3, 169.7, 170.2, 170.3, 170.4, 170.5, 170.7, 171.5 (9s, 7OAc, NHAc, CO_2Et); IR (neat): ν=3404, 2962, 1748, 1688, 1518, 1435, 1371, 1334, 1225, 1168, 1138, 1038, 939, 894 cm^{-1}. Anal. Calcd (%) for $C_{32}H_{45}NO_{20}$ (763.70): C, 50.33; H, 5.94; N, 1.83. Found: C, 50.62; H, 6.11; N, 2.02.

*4.6.6. lacto-Amino acid (S-**22g**)*

Colorless oil; R_f=0.34 (hexane/ethyl acetate 1:5); $[\alpha]_D^{20}$ +46.4 (*c* 1.00, $CHCl_3$); ^1H NMR (500 MHz, $CDCl_3$): δ=1.33 (t, *J*=7.1 Hz, $CO_2CH_2CH_3$), 1.96, 2.00, 2.04, 2.05, 2.06, 2.11, 2.15, 2.19 (8s, 3H each, 7OAc, NHAc), 2.64 (ddd, *J*=11.5, 9.3, 1.2 Hz, 1H, 2-H), 3.62 (ddd, *J*=9.8, 4.8, 1.8 Hz, 1H, 5-H), 3.72 (dd, *J*=9.7, 8.9 Hz, 1H, 4-H), 3.85 (dd, *J*=7.5, 6.0 Hz, 1H, 5′-H), 4.03 (dd, *J*=11.0, 7.5 Hz, 1H, $6'_a$-H), 4.14 (dd, *J*=12.0, 4.0 Hz, 1H, 6_a-H), 4.17–4.21 (m, 1H, $6'_b$-H), 4.21 (q, *J*=7.1 Hz, 2H, $CO_2CH_2CH_3$), 4.40 (d, *J*=7.8 Hz, 1H, 1′-H), 4.41 (dd, *J*=12.0, 1.8 Hz, 1H, 6_b-H), 4.93 (dd, *J*=10.4, 3.5 Hz, 1H, 3′-H), 5.01 (dd, *J*=9.2, 1.2 Hz, 1H, 7-H), 5.07 (dd, *J*=10.4, 7.8 Hz, 1H, 2′-H), 5.13 (dd, *J*=11.5, 8.9 Hz, 1H, 3-H), 5.33 (d, *J*=9.3 Hz, 1H, 1-H), 5.35 (d, *J*=3.2 Hz, 1H, 4′-H), 6.32 (d, *J*=9.2 Hz, 1H, NHAc); ^{13}C NMR (75 MHz, $CDCl_3$): δ=14.2 (q, $CO_2CH_2CH_3$), 20.3, 20.4, 20.5, 20.6, 20.7, 20.8, 20.9, 23.2 (8q, 7OAc, NHAc), 47.4, 48.0 (2d, C-2, C-7), 60.9, 64.4, 64.6 (3t, C-6, C-6′, $CO_2CH_2CH_3$), 66.6, 68.9, 69.7, 70.7, 70.8, 70.9, 73.4, 78.4 (7d, C-3, C-4, C-5, C-2′, C-3′, C-4′, C-5′), 91.6, 101.0 (2d, C-1, C-1′), 168.7, 169.0, 170.0, 170.1, 170.2, 170.3, 170.5, 170.8, 170.9 (9s, 7OAc, NHAc, CO_2Et); IR (neat): ν=3404, 2941, 1751, 1687, 1518, 1435, 1371, 1221, 1169, 1137, 1067, 953, 898 cm^{-1}. Anal. Calcd (%) for $C_{32}H_{45}NO_{20}$ (763.70): C, 50.33; H, 5.94; N, 1.83. Found: C, 50.02; H, 6.01; N, 1.86.

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Supplementary data

Complete characterization of all nucleophilic trapping products **16** is provided. Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2008.08.109.

References and notes

1. Books: (a) Giese, B. *Radicals in Organic Synthesis: Formation of Carbon–Carbon Bonds*; Pergamon: Oxford, 1986; (b) Fossey, J.; Lefort, D.; Sorba, J. *Free Radicals in Organic Chemistry*; Wiley: Chichester, UK, 1995; (c) Curran, D. P.; Porter, N. A.; Giese, B. *Stereochemistry of Radical Reactions*; VCH: Weinheim, 1996; (d) Linker, T.; Schmittel, M. *Radikale und Radikalionen in der Organischen Synthese*; Wiley-VCH: Weinheim, 1998; (e) *Radicals in Organic Synthesis*; Renaud, P., Sibi, M. P., Eds.; Wiley-VCH: Weinheim, 2001; (f) Zard, S. Z. *Radical Reactions in Organic Synthesis*; Oxford University Press: New York, NY, 2003; (g) Gansäuer, A. *Radicals in Synthesis, Topics in Current Chemistry*; 2006; Vol. 263, pp 1–190; (h) Gansäuer, A. *Radicals in Synthesis, Topics in Current Chemistry*; 2006; Vol. 264, pp 1–236.
2. Selected recent reviews: (a) Zard, S. Z. *Org. Biomol. Chem.* **2007**, *5*, 205–213; (b) Schiesser, C. H.; Wille, U.; Matsubara, H.; Ryu, I. *Acc. Chem. Res.* **2007**, *40*, 303–313; (c) Crich, D.; Grant, D.; Krishnamurthy, V.; Patel, M. *Acc. Chem. Res.* **2007**, *40*, 453–463; (d) Kim, S.; Kim, S. *Bull. Chem. Soc. Jpn.* **2007**, *80*, 809–822; (e) Miyabe, H.; Takemoto, Y. *Chem.—Eur. J.* **2007**, *13*, 7280–7286; (f) Oshima, K. *Bull. Chem. Soc. Jpn.* **2008**, *81*, 1–24.
3. (a) Beeson, T. D.; Mastracchio, A.; Hong, J.-B.; Ashton, K.; MacMillan, D. W. C. *Science* **2007**, *316*, 582–585; (b) Sibi, M. P.; Hasegawa, M. *J. Am. Chem. Soc.* **2007**, *129*, 4124–4125; (c) Bertelsen, S.; Nielsen, M.; Jørgensen, K. A. *Angew. Chem., Int. Ed.* **2007**, *46*, 7356–7359.
4. (a) Giese, B. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 753–764; (b) Giese, B. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 553–565.
5. (a) Giese, B.; Dupuis, J. A. *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 622–623; (b) Giese, B.; Dupuis, J.; Leising, M.; Nix, M.; Lindner, H. J. *Carbohydr. Res.* **1987**, *171*, 329–341; (c) Giese, B.; Dupuis, J.; Nix, M. *Org. Synth.* **1987**, *65*, 236–242.

6. Kessler, H.; Wittmann, V.; Köck, M.; Kottenhahn, M. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 902–904.
7. Giese, B.; Hoch, M.; Lamberth, C.; Schmidt, R. R. *Tetrahedron Lett.* **1988**, *29*, 1375–1378.
8. Very recent review: Chatgilialoglu, C. *Chem.—Eur. J.* **2008**, *14*, 2310–2320.
9. (a) Gröninger, K. Ph.D. Dissertation, University of Darmstadt, 1987; (b) Giese, B. *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 969–980.
10. (a) Ferrier, R. J. *Adv. Carbohydr. Chem. Biochem.* **1965**, *20*, 67–137; (b) Ferrier, R. J. *Adv. Carbohydr. Chem. Biochem.* **1969**, *24*, 199–266; (c) Somsák, L. *Chem. Rev.* **2001**, *101*, 81–135.
11. (a) Molander, G. A. *Org. React.* **1994**, *46*, 211–367; (b) Molander, G. A. *Chem. Rev.* **1996**, *96*, 307–338; (c) Krief, A.; Laval, A.-M. *Chem. Rev.* **1999**, *99*, 745–777; (d) Molander, G. A. In *Radicals in Organic Synthesis*; Renaud, P., Sibi, M., Eds.; Wiley-VCH: Weinheim, 2001; Vol. 1, pp 153–182; (e) Kagan, H. B. *Tetrahedron* **2003**, *59*, 10351–10372; (f) Edmonds, D. J.; Johnston, D.; Procter, D. J. *Chem. Rev.* **2004**, *104*, 3371–3403; (g) Jung, D. Y.; Kim, Y. H. *Synlett* **2005**, 3019–3032.
12. (a) Iqbal, J.; Bhatia, B.; Nayyar, N. K. *Chem. Rev.* **1994**, *94*, 519–564; (b) Dalko, P. I. *Tetrahedron* **1995**, *51*, 7579–7653; (c) Snider, B. B. *Chem. Rev.* **1996**, *96*, 339–363; (d) Melikyan, G. G. *Org. React.* **1996**, *49*, 427–675; (e) Linker, T. *Adv. Synth. Catal.* **1997**, *339*, 488–492; (f) Nair, V.; Mathew, J.; Prabhakaran, J. *Chem. Soc. Rev.* **1997**, 127–132; (g) Nair, V.; Balagopal, L.; Rajan, R.; Mathew, J. *Acc. Chem. Res.* **2004**, *37*, 21–30; (h) Nair, V.; Deepthi, A. *Chem. Rev.* **2007**, *107*, 1862–1891.
13. (a) Linker, U.; Kersten, B.; Linker, T. *Tetrahedron* **1995**, *51*, 9917–9926; (b) Linker, T.; Linker, U. *Angew. Chem., Int. Ed.* **2000**, *39*, 902–904; (c) Linker, T. *J. Organomet. Chem.* **2002**, *661*, 159–167.
14. Linker, T.; Hartmann, K.; Sommermann, T.; Scheutzow, D.; Ruckdeschel, E. *Angew. Chem., Int. Ed.* **1996**, *35*, 1730–1732.
15. (a) Lemieux, R. U.; Ratcliffe, R. M. *Can. J. Chem.* **1979**, *57*, 1244–1251; (b) Kinzy, W.; Schmidt, R. R. *Liebigs Ann. Chem.* **1985**, 1537–1545; (c) Bertozzi, C. R.; Bednarski, M. D. *Tetrahedron Lett.* **1992**, *33*, 3109–3112; (d) Nair, V.; Panicker, S. B.; Nair, L. G.; George, T. G.; Augustine, A. *Synlett* **2003**, 156–165.
16. Linker, T.; Sommermann, T.; Kahlenberg, F. *J. Am. Chem. Soc.* **1997**, *119*, 9377–9384.
17. (a) Yin, J.; Spindler, J.; Linker, T. *Chem. Commun.* **2007**, 2712–2713; (b) Yin, J.; Sommermann, T.; Linker, T. *Chem.—Eur. J.* **2007**, *13*, 10152–10167.
18. Gyóllai, V.; Schanzenbach, D.; Somsák, L.; Linker, T. *Chem. Commun.* **2002**, 1294–1295.
19. (a) Hartmann, K.; Kim, B. G.; Linker, T. *Synlett* **2004**, 2728–2731; (b) Kim, B. G.; Schilde, U.; Linker, T. *Synthesis* **2005**, 1507–1513.
20. (a) Sommermann, T.; Kim, B. K.; Peters, K.; Peters, E.-M.; Linker, T. *Chem. Commun.* **2004**, 2624–2625; (b) Elamparuthi, E.; Linker, T. *Org. Lett.* **2008**, *10*, 1361–1364.
21. (a) *CRC Handbook of Chemistry and Physics*; Weast, R. C., Ed.; CRC: Boca Raton, FL, 1986; (b) Fokin, A. A.; Peleshanko, S. A.; Gunchenko, P. A.; Gusev, D. V.; Schreiner, P. R. *Eur. J. Org. Chem.* **2000**, 3357–3362.
22. (a) Ferrier, R. J.; Prasad, N. *J. Chem. Soc. C* **1969**, 581–586; (b) Ferrier, R. J.; Zubkov, O. A. *Org. React.* **2003**, *62*, 569–736.
23. Igarashi, K.; Honma, T.; Imagawa, T. *J. Org. Chem.* **1970**, *35*, 610–616.
24. (a) Arai, N.; Narasaka, K. *Bull. Chem. Soc. Jpn.* **1997**, *70*, 2525–2534; (b) Chuang, C.-P.; Wu, Y.-L.; Jiang, M.-C. *Tetrahedron* **1999**, *55*, 11229–11238; (c) Snider, B. B.; Che, Q. *Tetrahedron* **2002**, *58*, 7821–7827.
25. (a) Martin, O. R.; Lai, W. *J. Org. Chem.* **1993**, *58*, 176–185; (b) Kobertz, W. R.; Bertozzi, C. R.; Bednarski, M. D. *J. Org. Chem.* **1996**, *61*, 1894–1897; (c) Spak, S. J.; Martin, O. R. *Tetrahedron* **2000**, *56*, 217–224; Recent review: Yuan, X.; Linhardt, R. J. *Curr. Top. Med. Chem.* **2005**, *5*, 1393–1430.
26. Ono, N. *The Nitro Group in Organic Synthesis*; Wiley-VCH: New York, NY, 2001.
27. (a) Coutrot, P.; Crison, C.; Coutrot, F. *Synlett* **1998**, 393–395; (b) Zhang, J.; Clive, D. L. *J. Org. Chem.* **1999**, *64*, 1754–1757; (c) Review: Dondoni, A.; Marra, A. *Chem. Rev.* **2000**, *100*, 4395–4421.